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Urban Transition

Perspectives on Urban Systems and Environments

Edited by Marita Wallhagen and Mathias Cehlin

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Published in London, United Kingdom

Urban Transition - Perspectives on Urban Systems and Environments
http://dx.doi.org/10.5772/intechopen.94994
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First published in London, United Kingdom, 2023 by IntechOpen
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, 5 Princes Gate Court, London, SW7 2QJ, United Kingdom

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Additional hard and PDF copies can be obtained from orders@intechopen.com

Urban Transition - Perspectives on Urban Systems and Environments
Edited by Marita Wallhagen and Mathias Cehlin
p. cm.
Print ISBN 978-1-83962-412-4
Online ISBN 978-1-83962-413-1
eBook (PDF) ISBN 978-1-83962-414-8

Meet the editors

Dr. Marita Wallhagen is an Associate Professor of Environmental Science at the University of Gävle, Sweden, with a Ph.D. from the Royal Institute of Technology (KTH). She is a visionary architect and researcher with a socio-eco-technological perspective on architecture, urban design, and sustainability. Her research involves design for sustainable buildings and districts, environmental assessment methods, ecosystem services, lifecycle assessment, and decision-making. Currently, she is the co-director of the Urban Transition research program and teaches about environmental assessment tools. Dr. Wallhagen has a passion for greening the urban environment and bringing together theory and practice concerning innovative sustainable designs, architecture, technology, ecology, and living environments. Besides academic work, she is active as an architect and is passionate about developing designs and research for more sustainable architecture.

Dr. Mathias Cehlin is an Associate Professor of Energy Systems at the University of Gävle, Sweden. He is a driven researcher in energy systems, appointed regional manager for the national competence center Resilient Energy Systems where academia, business, and public sectors co-create critical research and practice-based knowledge for the transition to resilient energy systems. He was the co-director for the strategic research area "Urban Sustainability" at the University of Gävle between 2019 and 2022, which aims to contribute to an urban sustainable development that improves people's living environment and health. Dr. Cehlin's current research projects include resilient energy systems, indoor and outdoor air quality, and energy-efficient buildings. He has written multiple successful grants funded by organizations such as the Swedish Knowledge Foundation and the government research council Formas.

Contents

Preface

Urban transitions are important because society today faces several different challenges, such as climate change, increased population, extreme weather events, environmental degradation, and the risk of collapsing ecosystems. To combat these challenges scientists and global leaders have called for a transition towards a more environmental society. Ideally, a society with urban environments and systems that are climate-positive, sustainable, and healthy and make the society function within the planetary boundaries. This is a great challenge. Huge transformations and new ways of thinking regarding the design and co-existence of technical, social, and ecological systems are necessary to turn the present challenge into opportunities. This book explores this challenge and several different topics related to possible, probable, or necessary urban transitions in the urban environment. It assembles a variety of aspects and the latest knowledge linked to urban transitions of the urban environment and the urban socio-eco-technological systems including urban, energy, transport, building, material, and ecosystems. Different systems that are responsible for a large proportion of the use of natural resources and energy, and the production of waste and emissions, also have a large influence on many areas of human life and wellbeing. These systems create value for many people, but often this value comes at a high environmental cost. Their complexity makes it difficult to evaluate and validate their impact on the surroundings. Therefore, it is a challenge to know how to plan, design, and influence these systems in an optimal way. It is important to find solutions for urban transitions, to navigate transitions in suitable ways, and to capture the innovation opportunities that come with them. This book proposes ideas to provoke and develop current research, debate, and new forms of practice. To reflect the broad context that urban transition concerns, the chapter authors discuss some of the many important urban transition aspects to consider when designing, making decisions, and constructing our future urban environments and working with solutions for a sustainable and resilient urban transition in society. The perspectives in the book vary from the importance of urban designing and the outdoor environment to the importance of indoor air quality, highlighting many aspects that are important for creating a good living environment. Because of the complexity of creating such an environment, it is necessary for researchers and professionals from different fields to plan and act strategically.

Many of the book chapters concern topics that researchers at the University of Gävle, Sweden, are studying. The university has a long history of studying the built environment. Today, the university's research is internationally renowned in sustainability science, energy systems, ecology, and urban sustainability. For example, the university has a strategic research area in Urban Sustainability which holds the research program Urban Transition where both Wallhagen and Cehlin are active. There is also an increased number of active Ph.D. students within the research school "Future Proof Cities" and the competence center "Resilient" at the university working with co-creation and urban transition towards a more sustainable society.

Section 1 is on "Urban Design, Transport, Safety, and Envisioning the Future – Influence on Urban Transitions". Chapter 1 by Johan Colding et al. is about "Promoting Partnership between Urban Design and Urban Ecology through Social-Ecological Resilience Building". It highlights the importance of a closer partnership between urban design and urban ecology. The authors show that if social-ecological resilience is used as a framework, it can open new ways of integrating design and ecology in urban planning. Chapter 2, "Sustainable Transport Developments for Dhaka City", by Md Mahabubul Bari, examines the consequences traditional traffic planning can have on mobility in a city like Dhaka. It reminds us about the importance of not getting trapped in only thinking about motor vehicles when considering mobility in a city, especially in a city like Dhaka where a lot of transports are pedestrian transports. Chapter 3, "Inclusive, Safe and Resilient Public Spaces: Gateway to Sustainable Cities?", by Asifa Iqbal, reviews how a city's public spaces are linked and affected by crime and fear of crime. Promoting positive urban transitions also includes creating safe and sustainable cities. Therefore, the built environment should be designed to prevent crime and fear of crime. Chapter 4, "Future Urban Environments in Science Fiction: Initiated Thought Experiments", by Britt Johanne Farstad, examines the important role science fiction literature has on the transformation of our visions and ideas about future cities. Ideas and the impact of science and technology on society, culture, and ethics can be tested and elaborated on in hypothetical thought experiments. This may help us fantasize and envision what future cities should look like and encourage us to explore transformations we today believe are impossible as well as challenge present ideas about the human condition.

Section 2, "Sustainable Energy Systems – Enable Urban Transitions", addresses the important role energy plays in the transformation towards a more resilient and sustainable society. Chapter 5, "Review on District Cooling and Its Application in Energy Systems" by Sana Sayadi et al., highlights benefits and limitations as well as implementations and applications of energy systems. District cooling systems are resource-efficient and can play an important role in meeting future cooling demands due to climate changes and the increase in comfort requirements in buildings. Chapter 6, "Photovoltaic-Thermal Solar Collectors – A Rising Solar Technology for an Urban Sustainable Development", by Diogo O. Cabral, explores the prospective contribution of photovoltaic-thermal (PVT) solar collector technologies in promoting urban sustainability. It underscores the need for rigorous and systematic decarbonization in the energy sector, where PVT technologies should be considered. Chapter 7, "Energy Audit of Two Multifamily Buildings and Economic Evaluation of Possible Improvements", by Alireza Bahrami et al., emphasizes the potential to enhance energy efficiency in our buildings, which is crucial for reaching the EU's carbon-neutrality target by 2050.

Section 3, "Resilient and Environmental Buildings – Central for Urban Transitions", discusses several issues relevant to the urban transitioning of buildings. Buildings use lots of energy and natural resources, contribute to waste, and influence our local environment and well-being, as most of our lives are spent indoors. In Chapter 8, "Viewpoints on Environmental Assessment of Building Certification Method – Miljöbyggnad", Jan Akander et al. discuss several aspects that the Swedish building environmental assessment tool Miljöbyggnad assesses. They also highlight improvements in measuring how environmental a building is, especially when the climate is changing. Climate change consequences are discussed further in Chapter 9, "Climate Change and Extreme Wind Events: Overview and Perspectives for a Resilient Built Environment", by Sofia Pastori and Enrico Sergio Mazzucchelli. The chapter clarifies that the increase in extreme wind events makes it necessary to prepare buildings for more extreme wind events when building resilience.

Section 4, "Sustainable Ventilation – Give Air to Urban Transitions", examines the importance of providing good air quality for human well-being in both new and existing buildings and in open spaces. The World Health Organization (WHO) has proposed that every individual's right to a healthy indoor setting should be considered a fundamental human right. Hence, proper ventilation is central to achieving this goal. Chapter 10, "Building for Sustainable Ventilation and Air Quality", by Mikael Björling, addresses the importance of not only ventilation rates but also efficient air distribution for achieving a healthy and comfortable indoor environment. This is also discussed in Chapter 11, "Some Aspects of HVAC Design in Energy Renovation of Buildings", by Taghi Karimipanah. This chapter discusses the design of efficient air distribution systems for improving the energy efficiency of buildings, but not at the expense of deteriorating indoor comfort and indoor air quality. Finally, Chapter 12, "Post Covid 19: An Innovative System to Supply 100% Treated Fresh Air for Improving City Liveability", by Esam Elsarrag and Mohammad Elsarraj, presents an all-in-one ventilating and air conditioning system for use in both open and enclosed spaces. The authors discuss drivers, challenges, and the technology to provide efficient treated fresh air whilst reducing energy consumption, especially for hot and/or humid climates.

Although the focus of this book is mainly on socio-technical systems, it is important to acknowledge the link between socio-technical systems and ecological systems. If we have an environmental perspective and a lifecycle perspective on the socio-technical systems, the ecological systems are always present, as the geobiosphere is affected by socio-technical activities. Finding ways for them to co-exist in a more beneficial way, for example by using more nature-based solutions, is another important aspect when creating a more just, sustainable, and resilient urban transition.

The work with this book and in our research program on "Urban Transition" at the University of Gävle has made us look for a definition of what constitutes a sustainable environmental and resilient urban transition. At this moment urban transition can be specified as "a goal-driven strategic transition towards a sustainable, attractive, and just built environment and society through comprehensive changes in technical, ecological, and socio-technical systems. It encompasses systems, artifacts, and ecosystems connected to the built environment as well as processes and people. The main goal is to solve environmental and societal challenges by promoting resilient, resource-efficient, and circular systems that improve the human living environment."

We look forward to following the essential urban transition in the built environment and we wish to thank all the authors for their valuable contributions to the book.

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Section 1

Urban Design, Transport, Safety, and Envisioning the Future – Influence on Urban Transitions

Chapter 1

Promoting Partnership between Urban Design and Urban Ecology through Social-Ecological Resilience Building

Johan Colding, Lars Marcus and Stephan Barthel

Abstract

A closer partnership between urban design and urban ecology can yield new knowledge with the predictive advancement of both fields. However, achieving such partnership is not always a straight-forward process due to different epistemological departures. This chapter provides a rudimentary background of the fields of urban design and urban ecology and familiarizes readers with some epistemological characteristics that are useful to consider in all forms of partnership activities between designers and ecologists. Social-ecological resilience offers a useful framework for inquiry of particular relevance for urban transition at a time when global societal challenges of massive biodiversity loss and climate change require urgent attention and where wicked environmental problems require creative urban tinkering. Such a framework could open up for more dynamic research approaches with a greater potential to bridge the gap between design and ecology that has tended to be dominated by relatively static design approaches in the past, ignoring a more non-linear understanding of the interconnectedness of social and ecological systems. The chapter ends by focusing on some important determinants for cooperation and dealing with 'Research Through Design(ing)' as a viable methodology for transition to urban sustainability.

Keywords: ecosystem services, natural disturbance, research through design(ing), urban ecology, urban design, social-ecological resilience

1. Introduction

Cities are prime examples of complex adaptive systems [1] - something early on recognized by Jane Jacobs, who described cities as "organised complexity" [2]. Pickett et al. [3] characterize cities as "ecosystems" in that they are composed of biotic and abiotic, organic and inorganic matter. A city could also be described as an *anthropogeographical* landscape, as the famous Italian architect Vittorio Gregotti once preferred to call it, denoting an environment modified by the actions and presence of human beings. In this paper we view a city as an overlapping zone between culture and nature that corresponds to the definition of an urban social–ecological system [4, 5], consisting of a set of critical natural, socioeconomic, and cultural resources (or, capitals). The flow and use of these resources are regulated by a combination of ecological and social systems, where the social system also includes technical systems [6]. At a micro-scale, individual buildings could be viewed as a microcosm of ecosystems, although they seldom integrate and express ecological elements and relationships in any profound and meaningful way. Hence, the process of designing and shaping the physical features of urban systems needs to be substantially improved in the transition to urban sustainability. Present-day urbanisation is, however, a particularly strong driver behind biosphere change, even to such a degree that it causes phenotypic changes in animal and plant populations [7]. Hence, we carefully need to think about how we design cities to more optimally support ecological determinants. Considering the global massive loss of biodiversity and ecosystem services (BES) [8], it is often argued that urban designers need to think more deeply about how cities should minimize their negative impacts on biodiversity [9]. Unless we do so, and given climate change, humanity faces the risk of crossing thresholds that will potentially trigger non-linear, abrupt environmental change with planetary-scale effects [10].

More crude and simplified forms of land-use classifications have for long made up the basis for decision making in urban planning [11]. The advancement of higher resolution multispectral imagery and an overall increase in scientifically derived knowledge at the local scale of cities [12, 13] have now made it possible to categorize the urban landscape in more detail. New attempts to combine descriptions in landscape ecology and urban morphology into a social-ecological spatial morphology have also opened up for planning and design of cities that bring the two fields together in a joint practice [14]. This provides new opportunity for designing and building cities with greater precision and could lead to a much closer coupling of urban design with urban ecology since it is at the local scales that urban designers tend to operate.

As urban design involves the physical organization of buildings and spaces towards a civic purpose, the authors behind this chapter argue that an important civic purpose is urban resilience building. *Resilience*, or the buffering capacity of complex adaptive systems [15], is the ability of people and human socio-cultural conglomerations to live and adapt to change [16]. The resilience approach emphasizes that social-ecological systems need to be managed and governed for flexibility and emergence rather than for maintaining stability. The authors behind this chapter also argue that social-ecological resilience offers a field of scholarship of particular relevance for urban design at a time when global ecological challenges require urgent attention [17]. Resilience thinking gives priority to more adaptive modes of urban designs that could more effectively respond to and deal with uncertainty and surprise and different types of disturbance [18]. Adopting resilience thinking in urban design is not a new idea. Pickett, Cadenasso, and McGrath [19] have devoted a whole volume to resilience building of urban design. Marcus and Colding [20], and Marcus, Berghauser-Pont, and Barthel [14, 21] have applied resilience thinking in urban spatial morphology, and Wilkinson, Porter, and Colding [17] have linked it to urban planning and design as a lens of inquiry.

1.1 Chapter outline

In this chapter we elaborate on how the science of urban ecology could partner with the profession of urban design, with the aim of enhancing social-ecological resilience. Given climate change, cities need to increase their preparedness to adapt to natural disturbance such as amplified flooding, heat waves, storms and changing biological processes. Achieving greater partnership between ecologists and designers is, however, by no means a straight-forward undertaking. Previous attempts have tended to be dominated by relatively static design approaches, ignoring a more non-linear and complex understanding of the interconnectedness of social and ecological systems [22]. While the urban design field lately has experienced an upswing due to renewed concerns of a diminishing ecological and urban quality, urban environments still display surprisingly few deliberate attempts to integrate ecological functions in urban architecture and design [20, 23–25]. While architects and constructors by tradition have had difficulties in translating ecological concepts in physical building designs [26, 27] this shortcoming is likely also due to a failure of merging urban design with ecology in any meaningful way. Even educational curriculums at many higher education institutions lack a commitment to promote ecological issues [28, 29]. This raises profound questions as to how professionals, academics and practitioners in both fields could overcome the riddles and closing this knowledge gap.

The authors behind this chapter has structured the content herein as follows: We start by providing a short backdrop of some key theoretical epistemological characteristics that are useful to consider in any attempts of bridging urban design and urban ecology. We begin by presenting some historical examples of bringing nature into cities, and proceed with a presentation of some basic characteristics of urban design and urban ecology as well as how the two disciplines could potentially be linked. We continue by proposing resilience thinking as a useful framework for improving urban systems. While there are many ways in which a closer bridging of urban design and urban ecology can come about [30, 31], it is here argued that resilience thinking needs to be more intimately linked with urban design. The chapter ends by elaborating on how *Research Through Design(ing)* [32] offers a viable design methodology for addressing more dynamic, non-linear, and complex interconnections between urban ecology and urban design.

2. Epistemological departures

The integration of natural elements in the design of cities is not a new undertaking. Before the intellectual lineage of such prominent landscape designers and planners as Fredrick Law Olmsted, Ebenezer Howard, Patrick Geddes, and others, European cities of the 16th century were designed with nature elements. For example, Paris began to decorate its boulevards with trees already in the 17th century - a practice that quickly spread so that by the 19th century street trees became the fashion in most European cities. These design attempts served not only aesthetic purposes. In fact, both Frederic Law Olmsted and Ebenezer Howard perceived natural elements in cities to provide functions to humans that we today would refer to as 'ecosystem services.' Olmsted spelled this out almost 150 years ago in his seminal paper *Public parks and the enlargement of towns* (1870) [33]: "Air is disinfected by sunlight and foliage. Foliage also acts mechanically to purify the air by screening it".

Following the urban park movement of the 19th century, Ian McHarg's work *Design with Nature* from 1969 renewed urban comprehensive planning by integrating ecology into city design. The applicability of systematic land-use planning in determining areas of development and areas for conservation, involving the map overlays of different natural features (e.g., hydrology, geology, soils, vegetation, and wildlife), is representative of this approach [34]. While Ian McHarg advanced the inclusion of ecology in the field of landscape architecture, he has been criticized for promoting an unappealing view of urban areas and for promoting a deterministic and anti-humanistic view in planning that disregards social values in the design process.

Among the different types of urbanisms that have emerged since the arrival of New Urbanism in the early 1980s and the charter of the New Urbanism in 1993 by Peter Calthorpe and colleagues, landscape architect Peter Connolly is often credited as having introduced the term 'landscape urbanism' into the design discourse in the early 1990s. It comprises a theory of urban planning in which landscapes replace architecture as the building block of organizing cities. The phrase 'landscape urbanism' first appeared in the mid 1990s, but has taken on many different uses, although most often cited as a postmodernist or post-postmodernist response to the 'failings' of New Urbanism and a shift towards environmental sustainability and ecology as a metaphor [35].

2.1 Urban design

Urban design is a humanist field that has grown over the last 50 years, and particularly so over the last two decades with a rapid growth of the discipline at universities, in academic journals, and as a subject for academic research [36]. While urban design involves an understanding of a wide range of subjects from physical geography, ecology to social science, and an appreciation for disciplines such as economics, political economy and social theory, the concept of 'urban design' is quite fuzzily defined in the literature, and a more precise definition has not yet been broadly accepted. At the birth of the urban design field in the United States at the Harvard Urban Design Conference in 1956, the conference convener, José Luis Sert, defined urban design as "that part of city planning which deals with the physical form of the city" [37] (p. 587). Urban design was in Sert's view a subset of urban planning that he described as "the most creative phase of city planning, in which imagination and the artistic capacities play the important part" [37]. Sert initiated the world's first degree-program in urban design at Harvard where he also brought art into the curriculum.

Urban design can be regarded as "an art or technical practice involving the physical organization of buildings and spaces, towards a civic purpose" [38] (p. 258). It draws on a wide range of scientific theories and artistic approaches, including Gestalt theory, postmodernism, information science and biophilia [38]. In textbooks urban design more generally denotes both the process and end-result, or artefact, of crafting places in cities and towns [35]. Lenzholzer, Duchhart, and Koh [32] (p. 121) distinguish between designing and design, the former signifies "the process of giving form to objects or space on diverse levels of scale", the latter signifies "the results of a design process". Hence, a normative definition of urban design could be the process of shaping places for people [36]. Urban design theory has, however, been criticized on grounds that it lacks a coherent theoretical basis of its own and as a partly pseudo-scientific field based on norms rather than on scientific validity and treating hypothetical suggestions and assertions as facts [38, 39]. It has also been criticised for a lack of scientific rigor that could lead to the stagnation of the design field itself [40].

2.2 Urban ecology

The study of the ecology *in* and *of* cities [3] arose in the early 1970s as a subdiscipline of ecology and has continued to develop into a distinctive science over the last 30 years. Interestingly, however, is the fact that urban systems for long were neglected by ecologists, witnessed in that only a mere 0.4 percent of all published papers in the nine leading ecological journals dealt with cities two decades ago [41]. More specifically, urban ecology represents a natural science field that could be defined as the study of the co-evolution of human-ecological systems [42]. While urban ecology is an amalgamation of several disciplines [43], it is primarily concerned with the description, prediction, and understanding of natural phenomena, based on observational and empirical evidence. Comprising a subset of ecology, it involves the scientific study of the relationship of living organisms and their distribution and abundance in and around cities, and on the biogeochemical budgets of urban areas [3]. Urban ecology grew in the 1990s with the concepts of ecological footprints [44], extended versions of urban metabolism [45], and with research on urban ecosystem services [46], patch dynamic studies and high-resolution land cover classification (see e.g. [47]).

Much knowledge concerning how urbanization changed ecological patterns and processes has been generated by way of quantitative analysis of urbanization gradients [48], which provide a broad generalization of features of the urban landscape. Such studies generalize the urban landscape, but does not quantify its underlying specific features such as e.g. how specific urban forms affect animal dynamics at finer scales of cities [49, 50]. Thanks to the improvement of higher resolution multispectral imagery it is now, however, possible to quantify the effects of individual urban features on biodiversity levels [12]. Urban ecologists are also increasing their efforts to understand how species *behave* at finer levels of the city, i.e., at the cognitive level of urban space [20, 50, 51]. Ecological qualities at this level could be referred to as 'perceptual qualities' [39] and as urban designers also tend to operate at this level, it is precisely at the micro-scale of cities that we see the greatest potential for increased cooperation between urban designers and urban ecologists.

3. Linking urban design and urban ecology

Batty [52] has suggested that the bridge between science and design is contained in the notion of prediction of the future. In this view science could be seen as a process about understanding the present in contrast to design, which is a process about inventing the future. As Batty puts it: "In contrast to science, design is about the future, about future knowledge and its evolution […] The present in no sense is plannable or controllable whereas the future surely is: thus, design is active in contrast to science which is rightly or wrongly regarded as passive" [52] (p. 154).

The distinction between how the world 'is' and 'ought to be' stems from the philosopher David Hume, and has remained a way of distinguishing the prerogative of science from that of design [38]. Hence, following Batty's line of argument, the key mission of urban design is to probe and invent new ways or designs to be further empirically tested in scientific studies. In Batty's terminology the design process is therefore as active as it is cyclic over time and often needs to be fine-tuned and improved over considerable time periods.

As the professional field of urban design is a humanist field that adopts methods that are primarily critical, or speculative, as distinguished from the science of ecology, one might question if it is possible or even desirable to merge the two fields. Some critics, for instance, object against the 'scientization' of urban design and question whether it can be reduced to scientific scrutiny. Architectural theorist Bill Hillier argues that the design process is a coming together of different knowledge forms, essentially generative knowledge about 'how things could be' and more scientific knowledge about 'how things are', where the latter in the design process have the role of, so to speak, correcting potential solutions of a designer and directing them into more appropriate solutions [53]. Such knowledge may be generated from urban design research and embodied in urban design theory [53] (p. 265).

Urban ecology could contribute to urban design theory by adding scientific validity and rigor when adopted in design research. It can also outline key challenges - i.e., climate change, biodiversity loss, ecosystem restoration projects, smart city digitalization etc. - that designers could grapple with and find tentative solutions to in various collaboration projects. Conversely, design with its aim on the future, could revitalize urban ecology by providing new perspectives, novel frames of analysis and new ways of thinking about urban social-ecological systems. Such partnership could create new research opportunities for ecologists [54]. For example, layouts, artefacts, ergonomics, and construction are elements that designers use that could help visualize things for ecologists. An important characteristic of the design process is the use of different types of drawings [55] and pictorial representations that serve the role of connecting expertise and innovation [56]. Drawings and other artwork that are developed by designers can also be used to structure discussions around, and formulate design elements as well as creating a mutual language between ecologists and designers. For ecologists to partner with designers could be especially worthwhile in order to find new solutions to confer social-ecological resilience in urban systems. Hence, working together with designers, ecologists could engage in inventing new concepts and technologies to accomplish this goal.

3.1 Social-ecological resilience as a linking framework

Considering the great challenges that humanity presently is facing, we suggest that research collaboration between ecologists and designers should primarily focus on the enhancement of social-ecological resilience. According to Erixon Aalto, Marcus, and Torsvall [22], attempts of bridging the gap between design and ecology has traditionally been dominated by relatively static design approaches, ignoring more non-linear and complex understanding of the interconnectedness of the social and ecological systems (but see e.g. [19]). Furthermore, they argue that contemporary urban design practices primarily tend to incorporate ecological issues in the prescriptive and preventive aspects of projects, and using ecologists mainly as consultants in various design proposals. Also, the main contribution made by ecologists often concerns the collection and classification of data about existing situations and seldom involves more future-oriented probing.

Central to a more dynamic and non-linear understanding of the interconnectedness of urban ecology and urban design that Aalto and colleagues are calling for, is a shift of focus where humans become resituated from being outside ecosystems to one being integrated within them, or more precisely "as stewards 'navigating' the system from within" [22] (p. 1). In this way, humans become co-creators of nature through the integration and management of ecosystem services in urban design projects and by adopting social-ecological resilience thinking as a guiding design principle [57]. The notion of social-ecological resilience reflects to a great deal the degree to which a complex adaptive system is capable of self-organization and build capacity for learning and adaptation [58]. Part of this capacity lies in the regenerative ability of ecosystems to continue to deliver ecosystem services essential for human livelihoods and well-being in the face of change and/or disturbance. Viewing cities as ecosystems (sensu [3]) means that ecosystem services become a key design- and management objective for the resilience building of functioning cities.

3.2 Conditions for cooperation

Whereas a closer partnership between urban design and urban ecology could yield new knowledge that could advance both fields, it is equally important to ask where such knowledge is best put to practice. For one thing, and adopting a resilience approach, it will be increasingly critical to find solutions to curb the dangerous interactive effects of urbanization, climate, and human health [59]. For example, climate induced natural disturbance such as fires, droughts and floods will have great adverse consequences both for humans and non-human species and could cause great damage to human physical conglomerations and infrastructures. Hence, Palmer et al. [59] propose that the creation of *designed ecosystems* represent one area where designers and ecologists could cooperate. Designed ecosystems involve coming to terms with slightly disturbed ecosystems through human manipulation as well as creating entirely new ecosystems where other alternatives do not exist. The latter should serve a combination of ecological, social, and economic purposes.

Facilitating so called *designed experiments* into the urban mosaic is another approach that could be harnessed, where the aesthetics and functions of urban design could be put to use with both ecological ends and social goals [54]. While both examples represent suitable areas for collaborative intervention, it is also critical to consider how such cooperation best can come about. As stated earlier, previous attempts have been dominated by more consultant-based relationships where various ecological issues have been incorporated in projects, ignoring more deeper forms of cooperation between designers and ecologists. Having a common framework to base cooperation around seems to be highly fruitful. Erixon et al. [22] used resilience thinking as the basis for such cooperation when constructing a vision for a new university area in Stockholm, Sweden. The principles underlying this work are outlined in Barthel et al. [57]. Applying resilience thinking in workshops that gather urban planners and other urban professionals has been found to be highly successful in research [17]. Educating urban designers about biodiversity and ecosystem services could also be an important aspect of improving the conditions for cooperation between urban designers and urban ecologists.

3.3 Research through design(ing) as a bridging methodology

Finding a common working methodology is another important factor to consider. In this context, *Research Through Design(ing)* (RTD) [32] offers an interesting design approach for addressing more dynamic, non-linear, and complex interconnections between urban ecology and urban design due to its alignment with ideas that are central to resilience thinking. The RTD-methodology views the designing activity as a research method in itself, elucidating a dynamic view of urban systems in recognition of that things change and that designing is seen as a process rather than an end product. It involves creating design propositions and/or artefacts and test them in an iterative fashion, and thereafter refine and calibrate the design. The methodology therefore satisfies the juxtaposition of the science- and design process called for by Batty [52], displaying an iterative relationship between science and design (**Figure 1**). Such a probing, where knowledge is gradually accumulated and continuously evaluated and

Figure 1.
The iterative relationship between science and design. Observations and scientific theories are used to make predictions of the future that can be probed and tested on specific problems to generate new design solutions that either could be refined through making new predictions, or generate new knowledge that contributes to theory development. Adapted and modified from Batty [52].

refined is also an important mark of resilience thinking where uncertainty and surprise are considered crucial parts of the management process [15] in recognition of that complex adaptive systems always exhibit a limited degree of predictability [60, 61].

The RTD-methodology shares also many features of *adaptive management*, which is a central tenet in resilience management, entailing the testing of different management policies, treating policies as hypotheses and the whole management process as an experiment from which managers can learn [61, 62]. This also involves *social learning* at the level of society, expressed in dynamic institutions and flexible management policies [63]. The sub-optimal outcomes that often are the result when managing complex adaptive systems are mirrored in the prognostic models of urban design due to that "new design relevant knowledge concerns future states of the environment that cannot be evaluated by empirical methods" [64] (p. 6).

The RTD-methodology is ultimately rooted in constructivism and therefore also entails studies on people's attitudes, beliefs, and experiences, affirming that people actively construct or create their own subjective representations of objective reality. Data gathering this way is often achieved through participatory observation and interviews [32]. The knowledge generated cannot be generalized, but is contextually based, the same way as many ecological relationships are related to a specific place or situation. However, it can be used for further comparative studies and be fine-tuned and calibrated over time.

The RTD-methodology also involves action-oriented research for bringing about change of a situation and to raise awareness among participants – an important determinant in any form of transition to sustainability. Hence, it can facilitate processes that empower a community or group of people that are part of the design process [65] and it therefore share many features of collaborative planning and its concern with the democratic management and organization of urban environments [66].

Erixon Aalto, Marcus, and Torsvall [22] describe how their design of a new university campus involved a transdisciplinary design process, comprising both professionals and researchers from the fields of ecology, urban design and architecture, landscape design, as well as local interest groups, planners, and developers. The group therefore organized and performed a series of workshops and meetings with civil society groups that had a stake in the area where the new campus is now located, making sure that their opinions and experiences were taken into account in the creation of the design vision [57]. Similar to the RTD-methodology, the group nurtured *adaptive co-management* where knowledge and expertise of different actors and stakeholders are put together in order to increase the chances for management success and for avoiding potential conflicts. Adaptive co-management acknowledges the important role that local institutions, norms and social networks play for resilience building of integrated social-ecological systems [67, 68].

The RTD-methodology embraces a pragmatic approach to design, adopting the notion of "what work works" [32](p. 125). With its roots in the U.S. around 1870, and drawing upon such prominent philosophers as William James, John Dewey and others, pragmatism applies a practical approach in solving problems in situations when knowledge is incomplete, emphasising the application of best available knowledge. The RTD-methodology also draws on multiple knowledge paradigms and involves "a series of different studies carried out in parallel or in sequence" [32] (p. 126). Research questions could, for example, comprise natural and cultural aspects as well as design options, often within a specific geographical context. It could also involve specific redesigns of urban spaces against climate change, studies of how new climate responsive designing can change people's mind sets, as well as how to create participatory action amongst citizens to adjust cities to the current challenges of our time. The strength of the pragmatic RTD methodology is that various knowledge paradigms and methods can enhance and complement each other; hence, science and design hold potential to be intertwined and progress in an iterative fashion.

4. Conclusions

Future urban environments will consist of human-influenced ecosystems that to varying degrees need to be managed in order to sustain ecosystem services [59]. This chapter has focused upon conditions that could promote a closer partnership of urban design and urban ecology. Such partnership, we argue, is especially warranted at a time when global ecological challenges of massive biodiversity loss and climate change require urgent attention and where wicked environmental problems require creative urban tinkering that involves adaptive probing, testing, and refining due to the inherent unpredictability of these challenges [69]. While there exist many ways in which a closer bridging of urban design and urban ecology can come about, we have here dealt with the specificities of both disciplines and highlighted some snags in the formation of such partnership. We have also suggested that collaboration to a greater degree should be centred on the sharing of a mutual framework that is geared at enhancing social-ecological resilience in urban systems, particularly so in urban projects that involve designed ecosystems and various designed experiments in the urban mosaic. The methodology referred to as Research Through Design(ing) share some key characteristics with resilience thinking, rendering it particularly useful for enhanced cooperation between urban ecologists and urban designers. For one thing, it holds a real potential to strengthen the scientific rigor of urban design and can as well invigorate urban ecology by providing new perspectives, novel frames of analysis and new ways of thinking about the future of urban systems. Suffice to say, a closer bridging between urban ecology and urban design could positively contribute to a faster and more fair and inclusive transition to urban sustainability.

Acknowledgements

Johan Colding's and Stephan Barthel's work have been funded by the Department of Building Engineering, Energy Systems and Sustainability Science at the University of Gävle, and is part of the Urban Studio program. Johan Colding's work has also been partly funded through a research grant (reference number: 2017-00937) received from the Swedish Research Council for Environment, Agricultural Sciences and

Spatial Planning (FORMAS), and through means provided by the Beijer Institute of Ecological Economics, Stockholm, Sweden. Barthel's work has also been funded by FORMAS/The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning. The project is called Spatial and Experiential Analyses for Urban Social Sustainability (ZEUS) (reference number: 2016-01193). Lars Marcus' work has been funded by the Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Chapter 2

Sustainable Transport Developments for Dhaka City

Md Mahabubul Bari

Abstract

The rapid urbanization process, high vehicular population growth and mobility, inadequate transportation facilities, and inadequate traffic management practices have created a significant worsening of traffic and environmental problems in metropolitan Dhaka. The greater challenge thus for transportation professionals is to develop a sustainable transport system that meets the basic mobility needs of all urban dwellers at desirable safety and avoids the unacceptable level of congestion. This article reviews the strategic transport plan for Dhaka in qualitative and quantitative method and points out that unsustainable transport initiatives were so far undertaken to improve traffic situations in Dhaka. A sustainable city is one designed to address social, environmental, and economic impact through urban planning and city management. It is high time to undertake a long-term approach as well as emergency remedial measures to rectify the damage caused by the injudicious transport initiatives to the economy, environment, poverty reduction initiatives, and sustainable development and recommend the key issues for the sustainable transport plan for Dhaka.

Keywords: Dhaka, policy, sustainable, strategic transport plan, transportation

1. Introduction

In Bangladesh, the growth of the urban population in recent decades has been tremendous and considerably more than the capacity of the urban infrastructure, resulting in low efficiency and severe shortages. The urban hierarchy of Bangladesh has been dominated by metropolitan Dhaka, the largest and most industrialized city with a population of about 13 million [1]. It is one of the most densely populated cities in the world and forms the world's 9th largest agglomeration.

The transport environment in Dhaka was in a chaotic condition characterized by chronic traffic congestion and delays, lack of traffic management, conflict of districts and poor coordination among agencies, and increasing air pollution problems. Like other cities in South Asia, transport in Dhaka is heterogeneous. Fuel-dependent (FDT) and fuel-free transport (FFT) share the roads without lanes or other road disciplines. Busses are unorganized and fail to maintain schedules; other mass transit is absent; traffic management is inadequate, and heavy congestion, delays, and high levels of air and noise pollution are prevalent, as well as a high rate of road mortalities, with about half of victims being pedestrians. Acute traffic problems undermine the ability of the transport sector to sustain economic growth and a reasonable quality of life. In light of this situation, the Dhaka Integrated Transport Study [2] and subsequent discussions with the Government have highlighted the elements to constitute an urban transport strategy for Dhaka, and it has become the basis for the design of the Dhaka Urban Transport Project (DUTP) in 1998. Under the DUTP, Strategic Transport Plan (STP) was prepared by Dhaka Transport Coordination Board in 2005. The objective of the STP was to develop a long-term strategic transport plan for Dhaka city. The STP was revised in 2015. The revised STP (RSTP) is being now implemented by different government agencies like Dhaka Transport Coordination Authority, Roads and Highways Department, Dhaka City Corporation, and RAJUK under the guidance of the Ministry of Communication.

Urban planning that makes sense is essential to a city's healthy expansion. Unplanned growth can result in several issues, causing suffering for city residents and making it difficult, at best, to solve such issues. However, poor urban planning is not much better—and might even be worse—than no urban planning at all. It is crucial to make sure the plan is properly thought out and likely to promote the health and well-being of urban residents when undertaking a task as monumental as creating a detailed area plan for a metropolis with 13 million residents.

Before discussing sustainable transport development for Dhaka city, it might be appropriate to see what is meant by it. Sustainable development is a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met in the present without compromising the ability of future generations to meet their own needs. Sustainable transport (or green transport) refers to any means of transport with low impact on the environment and includes walking and cycling, Transit Oriented Development (TOD), green vehicles, car sharing, and building or protecting urban transport systems that are fuel-efficient, space-saving, and promote healthy lifestyles [3]. It is not sustainable to build new roads and other infrastructure without simultaneously adopting restraining measures to keep travel demand under control. Any extra space provided by new roads simply induces extra demand for additional travel. Thus, effective demand management approaches should be integrated with any additional supply of facilities for personalized travel to ensure sustainable and balanced transport development. It is therefore imperative to conduct a detailed investigation by developing several package approaches combining both supply and demand management-oriented strategies to select the most appropriate package solution for Dhaka city.

In the article, both long-term strategic and recent transport policy directives adopted by the Dhaka Transport Coordination Authority and other concerned authorities in Dhaka city will be reviewed critically for raising awareness among the decision-makers and members of the public in general about the potential consequences of such initiatives from the perspective of sustainable transport development. The issues include:

Strategic Transport Project (RSTP 2015) [4] initiatives like elevated expressway, Eastern Bypass Project, underground metro, restriction on fuel-free transport, relocation of Kamalapur Railway Station, restriction on intercity busses, promotion of parking facilities, and recent transport policy actions that are being implemented by different government agencies like Dhaka Transport Coordination Authority, Dhaka City Corporation, RAJUK, Roads & Highways Department, Dhaka Metropolitan Police, and Bangladesh Railway that include reduction of bus routes, restriction on railway service from Kamalapur, providing absolute priority to car in lane use in major roads, restriction of crossings for fuel-free transport, widening of roads at the expense of footpaths, forcing pedestrians to use overhead crossings, and eviction of hawkers from footpaths.

This study is done by reviewing STP and RSTP as well as the outcome of those studies and trying to identify the impact of those through several data analysis results that are collected from different studies.

The objective of this paper is to identify the current condition of the transport system as well as the initiatives taken by different organizations that are not focused on sustainable transport system. Along with some of the proposed transport initiatives that will make more unplanned city toward future. Section 1 makes the scenario for the study. Section 2 explains the transport initiative, which was taken under STP. Section 3 explains the short-term transport directives. Section 4 explains the transport planning, which is taken under RSTP, and lastly, Section 5 includes the recommendations for a sustainable transport system.

2. Transport initiatives under STP

The key policy directives of STP were to develop a long-term strategic transport plan for Dhaka city to solve the transport problems for Dhaka city's ensuing economic developments. Although some of the policy directives of STP seem to be progressive and positive, the basic approach of the policy seems to be, to the some extent, flawed. The STP policy actions are mainly directed to provide maximum benefit to automobiles, ignoring the basic needs of sustainable transport modes like low-cost public transport, fuel-free transport (FFT), and pedestrians, which represent the majority.

The government decided to revise the STP in 2014–2015 and extend its timeframe to 2035 named Revised Strategic Transport plan (RSTP) and approved it in 2016. The RSTP expanded some STP programs while endorsing the majority of them. Around Dhaka, a two-layer arterial ring roads program was added. There are now only two BRT programs instead of the previous three. From three lines to five lines, the MRT lines program has been greatly expanded. Priorities given to the metro program were of a much higher order than other programs. The main features of RSTP are:

- Integration with the creation of the network plan, the land-use plan, and future urban structure.

- According to the network development strategy based on road hierarchy and amount of demand, the supply of road space is determined.

- RSTP keeps the fundamental ideas of STP.

- Coordinating the growth of public transportation with the motorway network.

- Utilizing current and upcoming road space for the fastest-growing modes of transit, such MRT and BRT.

- Prioritization of the CBD and immediate urban environment improvement.

Fully taking into account possible development areas and their requirement for effective public and private transportation networks.

STP	RSTP
• Construction of three Bus Rapid Transit (BRT Line 1,2 & 3)	• 2 Bus Rapid Transit (BRT) Line Construction [BRT Line 3 & 7]
• Construction of three Mass Rapid Transit (MRT Line 4,5 & 6)	• Mass Rapid Transit (MRT) Line construction [MRT Line 1, 2, 4, 5 & 6]
• Construction of Dhaka Elevated Expressway on PPP basis	• Expressways
• Construction of Gulisthan-Jatrabari Flyover	• Ring Roads
• Improvement of Tongi-Ghorashal Highway	• 8 Radial Roads
• Construction of Mogbazar Flyover	• 21 Transportation Hubs
• Construction of Dhaka Circular Road	• Improvement of Circular Waterway around Dhaka
• Some major highway projects	• Improvement of Traffic Management

Table 1.
Comparison of prime project between STP (2005) and RSTP (2015) [4, 5].

By 2035, there will be about 38 million people living in greater Dhaka, according to STP and RSTP. A commuter demand of 61 million to 65 million people per day will result from this. Of these figures, 45% might be various forms of nonmotorized and pedestrian transportation. Still, 35 million people will need to travel using different motorized vehicles. Main recommendation from RSTP are: Five MRT, Two BRT, Three Ring roads (Inner, Middle and Outer ring), Eight Radial Road, Six Expressways, and Twenty-one Transportation hubs. A comparison of prime project between STP and RSTP is shown in **Table 1**.

Implementation strategy of RSTP is in three phases-

- Short term (–2020)
  - MRT Line-6 and BRT Line-3 to be opened
  - Implementation of Traffic Management and Traffic Safety
  - Arterial road development at Mirpur and eastern Fringe Area to support urban development
  - Restructuring of bus networks, BRF (bus route francization), & replacement of bus terminals
- Medium term (–2025)
  - Development of new MRT lines in the CBD
  - Implementing TDM strategies Development of ring roads and arterial roads outside the DMA
- Long term (–2035)
  - East–West MRT line construction

- Construction of new MRT lines to connect regional centers and the CBD
- Reconstruction of interurban roads.

In the following sections, some of the recent transport policy initiatives undertaken by the government in the light of the STP directives have been analyzed to explore the potential consequences of these policy initiatives.

2.1 Basic concept of multimodal transport development and STP approach

2.1.1 Conceptual fallacy

The concept adopted by STP for transport development concentrates mainly on the movement of vehicles on a road network. However, in order to maximize mobility and accessibility under a multimodal context, one should set one's policy directives for the maximization of door-to-door movements of people and goods rather than of the movement of vehicles in a road network. In order to assess mobility of passengers in a mixed-mode urban environment like that of Dhaka city, it is imperative to evaluate transport alternatives with respect to door-to-door trips, not travel times within road links or vehicle-km. Link travel times or vehicle-km represent only a portion of a trip, which constitutes link travel times, waiting times, walking times, modal transfer penalties, and so on.

2.1.2 Sustainable transport development and STP initiatives

Considering the high demand of travel, environmental concern, and to balance the supply and demand sides in transport system, there is no alternative of sustainable transport system. Sustainable transport and congestion remain important topics of discussion in transportation research. Academic studies suggest that sustainable transport solutions, such as active modes of transportation, transit-oriented development, and intelligent transport systems, can help reduce congestion and improve environmental sustainability [6–8].

Considering the definition of sustainable transport development as stated earlier, it can be questioned if the ongoing STP initiatives pay due attention to sustainable transport development, due to the following reasons:

As regarding the STP decision-making process, it is obvious that in the top-down planning approach, the team was constituted involving a section of the urban privileged without wider participation of major stakeholders and socially deprived sections of the city. Currently, no effective public participation process is working in the planning and decision-making of Dhaka city, let alone transport planning. Public participation here is at the level of *Passive Participation*, that is, merely by informing people about different decisions made by the city authority without any consultation with the stakeholders or general people. Top-down planning approach is active in this total process. As a result, local problems and necessities are overlooked in most of the planning decisions taken here. Local interests come to direct conflict with the interests of the policy makers in most of the cases. Different urban local government institutes (e.g., Ward Commissioner's office) are also not sufficiently strengthened to facilitate the process of public participation. The poor are the worst victim of this process. This total planning scenario places the poor peoples in the most marginalized positions where the urban transport and other related issues are mostly handled by different ad-hoc top-down approaches.

Lessons can be taken from the experiences of different cities of Brazil prior to participatory budgeting [9], when decisions regarding urban developments were the exclusive right only for the elite and the powerful. As is always the case in such scenarios, the tendency is to allocate resources for car-friendly (pro-rich) and capital-intensive projects, as is also evident in the STP directives. On the other hand, participatory budgeting establishes a process in which the effects of people's involvement are directly seen in either policy change or spending priorities. It is not just a consultation exercise, but an embodiment of direct, deliberative democracy. In spite of widespread poverty, high levels of inflation, and widespread corruption, Porto Alegre was the first city in the world to implement participatory budgeting as an element of public policy. The "classic" approach that was created in Brazil is what led to the development of participatory budgeting in the UK and other countries across the world [10].

The approach of the STP might benefit the rich more by committing resources disproportionately in favor of either capital-intensive or auto-friendly options, which is not consistent with sustainable transport development and social equity for the present or future generation.

The STP presented a set of recommendations that allocate 63% of the resources for 8% of the total passengers, that is, metro passengers and 30% of the funds for the development of car-friendly projects, who represent only 5% of the city's population (see **Table 2**). Yet this focus on highly capital-intensive and auto-friendly projects (pro-rich) actually ignores the findings of their own study, which identifies only a bus rapid transit with some moderate improvement of road infrastructures represents the most optimum solution. No similar concern was seen toward ensuring a pro-poor transport system like pedestrian facilities, balanced development for FFT, or development of bus transport system, when they allocated tiny amounts, that is, 0.24%, 0.24%, and 0.41%, respectively, of the proposed investment for them. It is therefore evident that STP policy directives are not compatible with sustainable transport development in Dhaka.

The adopted recommendations of STP disregard their own evidence and standard procedures as outlined in the technical appraisal of the report and use an arbitrary approach to select highly controversial and environmentally disastrous policy options with an expenditure of 4.2 billion US dollars, which requires 237% more capital investment than that required by what they themselves ranked as the optimal option. This represents a significant waste of resources without any valid technical

Mode	Peak Hour Passenger	Passenger per Day	Modal Share	Allocation of resources (Million $)	% Allocation of resources
BRT	238,500	2,733,472	4%	266	6.27%
Bus	548,038	6,281,116	9%	17	0.41%
Metro	501,000	5,742,009	8%	2655	62.66%
Auto	1,888,424	21,643,410	31%	1279	30.18%
Pedestrian	855,067	9,800,006	14%	10	0.24%
FFT	2,076,590	23,799,999	34%	10	0.24%
Total trips	6,107,618	70,000,000	100%	4238	100.00%

Table 2.
Modal share and allocation of resources for passengers by mode for the year 2024 (after STP 2005) [5].

and economic reasons and is in no way compatible with the objectives of sustainable transport development.

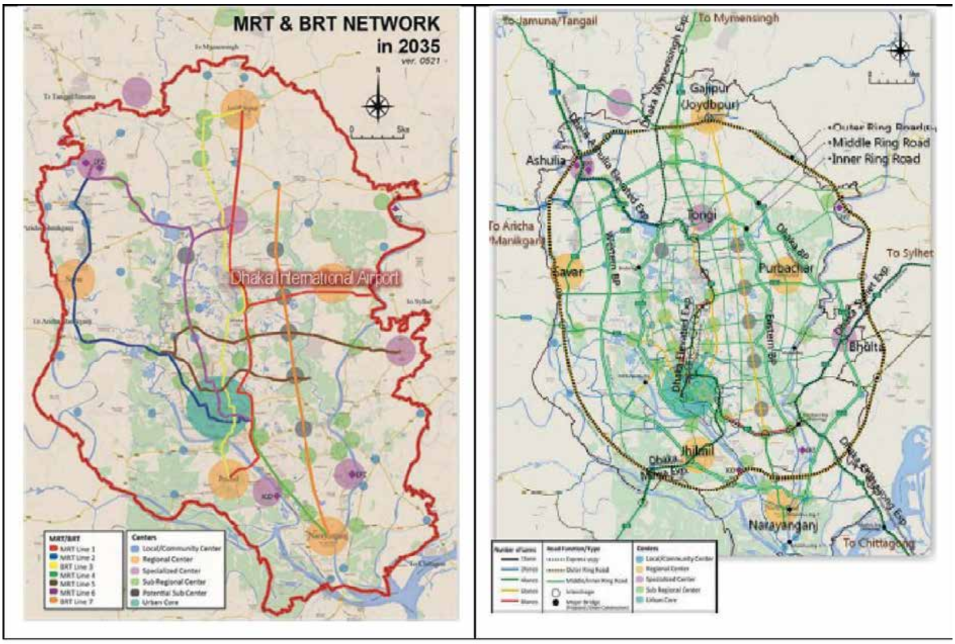
The STP planning process ignores the contribution of eco-friendly and sustainable transport modes like pedestrians, fuel-free transport, and all short trips, which constitutes the vast majority of trips (more than 76%) [11]. The term "multimodal" in the STP directives refers only to fuel-dependent transport, ignoring the contribution of pedestrians and fuel-free transport (48% of all trips) (STP 2005) [5] and all short trips (76% of all trips). Moreover, STP advocates the banning of eco-friendly and space- and energy-efficient transport modes, that is, fuel-free transport, from main roads, as well as termination of railway and inter-city bus services within Dhaka in order to facilitate movement of automobiles. These policy directives go against the very foundation of the sustainable transport development, which seeks to promote eco-friendly and space- and energy-efficient modes like FFT, busses, and trains.

Under a multimodal transport study like STP, as expected, the higher the relative investment in roads and autos, the greater will be wastage of fuel, damage to environment, and hence the overall disbenefits, as demonstrated in both the subjective and objective evaluations of the alternatives of the STP study [5]. More importantly, the STP study clearly demonstrates that there is no transport benefit from the Eastern Bypass Project (STP 2005) [5], a project designed to divert traffic by constructing a road cum embankment on the eastern side of Dhaka city, which has the potential for significant environmental and ecological damage. It also exposes the potential disastrous transport and environmental consequences of the elevated expressway project. Despite these facts, the STP recommended the inclusion of these auto-friendly projects with an increase of 64% in investment in roads, thereby defying the conclusive evidence of the negative consequences of such projects in the STP study [5]. This is in no way consistent with the objectives of sustainable transport development.

The STP study selected a series of eleven (original ten and a modified option) alternative transport strategies on the basis of initial assessment of technical information from a travel demand model as demonstrated in **Table 3**.

Transport Strategy	Level of Road Investment	Level of BRT Investment	Level of Metro Investment
Base Case	ROADS	NO BRT	NO METRO
Strategy 1a	ROADS+	ALL BRT	NO METRO
Strategy 1b	ROADS+	BRT	METRO
Strategy 1c	ROADS+	NO BRT	ALL METRO
Strategy 2a	ROADS++	ALL BRT	NO METRO
Strategy 2b	ROADS++	BRT	METRO
Strategy 2c	ROADS++	NO BRT	ALL METRO
Strategy 3a	ROADS+++	ALL BRT	NO METRO
Strategy 3b	ROADS+++	BRT	METRO
Strategy 3c	ROADS+++	NO BRT	ALL METRO
Strategy 3d	ROADS+++	NO BRT	NO METRO

Table 3
Alternative transportation strategies of STP (STP 2005) [5].



A B

Figure 1.
Proposed transport network in RAJUK area (source: RSTP, 2015) [4]. (a) Proposed MRT/BRT network for 2035. (b) Proposed road network in Rajuk area.

The study appears to be more or less successful in finding the preferred mass transit option for long trips, namely, Strategy 1a: Roads+, ALL BRT, and NO Metro, despite the STP model having a number of flaws. Strategy 1a represents a combination of moderate investment in roads and an intensive bus rapid transit (BRT) and mass rapid transit (MRT) system as the means for mass transit as shown in **Figure 1**.

The option requires only a fraction (42%) of the total amount of USD 4.2 billion required by the alternative preferred, that is, Modified 2b Strategy in the STP. The Modified 2b Strategy represents a blend of mass rapid transit system of BRT and underground metro, complemented by 56 highway projects of varying widths, including an elevated expressway system of approximately 29 km length and two bypasses, that is, a midway venture between strategy 2b and 3b. It may be mentioned here that the Strategy 1a also represents the best option considering economics, safety, social development, affordability, and sustainability. The surplus resources could be better utilized for the development of a balanced multimodal transport system. To proceed with the planning, design, development, and implementation of the policy directives of STP, it is likely to involve the significant waste of scarce resources and damage to the cause of sustainable transport development.

In this connection, it might be appropriate to take lessons from the dismal failure of Dhaka Urban Transport Project (DUTP) [12, 13]. The strategy used in the DUTP was comparable to the STP's suggested course of action. The project's key features include the building of several flyovers, the prohibition of fuel-free vehicles from main highways, the need that pedestrians use elevated crossings, the widening of roadways at the expense of sidewalks, and so on. It should be noted that the project's overall travel-time drawbacks outweighed its minimal transit time gains by at least a factor of twenty.

The project's main conclusion is that there is no justification for wasting public funds on development projects like DUTP that harm the economy (well over Tk 7.78 billion per year), reduce mobility of people and goods, divide neighborhoods, sever service facilities, inflict environmental degradation, destroy the fundamental framework of sustainable development, deny vulnerable segments of society their fundamental rights to accessibility and inclusion, and all of these things [13].

2.1.3 Integrated multimodal approach

Both the STP approach and the existing transport planning approach tend to consider only motorized vehicles as the sole determining criteria in recommending steps to be taken for transport development in the city, completely disregarding other transport modes. Thus "passengers" as defined in this approach includes only those traveling by car, bus and underground metro. Rickshaw passengers, cyclists, and pedestrians are excluded from the data collection, analysis and transport model building process. Thus, those who travel with the least impact on the environment, use the least space, and cause little or no economic harm to the country, are considered unworthy of consideration in the overall traffic system. The Urban Transport Model used in STP disregarded all Fuel-Free Vehicle (FFV) and pedestrian movements, and all short trips considering them not relevant for a strategic transport plan, yet FFV and pedestrian movements represent about 50% of the total trips [4] and short trips constitute 76% of the trips in Dhaka City [11]. Therefore, the model or the planning process that disregards the majority of trips cannot be a valid one.

There is in fact no reason to believe that the options selected in STP represent an optimum solution. Recognized transport development organizations, such as the Department for Transport, UK which adopts much broader base approach no longer consider such approaches as valid practice under multimodal transport appraisal [14].

2.1.4 Integrated demand and supply management approach

It may be mentioned that the STP approach assumed an unconstrained increase of travel demand and considered only the supply side of the transport system, with an inherent bias toward auto-only development. Nowhere in the world has such car-centric transport policy been successful at easing traffic jams, reducing pollution, or increasing people's mobility. The main beneficiaries of such a policy would be the richer section of the society.

One of the major key weaknesses of STP is its attempt to match demand for transport by constant supply of new infrastructure and road building under the assumption of unconstrained demand. Aggravating the problem is the failure to appreciate the fact that FFT acts as a deterrent on growth of future traffic demand.

2.1.5 Balanced development of local and regional transport

In order to develop a well-integrated multimodal transport system, it is imperative to strike a balance between the often-conflicting needs of local and nonlocal transport, where local transport involves both short and "within neighborhood" trips *and* access to longer distance transport facilities. In general, nonlocal transport, which represents long distance trips, is provided by motorized vehicle modes. On the other hand, local transport modes are predominantly pedestrian, cyclist, and cycle rickshaw. Although there is a tendency among decision makers, who generally represent the elite, a section of bureaucrats, and powerful section of the society, to replace FFT by fuel-dependent modes (particularly cars and motorcycles).

Equitable transport planning needs to ensure that the needs of both local and nonlocal transport are properly catered for and are well-balanced. However, in practice, urban transport planning is typically carried out through the use of transport master plans like STP, which formulate strategic long-term transport plans for a wide metropolitan area. Such master plans, by their very nature, inevitably put more emphasis on providing infrastructure for cross-city transport than on designing local transport measures. In situations of scarce resources, this can lead to a serious imbalance in planning priorities, with local transport frequently being "ignored," as is the case with STP.

2.1.6 Road space vs. Total number of vehicles

According to specialists on the subject, the STP and current planning methodology appear to view Dhaka city's transportation issues from a fairly limited viewpoint that does not take into account the overall number of cars. In a megacity like Dhaka, it is impossible to fix the transportation issues by building new roads and other facilities without also enacting restraints to keep travel demand in check. The concept, for instance, that any modern city needs 25% of space for roads is outdated and without any scientific basis. For example, Los Angles, which has 30% space for roads, is the most congested city of America. On the other hand, many cities in Europe, which have comparatively far lower proportions of road space, solve congestion problems by an integrated demand and supply management approach.

Any additional space created by new roads only increases demand for travel. In order to ensure a sustainable and balanced development of the transportation system, effective demand management strategies such as parking control, giving priority to fuel-free transportation, and controlling the growth of cars should be integrated with any additional supply of facilities for individualized travel. Instead of focusing solely on maximizing the movements of vehicles within the road network, the entire problem of congestion management should be examined from the perspectives of accessibility and door-to-door movements of people and products.

However, there is no denying the significance of figuring out the ideal amount of highways for Dhaka city. The STP research report states that the development of the ROAD+ option, which consists of 42 fundamental road improvement projects (29 new roads +13 currently opened for traffic or under construction), is the most optimal and well-balanced investment for the road network in Dhaka city. However, it is regrettable that the STP advisory group went well beyond the required level of investment in roads and suggested a solution that would not only need 231% more resources but also increase congestion and pollution, according to the study's conclusions [5].

Additionally, the efficient use of urban space should not be seen from the standpoint of creating ever-larger roads for cars; rather, it should be considered from the need to facilitate an ideal number of trips, which includes reducing the need for travel by making sure that most facilities are located close to homes. The selected growth pole land use scenario of STP, which necessitates a higher number of long-distance trips, increases the need for travel and favors substantially higher road links and is not consistent with sustainable and "Smart Growth", which favors the integration of mixed land uses in communities as a critical component to reduce congestion and achieve better living environments.

2.2 Construction of series of elevated expressways

It would appear that the decision makers including the top government officials are sometimes inclined to capital infrastructure development project despite the fact that they could have detrimental consequences like increase in congestion, pollution, expense, and significant reduction of accessibility for pedestrians and other sustainable modes of transport. The government just approved a project to construct a system of elevated expressways and flyovers of about 31 km. length. This system will cost roughly US $ 2 billion, or Tk 14,000 crore, to build.

Elevated expressways take traffic off of other roadways and produce their own traffic. They only benefit a tiny fraction of people who drive cars; frequently only move congestion from one location in the network to another; increase noise, pollution, congestion, and fuel consumption; and make walking and other sustainable means of transportation less accessible. As the former Mayor of Bogotá, Enrique Penalosa, rightly remarked, "There are two ways to destroy a city. One is through nuclear bombing, and the other is with elevated roads."

In its model result findings, the STP study itself demonstrated the potentially disastrous consequences of elevated expressways. According to the STP study report, with the inclusion of the elevated expressway system, the overall transport system would suffer major deterioration in terms of increase in congestion and significant deterioration of the city's environment. It is therefore evident that there was no justification for the huge investment for the potentially regressive and environmentally disastrous elevated expressway projects.

Evidence 8 also suggests that existing flyovers have actually caused an increase in traffic congestion on the roads below the flyovers. Many cities in the world have constructed multi-level elevated expressways but still could not reduce their congestion level. As a result, they stated to demolish them. Notable among them are Seoul in South Korea [15], San Francisco in the USA [16], and Tokyo in Japan.

2.3 Implementation of eastern bypass project

The Government of Bangladesh has decided to implement the Dhaka Integrated Flood Control Embankment-cum-Eastern Bypass Road Multipurpose Project with its own fund as it failed to find any international funding to finance the Tk 2750 crore (USD 400 million) megaproject. The main objectives of the project are to protect the people in the 124 square kilometers eastern part of Dhaka city from flooding and to reduce traffic congestion in Dhaka. The project is expected to begin under the current fiscal year 2010 and to be completed by 2016.

The Eastern Bypass, as experts and officials of the World Bank believe, will be another concrete jungle in the eastern side of the capital with a potential for huge negative environmental and ecological impacts. Such a project could induce siltation and in turn aggravate water logging and flooding problems, as experienced from similar misguided initiatives in many floods control projects in the Khulna-Jessore region (Bil Dakatia area) of the country. Environmentalists and experts worry that the "new city extension" on the eastern edge would be an environmental nightmare, resulting in permanent water logging and other hazards, similar to the western flood protection embankment, because no effort has been made to preserve the natural canals and water retention ponds before the project begins.

The model findings of the STP study indicate that the project has had no appreciable effects on the city's general traffic situation in terms of reducing congestion. It demonstrates that there is little to no basis for this massive investment project and that there will be no real benefits to the economy or transportation from the construction of the Eastern Bypass. This is because the majority of journeys to Dhaka city are return trips [5]. A level of investment this high cannot be justified by the meager number of through trips. Despite this, the STP team unilaterally chose to include the Eastern Bypass as one of the core projects, despite the fact that it might have far-reaching detrimental environmental and ecological effects and has no ability to help the traffic problem in Dhaka city.

2.4 Promotion of more parking areas

There seem to be misconceptions that congestion can be reduced by providing sufficient parking facilities, as demonstrated in their parking policy and a number of recent initiatives. Free and inexpensive automobile parking spaces actually increase demand for car ownership and use, which in turn causes traffic congestion and pollution to worsen. Megacities all over the world have implemented a variety of parking restriction measures to lessen negative effects on the transportation system, including moving parking facilities outside the city center with park and ride facilities, completely banning the construction of new parking lots, and pricing parking to account for the opportunity costs of space use. Therefore, the idea of adding more parking places is counterproductive and a recipe for more traffic.

Cars are private property, whereas streets are public spaces. Car owners should be charged for the space that their parked cars take up, regardless of where that parking happens (with the obvious exception of the car owner's private property), as they are one of the population groups least in need of a subsidy. There should be no subsidies for parking at any place because land is so expensive and in such high demand in Dhaka. Subsidies and space ought to be given to the majority rather than to the wealthy few, especially those who drive expensive cars, and should only be given to those who truly need them.

The Dhaka Transport Coordination Authority's current parking policy has to be updated to set the maximum number of parking spots permitted rather than

Figure 2.
Chaotic state of on-street free parking facilities in Dhaka (source: The daily sun, Dec 20, 2017) [17].

the minimum necessary. As a result, there would be no need to fine or tax property owners for not providing enough parking places, and it would be prevented from wasting a lot of money and land trying to satisfy the insatiable need for parking. It is necessary to change the Bangladesh Building Code to remove the requirements for required parking in commercial and office buildings. Many cities throughout the world, including San Francisco (in the US) and several cities in Europe, establish maximum rather than minimum numbers of spaces to be set aside for parking. On no account should property owners be forced to provide more parking than they wish, or be penalized for failing to provide "enough" spaces. This is because there are many alternative economical and environmentally friendly uses of the precious space of a city rather than allocating them mainly for car parking (**Figure 2**).

2.5 Construction of underground metro

Although the Metro option does not represent value for money, as it requires 63% of the total investment while serving only 8% of trips, the STP team opted for it without any tangible technical or economic benefits. Along the same lines, efforts are being made to construct an underground metro on a commercial basis. Building a mass transit system as a for-profit business operating on a profit-or-loss basis might not be appropriate. Despite the baseless claims of the investor, who claimed to create an underground metro system for a price that was far lower than a realistic estimate, a profitable public transit system would likely be expensive and out of the grasp of the average person. Social equality and integration would suffer if a business was run for profit. The right to accessibility and mobility would be denied to the most vulnerable members of society by such a transportation system. If a mass transit system is operated for profit, its basic purpose—to give the general public access to an affordable public transportation system—will be defeated. This is because it is very difficult to run an underground metro system within affordable price to common people without providing sufficient amount of subsidy by the government.

Before moving forward with the planning of the underground metro, it is also necessary to address serious issues with feasibility, such as cost (constructing an underground metro cost about 100 times as much per kilometer as building a bus rapid transit system), the need for abundant and guaranteed electricity, and difficulties with digging deep enough in a city that is prone to flooding.

Given the enormous expense of an underground system, a full cost–benefit analysis should be carried out to investigate other, significantly less expensive and difficult public transportation options, such as trams, guided busses, and Bus Rapid Transit (BRT). The STP team has failed to recognize some major disadvantages of an underground Metro system. Before embarking on such a huge investment with comparatively little anticipated gain, policy makers should consider the following key facts in relation to an underground metro:

- Without a proper integrated demand-and-supply management approach, it is unlikely that only an underground metro will solve the transport problems of Dhaka city.

- According to travel demand analysis of the STP, there is no need of a metro system within the foreseeable future. The STP project travel demand model shows that even with a daily passenger demand exceeding 6 million passengers on a Dhaka BRT Phase 2 network in 2024, the peak volumes on particular corridors will not exceed 25,000 passengers per hour per direction, comfortably within the range of passenger capacities of BRT.

- Metros have extraordinarily high operating expenses, necessitating the use of pricey electric rail vehicles. It will be extremely difficult to secure a consistent and ample supply of electricity for metro systems in Dhaka city. Globally, the majority of metro systems are operating at significant losses.

- Worldwide experience is that, except in a few cases, the fare of the metro ride is subsidized, often heavily. The experience demonstrates that all of the Build-Operate-Transfer (BOT) projects from the late 1990s are experiencing financial difficulties and are not in any position to become profitable.

- In the Sao Paulo Metro, the City Government provides a $0.20 (25%) per-trip subsidy (total trips are 2.1 million per day). One of the more notable recent Metro and LRT disasters has occurred in Kuala Lumpur, Malaysia. There was a large fare subsidy in the system. As a result, the system experienced a financial catastrophe and was nationalized in late 2001. The system ran up debts of more than US$1.4 billion after just three years of operation, resulting in the largest corporate bankruptcy in Malaysian history. The 20 km Metro in Singapore, which cost US$2.9 billion to build, lost US$1.1 million each month in operations in 2004.

- The STP suggested that the underground metro for Dhaka city have a minimum charge of Tk. 10.0 for a journey of 1 km. distance, which will be affordable for only a very tiny fraction of passengers if it is built and operated. It will be necessary for the fare to be at least 50% subsidized in order to make it affordable for people with middle-class incomes. The STP forecasts that the metro will carry roughly 57,42,000 passenger journeys per day with an average trip length of 5 kilometers. The daily subsidy will therefore be Tk. 143.55 million, and the annual subsidy will be Tk. 5240 crores.

- Metro line building is frequently excruciatingly slow. For almost 8 years, work was being done on Singapore's 20 km Metro. The 21 km long Blue Line Subway in Bangkok took roughly 7 years to build.

- Any public transit system must also have the flexibility to grow and adapt to changing circumstances. Dhaka is expanding quickly, and the local environment is changing quickly as well. However, expanding the metro system is an extremely difficult task.

- The cost of building a metro system per kilometer is around 100 times more than that of a Bus Rapid Transit (BRT) system; hence, it is likely that the metro system will only cover a relatively small area of the city and be of little utility if private auto customers are not directed to the metro service.

2.6 Relocation of central Railway Station from Kamalapur to Gazipur

The suggestions for relocation of the existing railway station and container depot relocation of existing railway alignment and termination of rail line and all rail services at an appropriate northern point and relying upon intra-urban modes to distribute and collect passengers and goods throughout the city, which are among the recommended options of STP, are fundamentally flawed and counterproductive.

Discontinuing a vital and efficient transport mode does not mean disappearance of travel demand. If there remains a substantial demand for intercity travel at the heart of the city, it is pointless to make journeys fragmented for such trips, thereby significantly increasing travel time, discomfort, and modal transfer penalties. Some people may think that sixteen railway crossings are likely to slow road traffic and contribute to congestion if trains are allowed to run through the center of the city. However, they ignore the fact that the termination of rail service does not mean disappearance of travel needs to the center of the city for long-distance travelers. Since the demand for travel toward the city center will likely continue for most of the long-distance travelers, they will be forced to travel into the city center using a relatively larger number of smaller vehicles or taxi services, thereby contributing to more congestion and delays.

Dhaka Railway Station was shifted from Fulbaria to Kamalapur with a plea to reduce congestion. Instead, it proved to be a contributor of congestion rather than relieving it. In this connection, one should look into the examples of other successful megacities of the world. It is rare that a balanced multimodal transport system is developed in any city by relegating railway outside of its core area. The world's busiest train station, Tokyo, was erected in 1872, and no one has ever considered moving it. It is where the famed bullet trains, as well as a variety of other long-distance and commuter trains, arrive and depart virtually daily.

It might not be economically feasible to run all trains in the city either overhead or underground while traveling within the city center. However, one should bear in mind that public transport such as railways should be assigned higher priority in comparison to auto travel or highways, and rail crossing waiting time can be optimally reduced by good signaling.

Instead of shifting rail stations from the center of the city, more rail stations need to be established to provide adequate inter-urban and long distance services. The railway stations within the city center must be easy to access and have entrance-level platforms, provisions for busses to pick up and leave passengers, space for taxis to wait in line to pick up passengers, and other facilities.

2.7 Proposal for segregation of Dhaka into different functional areas

The ongoing initiative for demarcation of Dhaka into different functional units is a matter of serious concern as regards development of a balanced transport system. Creation of more single use functional areas for Dhaka is a recipe for more transport demand and hence increases in congestion. A city as densely populated as Dhaka should consider the advantages of a mixed land use scenario similar to that of "Smart Growth". Smart growth[1] involves mixed land uses, an emphasis on access by proximity rather than bylong-distance travel, and therefore encourages the pollution-free modes of walking, biking, and cycle rickshaws. With mixed land use and high density,

[1] According to Wikipedia (http://en.wikipedia.org/wiki/Smart_growth), the free encyclopedia "Smart growth is an urban planning and transportation theory that concentrates growth in the center of a city to avoid urban sprawl; and advocates compact, transit-oriented, walkable, bicycle-friendly land use, including neighborhood schools, complete streets, and mixed-use development with a range of housing choices"

it is possible to achieve the sizable and diverse population and commercial base needed to support public transit.

Additionally, under the Central Spine Scenario, the choice of mixed land uses will be more in accordance with the Land Use Plan of the Dhaka Metropolitan Development Plan (DMDP), which chose a concentrated and mixed-use land development comparable to that of "Smart Growth." In addition, such an approach would ensure provision for adequate open space and natural water retention areas and waterways as an integral part of all urban developments. The development of sustainable and "Smart" growth of a city demands adherence to a number of key features, such as: (a) development of mixed land use, (b) provision for a variety of transport choices, (c) reduction of the need to travel, and (d) creation of walkable environments.

By moving marketplaces, shops, places of employment, and schools into designated zones, Dhaka may be divided along functional lines, but doing so would just raise demand for long-distance travel and lead to further congestion.

2.8 Restriction on movement of intercity busses into the City

The government has decided to prevent the Dhaka bound inter-districts busses from entering the metropolitan area, which is also one of many policy directives of STP [4]. It is crucial to guarantee uninterrupted and smooth public transportation routes in order to increase transportation efficiency between and between various modes while acknowledging their complementary roles within a transportation system. Activities for the creation of high-quality logistics that account for all sources of transportation are included. It is important to handle intramodality in passengers and freight by implementing activities like terminal integration across all modes of transportation and offering seamless and competitive solutions.

Since the origins and destinations of the majority of travels for both intercity and local trips lie within the central area of the city, there is no justification for shifting intercity bus terminals or the railway station from the center of the city. The notion that reducing intercity travel by arbitrarily doing it at the edge of the city will result in fewer journeys is deceptive and useless. People will travel to the city's center if there is a demand for it, possibly in less efficient, smaller vehicles that will cause additional traffic and pollution.

The development of a well-integrated public transportation system was set back by the construction of four independent intercity bus terminals without any means of interconnecting them. Smaller cars cause more traffic and pollution. In addition to severing innumerable journeys and encouraging the rise of relatively inefficient taxi services, this short-sighted strategy also encouraged less space-efficient automobiles within the city in comparison to more effective bus or rail systems, which proved a formula for additional congestion. Therefore, it is crucial to reinstate a Central Bus Station in the city's center provide connections between all bus stations and let all intercity busses to use city roadways. But it would not be a good idea to use the Central Bus Station/Stations as nothing more than bus parking lots. Strict time schedules should be upheld for the prompt arrival and departure of busses to and from the Central Bus Station in order to maximize efficiency.

2.9 Planning for freight transport

It appears that there is lack of provisions for goods vehicle travel in the existing STP model and other planning approaches in Dhaka city. The requirements for adequate modeling of goods vehicle are threefold (a) to assemble base year patterns of movements by goods vehicles, (b) to develop procedures for forecasting goods vehicle movements over time, and (c) to establish procedures for modeling the responses of goods vehicles to changes in the transport system.

It is desirable to assign due importance to planning for freight transport in order to develop an integrated and sustainable transport system for Dhaka city.

3. Proposed short-term transport directives

3.1 People-oriented vs. vehicle-oriented approach

From the perspective of transportation planning, it is crucial to implement a strategy that would maximize mobility for the vast majority of road users, not simply car drivers. The importance of pedestrian uninterrupted network is illustrated in many journals [18, 19]. The focus of transport development strategies might be on the movement of either people or vehicles. That is, it is sensible to give priority to the majority of road users like pedestrians, bicycles, and rickshaws, who create no pollution, use no fuel, use minimum space per passenger, and contribute the least to traffic congestion, as opposed to giving priority to the minority of road users, like car users who create the most pollution and congestion, as demonstrated in **Table 4.**

In the urban context, the focus on movement of vehicles, which is analogous to minimization of vehicle-hours, tends to favor long distance and high-speed travel by any mode (but especially car), whereas the latter favors long distance and high-speed travel only by bus while giving emphasis to short distance travel by FFT and walking. Considering the nature of trips under mixed urban environments—that is, predominantly short trips—a people-oriented approach would ensure maximum mobility of the majority of road users by giving the pedestrian the highest priority followed by bicycle, rickshaw, and bus. On the other hand. The motorized paratransit should get lower priority, and cars should be assigned the lowest priority within a framework of an effective restrictive regime. Such a system would ensure the maximization of overall social and environmental benefits.

Traffic	PCU Value	Occupancy per vehicle	Occupancy /PCU	Fuel Use	Pollution Rating	Priority
Car	1.00	2.20	2.20	Very high	Very high	Lowest
Motorcycle	0.45	1.44	3.20	Very high	Very high	Low
Auto-rickshaw	0.70	2.08	2.97	Very high	Very high	Low
Minibus	1.50	41.50	27.67	Moderate	Moderate	High
Large Bus	2.00	88.40	44.20	Moderate	Moderate	High
Bicycle	0.12	1.10	9.17	Fuel Free	Zero Emission	High
Rickshaw	0.40	1.36	3.40	Fuel Free	Zero Emission	High
Pedestrian	Least Space	Very High per sqm	Very High	Fuel Free	Zero Emission	Highest

Table 4.
Space, fuel use and pollution rating of vehicles [5, 12].

The current practice in Dhaka city tends to give undue advantages to a small segment of the urban elite—car owners—by giving them absolute priority in every aspect of the city's transportation system at the expense of the mobility and convenience of the vast majority of road users, including pedestrians, rickshaw drivers, and bicycle riders. The undue privilege to cars has been manifested in terms of providing them with unlimited space for parking free of cost, creation of a high priority fast transit lane, giving preferential access along road links, ensuring uninterrupted movement at pedestrian crossings, giving undue long green times at traffic signals, reduction of bus routes, restriction of train timing, and so on.

In the following paragraphs, a description of different ongoing car-friendly initiatives and their potential consequences is outlined in brief.

3.2 Reduction of bus routes

Since the current initiatives are mainly directed to provide absolute priority to car owners, who represent less than 5% of the population, both approaches proposed significant increase of the modal share of cars at the expense of public transport. In addition to the investment of 4.2 billion dollars on capital-intensive projects, STP proposed to increase the share of motorizedd (non-transit) vehicles from the existing 18–31% at the end of the project in the year 2024 at the expense of public transport, as shown in **Table 5**.

Along the same lines as the STP approach, it is proposed to reduce the number of city bus routes to 40 from the existing 129 in the name of congestion management. Such an approach can neither reduce congestion nor ensure optimum utilization of road space when a car requires 88 times more road space per passenger in comparison to that of a bus (see **Table 4**). This will not only aggravate congestion but also increase the sufferings of the commuters drastically.

What the city needs is the consolidation and expansion of bus operation from the existing large number of uncoordinated small operators into a small number of well-integrated operators, rather than the reduction of the role of bus service in the future transport system of Dhaka. The STP study shows that some 800 individuals own approximately 1450 busses and minibusses, which represents the bulk of the bus fleet operating in the city. There are only about ten private operators having fleets of more than thirty busses, predominantly in the large-bus sector but including some prominent large minibus operators. It is therefore evident that the overall fragmentation of the industry remains very high. Such fragmentation has adverse impacts on on-street operational behavior; coordinated operation planning, vehicle safety, and travel time scheduling; and the optimum utilization of resources.

However, while consolidating the bus industry, care should be taken to avoid monopolies and corruption. In order for such measures to be successful, it is imperative to ensure proper implementation of a well-coordinated timetable. Moreover, care should be taken to ensure that any subsidy provided by the government for the

Travel Mode	Base Case Scenario (year 2004)	After Project Scenario (year 2024)
Public Transit	34%	21%
Motorized (Non-transit)	18%	31%

Table 5.
Comparison of modal share of motorized traffic between base case and after project scenarios of STP [5].

consolidated bus operation indeed passes to its intended recipients, for example, passengers with special needs, women, the vulnerable, and the disadvantaged sections of the society.

3.3 Widening of roads at the expense of footpaths

Apparently guided by the erroneous notion of road and auto-only developments, the government has taken initiatives to provide automobiles absolute priority at the expense of pedestrians. Along a large portion of the routes in the city, all the shade trees were cut down, and the width of footpaths were reduced to widen the road, despite the obvious negative effects for pedestrians (see **Figure 3**). Such an approach promotes tiny or nonexistent decreases in travel time for one group, as against increases in inconvenience and travel time of another, who are in fact the majority.

3.4 Restriction on fuel free transport (FFT)

3.4.1 Banning FFT from some major roads of the City

A number of roads in Dhaka city have had their FFT bans extended as part of ongoing strategy, including Kuril Biswa Road to Syadabad, Kakrail to Rajarbag Police Hospital, and Dainik Bangla Crossing to Syadabad. We should encourage rather than prohibit FFT use because it is more efficient in terms of space occupancy, energy use, and pollution rating (mainly rickshaws and bicycles). As shown by the conclusion of the DUTP after project study report, we should also take lessons from the past [12, 13].

Figure 3.
Road widening at the expense of footpaths and shade trees at Sewrapara-Farmgate road under DUTP (source: WBB trust) [20].

Discussions about the problems with Dhaka's transportation have centered exclusively on the need to increase vehicular mobility and the claimed role that cycle rickshaws play in causing traffic congestion for a number of years. According to this evaluation of the transportation situation, several projects have been started, with an emphasis on eliminating rickshaws and rickshaw vans off busy roads and occasionally confining them to rickshaw lanes. None of these transportation-related decisions were reached after a careful scientific analysis. Making important policy decisions in a somewhat haphazard manner has been the norm, whether it be with regard to the rickshaw ban or the city's Strategic Transport Plan (STP).

The results of various anti-NMT initiatives have been made clear through government-mandated studies, including the HDRC report on the rickshaw ban on Mirpur Road (HDRC 2004) [11], and the DUTP after-study report [13]. The results, almost astonishingly negative, would suggest that the bases for the policy decisions and transport plans are flawed as important transport policy decisions were taken without employing any scientific study. Despite a 50% traffic growth of motorized vehicles from2000 to 2005, the traffic in terms of PCE (passenger car equivalent) in the Mirpur Road Demonstration corridor was significantly lower in 2005 in comparison to that in 2000. However, despite having fewer vehicles in 2005, the performance of the corridor in terms of key congestion indicators was significantly worse after the rickshaw ban.

Furthermore, despite abundant evidence of rising travel expenses and traffic congestion, transportation planning is emphasizing increasing the importance of the car and decreasing the role of fuel-free transportation. The ongoing expansion of the rickshaw prohibitions onto other metropolitan highways reflects this pattern. Without a doubt, rickshaws are superior to cars as urban transportation options in terms of the use of road space, energy use, and environmental concern. These are scientific facts [12, 13]. It would be better if we reintroduce rickshaws in all roads where rickshaws are currently banned, as an integrated public transit (PT) priority supplemented by FFT-only roads. In this connection, the recommended approach by STP consultants is worth mentioning. The STP Consultants in the Working Paper on Mass Transit [21] demonstrated that there is no need for bans of fuel-free transport. The Working Paper recognized the superiority of a combination of FFT, pedestrian, and BRT options and proposed three possible alternatives for roads of Dhaka city, namely: (a) a pedestrian lane +a single-lane bus rapid transit (BRT) for very narrow roads, (b) a pedestrian lane + a mixed mode lane + a single lane BRT for intermediate to major corridors, and (c) a pedestrian lane + one/two FFT-only lanes + one/two BRT lanes for intermediate to major corridors.

It is important to note that, unlike the main report, the STP Working Paper on mass transit did not propose any combination of BRT and fuel-dependent transport (FDT) solutions. If Dhaka introduces public transit (PT) priority measures, such as BRT or any other bus priority measures, there will be no need to give additional priority to cars and motorized paratransits. In conjunction with FFT priority measures, BRT or the specified bus priority measure will be able to meet the demands of intermediate and long trips. The majority of short journeys, which make up around 76% of all travels, will have their demands met by these.

3.4.2 Limiting the number of rickshaws

Neither of the two major studies so far conducted in Dhaka city, that is, STP (STP 2005) [5] and DITS (DUTP 1997) [22], recommended imposing any restriction on the number of rickshaws. These instead recommended that the optimum number of rickshaws should be determined by market forces. Despite this, the Dhaka City

Corporation has arbitrarily come up with 89,000 as the number of rickshaws that will be allowed to ply in the Metropolitan area (**Figures 4** and **5**).

According to a study on rickshaws, they have been functioning under long term marginal equilibrium circumstances and are quite economically efficient (Bari 2000). This suggests that whether they are "legal" or "illegal," the current number of rickshaws is optimal in terms of economic efficiency. There is no need to limit their population. Any suboptimal number may encourage monopolies, corruption, or unfair fare systems.

Rickshaws are in fact a better mode of transport especially in a megacity like Dhaka, in terms of energy efficiency, pollution control, traffic congestion, and travel

Figure 4.
So called "illegal" rickshaws seized by law enforcers being transported to the 'rickshaw graveyard' at Agargaon. (source: The daily star, Jun 02, 2018) [17].

Figure 5.
Hundreds of rickshaws kept haphazardly in the Agargaon dumping ground (source: The daily star, November 03, 2004) [23].

demand management. There is no scientific basis of providing absolute priority to a tiny minority of car owners, who are the main contributor of congestion, while at the same time confiscating and destroying thousands of environmentally friendly and efficient rickshaws (Bari 2000) [24] as far as congestion management is concerned This is also tantamount to the infringement of the fundamental rights of the vulnerable rickshaw pullers to earn a living by legal means.

3.5 Restriction of railway services from Kamalapur

All over the world, train service is widely regarded as one of the most efficient and people-friendly modes of transport. It is almost impossible to develop a congestion-free transport system for a megacity without development of an integrated mass surface rail transport system. A train can carry thousands of passengers using a minimum amount of city space, thereby relieving congestion to a great extent. Yet guided by the policy directives of STP, which advocates termination of rail services within the city, city authority proposed significant reduction of flexibility of train operation within the city by restricting train services from 08:00 to 09:30 and 16:00 to 18:00 in order to ensure uninterrupted movements of cars. This will no doubt further hamper effectiveness and efficiency of a major public transport system of Dhaka, that is, railway at the expense of car owners, who represent 5% of the modal share.

3.6 Proposal for forcing pedestrians to use overhead or underground crossings

Serious contradictions exist between the stated policy directives and the desire to provide sufficient resources to support the objectives in the STP and the ongoing approach. While the STP recognized the need to adopt the "Pedestrian First Policy" in developing a balanced multimodal transport system, the policy was later abandoned while developing different alternative transport strategies. In the preferred alternative Strategy Modified 2b, only a tiny fraction, that is, 0.24% of the total investment, was proposed for pedestrian-oriented developments.

A pedestrian-friendly transport system is not possible to develop by providing inadequate resources for the development of pedestrian facilities. Moreover, in line with STP, Dhaka Metropolitan Development Plan (DMDP) (1995–2015) recommended construction of 41 pedestrian bridges and 5 pedestrian underpasses to ensure pedestrian safety. It is impossible to create a pedestrian-friendly transport system by hampering pedestrian movement by forcing them to use overhead or underground crossings. Despite the fact that these precautions were introduced in the name of pedestrian safety, **Table 6** shows that pedestrian bridges have some of the worst records for pedestrian safety globally.

With the exception of high-speed limited access expressways, pedestrian bridges should be avoided except where there is a natural change in elevation, where direct

City	Pedestrian deaths/100,000 population/year	Use pedestrian over bridges?
London	1.9	No
New York City	2.2	No
Mexico City	15.4	Yes
Cape Town	19.4	Yes

Table 6.
Pedestrian bridges and pedestrian safety.

entry to a building or an elevated pedestrian network is provided (as with the long-elevated walkway connecting Kamlapur railway station to Atish Dipankar Rd), or for crossing a waterway.

Pedestrian bridges are particularly burdensome to bus passengers, who as a group tend to more frequently cross roads than many other pedestrians. Instead of being viewed as facilities for pedestrians, the pedestrian bridges currently in use in Dhaka should be seen as facilities to improve the flow of motorized vehicles that would otherwise have to stop so people can cross the roads securely and conveniently.

In a densely populated urban area like Dhaka city, it is important to design intersections and other crossings by assigning pedestrians priority over vehicles, such as by: (a) ensuring uninterrupted movements of pedestrians, (b) forcing the vehicles to slow down or eliminate free-flowing motor vehicle turnings, (c) facilitating safe and priority pedestrian movements on all legs of the intersection, (d) allowing pedestrians to cross in a direct line across the intersection and clearly identifying the direction of travel for all pedestrians, and (e) letting the pedestrian see and be seen.

It is crucial to provide pedestrians with crossings at street level throughout the city. Only under extreme circumstances, such as when pedestrians must cross a busy road, a rail yard, a railroad, or a body of water, is grade separation practical. Using traffic calming techniques or installing a pedestrian-activated signal for an at-grade crossing is more appropriate for metropolitan streets. General experiences of grade-separated crossings have shown that the majority of pedestrians will not use an overpass or underpass if they can cross at street level in about the same amount of time, even though illegal road crossing jeopardizes their safety. It should further be noted that pedestrians must often travel significantly out of their way in order to reach an over-bridge or underpass, further adding to trip time and effort. Given that it is cars that are deadly, the onus for safety should be on them, not on pedestrians; rather than pedestrians dodging cars, cars should be forced to slow down and stop for pedestrians (**Figure 6**).

Figure 6.
Just to escape the "hassle" of utilizing the foot-over-bridge, people choose the dangerous option of crossing the road. The image was captured in the capital in Banani under the foot over bridge (the Bangladesh post, September 03, 2020) [25].

Figure 7.
Dhaka South City corporation, widely known as DSCC, evicted hundreds of street vendors from Gulistan (source: The new age, 11 September 2022) [26].

3.7 Eviction of hawkers

Despite the fact that one of the main causes of footpath blockages is parked cars, city authorities time and again start drives to evict hawkers and vendors in the name of facilitation of vehicular and pedestrian movements. The government's preoccupation with drives is to remove hawkers/vendors from pavements while ignoring the problem created by unauthorized parking of cars as well as encroachment of footpaths by construction material. The city authorities systemically ignore the real problems that pedestrians face, including the unpleasantness and danger of walking along roads heavily trafficked by fuel-dependent vehicles, with their consequent fumes and noise.

Vendors can actually play an important role in attracting pedestrians, by providing something to look at and purchase and a presence that makes footpaths safer. Vendors should not be allowed to occupy the entire width of the footpath, but neither should they be banned altogether. They should be properly regulated under a comprehensive program to ensure that they remain as an integral part of footpaths without seriously hampering the pedestrian movements. In fact, many developed cities in the world, such as London, integrated street vendors properly by implementing a number of measures, such as allocating designated place for hawkers in the footpaths, converting a number of city roads into pedestrian-and hawker-only roads during working hours, and so forth. There is no reason why such pedestrian- and vendor-friendly approaches cannot be implemented in Dhaka city (**Figure 7**).

3.8 Priority for private cars

The ongoing initiatives are designed to generate undue advantages to car owners by giving them priority in all spheres of the city transport system at the expense of mobility and convenience for the majority of the road users, that is, pedestrians, rickshaws, and bus and rail passengers. The undue privilege to cars has also been manifested in terms of providing them with unlimited space for parking free of cost, providing tax relief for car imports, giving preferential access along road links in the name of rapid transit lanes, ensuring uninterrupted movement at pedestrian crossings and giving undue long green times at traffic signals, and so on.

3.8.1 Promotion of the import of reconditioned cars

While the ongoing bureaucratic initiatives have focused on restricting the number of rickshaws, bus routes, and even flexibility of train operation, there have been endless efforts to increase the number of private cars, which is the main contributor of traffic congestion. The government has recently relaxed restriction on import of reconditioned vehicles and allowed import of automobiles up to six years old, amending the existing limit of four years. This policy initiative has the potential for not only significant increase of congestion but also increasing pollution and fuel consumption.

3.8.2 Creation of rapid transit lane for cars

According to the Daily Ittefaq dated August 14, 2008, in order to ensure absolute priority of cars over busses and other public transport, the Traffic Division of Dhaka Metropolitan police has implemented the so-called Rapid Transit System (Lane System), which allocates an exclusive "Car only" lane in Mirpur Road and Airport Road in order to provide a tiny minority of car owners, who represent less than 5% of the population in Dhaka City, absolute priority over other modes of transport. While modern cities around the world have been putting restrictions on cars for effective demand and congestion management, officials in Bangladesh have been promoting car-oriented facilities for transport development.

3.8.3 Providing priorities for autos over other modes of transport at traffic signals

With its main goal apparently to provide convenience for cars along the main corridors with no regard to the effect on all other road users, the authorities in Dhaka City Corporation have set very high cycle times in the order of 150–180 seconds, with corresponding unreasonably long green times for the autos, ignoring the needs of pedestrians and other FFT modes. However, it is a standard practice to optimize signal setting within the domain of maximization of economic efficiency[2], as in the widely used signal optimization tool, TRANSYT [27].

Logically, all signal timings should be set primarily in accordance with economic principles. At the same time, efforts should be made to maintain a people-oriented hierarchy of priority, that is, flowing downward from pedestrians, FFT, and busses, with cars gaining the least preference. On the contrary, the current practice provides undue priority to cars in the main corridors, thereby inconveniencing other road users as well as traffic in the minor roads. As a result, traffic in the minor roads regularly suffers long delays, and it has become almost impossible for a pedestrian to cross roads within a reasonable time [12].

4. Brief review of revised strategic transport plan (RSTP)

RSTP (2015) follows the same alleyway in policy level which is mentioned in STP (2005).

[2] It is essentially a traffic model of the network, which calculates a Performance Index (PI) in monetary terms, whilst an optimizing routine searches for the timings that reduce the PI to a minimum value, subject to minimum green and other constraints.

4.1 Shifting of inter-city bus terminal outside urban area

RSTP (2015) proposed shifting of intercity bus terminal outside the urban area. Prior to recommending indirectly for shifting intercity bus services outside urban area, it is essential to undertake a detailed traffic impact study.

In order to ensure seamless travel for long distance public transport travelers without much disruption or modal transfer, it is important to locate the interchange facility/terminal very near to the location of highest travel demand for such travelers, which are in general the City Centers or the Central Business Districts (CBD) of the City or town. While proposing multimodal transfer facilities, care should be taken not to shift intercity public transport terminal unnecessarily far way for the Central Business District (CBD). Discontinuing a vital and efficient transport mode, like intercity bus, does not mean disappearance of travel demand. If there remains a substantial demand for intercity travel at the heart of the city, it is pointless to make the journeys fragmented for such trips, and thereby significantly increasing travel time, discomfort, and modal transfer penalties.

Many developing countries follow the second model and intercity busses are not allowed to enter into the city center. However, validity of such a concept is questionable bearing in mind that a passenger bus is 30 to 50 times more efficient in terms of passenger carrying capacity per Passenger Car Unit (PCU) in comparison to a private car. There is no need to impose restrictions on intercity bus as far as congestion management is concerned.

It is not appropriate to propose public transport transfer facilities for intercity bus services on the basis of some pre-determined concept without any regards to the present and future travel demand patterns of long-distance travelers. Such a proposal could have far reached negative impacts for the development of a sustainable transport system for Dhaka City. It is better not to make any direct or indirect recommendation for shifting intercity bus terminal outside urban area without undertaking further study.

4.2 Transport planning in RSTP

The secondary and tertiary networks were not included in the traffic modeling; it solely examined the 1297 km primary road network. The majority of the subsidiary and tertiary roads in Dhaka are already severely congested; thus, the projected expansion of the main road network would greatly increase traffic volumes on those roads and cause delays (but this was not reflected in the traffic model). Along with this, 141 number of Traffic Analysis Zone (TAZ) are considered, which does not capture the intrazonal traffic.

In RSTP only, 5 modes, bus, car, motorcycle, rickshaw, and three-wheeled motorized vehicle, are considered for base year model (2014) and future model year. Pedestrian and rail are not considered in planning. But pedestrian needs to be prioritized for policy level.

4.3 Capacity of road and vehicle number in RSTP

RSTP (2015) has not analyzed the capacity of the road in Dhaka and how much vehicle can be allowed for Dhaka city. The RSTP does not explicitly show forecasts of future vehicle numbers in Dhaka. However, these can be roughly estimated from information in the draft report, particularly from: (i) current vehicle numbers and (ii) present and future (predicted) modal split. In fact, the current number of vehicles in Dhaka is not accurately known. Even auto numbers are not accurately known, because of weaknesses in the vehicle registration system.

4.4 Private sector investment

The RSTP primarily included future public sector investments in infrastructure; it did not consider broader private sector investments in Dhaka's transportation, including the cost of purchasing and maintaining all the cars that make up the city's transportation system. In a way, the RSTP did take these expenses into account when it identified "travel time savings" and "savings in car running costs" as the new infrastructure's primary advantages. However, by concentrating on the 'savings,' we fail to comprehend the overall picture of the investment made in Dhaka's transportation.

5. Conclusions and recommendations

This section provides a brief discussion together with the conclusions drawn from the paper. This is followed by a list of recommendations for corrective measures for strategic policy directives and immediate remedial measures to avoid the adverse impacts of the ongoing and unsustainable transport interventions for relieving traffic congestion.

5.1 Conclusions

The key conclusions, as drawn from this paper, are presented in the following sections.

5.1.1 Bureaucratic reform

The success of any transport policy intervention would likely to be slim unless a thorough overhaul of the existing age-old bureaucratic system is undertaken, a people oriented reform of the bureaucracy is initiated, and a participatory and knowledge-based transport planning process is adopted without further delay.

5.1.2 STP policy directives

The STP initiatives cannot be regarded as sustainable transport initiatives because the approach:

- Shows disregard to the majority of trips, that is, all short trips (76% of the total trips) and fuel free transport (48% of the trips).

- Recommends to ban fuel-free transport in major roads and to restrict intercity busses and railways.

- Invests maximum amount of resources (237% more) for the less optimal transport solution.

- Promotes auto-friendly, inefficient, and environmentally unsustainable projects like Eastern Bypass, elevated expressways, and unnecessary road projects, defying findings of the STP study.

- Encourages long distance travel and the demand for extra travel, both of which are likely to increase traffic and pollution.
- Fosters long distance travel and the need for further travel, which will probably result in additional traffic and pollution.
- Gives insufficient money and provisions for sustainable transportation systems, such as pedestrians, fuel-free transportation, and an integrated waterway system, and provides an excessive amount of resources for capital-intensive and car-friendly initiatives.
- Promotes inequality and social injustice.

5.1.3 Current transport initiatives

The majority of the ongoing transport policy directives like reduction of bus routes, restriction on train services, providing absolute priority to cars in lane use, provisions for more parking spaces, and putting more restriction on FFT have the potential for negative impacts for the development of a congestion-free and sustainable multimodal transport system for Dhaka city.

5.2 Recommendations

The complete failure of auto-friendly and unsustainable transport initiatives so far undertaken to improve traffic situations in Dhaka should be a good lesson for transport and city planners. It is high time to undertake a long term approach as well as emergency remedial measures to rectify the damage caused by the injudicious transport initiatives to the economy, environment, poverty reduction initiatives, and sustainable development. The key recommendations of the article are presented below:

5.2.1 Knowledge-based and participatory planning process

In order to promote sustainable and pro-poor transport development, it is imperative to establish a knowledge-based and participatory transport planning process more or less analogous to the participatory budgeting approach of South America.[3]

5.2.2 Strategic policy initiatives

Rather than fixing a flawed STP study and set of recommendations, it would have been preferable to select a team for the strategic transport planning that has an interest in a broad range of issues, including health, environment, people's well-being, and poverty reduction, as well as sustainable transport developments. Input from others all along the process would have helped to lead to a less biased result. However, as it is too late to change the entire process, it is important to consider

[3] The participatory budgeting, which has been in operation in Brazil (Souza 2001) since 1989, is emerging as an innovative urban development management theme with an enormous potential to support cities in the adoption of socially integrated, inclusive, accessible, transparent, participatory and accountable urban governance and management, with a view to ensuring equitable and sustainable urban development.

what can be done to prevent any further, significant harm from occurring as a result of the misdirected process.

It is possible to incorporate provisions for sustainable development keeping the basic findings of the STP study. Despite the fact that the STP model has a number of shortcomings, the study appears to be more or less successful in identifying the preferred mass transit option for long trips, that is, Strategy 1a: Roads+, ALL BRT, NO Metro. Strategy 1a represents a combination of moderate investment in roads and an intensive BRT system as the means for mass transit. The option only needs a small portion (42%) of the total USD 4.2 billion that the STP-preferred alternative needs. In terms of sustainability, affordability, affordability, social development, safety, and economics, it also stands out as the greatest choice. By giving careful consideration to the following crucial problems, the extra resources could be used more effectively for the creation of a balanced multimodal transport system.

Based on the gap analysis between existing considering and best practice. Following are need to be improve:

a. Integrated transport planning and management

   ◦ Adopt an integrated demand and supply management for sustainable transport.

   ◦ Assess transport policy by examining wider policy issues.

b. Sustainable land use and development

   ◦ Adopt a sustainable and smart land use policy to reduce travel demand.

   ◦ Work with planning authorities to prevent new single use areas

c. People-cantered transportation

   ◦ Prioritize door-to-door accessibility and mobility for people and products.

   ◦ Reorient traffic priority, putting pedestrians first.

   ◦ Provide street-level crossings for pedestrians.

   ◦ Allocate signal timings using a people-oriented priority system.

   ◦ Create cycle lanes and a continuous cycle network.

d. Support for alternative transport modes

   ◦ Invest in upgraded rickshaws and reverse efforts to reduce their numbers.

   ◦ Restore rickshaws and integrate them into a fuel-free public transit system.

   ◦ Implement car-free zones in major shopping and business locations.

   ◦ Provide staff bus services and incentives for active or public transportation.

e. Restrictions on private vehicle use

- Prohibit parking on public sidewalks and charge for parking based on market rates.

- Implement restrictions to reduce vehicle expansion, such as fewer licenses, import limits, and higher charges.

f. Research and policy development

- Explore greener and more sustainable transport options.

- Conduct research on effective transportation policies that consider all consumers and providers.

Acronyms

BRT	Bus Rapid Transit
DAP	Detailed Area Plan
DITS	Dhaka Integrated Transport Study
DMDP	Dhaka Metropolitan Development Plan
DUTP	Dhaka Urban Transport Project
PT	Public Transit
RSTP	Revised Strategic Transport Plan
STP	Strategic Transport Plan

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Chapter 3

Inclusive, Safe and Resilient Public Spaces: Gateway to Sustainable Cities?

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Abstract

The rapid urbanization process of cities is majorly coupled with extreme climate change, housing shortage and urban safety issues. These issues are raising new challenges to address the capability of urban resilience. Enhancing Urban Safety and Security is one of the major principles addressed by UN-Habitat in Sustainable Development Goal number 11. Making cities safe and sustainable means ensuring access to safe and affordable public spaces for all. This book chapter aims to highlight how do the city's public spaces are linked and affected by crime and fear of crime? How do crime and fear of crime interconnect to the built environment in cities while promoting positive urban transitions in terms of safe and sustainable cities? This book chapter explores answers to these questions through the parks and public spaces of the city as a case study. In other words, the book chapter deals with the issue of safety and security by (1) showing links between parks and public spaces, and crime and fear of crime, (2) highlighting how different attributes in the built environment can affect people's perception of safety, (3) understanding socio-technical perspectives i.e., how technological systems and equipment's (such as lighting sensors, security alarms, security electronic devices, closed-circuit television (CCTV), smartphones or other technological instruments) are influencing safety/security and sustainability, (4) demonstrating the issues and challenges found in Stockholm, Sweden, and, (5) providing recommendations on how these places can be planned and designed to become more sustainable.

Keywords: public spaces, perceived safety, fear of crime, sustainable cities, urbanization

1. Introduction

When the UN has adopted Agenda 2030 in 2015 for sustainable development, it committed itself and the member states to work on achieving a social, environmental, and economically sustainable world by the year 2030 [1]. According to Agenda, by 2030 everyone will have access to safe green areas and public places. Unfortunately, not all green areas and public places are perceived as safe. According to the Swedish National Council for Crime Prevention (Brå) due to the fear of being exposed to crime, people change their pattern of movement [2]. Almost a quarter of the population in Sweden takes a different route or a different mode of transport than desired due to the fear of crime [2]. According to the Swedish security survey [2], those areas that have exposure to crime generated a higher level of concern for the respondents to be exposed to crime themselves. This worry left people with a limited choice in terms of when and where they move within the city [2]. It has been argued that sustainability as a whole cannot be achieved unless all of the residents feel safe [3].

The feeling of being unsafe can be problematic both at a personal level and at the level of society. Several empirical studies have sought that there is not always a connection between feeling unsafe and being actually in danger, conversely, it is quite possible to feel unsafe in an environment that looks completely safe. Safety is a concept that is based on subjective experiences, which means that it can be defined differently. According to UN-Habitat [4], security is defined as the statistical risk to be exposed to criminal acts in one place. If the risk is low, security is high. Whether you are in danger or not, it is the subjective feeling of insecurity that creates a problem in society because it affects human behavior and freedom [5] and makes it difficult to achieve social sustainability. Social sustainability is a concept that contains several factors where the safety aspect is included. Safety is one concept that can vary depending on the context in which the research is presented. Subjective safety reflects the perception of social safety and encompasses fear or anxieties caused by real or presumed fears [6]. Research that exists on safety is most often associated with crime preventative measures and it is therefore important to distinguish between crimes that have taken place and perceived fear of crimes. There is a willingness on the part of actors to work actively with issues of safety in urban planning, but most often there is little or no natural cooperation between them. More knowledge, clearer guidelines, and better coordination can help actors to work more on these issues together [7] to promote smooth urban transition and achieve resilience as a whole. Resilience is mostly defined as ecosystems and climate change. However, this is not the only dimension that is connected to resilience. The demand for safe and secure places continues to upsurge [4]. The challenge for providing such places in developing and third world countries is another serious issue to demonstrate that design can meet the needs of the residents around the world. In this book chapter, the term safety is used as it is explained by Iqbal [8] "the risk of being a victim of crime, the perception of risk of being a victim of crime, and the expression of fear/anxieties of crime". The term "urban safety is considered to be the quality of the environment and is defined for a person or group in an urban area" [8].

This book chapter aims to highlight the connection between public spaces regarding crime and fear of crime by (1) showing links between parks and public spaces, and crime and fear of crime, (2) highlighting how different land uses and people's activities in the built environment can affect people's perception, (3) understanding socio-technical perspectives i.e., how technological systems and equipment's (such as lighting sensors, security alarms, security electronic devices, closed-circuit television (CCTV), smartphones or other technological instruments) are influencing safety/security and sustainability, (4) demonstrating the issues and challenges found in Sweden, and, (5) providing recommendations on how these places can be planned and designed to become more sustainable. This book chapter presents a synthesis of earlier work on fear of crime, perceived safety and parks by the author [8–13]. The book chapter begins with a discussion of factors that influence fear of crime and perceived safety in parks and public spaces. Second, a review of the recent literature about perceived safety associated with the physical design perspective of the built environment. Third, how technological systems and equipment (such as lighting sensors, security alarms, security electronic devices, CCTV, smartphones or other technological instruments) are influencing safety/security and sustainability is outlined. Fourth, the issues and challenges found in Stockholm, Sweden will be demonstrated. The context of the empirical studies was the city of Stockholm, therefore, the policy and design recommendations for being safe in the public space discussed in the last section are applicable to other major cities of Sweden or the cities similar to those as Stockholm.

2. Fear of crime and perceived safety in public spaces

Public space is characterized as an open space that is accessible to people. In other words, public spaces are the places that provide opportunities for social interactions within the communities. Parks, public squares and streets are some examples of public spaces. To create an inclusive public space, it is important that the various groups of people feel safe and can freely participate in society. Due to its blurred nature of definition boundaries the terms public place and public space are used in this book chapter interchangeably (i.e., for discussion, see [14, 15]. Several studies have shown the positive impact of parks and public spaces on human health and well-being [16] while, others have shown that such places can be a reason for stress and anxiety [5, 17] and affect human life negatively. According to Iqbal and Wilhelmsson [11], not all parks and public spaces have equal amenity value and some may be valued as disamenities. For example, noise around parks, high beam lights from sports arenas, and traffic congestion around parks, street parking near parks, garbage, vandalism, and the gathering of undesirable groups (such as alcoholics, drug addicts, etc.) in public spaces affect individuals negatively [8]. Poor maintenance and criminogenic conditions of the park and public spaces are highlighted by several researchers [9, 11, 18]. A small number of studies have also shown that potential buyers may avoid buying properties located near parks and public spaces with high crime rates [10, 11, 19].

According to UN-Habitat [4] "crime is defined as an antisocial act that violates a law and for which a punishment can be imposed by the state or in the state's name". While fear of crime refers to the "fear of being a victim of a crime instead of the actual possibility of being a victim of crime" [20]. Fear of crime or feeling unsafe is a concept that is complex and based on subjective experiences attached to various other contexts such as age, gender, socioeconomic status and emotional responses to worry or anxiety [5]. According to Ceccato [21], safety is a concept that is shaped by an individual's actions and interventions in everyday life. Safety is affected by many different factors. These factors can be more easily understood in their context if they support personal, social and physical attributes. For example, there are several strands of literature analyzing the personal and social attributes such as age, gender and socioeconomic status that affect the perceived safety of public spaces [22, 23].

According to Furedi [24] social and cultural processes guide people on how to respond to threats to their safety [24]. Several researchers highlighted the fear of crime in parks as the most important factor that keeps women out of public spaces [25, 26]. Fear of crime also encourages the separation of women from men in public space [12]. For instance, the creation of safe places for female social interactions and activities to accommodate their outdoor space needs [12, 27]. The international literature shows that some women are mainly fearful of sexual assault [25]. According to Hilinski et al. [28], young age women are targeted for sexual assault and rape [28] then old age women [29]. Following this, there are many places in the world, where the openness in public space is not open for all [12]. In those places, public space is considered as a place where men have more rights than women and where women are often left out because of the fear of harassment [30]. Marginalized groups tend to be more fearful in society because of their vulnerability and feel segregated. Exclusion and loneliness are some of the social attributes in society that enhance the fear of crime. Social integration is essential to reduce the fear of crime and increasing perceived safety. A neighborhood is perceived as safe when it has a social network that includes both regular communication and offered help to all groups. According to Olsson [31], the socially defined space applies when there are social ties between the inhabitants and it is easy to understand and use the public space. It is important to the public space feels open and welcoming for people to make them stay. If the connection with space is missing and identities become unclear, the social control becomes more difficult which resulted in an unsafe place. A socially sustainable, cohesive and resilient public spaces can be achieved by promoting social inclusion and by empowering all groups of people.

3. Fear of crime and perceived safety: physical design perspective

In this book chapter, physical design perspective refers to the design attributes of the physical environment of public spaces such as design layouts, mixed land use, street patterns, street furniture (garbage bins and seating arrangements), barriers (actual and symbolic), lighting, accessibility, landscape design and maintenance. Previous research about fear of crime and safety in the urban environment has dealt with situational crime prevention measures [32, 33] and how the physical environment should be designed safely [34–36]. Situational crime prevention measures are applied when a criminal is motivated to commit a crime and the design of the place makes it difficult to carry out the crime. Situational crime prevention methods deal with the physical, social, and psychological aspects of the place to counteract crimes [37]. The role of the physical environment in promoting safety highlighted by several researchers [34, 35]. Crime prevention through environmental design (CPTED) is a concept that explains the relationship between environmental features and crime occurrence through the principles of surveillance, territoriality, access control, target hardening, activity support, and image/maintenance. CPTED is a method that is about how proper development of physical environments can be designed to prevent crime and increase the sense of safety in the built environment. The importance of using CPTED principles is highlighted by many researchers as an inventory in public spaces such as parks [9, 38].

The best-known theory that explains environmental preferences from an architectural, interior and urban planning perspective and its impact on people is "Prospect-refuge theory". This theory seeks to describe why certain environments feel secure and thereby meet basic human psychological needs. It is a strategic assessment of how different potential environments enable the ability to observe (prospect) without being seen themselves (refuge). By emphasizing subjective references such as experiences, behaviors and relationships more than architecture, Appleton [39] claims that people evaluate environments functionally and search for strategic opportunities that environments can provide. According to Dosen & Ostwald [40] the physical elements in the planning that creates a perception of spatial arrangements of different components affect human perception and thus the perception of safety. Components that provide the opportunity to move and explore in an environment and whether the effect of shadow and sun is taken into account affects the human perception and experience of safety [40].

In her seminal work, 'The life and death of the great American cities' Jane Jacobs [36] argue how the safety aspect is an important part of a livable urban environment. Jacobs [36] brings forward the idea of mixed land uses of buildings and people by analyzing the uses of different urban elements, such as sidewalks, neighborhood parks, and city neighborhoods. According to Jacobs [36], three requirements should be fulfilled to create perceived safety in the streets. First, a clear division of the public and private space is important. Second, businesses along the street should have large windows facing towards the street. This can create more "eyes upon the streets" that can perceive what takes place in the street space and can help to intervene in potential crime events. The third and the last is to create a continuous flow of people passing by. This increases the number of eyes while encouraging people in the surrounding buildings to look out at the street and observe the events happening in street space. Jacobs believes that no one is interested to look out on an empty street, on the contrary, many people feel entertained when observing a living street [36]. To create the flow of people that makes the street space come alive, Jacobs mentions the importance of having a mixed type of activities that attract people at all hours of the day and provide guardianship. The concept of guardianship is mainly highlighted by Cohen and Felson [41] in routine activity theory. According to them, "in order to take place a crime event, the presence of a motivated offender, the presence of a suitable target, and the absence of a capable guardian is required" [41]. Capable guardians can be provided with the help of planning a mixed type of activities and mixed land use.

The role of mixed land use in the built environment is highlighted by various researchers, architects and urban planners. It has been argued that mixed land use activities lead to an active day for a longer period, which contributes to natural surveillance and leads to an increase in the feeling of safety [42]. In a study of parks and crime, Groff and McCord [43] found that mixed land use reduces crime. Larger parks that generate more activities have lower crime levels, which in turn are connected to greater numbers of people using these parks [43]. Contrary to this Iqbal and Ceccato [9] found that large parks can have safety issues due to the big area of the park. Parks can attract criminal activities and in turn have a high number of crimes in certain areas. For instance, cafes, restaurants and sports arenas in summers can also have an increasing number of crimes in parks, such as mishandling incidence, pickpocketing and vandalism [9]. When explaining the fear of crime in parks, overgrown trees and vegetation has an important role in association with fear of crime and disorder and affect perceived safety negatively. The major proposition is given to the idea that trees and vegetation can block the view and can create hiding places [44, 45]. Proper maintenance can help to avoid hiding places and in turn deter the incidents of crimes. Vegetation is also a physical element that is used to define demarcation or create symbolic barriers that question the accessibility of public places. Gehl [46] emphasized the need to eliminate such barriers (both physical and mental) to increase space accessibility (**Figure 1**).

Accessibility in public places has an important role from the physical design perspective. A public place should feel accessible and open to everyone. Accessibility can be seen from two perspectives. It could be either actual or symbolic barriers that prevent visitors from visiting or staying at a place. Within the physical aspect, accessibility can sometimes be associated with the lack of obstacles and barriers. The perceived accessibility is instead about whether the place is perceived as inclusive

Figure 1.
(a) Presence of dark tunnels often limits the prospects and provides refuge for a criminal. (b) Padlocks can increase fear of crime. (Source: Iqbal, A) *All photographs were taken by the author.*

for all. It is also very important to understand the dilemma of "public spaces as a public good" — that nobody feels the responsibility of being in charge of publically owned spaces [9, 43] however, at the same time everyone wants to get benefit from it. While explaining accessibility in the public urban space, Olsson [31] argued that an accessible and well-planned public space must be identified as open and attractive. In order to create attractiveness, the presence of other people is identified as the crucial element [31, 46, 47] and a prerequisite for a well-functioning city [31]. Urban events such as cultural events and sports were criticized by Olsson [31] as they are not sustainable solutions to create accessibility and attractiveness in the city.

Another important physical element that helps to feel safe in an urban environment is the use of street furniture such as the placement of garbage bins and seating arrangements in a public space. In order to investigate how people use the spaces and interact in public places such as squares and parks in New York, William Whyte [47] stated an essential prerequisite for attracting people to squares and parks in the presence of other people as well as access to the seating. Food sales, the presence of water, movable chairs and access to the sun were identified as other significant elements [47]. Public spaces that provide seating with a natural overview mainly allow for social interaction and automatically generates perceived safety. Saville & Cleveland [48] found that park furniture can create natural surveillance if place adequately. The placement of park furniture can work as a source of creating eyes on the street on the other hand they are a major source of creating a social connection among park users. At the same time, they can be part of the noise and other problems in parks [48]. A park or public space with well-groomed trees and vegetation, good lighting, and cleanliness increase the perceived safety.

Perceived safety is also associated with the disorder in the surroundings. The disorder is mainly affected by physical attributes such as graffiti, poorly maintained landscapes, debris (garbage), vandalism, and poor lighting. According to Broken Windows Theory, physical and social deterioration can affect residents' perceived safety and may result in a higher fear of crime [23]. The relationship between perceived safety and disorder is recurring. An increase in disorder decreases people's perceived safety which in turn leads to place avoidance. On the other hand place avoidance leads to further disorder [49].

When emphasizing crime preventative measures, several researchers found street lighting as an important part of physical features that helps in feeling safe in public spaces [14, 50]. However, there are mixed trend results in research that show both positive and negative effects of lighting. In a recent systematic literature study, Ceccato and Nalla [14] mentioned that 72 percent of studies (from their sample research papers) show that good lighting affects positively by reducing crime and/or fear of crime however, the impact on the safety of other security technologies, are inconclusive [51]. According to Rezvani and Sadra [5], lighting and visual accessibility of public places lead to strengthening the sense of feeling safe in the neighborhoods. Physical design affects perceived safety, but it is not just physical planning that administers how safe a public space can be. Sreetheran & van den Bosch [52] argues that physical attributes can be apparent like vandalism or sometimes even more prevailing factors such as lighting or maintenance of an area. Physical factors that indicate disorder in society generate fear and can be perceived as a warning sign of an unsafe place. It is important to keep in mind that the personal, social and physical attributes are interdependent to achieve perceived safety. Investigating negative aspects of light pollution on ecological systems and health, Chepesiuk [53] shows that lighting also has divergent effects on both flora and fauna. It has also been highlighted that light pollution in cities shown a negative effect on people's sleeping habits [53].

4. Fear of crime and perceived safety: a socio-technical perspective

Our cities have developed a lot and access to modern technology such as smartphones, laptops, the internet, etc. has most likely had an impact on how public places are used and how people interact with each other. Since this new era of smartphones and location-based services has started an increasing trend of debate is taking place between various actors in society on the role of socio-technical perspective to design cities that can help to reduce crimes. Cities are comprised of people, infrastructure, physical forms, services, ecosystems and communications. The interaction between society's complex infrastructures and human behavior has a great role in interconnecting all three forms of sustainability that are, social, physical and ecological. However, it is inappropriate to expect that the sustainability challenges that our cities are facing can be solved by only traditional disciplinary methods of research. Cities require a socio-technical approach rather than a purely technological one because societal functions are achieved by a combination of technology, infrastructure, production systems, policy and legislation, user practices and cultural meaning [54]. When it comes to explaining socio-technical perspectives about crime and fear of crime the most important element is how the use of technological systems and equipment (such as lighting sensors, security alarms, security electronic devices, CCTV, smartphones or other technological instruments) are influencing safety/security and sustainability. So what makes a public place inclusive, safe and resilient from the socio-technological perspective?

Video surveillance cameras are a common part of the modern world today. The implementation of CCTV cameras has been considered a supplemental tool for surveillance and a potential means of facilitating social control [55]. However, still there are some significant legal and social limitations associated with it [56]. Besides the subjective nature of feeling safe, some people feel that the presence of CCTV makes them feel more confident and safe while others feel it reduces their confidence [57]. To identify the crime prevention effects of CCTV and street lighting Welsh and Farrington [58] found that "CCTV and improved lighting were more effective in reducing property crimes than in reducing violent crimes, with CCTV being significantly more effective than street lighting in reducing property crime" [58]. More focus was given to parking lots and/or garages and little is known about the effectiveness of these crime prevention effects in other public spaces. One example of research on the effectiveness of urban video surveillance in public spaces was assessed by Socha & Kogut [56]. The authors found that the installation of smart surveillance and analysis system in public space supports the use of monitoring systems to prevent and reduce crime and improve safety in public space [56]. Similarly, McCormick and Holland [59] found that CCTV cameras can decrease criminal activities in urban parks. Contrary to this, Surette and Stephenson [60] investigated the relationship between safety and video surveillance camera. The results show that the surveillance cameras had an insignificant effect on the disorder in parks. Ratcliffe [61] identified installation of video surveillance cameras as a tool that increases the risk of facilitating the arrest of the offenders. However, the same study also demonstrated that in general cameras can serve to reduce criminal activity, some locations do not get any benefit from camera installations [61]. In another study, Welsh and Farrington [58] suggest that CCTV works better in well-defined conditions (especially in car parks) than in public places and has the greatest impact on car crime, without having any impact on violent crimes.

The age of new technology has also contributed to the development of methodological, and ethical challenges. For example, Ceccato [62] emphasized on what happens in public space is getting new expressions, for example, the role of guardians in surveillance has been redefined. "Eyes on the streets" by Jane Jacob [36] is complemented by "apps on streets" [62]. Ceccato explored the concept of surveillance and related terms by evaluating the nature of the data captured by users of an incident-reporting app. Results from this study suggest that the app is often used to report a crime, mostly in residential areas (as opposed to inner-city areas). Findings also indicate that data from a survey of app users can rarely represent the actual population of those using the tool, or the population residing and working in these areas [62]. While exploring spatial patterns of guardianship through civic technology platforms at the level of neighborhood units in England, Solymosi [63] found that it is possible to make use of civic tech data to explore people's engagement in guardianship and map their guardianship capacity in physical space by using digital traces of behavior available online, however, there are limitations associated with crowdsourced data as they are characterized by bias sample self-selection as well as participation inequality [62] also highlighted technological, legal, institutional, ethical, and cultural—that limits the use of apps/smartphones for planning purposes. The author emphasized that the issues of data privacy, the responsibility of actions (e.g., intervening) and accountability should be addressed before data of this kind is used [62]. So what makes a public place inclusive, safe and resilient from the socio-technological perspective? Beginning from the installation of appropriate street lighting sensors, alarms to CCTV, using smart mobile phones to location-based services, and reporting crimes digitally to crowdsource data reporting various surveillance techniques can work in both ways as they increase the sense of security, and at the same time creates certain worries among people.

5. Fear of crime and perceived safety in Stockholm, Sweden

Stockholm the capital of Sweden, is one of the green and also one of the safest cities in Europe and the world. Stockholm is chosen as the case study area for several reasons. First, Stockholm is built in between and around plenty of parks and natural green open spaces (**Figure 2** shows 1,046 parks and green spaces in Stockholm. For

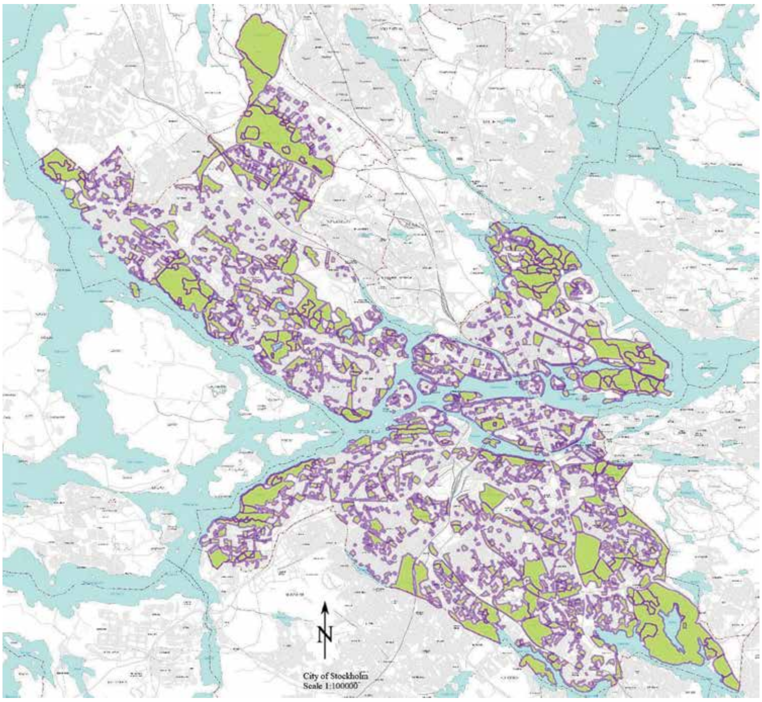

Figure 2.
Public green areas in Stockholm. Source: [2].

more detail, see [64]). Second, little research has been done to know the relation between crimes in parks and public spaces in Stockholm [9–11].

According to the Swedish National Council for Crime Prevention [2], a total of 31 percent of the population (aged 16–84) state that they feel very unsafe or quite unsafe when outdoors alone at night or that they avoid going out alone at night due to the feeling of being unsafe in Stockholm. In particular, Women (42%), complained of feeling unsafe than men (20%). In 2020, 28 percent of the population (aged 16–84) state that they often have chosen another route or another mode of transport as a result of concern about being a victim of crime, while 15 percent have avoided doing an activity often as a result of this concern. Lastly, 10 percent state that their quality of life is affected as a result of being concerned about being a victim of crime in Stockholm [2].

At a macro scale, field survey observations in a pilot study in 2011 were conducted by the author at twenty-five parks in Stockholm [13]. The main aim behind the fieldwork was to understand the nature of parks and to categorize them as either 'amenities' or 'disamenities' according to the attributes that exist in the park. During the study, the author investigated activities/functions, aesthetical features, location and management (crime, the safety and security situation) as the main categories. All parks were inspected at two different periods of the year (winter and the summer of 2011. See [10]). The result of the study shows that Stockholm's central areas are targeted by different types of crimes, with some parks becoming crime attractors [13, 18]. By investigating the incidence of crime in parks, we found that more serious crimes including violence, drugs, assault and graffiti occurred within Hilly Park and Inner City Parks in Stockholm, however, not all parks have high crimes [10].

Some parks, especially parks with Play Grounds, Parks with Squares and Neighborhood Parks had comparatively low crime rates. Several reasons can justify these trends. For instance, no one can deny the existence of students, coaches and parents —who work as capable guardians and have an important role in perceived safety in such public spaces [10]. These findings are in line with the routine activity theory [41] where such guardians assume personal responsibility to react at such places. However, there have been studies that highlight the fact that capable guardians are not always present [65]. Findings also suggest that easy access to a neat, well-managed, and relatively safe Neighborhood Park is valued more in Stockholm. In addition to this park's location plays a crucial role. The crime and safety situation of a park is directly linked to the management and design of park, without taking into account park location in the city. For instance, parks located at or near the city center are valued positively as compared with parks located in the city's periphery [10].

At a micro-scale, Iqbal and Ceccato [9] studied the nature of a park with high crime rates in Stockholm—'Tantolunden'. Tantolunden is located in the southern part of central Stockholm, Sweden. Tantolunden was nominated as one of the most dangerous parks, with the topmost violent reported crimes in Stockholm [66]. Regarding the effectiveness of CPTED in parks and public spaces, a detailed inventory was developed based on CPTED principles [9]. Sweden like its other neighboring Scandinavian countries was quite late to adopt such an initiative that incorporates the CPTED principle [67]. New sustainable housing was built by using CPTED principles in design and planning [67]. Stockholm police with the National housing board in Stockholm launched the most famous strategical document BoTryggt05 in 2005 that was about the inclusion of CPTED measures in housing construction guidelines. In 2017 Stockholm has adopted a strategy for "Greener Stockholm" that provides guidelines for planning, implementation and management of the city's parks and nature areas in Stockholm. The main agenda is to highlight the importance of a safe and equal urban environment to promote perceived safety and social cohesion among all groups of people in Stockholm. Well-designed and illuminated squares, streets, sidewalks, parks and playgrounds were highlighted as important measures for the increased experience of safety in the document. However, still, these principles are not being used as the standards in Sweden. For instance, while implying these guidelines, Stockholm park plan documents for individual districts in Stockholm mainly show concern about missing lights and overgrown bushes and trees. No more information at a deeper level has been provided (for details see park plan of each specific area [68]). Recently, BoTryggt 2030 has been launched — that claimed as a tool for building safer cities that covers not only housing but also neighborhoods, public space, commercial places and more to respond to today's holistic approach in urban planning [69]. To understand authorities' point of view on the use of CPTED principles and collaborative planning in this large nature area park, a questionnaire was sent by e-mail to the park manager and a crime prevention coordinator working in Stockholm municipality. Findings from the questionnaire suggest that safety guidelines that are used in Stockholm are not categorized under the CPTED umbrella yet. These results are in line with the previous findings that CPTED has not been used in its full capacity as it is used in other parts of the world [66]. A policy recommendation on incorporating CPTED principles could be derived from these results.

A great deal of CPTED is mainly about increasing natural surveillance, protecting targets, access control and creating environments that encourage activities that can help to limit crimes. CPTED also helps to focus on criminal activity patterns. If compared to the other similar Hilly Parks in Stockholm such as Vitabergsparken, Kronobergsparken and Vanadislunden, Tantolunden still stays at the topmost reported crimes [70]. According to police statistics [70], vandalism is still the topmost reported crime in Tantoulnden between 2017 and 2019 following narcotics and theft that happens mostly in the afternoon and evenings (see **Figure 3**). The authors found that parks that have large nature areas may have in-between spaces that transform into desolate spaces and, as a consequence, have the potential to attract litter and graffiti that may affect inhabitants negatively [10]. These desolate spaces are also perceived as obstacles to access to other parts of the city. Some of these large-area nature parks are not easy to maintain, and they adopt an atmosphere of disorder and affect negatively [9]. These results are in line with the previous findings of the cyclic relationship between perceived safety and disorder [23, 49]. It has been suggested that a well-maintained park with a sense of belonging among residents and park users can create a positive image [8].

Results from the interview showed how residents feel about the safety conditions of this large area nature park [9]. A total of four interviews were conducted with park users (two males and two females aged 18–40 years). All of the interviewees showed concern for the presence of the so-called "illegitimate" park users [18] such as homeless individuals, alcoholics/drug users). All of them pointed out that public toilets in the park are frequently being used by illegitimate users [9]. This study also concludes that crime in parks must be considered in perspective with crimes in the neighboring areas because any park with high crime rates is usually associated with high crime rates in the surrounding area [11].

Regarding the socio-technical perspective, neither CCTV cameras nor security guards were found in this large nature area park at the time of field inspection (for instance., see details [9]). This can be associated with the Swedish government policies that require authorization to install CCTV cameras. That also put a limitation on the general use of CCTV cameras in parks and other public spaces. Several researchers found that implementation of technical systems and tools such as CCTV cameras can affect criminal activities in urban parks [59], however, it has been also suggested that "none of these measures could reduce all crimes but each may work for a specific offense category and cumulatively lead to an overall crime reduction" [71].

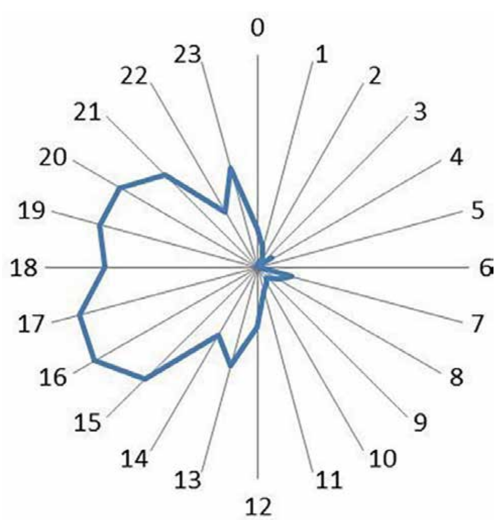

Figure 3.
Reported crimes per crime hour in Tantolunden Park (2017–2020). (Source: [70]).

6. Conclusions and recommendation

Fear of crime has been regarded as a significant social problem in urban areas. As Rezvani and Sadra [5] stated, "the presence of fear of crime in urban environment shows troubles of communities in the modern age" [5]. The ability to be in a park or public space without being fearful is regarded as an individual right and important for the quality of life in a city. The previous discussion shows being safe in a city is such a broad concept that it is not just associated with the actual crimes, many dimensions of the perceived safety that are linked to the built environment should be considered in planning and designing such places to reduce the fear of crime and increase safety. But then which policy or design solutions can create a sense of safety? Which physical attributes discourage crimes in public spaces? Based on the previous discussion, this section provides some of the general policy and design recommendations for being safe in the public space that should be applicable to other major cities of Sweden or cities similar to those as Stockholm.

This book chapter has mainly focused on safety and the influencing physical factors however, other social conditions and factors also play a role in the origin of the crime, and sometimes it is a combination of several factors [52]. Findings suggest that no one can deny the importance of the physical design layout of the parks and public spaces that have an impact on perceived safety. Small area parks and public open spaces with playgrounds are more "preferred" than large nature area parks. Working with the large nature area park's design can help to remove unused in-between spaces, to reduce criminal activities in parks and public spaces. This can be done by splitting park areas into two or more parts according to the design and its requirement. Introducing new activities also encourages mixed land use or mixed activities/functions that can create the flow of people at different hours of the day. This can also help in providing activity support in terms of new guardianship with more eyes on the streets [36]. In contrast, other environmental characteristics in parks, such as maintenance and management of trees and bushes, access control, installation of CCTV cameras can help to create a positive image of the park. Perception of safety also differs according to the time of the day and the presence of more street lights can contribute to the feeling of being safe in a public space.

A way forward, for the implementation of safety and security guidelines in public spaces in Stockholm, is the creation of programs that highlights the implementation of CPTED principles guidelines in public space. Such practices should be encouraged as good practices designed with people not for people and should be showcase as successful and appropriate approaches. Another important issue is to think about the implementation of CPTED's appropriateness to ensure safety on a global scale for instance, in other continents. What CPTED can do to create safer cities must also be complemented by other social sustainability measures. CPTED provides tools and good conditions for reducing crime, however, the active participation of community members in the process can help to implement safe public spaces in Stockholm and to maintain them in the longer term. This way public space can work to empower people and a prospect to create social capital.

Creating safe and sustainable cities requires inclusive and collaborative planning between different actors both at the national and the local level [54]. We can create long-term safe and sustainable cities with the help of strategic planning by including social sustainability besides the economic one [72]. For achieving socially sustainable cities and thus also safe cities, the role at the municipal level is extremely important. As per discussion in the previous section, there are many legal and social restrictions associated with such socio-technological systems that put limitations to their use (such as the need for approval to install CCTV cameras in public places). To improve the image of the park or public space an interface between all stakeholders can create a sense of attachment. Following this, it is also important to understand that new solutions demand new forms of policy formation and collaboration. For instance, about the use of technological systems and equipment. It has long been suggested that risks are attached to human activities and managing and controlling these risks has been built on the experience of generation [73]. Similarly, using these technological systems in creating safe cities is not free from risks, for example, techno trash, pollution, malware, and hacking and privacy issues. It is high time to think of other solutions for producing circular and resilient places.

Public spaces have played an important role in building resilience in the cities. Can we promote a positive urban transition where we design our public spaces in a way that supports better resilience and thus creating sustainable cities? In quest of finding an answer to the above question, this book chapter suggests that despite their intangible and immaterial nature overall, parks and public spaces affect positively and investing in the safety of public spaces does not only affects the quality of a place but also increases the quality of life as a whole because safety is an important indicator of overall social health [5] and quality of life [2]. However, the outcomes of this investment depend on the types of public space and the types of crime that are committed at or near the place. It is important to remember that if these physical designs and improvements will be implemented in public spaces, it does not mean that the crimes will disappear completely. Continuous work with all stakeholders involved and getting to the depth of what causes these crimes is equally important. These findings are important for different groups of people: individual citizens who use such public places in their daily life, police and other safety experts who work with these issues in the city, researchers and practitioners who are involved in the process of creating the safe, sustainable and resilient cities.

Acknowledgements

Part of this research was undertaken under the supervision of Prof. Vania Ceccato while the author was a student at the School of Architecture and the Built Environment, KTH Royal Institute of Technology, Sweden. The author would like to express her thanks to Mikael Blomgren from Stockholm police for providing the current dataset used in this analysis. Special thanks go to Roya Bamzar and the editors of this book for their valuable feedback.

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Chapter 4

Future Urban Environments in Science Fiction: Initiated Thought Experiments

Britt Johanne Farstad

Abstract

Is it possible that science fiction-films have influenced modern architecture and buildings in the real world? Ideas about the design and purpose of future cities often start with visions. Science fiction can be understood as a kind of thought experiment. The experimenter, the writer or filmmaker, begins with a hypothesis and sets up initial conditions. SF writers take notice of their colleagues' work and results; they often borrow fundamental concepts from previous generations of writers. Authors elaborate on and transform these concepts, apply and test them in new situations, and add new ideas. I argue that our capacity to imagine things and phenomena that do not yet exist is important in the process of constructing and reorganizing human life and, hence, also urban environments. The concepts of "city" and "countryside", both of which are often projected and experienced as opposites, with contradictions and conflicts built into them, are examined. Urban Transition through some of the most influential dystopian sf-movies with *Metropolis* is my starting point, films where the idea of the city can be said to be the main protagonist.

Keywords: science fiction, dystopia, archetypes, *city*, *countryside*

1. Introduction

> *You know, there's one thing about Blade Runner: Yes, it's gritty and it's scary, and it is obvious unbelievable unequal as a future society – but the nightlife looks amazing [1].*
>
> *I've seen things you people wouldn't believe. Attack ships on fire off the shoulder of Orion. I watched C-beams glitter in the dark near the Tannhauser Gate. All those moments will be lost in time, like tears in rain. Time to die. Roy Batty, Blade Runner*

Is it possible that science fiction-films have influenced modern architecture and buildings in the real world? "Urban transition" is a highly interesting topic, and I started to wonder if it was possible to find robust links between the SF-genre and modern architecture. It was almost too easy to establish connections between the sphere of fantasy and real-world architecture. A simple google-search settled the question: science fiction plus modern architecture led me directly to interviews with the architects who built the most spectacular buildings during the last decades. Furthermore, I found several articles exploring these connections. Professor of Urban Historical Geography J. R. Gold, states quite simply that the "relationship between cinematic film and the city is close and multifaceted" [2]. My own knowledge in the genre helped to ask relevant questions to the material I found. SF can be said to be an expression of a "Zeitgeist", or 'spirit of the age' [3]. It became obvious in this material that certain ideas in fact have wandered from fiction to reality. Other thoughts have wandered the other way, from reality to fiction. It's an ongoing dance of ideas.

What are the prominent features of the science fiction genre (SF) that make it relevant to focus on in relation to ideas and discussions about "urban transition"? Although technology plays an important role in many SF texts and films, the genre is intensely occupied with ideas about human life, its meaning and purpose, and other existential questions. SF is often labeled "a literature of ideas", which indicates that the genre provides good models of thought concerning science and ethics and provokes and challenges ideas about the human condition. SF literature is by tradition didactic, and many writers and creators working within the genre have played important roles in the ethical and social debates of their time [4].

As technology and science are both integral parts of contemporary culture and society, the effects of science on human lives and societies have increased. Given that SF is characterized by hypothetical thought experiments, it is well suited to debates about how future cities could or should be organized. Scientist and SF author Karlheinz Steinmüller argues that SF is the mythology of the modern, scientific age [5] and states that SF "has become a unique medium for discussing science and technology, their prospects and hazards, and more generally their social and cultural impacts" [6]. As part of postmodern culture, the SF genre has influenced the different forms of media. Steinmüller writes that for "many scientists and engineers, science fiction provides the imaginary of their visions" and claims that SF can be understood as a kind of thought experiment similar to those in science: "The experimenter – the writer – begins with a hypothesis and sets up initial conditions" [7]. Steinmüller argues that in some ways, "SF is quasi-scientific and, like science itself, a collective enterprise. Like scientists, SF writers take notice of their colleague's work and results; they borrow the fundamental concepts from previous generations of writers. They elaborate on and transform these concepts, apply and test them in new situations, and add new ideas" [7]. Hence, I find it relevant to explore ideas about *the city* in SF films and investigate whether or how SF visions have influenced the design and structure of the actual cities that are built? Here, I look at the ideas and the fantasies that appear in architectural visions and real life.

Three connecting topics concerning *urban transition* are discussed in this chapter. In the first part I argue that our capacity to imagine things and phenomena that do not yet exist is important in the process of constructing and reorganizing human life and, hence, also urban environments. SF as "initiated thought experiments" is discussed in this part with *Metropolis* (1927) as the starting point.

In the next part I examine the concepts of "city" and "countryside", both of which are often projected and experienced as opposites, with contradictions and conflicts built into them. The ancient notion, in fact built on mythological tales, of one as better and the other as worse is constantly reproduced in fiction and film. According to these myths, *human life takes place between the mythical and lost Garden of Eden and the New Jerusalem to come. One significant occurrence between these events is when human beings build their first great city, the Tower of Babel*. Hence, mythological conflicts influence the creation of SF films, many of which are often occupied with existential questions. This is important when it comes to ideas about the organization of city life, as well as in depictions of life in the countryside. I argue that notions about what is preferable can be found in some of the mythological tales that have been reproduced in fiction.

In the last part I discuss the connections between SF films and the construction of modern cities around the world. My idea is that our fantasies affect what we want to achieve in the real world. Furthermore, I ask if some of these fantasies and ideas stem from literature and film. For over a century, SF films have depicted futuristic cities. Some of these cities are bright, shiny and positive, while others are described as dark, dirty and rough. In these chapter focus is on the dystopian branch of SF: film history become relevant when it turns out that prominent architects in our time are deeply influenced by the visual visions they experienced as young persons. However, we may need to look elsewhere to find film visions of green, sustainable, future cities, as these do not seem to appear in SF films. Where, I wonder, might such film visions be found?

2. "In the beginning there was Metropolis"

In some of the most significant SF films and their visions of the future, the City can be said to be the protagonist [8]. In a review of SF films and authentic modern architecture, film critic Rich Haridy states: "In the beginning there was *Metropolis*" [8]. *Metropolis*, by Fritz Lang (1927), is a vision of a vertical city and an important film when it comes to real world images of the city. The film is also depicting a society with deep conflicts between classes in the society with a harsh hierarchy between rulers and the ruled. A much later film that was strongly influenced by *Metropolis* is *Blade Runner*, by Ridley Scott (1982). Here, hypothetical visions of architectural concepts of the future city are visualized in a more technically advanced and globalized world than in Lang's film, which was created in the early days of the industrial world. *Blade Runner* is set in 2019 and is an example of how earlier ideas are developed and reproduced. With the film, Scott builds a bridge between 1927 and 1982 in film history. Social hierarchies are even grimmer than in *Metropolis*: the rich have left the planet for another world. Acid rain is falling to let us understand that Earth's climate is seriously disrupted.

In *Blade Runner 2049,* also by Ridley Scott (2017), the themes and motifs are developed further. This is a sequel to *Blade Runner* released in 1982 and according to the film's narrative, 30 years have passed. In both films, Scott deals with the climate crisis and the challenges that future generations may have to deal with in megacities. In these visions of future cities and city life, architecture, infrastructure and human life are representations of extreme abundance and extreme impoverishment, highly advanced technology and collapsing systems, decaying buildings and shattered infrastructure. The vision of future life in cities that is portrayed in this SF film is bleak. The rich and healthy have left Earth to live in new settlements in the colonies. Even in the film *Cloud Atlas* by Wachowski, Wachowski and Tykwer (2012), human beings have fled from the cities to try to make a living for themselves elsewhere [9]. Fantastic technology and architecture are hidden and forgotten. The only way for human beings to survive is for them to leave the planet and find a new and greener one.

Frederik Pohl writes in "The Politics of Prophecy", that to "speak of 'political science fiction' is almost to commit a tautology, for I would argue that there is very little science fiction, perhaps even that there is no good science fiction at all, that is not to some degree political" [10]. Pohl was the initiator of the New York association "The Futurians", which was active in the late 1930s and early 1940s. This was a group of SF writers, critics, publishers and illustrators who believed that "SF fans should be forward-looking ('futurian') and constructive" [11]. Socially critical SF was important because:

> *Their injection of social consciousness into the fandom world had an enduring effect at a time when the pulp stories were beginning to address the future of authoritarian social orders. Graduating to the ranks of professional editors and writers at the end of the decade, they eventually formed something of a counterculture operating against the established power of the field's publishers and editors [11].*

Media researcher Jenkins writes that "the Futurians were committed to the idea that science fiction might function as a vehicle for social criticism and political transformation" [12]. Philosopher Hans Jonas argues that fiction provides thought models for ethics and morality and writes that the "serious side of science fiction lies precisely in its performing such well-informed thought experiments, whose vivid imaginary results may assume the heuristic function here proposed. (See, e.g., A. Huxley's Brave New World)" [13].

Jonas highlights Aldous Huxley's *Brave New World* as an example of an initiated thought experiment and argues that in hypothetical thought experiments there is an opportunity to find ethical foundations through statements that can claim probability. This is sufficient where they should not be evidence but illustrations [14]. As society is becoming increasingly complex, and technological development is rapidly accelerating, it is becoming increasingly difficult for people to have an overview. Jonas writes that "the knowledge of the possible" is "heuristically sufficient for the doctrine of principles" [14]. A complex narrative can accordingly help to get a grip of the challenges that lie ahead [15]. The SF genre, as the Zeitgeist of modernity and an artistic expression with the ability to put real, complex, moral and ethical problems under the microscope, can visualize possible futures. By analyzing futuristic fiction by scientifically trained authors as "initiated thought experiments", as Hans Jonas puts it, it is possible to say something about the hopes and fears that well-informed researchers associate with new technologies. Further, the SF genre's fictional representations of science and technology make it possible to discuss complex thought models based on hypothetical consequences. In Hans Jonas' opinion, these initiated thought experiments can add knowledge about ethical difficulties related to scientific research. Prof. J. R. Gold's opinion is that it "is seldom the case that the film-maker reveals the future city with extraordinary accuracy, and it unquestionably pays to be sanguine about science-fiction film as a medium of prediction" [16]. At the same time, he thinks that "such film can supply us with an accessible and intriguing route into a series of core issues about representations of place" [16]. As Hans Jonas even Gold thinks that the more distinguished SF-films "can supply incisive images that help us to pose questions about the relationship of people and place, and where that relationship is headed."

SF films can thus be helpful when it comes to discussions about different kinds of dangers. One problem that becomes obvious in my project is that futuristic cities are mostly portrayed in ruins in SF films, and it is too late to survive in them. People instead flee to the countryside or to other worlds in order to survive. Prof. J. R. Gold writes that

> *Representation of the city stems from the development and constant reiteration of a handful of urban prototypes. Certainly, in the 75 years since Metropolis codified the essence of the vertical city, only the future noir city has emerged as a fully-fledged alternative [17].*

Ursula Heisse also states that dystopian "views of the cities make up the overwhelming majority of futuristic urban literature and film" [18]. In short, in dystopias the big cities are always in ruins and life is over. The future exists on alien green planets or in rural districts outside the city gates. I will come back to this futuristic vision – which in fact may well be a SF vision of the "New Jerusalem".

3. Human life between the garden of Eden and the New Jerusalem

The archetypical concepts of "city", "country" and "countryside" are relevant in relation to "urban transition" and SF films depicting images of future cities. Modern SF has repeatedly reproduced contrasts between the city and the wilderness surrounding it. The city can be enclosed in huge plastic domes - thus making it easy to differentiate between city life and rural life. Another commonly used narrative is that of old cities that have fallen into disrepair, where memories of lost greatness are uncovered in reminiscences of decay. Narratives of a future city environment in which humans move in the shadow of hostile artifacts are also common. The central idea is the city as fundamentally dystopian. In this text I mention three of the most influential twentieth century dystopias, Zamiatin's *We* (1924), Huxley's *Brave New World* (1932) and Orwell's *Nineteen Eighty-Four* (1949). These books and the film-adaptions films have laid a fundament for the following dystopias. The narrative take place in cities from which escape is impossible. The city is an artificial place, is potentially dangerous and will eventually disrupt. In the end it will be a danger to human beings.

Scientists warn for an ecological disaster at a global level. At present, with global warming and rising sea levels as a result, it is obvious that many of our megacities around the world are facing challenges. Cities located near the coast will be dramatically affected by rising sea levels. Consequently, an important topic in scientific research, politics and popular culture is the narrative about the threat of great floods. This archaic theme has been communicated over thousands of years by word of mouth, as written and printed texts and now through modern films. In SF, several parallel movements occur simultaneously and human life in cities is scrutinized more than ever. As SF expert John-Henri Holmberg states: "The city is the focal point of our civilization, and images of the city of the future bring into sharp relief the expectations and fears with which we imagine the future of civilization" [19].

In my view, mythical contradictions and conflicts have been built into concepts and ideas about the city and the countryside. These contradictions have often been reproduced, and mythical conflicts have influenced the creation of fiction and to a certain degree people's mindset when thinking about future megacities. The starting point for this idea is to be found in the first chapters of *Genesis*, the first book in the *Old Testament*, and in the last chapters in *Revelation*, the last book in the *New Testament*. Hence, we look backwards before looking forwards.

To understand the ideas behind this conflict we will turn to the first mythological home of mankind - the Garden of Eden - as it is described in *Genesis*:

> *Genesis 2:8 And the Lord God planted a garden eastward in Eden; and there he put the man whom he had formed. 2:9 And out of the ground made the Lord God to grow every tree that is pleasant to the sight, and good for food; the tree of life also in the midst of the garden, and the tree of knowledge of good and evil. 2:10 And a river*

> *went out of Eden to water the garden; and from thence it was parted, and became into four heads. 2:15 And the Lord God took the man, and put him into the garden of Eden to dress it and to keep it [20].*

As we know, Adam and Eve failed to live according to God's will and were therefore banished from the flourishing garden. As yet there is no city in sight. The next narrative is the first fratricidal murder in our narrative history. Cain murders his brother Abel and is expelled from the land. He is said to build a city, which is the first to mentioned in these ancient stories:

> *Genesis 4:15 And the Lord said unto him, Therefore whosoever slayeth Cain, vengeance shall be taken on him sevenfold. And the Lord set a mark upon Cain, lest any finding him should kill him. 4:16 And Cain went out from the presence of the Lord, and dwelt in the land of Nod, on the east of Eden. 4:17 And Cain knew his wife; and she conceived, and bare Enoch: and he builded a city, and called the name of the city, after the name of his son, Enoch [21].*

After these mythological events a famous city is built. The Tower of Babel rose in the land, perhaps built on the foundation Cain once made:

> *Genesis 11:4 And they said, Go to, let us build us a city and a tower, whose top may reach unto heaven; and let us make us a name, lest we be scattered abroad upon the face of the whole earth. 11:5 And the Lord came down to see the city and the tower, which the children of men builded. 11:7 Go to, let us go down, and there confound their language, that they may not understand one another's speech. 11:8 So the Lord scattered them abroad from thence upon the face of all the earth: and they left off to build the city [22].*

This is one of the most important myths to be retold and reproduced from the biblical tales: how God denigrated the hard work of human beings. The annihilation is extreme – their language is confused so that they can no longer communicate. Hence, they can no longer make elaborate plans and agree on great achievements. Too advanced technological skills and advanced constructions are equated with megalomania and struck down. It is like eating the apple once again. The Great Flood and the Tower of Babel are two major events in which God strikes hard against people's creative powers.

The Biblical Apocalypse is described in the *Book of Revelation* in the New Testament. First, the dystopian future to come is described. Finally, the heavenly city is revealed to the prophet as it emerges from the sky:

> *Revelation 21:10 And he carried me away in the spirit to a great and high mountain, and shewed me that great city, the holy Jerusalem, descending out of heaven from God, 21:19 And the foundations of the wall of the city were garnished with all manner of precious stones [23].*

> *Revelation 22:14 Blessed are they that do his commandments, that they may have right to the tree of life, and may enter in through the gates into the city. 22:15 For without are dogs, and sorcerers, and whoremongers, and murderers, and idolaters, and whosoever loveth and maketh a lie [24].*

The future paradise is a city with the tree of life in the middle of it. It is in fact the vision of Eden restored, this time within the walls of a marvelous city made of gold and all the emeralds they could ever name. Even the future city of peace and love needs high walls to keep evil out. This heavenly city is obviously a place for the chosen ones, the privileged and the blessed.

The Garden of Eden is an idea about the lost utopia. A major part of mankind's mythical and historical existence thereafter plays out between two contrasting ideas: The heavenly Garden of the long-gone Paradise Eden and the Paradise to come. The last of this complex book that we call the Bible ends up in a narrative circle, where the first main tropes are combined into one. The New Jerusalem is about doom and salvation and, finally, the City represents salvation from disaster and chaos. There are laws, order and structure, high walls, streets, clean house bodies – everything built with the most precious of materials. Chaos still exists but it is outside the gates. The shining city represents enchantment, order and security, as opposed to chaos in the unbridled landscape outside the city walls. The narrative about the return to Paradise happens in harmony with nature. The city in *Genesis,* the Tower of Babel*,* represents a society that collapses into chaos.

On the other hand, the much-acclaimed SF author Ursula K. Le Guin's novels emanate from another idea. One of her novels is called *The Word for World is Forest* (1972) and is a landmark when it comes to contrasting the position of the city and rural areas. Her narrative uses nature as the starting point, the focal point, and cities are the unfamiliar and unnatural habitat. She depicts Nature as the normal place for human beings to live and thrive in contrast to glittering – and hence artificial – cities. The novel can be said to start a movement and growing sub-genre in SF literature called "eco-fiction". In his dissertation *Places of Rest: in worlds of Ruin: Havens in Post-Apocalyptic Fiction* (2021), Andreas Nyström investigates the lost paradise as a focal point in the dystopian branch of the sf-genre. He writes that the "pastoral sensibilities expressed in many post-apocalyptic havens are part of a millennia-long, cross-cultural history of mythologization of paradisiacal gardens" [25].

The "New Jerusalem" in *Revelations* represents a glittering utopian city, where important elements from the lost Paradise are incorporated, such as significant trees and the river that according to the first myth is said to float through the paradise city to come. Our mythological history and background are important allusions and intertexts in the narratives that follow, as mythological ideas and contradictions are recreated and reproduced in modern narratives.

4. "The Burj Khalifa is not just a skyscraper, and *Metropolis* is much more than a film"

Robust evidence of connections between fiction and modern architecture exists in several articles about one of the most famous architects of our time, Adrian Smith (1944) [1, 26]. Among other assignments, Smith is a Senior Fellow of The Design Futures Council. This is an interdisciplinary network of design, product and construction leaders exploring global trends, challenges and opportunities to advance innovation and shape the future of industry and the environment [27]. What is interesting in this context is that references to a film immediately pop up in interviews with the architect. The vision of the biblical New Jerusalem is here as well. In *The Wizard of Oz* we find an emerald city with deep roots in this very old narrative:

> *21:19 And the foundations of the wall of the city were garnished with all manner of precious stones. The first foundation was jasper; the second, sapphire; the third, a chalcedony; the fourth, an emerald... [23]*

The film version of *The Wizard of Oz* (1939) is referred to as a vision and his pictorial starting point. As Adrian Smith designed Burj Dubai, he claims to have been thinking of "another metropolis: the forest of gleaming towers that is the Emerald City, as glimpsed by Dorothy and her friends from the poppy field in the film version of *The Wizard of Oz*". Smith says that the vision from the film was in his mind when he planned the extravagant skyscraper in Dubai, "although in a subliminal way. I didn't research the way it looked -- I just remembered the glassy, crystalline structure coming up in the middle of what seemed like nowhere" [28]. The reference to *The Wizard of Oz* is also important in an older presentation of Adrian Smith's work:

> *If Chicago were the modern-day Land of Oz, the Trump Tower would be its Emerald Palace. (...) As I approach the beaming building there's an extra bounce in my step, and I can't help but think of Dorothy, Toto and her storybook friends skipping along the yellow brick road. Instead of a yellow road, the tower has the Chicago River – and the two have a lot in common. Like the river, the tower is made up of curves and is predominantly blue [29].*

In the interviews with Smith, the connection between the film and the architect's visions is highlighted. The ideas for the design of some of the most startling buildings in modern times originate from films depicting fantasies. Can we then say that ideas forego reality?

What is striking now, is the tendency for some futuristic cities, such as Dubai, to be so explicitly influenced by SF visions that are profoundly rooted in dystopian perspectives. Inspired by video games and big Hollywood cinema, this new wave of big oil-led design is dominated by multi-billionaires developing futuristic worlds. Dubai is a hotbed of Gulf futurism. Syd Mead, Hollywood's much-acclaimed futuristic conceptualist, designer, artist and one of the key designers behind *Blade Runner,* says that the Middle East is a "fantastic example of how reality is catching up with the future as the size, scope and vision of some of the region's projects clearly show. I would like to be a part of the region's horizon and help shape it for a better tomorrow" [30]. Mead claims that life imitates art, and art imitates life, and that this ceaseless movement back and forth can be seen explicitly in the evolution of our cities over the last century [30].

In an article investigating SF cities, Rich Haridy wonders "How our future visions influence the cities we build" [26]. Haridy refers to Fritz Lang, the "granddaddy of all futuristic urban visions" and *Metropolis* as a vision of a future city that has influenced a century of filmmakers. Haridy also claims that *Metropolis* has influenced a century of architects:

> *Taking us through the looking glass, one of the strangest ironies in 21st century architecture is the growing influence films such as Blade Runner are having on real-life constructions. The recently termed movement, gulf futurism, describes a very particular brand of architecture and urban design that is powering through the Middle East [26].*

Once again, architect Adrian Smith's spectacular buildings are used as an example of how fiction impacts modern architecture. Even Haridy stresses that Adrian Smith's hugely influential practice in Chicago, which designs most of the world's supertall skyscrapers, has shown that "his inspiration for designing the Burj Khalifa came from watching *Wizard of Oz* as a child — the Emerald City being these gleaming towers looming high above flat, endless plains" [1].

John R. Gold has examined SF films and the role of futuristic depictions of cities. In the article *Under Darkened Skies: The City in Science-fiction Film,* Gold writes: "Nevertheless, if *Metropolis* is regarded as the work that crystalized the screen portrayal of the vertical city, then Ridley Scott's *Blade Runner* (1982) codified the future noir city. Blade Runner created a bridge in film development" [31]. *Metropolis* is a "dystopian vision of a vertical city and *Blade Runner* develops and transforms the idea to the modern world of 1982" [8]. It is possible that the idea behind this vertical city design in films is that future megacities will be dominated by massive skyscrapers and the "urban footprint will not spread outward but instead we will build taller and taller buildings that will ultimately encompass all aspects of a human society within a single tiered building" [8].

However, it is more likely that the vertical city was an effective way of visualizing inequalities in economic and political power: the high city rises from a fundament consisting of a base of workers and slaves living and producing necessary goods underground. For much of the 20th century, the vertical city idea became intrinsically interlinked with dystopian SF visions. The rich lived at the top and the poor scrambled about on the grim streets below in exactly the same way that Fritz Lang pictured the future city in 1927. This literal illustration of a class-based hierarchy has been portrayed in a number of interesting SF novels and films from the early days of film to more recent stories, such as *Elysium* (2013) and *Altered Carbon* (2018) [8]. The world of *Blade Runner* is a compact industrial, ethnic and lingual mishmash. The city center, where the enormous Tyrell concern is situated, is constructed upwards. Images of the city with skylines and flying vehicles remind us of *Metropolis*, but the Tyrell building reminds us even more of an ancient Mayan temple and paintings of the Tower of Babel. The Fredersen headquarters in *Metropolis is called* the New Tower of Babel. As we can see, Biblical allusions are frequent in these narratives.

Stephen Graham, Professor of Cities and Society with a particular focus on cities and speculative fiction, sees a somewhat unsettling trend playing out in some of these new, large-scale architectural visions. In *Vertical: The City from Satellites to Bunkers* (2016), he describes the almost shocking experience of landing in Dubai in 2020 and seeing the 830-metre high Burj Khalifa: "It felt as though we'd arrived on some vast stage set for a highly sanitised sequel to *Blade Runner* made by Disney" [32]. He describes the horizontal vs. vertical constructions and their impact on the landscape, water supplies and so on. The first priority in the new megacities is hardly sustainability. In the article "How science fiction dystopias became blueprints for city planners" [1]. Graham says that there is "a really startling and disturbing similarity between a lot of these sci-fi vertical dystopias and the current practice in, say, the Gulf, where the elites inhabit their penthouses and fly around in helicopters and business jets while literally thousands of workers are dying every year to construct these edifices" [1]. He emphasizes that: "These are not just imagined cityscapes: The way these putative futures are imagined have enormous implications for our contemporary urban life" [1]. These examples thus make it possible to suggest that the ideas behind planning and construction stem from ideals and archetypes shaped out of images and impressions inflicted on us as individuals and as collective consumers of pictures, films, fiction and narratives. Super-rich builders are obviously attracted by the idea of the vertical city.

The time may have come when the two separated worlds will be combined. The best parts of life in the green, flourishing rural world merged with the best parts of urban life to make life more sustainable for more people. Green sustainable cities emerge as visions in the fictive and political landscapes. In SF, the Lost Paradise and The Tower of Babel have been portrayed time and time again. It may be time for the New Jerusalem to be the new vision to be investigated in narrative form.

5. Green cities: a synthesis and a sustainable vision?

In the introduction to the film *The Human Scale – Bringing Cities to life* (2012), film director Andreas Møl Dalsgaard states that: "The megacities are a reality, and it looks a lot like the visions of the science fiction-films, gigacities are soon to be" [33]. More than half of the world's population live in cities and, among other things, face the challenges of climate change, urban development and overpopulation. Urbanization is rapidly increasing. It is estimated that by 2050, 70 per cent of the global population will be living in urban areas [34]. Climate change adaptation, green cities and smart cities are buzzwords. Stimulating urban transition and transformation to achieve sustainable and resilient cities is one of the greatest challenges of our time [35]. Policy documents and political agendas are debated and written at national and global levels: "In this unprecedented era of increasing urbanization, and in the context of the 2030 Agenda for Sustainable Development, the Paris Agreement, and other global development agreements and frameworks, we have reached a critical point in understanding that cities can be the source of solutions to, rather than the cause of, the challenges that our world is facing today" [36]. The idea is that "well-planned" and "well-managed" urbanization can be a powerful tool for sustainable development for both developing and developed countries [36].

Urban transition implies that urban environments will undergo important changes that are critical from many points of view. Agreeing on sustainable solutions to the multitudes of challenges that humanity is facing is difficult due to conflicting values and views about natural resources [37]. One obstacle that can be difficult to overcome is determining what a sustainable city really is. Hence, we need to discuss *the city* as a phenomenon: one that is both an abstract idea and a physical and mental reality. Ideas about "a city" consist of resilient stereotypes and mental conceptions, where the countryside or rural environments are the most recognizable opposites and juxtapositions.

Cities are economic and administrative centers in nations and societies, as opposed to the peripheral areas outside a city's boundaries: the rural countryside that provides the city with necessary goods. Cities thus represent power, and rural areas less power. City dominance is manifested in complex buildings, advanced logistical systems and infrastructure to make all parts of the city function. Status and power are manifested in the number of luxurious homes and business districts for the people in power. At the same time, there are poor districts within cities, bad housing and crowded spaces for the less fortunate living there. In good times, cities represent abundance, law and order, often in contrast to insufficiency and less control outside the city's domain. The precondition for people to live in cities is that the countryside provides them with the necessary goods and resources. In times of economic problems, war, famine or pandemics, the situation is drastically reversed. Major cities are the most vulnerable and will be attacked first if war threatens. People will try to escape to the countryside, which will then become a place of shelter and survival.

Cities can be said to be in a constant state of *transition*. The sustainable and dignified conditions that we try to realize in modern cities, and the notions of how modern urban societies could be organized, start with ideas. These ideas affect how we think that cities could be constructed, what ought to be prioritized, what we consider to be a good life and how a good life can be organized. What role might SF have in envisioning the future? Hopes and fears are often concretized in the SF genre's hypothetical narrative method: what will be the result if …? There are plenty of dystopias and doomsday stories and a noticeable lack of optimistic narratives.

6. Conclusions

Earlier I stated that we may need to look elsewhere to find film visions of green, sustainable, future cities, as these do not seem to appear in SF films. The great blockbuster films continue to reproduce the archetypical narrative of the conflicts between cities and rural districts. The disasters are due to environmental problems as we know them from scientific and news reports all over the world. Tipping points are pandemics, overpopulation, rising sea-levels, a new ice age, genetic manipulation, AI, intelligent robots and so on, all of which are said to cause the world as we know it to collapse. The stage may be set in intergalactic contexts, but the story remains the same: the countryside, which may be our old Earth, in conflict with new cities, in the form of interstellar societies to which the rich and powerful have emigrated. SF films, as opposed to novels in this case [38], seem stuck in archetypes as well as being dependent on big money.

Despite this, films are created by actors other than large corporations and money machines. Many of them also tell other and different stories. Under the parole "More Than Movies: A Movement", the San Francisco Green Film Festival is working to tell other stories. As a non-profit organization "committed to using the power of film to bring audiences into the global conversation on environmental solutions" [39]. And to "spark green ideas and actions". According to the presentation, it is "dedicated to sharing stories from the environmental front-lines that inspire, inform, and ignite change" [40]. Under the heading "Films for the Earth", educational films are collected on a website in the same spirit to inform that change is necessary and possible to achieve [41]. Perspectives are turned upside down: finally, human beings are at the center of the planned transformations in cities. In a film called *Edible City: Grow the Revolution*, activists and initiatives from people living in cities demonstrate how they grow their own food. People spread knowledge, develop local economic cycles and find hopeful solutions to monumental problems. The film demonstrates how people develop models for healthy and sustainable local food systems that are environmentally friendly and crisis resistant [42]. In the film called *The Nature of Cities*, architecture professor Timothy Beatley visits several cities to investigate how city planners, landscape architects, ecologists and residents view the symbiosis between cities and rural landscapes. Here, two archetypes merge into visions about the new cities.

Filmmakers are creating new and sustainable visions of futuristic cities in which the inhabitants produce food and take nature into their towns. Plants grow on house walls and on roofs, while vegetables grow in open green areas in the middle of the city. The filmmaker's idea is to inspire people around the globe to make this happen and be part of a solution for sustainable city life. They film to visualize new futures but without the cataclysmic conflicts that SF films are in need of for the dramaturgy to work. In SF-films we find dystopias which can be helpful when we can discuss what went wrong, but we seldom find the utopias where inspiring ideas of solutions are found. When it comes to literature it's a totally different story [43]. The circle of ideas continues the dance, where reality and fiction affect one another. Despite this, blockbuster SF films about well organized, beautiful and thriving green cities are still missing in the world.

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Section 2

Sustainable Energy Systems – Enable Urban Transitions

Chapter 5

Review on District Cooling and Its Application in Energy Systems

Sana Sayadi, Jan Akander, Abolfazl Hayati and Mathias Cehlin

Abstract

This chapter investigates the implementation of district cooling systems by exploring several research studies reported in the literature. The topics addressed include typologies and design parameters, benefits and limitations, applications of the system, and the technology readiness level. District cooling systems are generally regarded as cost-efficient and environmentally friendly solutions. One might think that district cooling is only a solution for areas with a very warm climate. However, based on the reported results of the surveyed studies, the number of operating district cooling systems has increased over the years, with the Scandinavian countries taking the lead in this market within European countries. Implementation of these systems concluded reduction in primary energy and electricity use, they also proved to be an environmentally efficient way.

Keywords: district heating and cooling system, district cooling, free cooling, energy systems, energy efficiency

1. Introduction

With the increase in population and urbanization, energy use also has grown rapidly worldwide. Energy use in the building sector (commercial and residential buildings) has increased between 20 and 40% in developed countries [1]. Several researchers have worked on moderating the use of fossil fuels by introducing alternative energy sources such as industrial waste heat, biogas and biomass, nuclear energy, geothermal and solar energy, groundwater [2–5]. The European Union is responsible for 33% of the total CO_2 emission [2]. Based on the European Green Deal, the European Commission has provided an action plan to ensure energy transition as the EU aims to become the first climate-neutral continent by 2050 [6]. To oblige with these implications, energy-saving technologies have to be integrated into different energy sectors, especially the building sector since the energy demand is 36% of the global final energy use [7]. Studies have been conducted to analyze the increased use of biomass to reduce CO_2 emission in different sectors such as transportation and building sectors [8, 9]. One way of reducing the amount of resource use is to connect several customers' heat and cold demands with the available sources [10]. District energy systems are said to promise energy security as they offer flexibility in their energy use compared to individual energy systems [11]. The heating or cooling resources can be from renewable sources of energy as well as non-renewable sources.

The cooling energy demand for buildings varies depending on countries and their outdoor temperatures. Buildings have various cooling demands due to the differences in the construction material, size, occupant behavior, the purpose of the building, etc. However, it should be pointed that even identical buildings have different cooling demands depending on the kind of activities within the building. Due to the recent changes in climate and its implications on the energy performance of the buildings and indoor thermal conditions, different space cooling technologies have gained more attention. It is likely to predict the growth of cooling demand in Europe due to rising ambient temperatures (including heat waves), heat island effects, higher thermal insulation levels, increased comfort desires/requirements, and the fact that saturation of cooling demand is significantly lower than in the USA and Asia. Estimated cooling saturation for commercial and residential buildings in the USA was 80 and 65%, respectively, and Japan had 100 and 85%, respectively, in the year 2005. Corresponding cooling saturation numbers for Europe were 27 and 5%, respectively [12]. The cooling saturation for EU27 has passed 40% for the service sector and is around 7% for residential buildings [12]. It has been estimated that 10% of all building areas in EU28 were cooled and covered around 16% of the total cooling demand in the year 2014 [13]. In Europe district cooling was introduced in the 1990s; however, it is still a rather uncommon cooling solution with a market share of only around 1% of the cooling market in 2014 [12].

The desired indoor conditions can be met using individual cooling devices such as air conditioners, central air conditioning systems, or district cooling system (DCS). The district cooling system supplies chilled water for cooling and dehumidification to a group of buildings in a district (city, neighborhood, or campus). The coolant (usually water) is typically generated at a central chiller plant and circulates through a distribution network between a central cooling plant and the buildings in the district [14, 15]. **Figure 1** depicts a DCS using a natural source such as a lake/sea to cool the buildings. It is generally referred to as free cooling.

Water in the district cooling network gets cold from nearby natural cold sources, such as a river/sea, and if needed from the cooling machines, that is, when the temperature of the cold source (the river) is high. The combination of free-cooling and cooling machines demands less electricity compared to separate heat pumps or cooling machine installations in every building.

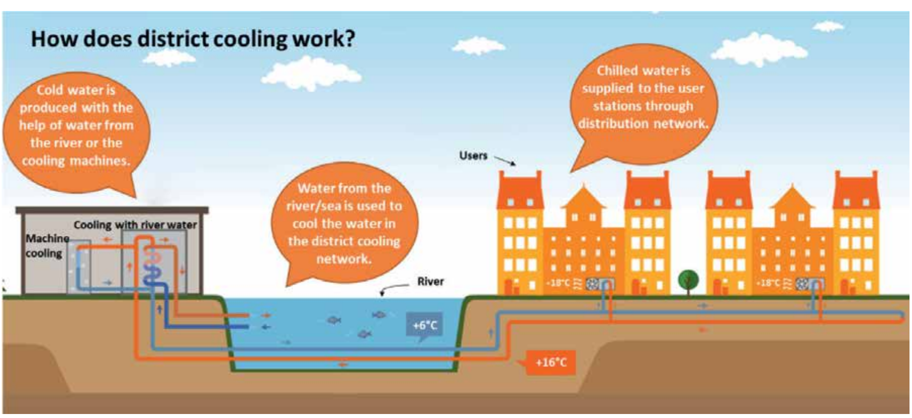

Figure 1.
Schematic of a district cooling system (DCS). Reprint with permission from Gävle Energi AB [16].

Water from the river/sea is used to cool the water in the district cooling network. When the district cooling water is cooled to 6°C, it is pumped to the connected building/consumers through the distribution network that comprises supply and return pipe. The cold and heat carriers in the district network are generally in the form of pressurized water and to be economical, the dense urban areas appear to be a fulfilling choice as the distribution pipes should be short [10].

Cold is delivered to the consumers (offices, buildings, industries, server halls, etc.) through the district cooling network with the help of the heat exchangers at user buildings [17]. Cold can be delivered to the cooling coils (to cool the supply air in the air handling units) or via chilled beams installed in the building zones.

Overall, as seen in **Figure 1**, four major parts could be introduced in a district heating or cooling system: the main supply unit, distribution networks, user stations, and finally the heating or cooling system inside the building's zones. Cold can be supplied for industrial purposes too, such as food preparation, although it is beyond the scope of this chapter.

It is possible to incorporate either a single or multiple cooling technologies in the DCS central chiller plant depending on the available energy sources (thermal or electrical), environmental and economic considerations as well as the demand profile. Absorption chillers are among the available options for chiller plants. Absorption chillers use heat and not electricity as their primary source of energy [18]. They possess a lower COP (coefficient of performance); however, the electricity consumption and primary energy use are reduced in these chillers and the mechanical compressor of a compression chiller is substituted by a thermal compressor [19]. Renewable thermal energy such as biomass waste or solar energy could be utilized using heat-driven chillers or thermal power plants. In such plants, the heat could be transferred to electrical or mechanical energy to drive the vapor compression chillers. The triple-effect lithium bromide absorption chillers could be exploited for DCS as they could be driven by higher-grade sustainable heat sources [20].

Free cooling is another option for a central plant. The available natural cold sources are involved in cooling the building; the heat will naturally flow out without the need of the compressor and the vapor-compression refrigeration system [15, 21–23]. Rivers, lakes, the sea, and outdoor air are among the natural cold sources. By using seawater air conditioning, deepwater conditioning could be employed as in this situation, and the water temperature is well below the ambient temperature (generally around 5°C). For such DCS, it is possible to utilize 100% free cooling. However, given the lack of natural cold sources, free cooling could be combined with other cooling technologies such as absorption chillers to compensate for the lack of available cold from the lake/sea, especially on a seasonal basis. An approach to using naturally cold water is cold district heating and cooling [24]. In this context, the cold water from the lake, sea, etc., is used for direct or active cooling in the system and serves as the cooling fluid. With the help of the decentralized chillers or pumps, the water is chilled or heated for the district system. A research project introduced seawater district cooling and analyzed the system through a case study in Diego Garcia [25]. It was concluded that the system was economically efficient and reduced maintenance and electricity usage.

This book chapter aims to investigate the implementation of district cooling systems by exploring research studies reported in the literature. The topics addressed include typologies and design parameters, benefits and limitations, applications of the system, and the technology readiness level.

2. Review method

To provide an overview of the available district cooling systems and their performance for different applications in various climate conditions, a literature review was performed.

Different databases have been used to identify available books and academic literature, including ScienceDirect, Google Scholar, and Scopus.

Keywords such as district energy, district cooling system, free cooling, absorption chillers, the resilient building were used. No limitation was applied on the publication period, though recently published works were prioritized.

3. Typologies (classifications) and design parameters

In this section, three different classification groups are proposed. The primary proposed classification is based on the system: Centralized and decentralized DCS. The former category is suitable for large-scale regions where the energy is distributed among several buildings in an area. The latter category is more suitable for small capacities where the energy conversion takes place in the units outside the buildings and then is transferred to the buildings [2, 26–28].

The second proposed category is based on the central plant: free cooling systems or the use of heat pumps and chillers [29–31].

The third category is based on the occupant behavior as well as the building typology, which is design parameters that can affect the energy use in the buildings. Occupant behavior mainly consists of interactions with operable windows, lighting, blinds, thermostats, and plug-in appliances. Building types are such as villa, retail, public office.

4. Benefits and limitations

Literature covers the benefits and limitations (disadvantages) of DCS. These benefits and limitations are categorized from three perspectives; environmental, operational, and economical.

Environmental advantages:

- District heating and cooling (DHC) possesses the ability to be integrated with renewable resources, consequently reducing greenhouse gas (GHG) emissions, and saves energy. The central water-cooled chiller plants on the large scale use a lower amount of energy and appear more efficient compared to the on-site small capacity systems [20, 32–34]. Therefore, DCS appears more successful in dense areas in a city or municipality since nearby these areas, there are generally some natural cooling or waste energy sources available [35]. However, these two criteria can be found in many areas and cities.

- A DHC system aims at saving primary energy, electricity, space, inhibiting air pollution, and reducing environmentally harmful refrigerants [36].

- A DHC system aims at saving energy and space, and inhibiting air pollution, and helps to eliminate environmentally harmful refrigerants [36, 37].

- District cooling can greatly reduce the electricity use and peak power demand, and thus reduce energy use, during the cooling season [35].

Environmental disadvantages:

- Depending on the central plants, DCSs may not totally be environmentally friendly as long-term use of the free cooling sources such as sea or lake might affect the temperature of the sources and limit the cooling capacity if no anticipating measures are considered. It also could affect the ecosystem of the sources [38].

- A free cooling system uses a vast amount of water, which is a problem in areas lacking water [30].

Operational advantages:

- Prevention of intensive use of chillers and machinery space in the user stations [39].

- Noise and structure load reduction [39].

- Saves space by removing the cooling tower and chiller plant from the buildings or roofs [39].

- A wide range of production methods and always the latest type of equipment are integrated with DCS due to mitigation measures against global warming [30, 40].

- District cooling has less requirement for technical staff on building level [34].

Operational disadvantages:

- Heat loss within the plant itself as well as the building serviced by the DHC due to distribution losses in pipes and heat exchangers is inevitable [41, 42].

Economic advantages:

- The transparency of costs and future proof investment due to easy payment of utility bills [30].

- The DCS is relatively flexible as different central plants could be utilized based on the fuel cost, therefore reducing the cooling cost [20, 35, 43].

- Owned by the municipality, a district cooling system can capture cash flows that were previously paid for imported natural gas or electricity [35].

- DCS can provide more job opportunities as it provides more reliable and flexible services by a specialized professional team [39].

Economic disadvantages:

- Selection of a system that shows large environmental benefits may, in fact, end up not being economical as both the environmental and economic aspects have to be considered together [32].

- In purpose to utilize cogeneration of district system and electricity, larger DHC is required [44].

- High initial investment costs and lack of negotiable prices and tariffs from the customer's side as DCS are often owned by few local energy companies, and there is a risk of monopoly for the cooling prices and tariffs [10].

5. Application, technology readiness level, and performance with a focus on resilience

In this section, DC cooling technologies, energy sources, operational aspects, and the applications of DC systems are reviewed based on implemented DC technologies through published DC design and analysis research. Before heading to the applications of the DC systems, the concept of resilience is introduced.

The resilience of the building is its ability to withstand extreme weather conditions and recover from the possible incurred damages efficiently and quickly [45]. Chen et al. [46] investigated the resilient cooling strategies and Hay [47] investigated resilience as a developing planning tool for communities. District energy was recommended as the technology that can balance the relationship between the communities and the region [47]. Sharifi et al. advocated for developing district energy systems, net-zero buildings, and neighborhoods as criteria for assessing urban energy resilience [48].

Based on a report from International District Energy Association (IDEA) [49], in 2019, 303 buildings and Ca 10.8 million ft^2 were added to the district systems, beyond North America, which is a strong growth in the district systems employment. The number of buildings and the area that was used for the system in 2018 correspond to 156 buildings and Ca 50 million ft^2. Based on the statistics in [50], 70% of residential end users in high-population areas in Europe were powered by fossil fuel in 2015. Hence, DHC networks show great potentials that can help in decarbonization and improvement of indoor air quality as these systems help to reduce the primary energy use by utilizing renewable sources of energy and reducing the thermal losses [51].

A few studies are introduced to show the performance of DCS through simulation and real data collection in different climate conditions and their effects on building's cooling loads. The studies that were dedicated to Asian countries are presented to show the diversity of DHC systems as Asian countries are developing more DHC systems to reduce air pollution, primary energy use, etc. Later in this section, research projects dedicated to DHS in Europe are introduced.

A study was conducted on the performance of DCS vs. individual cooling systems (ICS) in Hong Kong considering different chilled water pump schemes [52, 53] for commercial buildings. Based on the simulation results, DCS consumes around 15% less energy compared to ICS. The annual operation cost of DCS also is 10% lower than ICS under the electrical tariffs of Hong Kong.

Energy modeling of DCS was conducted in [14] in the South East Kowloon Development Project in Hong Kong for residential and commercial buildings. Based on the simulation results, chilled water, eutectic salt, and ice storage could respectively result in a 38, 38, and 22% reduction in installed cooling capacity. An et al. [54], Yan et al. [55], and Nagota et al. [56] analyzed the performance of DCS in districts in China and Japan and concluded the energy-saving effect of DCS. Studies were conducted with absorption chillers as the cooling technology in other parts of Asia such as Thailand [57], Turkey [58], Iran [59] and concluded the energy and carbon emission-saving effect of DCS. As it could be seen from the mentioned studies so far, the positive economic implication of the DHC system is generally observed from the conducted studies.

The Scandinavian market is taking the lead with 49 operating DCS, followed by Germany (28 operating DCS) and Italy (14 operating DCS) [30].

A detailed study on the market of DCS in Sweden is done by [60]. Major district cooling systems appear in Stockholm, Gothenburg, Linköping, Solna-Sundbyberg, Lund, and Uppsala. Based on the statistics reported by Energiförtagen [61], deliveries for 2018 totaled 1156 GWh. It was a record year for Swedish district cooling and an increase of 26 percent compared to 2017, due to an exceptionally hot summer. The total length of district cooling pipelines increased to 627 km, while in 2019, deliveries totaled 991GWh. **Figure 2** shows deliveries and network length from 1996 to 2019 [61].

From **Figure 2**, and the economic and environmental benefits provided through the expansion of DC capacity, a continued growth in DCS is expected.

Fahlén et al. [62] presented a study based on the DHC system of Gothenburg. Combined heat and power (CHP) plants and excess heat from industries supply about 80% of the heat. The study assesses the potential of absorption cooling technology

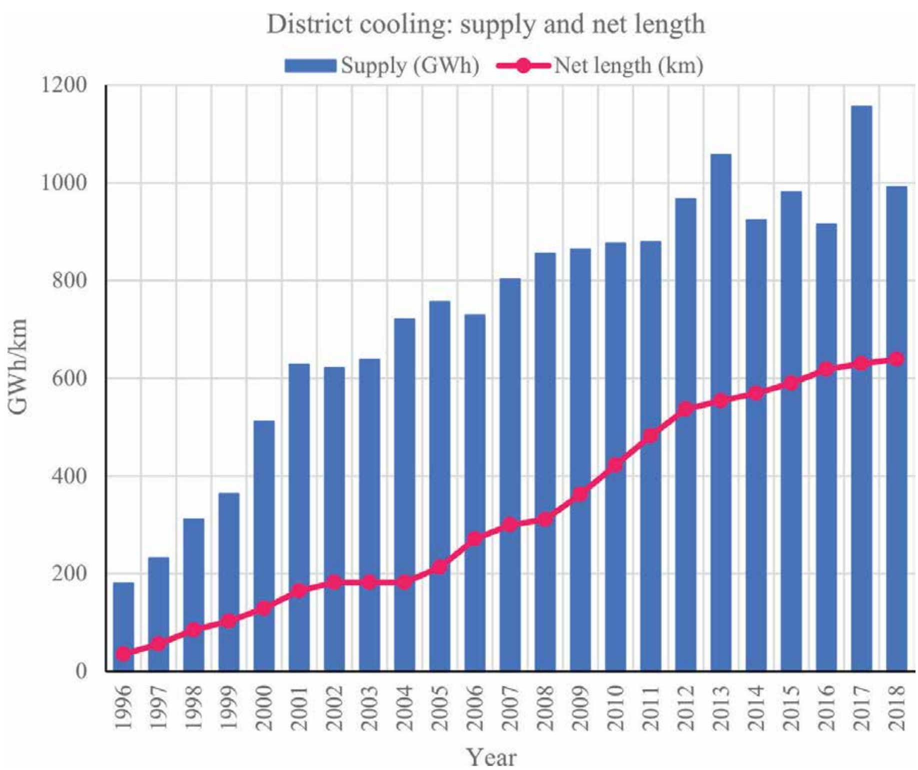

Figure 2.
District cooling deliveries (GWh) and network length (km) in Sweden [61].

to improve the economic and environmental performance of the DHC system. The results show potentials for cost-effective CO_2 emission reduction.

The use of absorption chillers in a DCS in Sweden was studied in [63, 64] and the energy performance of the system appeared to improve. A DCS was initiated in 1995, in the city center in Södermalm, Stockholm. Later, it was expanded and another area was added to the system. Both the districts are connected by pipes located in lake Mälaren [65]. In the Södermalm DCS, existing heat pumps in Hammarbyverket were used.

DCS design has evolved over the years from for example constant to variable flow in the distribution loop. These evolutions and updates in design practices have continuously been upgraded and employed in the system. A long-term security of supply is a driving factor in the heating/cooling systems especially in DHC since the heat/cold is generally supplied by local units. Therefore, it is important to upgrade the design in such a way as to achieve this aim. To be able to express a general reliability level, a definition has been anticipated as the system reliability rate for a DH system [10]. The rate is regarded as the ratio between the numbers of supplied available district heating to the customers during a year by total hours in a year [10]. Many factors are responsible for low system reliability rates such as the fuel supply, pipe failures in the distribution networks, water leakages caused by corrosion or pressure surges, and power outages. The latter mentioned factor also influences the short-term reliability of the system. All the mentioned incidents affect the resilience of the system. To compensate for the power outage, a backup electricity generation is generally anticipated for the main distribution pump. To measure the technology readiness level also, the U.S. Department of Energy has introduced a method to calculate the readiness level [66].

Another problem associated with DHC systems that affect the resilience of the system is the high delta-T syndrome. Due to several reasons, degradations occur over time, which deteriorates the standard temperature difference between the supply and return water that in turn affects the performance of the system. A research project was conducted on the low delta-T problem of the DCS in Gothenburg, Sweden [67]. The problem was analyzed by collecting operational data from the Gothenburg district cooling system along with chilled water systems from 37 of the connected buildings. The results depicted several solutions in the district cooling system to overcome a low delta-T and increase the return temperature. For instance, it was recommended to comply with the building design guidelines as well as limit the flow on the primary side of the heat exchanger, and this helps to restrict the operation in the saturation zone of the heat exchanger. A similar study was carried out by Henze et al. [68] on two university campuses in Massachusetts and Colorado and proposed a solution that provided additional cooling load to the campuses with the same central plant system. The mentioned issues raise the importance of maintenance of the system since the system has to be able to retain its ability to withstand future shocks such as those mentioned above, as well to extend its technical lifetime to remain resilient.

6. Energy efficiency and life cycle analysis

To quantify the energy efficiency of the DCS, three energy efficiency factors were proposed [55]. These factors are presented using Eqs. (1)-(3) and each is explained in this section.

"Coefficient of performance" of the chiller plant is represented by COP_{Plant} (Eq. (1)) where Q is the total cooling supply of the chiller plant. W_{plant} is the energy use of the DCS plant.

$$COP_{\text{plant}} = \frac{Q}{W_{\text{plant}}} \tag{1}$$

WTF_{distri} represents the “water transport factor” of the cooling distribution network system (Eq. (2)) where W_{distri} is the energy use of the cooling distribution system which is the total energy use of all secondary water pumps for chilled water.

$$WTF_{\text{distri}} = \frac{Q}{W_{\text{distri}}} \tag{2}$$

SCOP represents the “system coefficient of performance,” which is the overall energy efficiency of the chiller plant and the distribution system (Eq. (3)). Based on the previous studies, 80% of the energy consumed by the chilled water pumps leads to cooling loss, which is due to the chilled water distribution; therefore, it must be accounted for in the calculation process.

$$SCOP = \frac{(Q - 0.8WTF_{\text{distri}})}{W_{\text{plant}} + W_{\text{distri}}} \tag{3}$$

Keeping the efficiency of the system aside, the feasibility of a DHC system could be investigated by taking into account the cost analysis. To provide an effective evaluation of the energy system and the cost-effective alternatives, life cycle cost analysis (LCCA) could be considered. The energy performance and cost analysis of DCS have been evaluated in several studies [69–71].

LCCA takes into account the costs involving the construction, operation, and demolition phases [72]. The life cycle cost (LCC) is as below [71]:

$$LCC = C_{IC} + \sum_{1}^{n} PWF(i, n) \times (C_{\text{fuel}} + C_{OM}) - PWF(i, n) \times C_{\text{Dispose}} \tag{4}$$

$$PWF(i, n) = (1 + i)^{-n} \tag{5}$$

where $PWF(i, n)$ is present worth factor; C_{IC} is initial capital cost; C_{fuel} is natural gas cost; C_{OM} is operational and management cost; C_{Dispose} is abandoned equipment cost; n is life cycle period and i is interest rate.

The dynamic payback period (PP) of investment, considering the time value of the capital, is calculated using Eq. (6):

$$PP = \frac{\ln\left[\left(1 - \frac{i \times C_{IC}}{C_{\text{power}} + C_{\text{cool}} + C_{\text{heat}} + C_{\text{hotwater}} - C_{\text{fuel}} - C_{OM}}\right)^{-1}\right]}{\ln(1 + i)} \tag{6}$$

where C represents cost and the subscripts represent the respective parameters.

7. Conclusions

With the increase in energy demand, especially cooling energy due to climate changes and the rise in comfort requirements in buildings, meeting the future energy demand has gained more attention. Resilient, economic, and environmentally friendly solutions are required to meet the future energy demand. To fulfill the growing cooling demand and the community's growing concern about carbon footprint reduction and energy resilience, DC systems are becoming increasingly attractive to communities. District energy is a flexible system in terms of the sources as they can accommodate both cooling and heating. The main focus of the chapter was the district cooling systems and it was aimed to outline the possibilities and benefits of using a district energy system specifically the DCS. Three classification groups based on the system, central plant, and occupant behavior were proposed.

DCS can reduce electricity use and peak demands and be integrated with renewable resources, and, therefore, contributes to reducing greenhouse gas emissions and air pollution. Several sources can be used—free cooling together with electricity or thermally driven chillers. These systems are more efficient in more populated districts. Since the coolant is produced in the central chiller plant, not only the use of space in the building is minimized, but the noise pollution also is reduced. District cooling systems have been reported as economic and environmentally friendly solutions to meet the cooling demand of buildings. The investigated studies in this chapter reported a decrease in energy use when DCS was implemented.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

Funding of the study by the Swedish Energy Agency, Termo program, is greatly acknowledged (District cooling vs. local solutions for space cooling, project number 48296-1, Dnr: 2019-003410).

Abbreviations

CHP	combined heat and power plant
CO_2	carbon dioxide
COP	coefficient of performance
COP_{plant}	coefficient of performance of a chiller plant
DC	district cooling
DCS	district cooling system
delta-T	temperature rise of the cooling water
DH	district heating
DHC	district heating and cooling
GHG	greenhouse gases
ICS	individual cooling system
SCOP	system coefficient of performance

Q	cooling supply of a chiller plant
W_{distri}	energy use of a cooling distribution system
W_{plant}	energy use of a chiller plant
WTF_{distri}	water transport factor
$PWF(i,n)$	present worth factor
C_{IC}	initial capital cost
C_{fuel}	natural gas cost
C_{OM}	operational and management cost
C_{Dispose}	abandoned equipment cost
C_{cool}	cooling cost
C_{heat}	heating cost
C_{hotwater}	hot water cost
n	life cycle period
i	interest rate

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Chapter 6

Photovoltaic-Thermal Solar Collectors – A Rising Solar Technology for an Urban Sustainable Development

Diogo O. Cabral

Abstract

The increasing global warming awareness related to climate change due to the high emissions of carbon dioxide in recent decades linked all nations into a common cause, which requires ambitious efforts to combat climate change by adapting energy systems to its effects. This book chapter aims at investigating the potential role of Photovoltaic-Thermal (PVT) solar collector technologies for an urban sustainable development based on the current state-of-art, system components and subsidies for PVT technologies. PVT technologies are a practical solution to compete with isolated systems such as photovoltaic (PV) modules and solar thermal collectors if a significant reduction in manufacturing cost is achieved, coupled with an increased energy production performance. Therefore, its success is intensely linked to the capacity of the PVT industry/researchers to scale down its current system cost and complexity in a way that can shorten the cost/performance gap to both PV and Solar Thermal (ST) technologies. The knowledge gained presented in this book chapter has been acquired through an extensive literature review, market surveys and project development made by several PVT experts with extensive expertise in the development of PVT technologies, which establishes the foundations for more efficient and cost-effective PVT solar collectors.

Keywords: photovoltaic-thermal collector, PVT system assessment, performance evaluation, urban development, sustainable development

1. Introduction

1.1 Fundamentals of PVT collectors

The quest to decarbonize electrical and solar thermal (ST) systems has never been more urgent. While decarbonisation of the electrical system is on track, the decarbonisation of ST systems has not been tackled. ST systems typically make up about 50% of the final energy demand and [1] suggests that a large portion of the demand could potentially (i.e., while requiring significant technology developments) be supplied by renewable photovoltaic thermal (PVT) solutions. PVT solutions address another important and increasingly emerging issue—spatial and network constraints, thus requiring less space than a PV or ST collector would.

Solar energy systems are progressively increasing their installed capacity due to subsidies and incentives as well as due to their increased efficiency [2]. Higher efficiencies and economic competitiveness increase annually, which leads to more investment and a sustainable energy mix.

The active application of solar energy technologies relies mainly on the use of photovoltaic (PV) systems for electricity generation and ST systems for heat generation.

The electrical efficiency of PV cells is typically around 22% for multi-crystalline and 27% for mono-crystalline silicon wafer-based technology [3], which corresponds to a fraction of the incident solar radiation. The remaining share is converted into heat. Additionally, the highest lab efficiency for thin-film technologies, CIGS and CdTe, is 23% and 21%, respectively.

The higher combined thermal and electrical efficiencies (per unit area) of a PVT solar system have the potential to overcome the typical low surface power and energy density of PV modules, and the relatively low exergy of the ST solar collectors, as well as the limited available roof/ground area [2]. This is particularly important if the available roof area is limited, but integrated solar energy concepts are needed to achieve a climate-neutral energy supply for consumers, such as in residential and commercial buildings.

By co-generating both heat and electricity from the same gross area, PVT collectors extract the excess thermal energy generated by the PV cells by employing a heat transfer cooling fluid (HTF), increasing electrical efficiencies due to lower PV cell temperatures.

For solar energy applications, the wavelengths of importance for solar energy applications are typically from around 0.3 to approximately 2.4 μm of the solar spectrum (i.e., ultraviolet, visible and infrared region). PV cells optimally operate at a narrower range of the solar spectrum (i.e., from around 0.3 to approximately 1.1 μm), therefore the radiation that is not within this range merely warms the PV cells and can be used as thermal energy, thus limiting the maximum electrical efficiency [2].

Due to the co-generation of heat and electricity, PVT collectors utilise a broader solar irradiance spectrum, which makes them more attractive in terms of energy conversion effectiveness as can be seen in **Figure 1**.

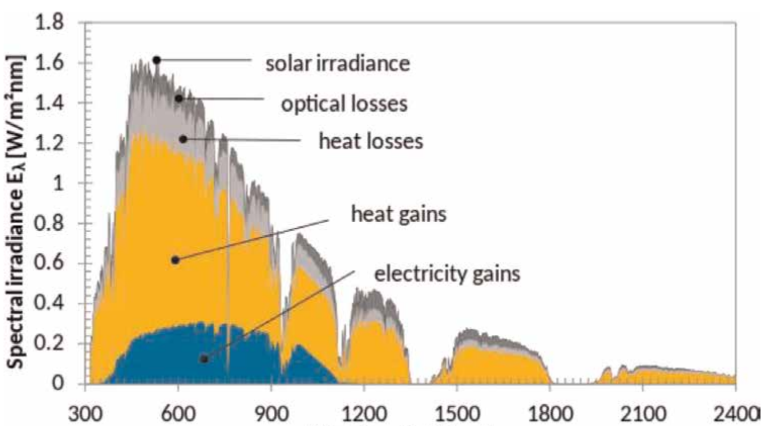

Figure 1.
Spectral distribution of solar irradiance, optical and heat losses, and heat and electricity gains. Provided by Manuel Lämmle.

Figure 1 presents the wider range of spectral irradiance operation of PVT technologies, by employing both thermal absorbers and PV cells in the same solar collector box. As previously stated, PVT solar collectors are the combination between a PV module and an ST collector into a single unit. The PV elements convert the incoming solar energy into electricity, which is typically encapsulated with ethylene-vinyl acetate (EVA) or a solar silicone gel in case of low concentration PVT solar collectors [2].

On the other hand, the thermal elements of the PVT collector convert the solar energy into heat gains typically by absorption. The absorption is done at the receiver level, in which the harvested heat from the PV cells (highest material share exposed to the solar radiation) and PVT absorber (e.g., thermally couples the PV cells to the HTF) is transferred into an HTF. A schematic cross-section of a PVT collector is presented in the following **Figure 2**.

1.1.1 Temperature dependence overview

For a solar collector to produce usable thermal energy, the HTF must be at lower temperatures than the absorber (i.e., in solar thermal collectors) and PV cells (i.e., in PVT collector) as "heat can never pass from a colder to a warmer body without some other change" (statement by Clausius from 1854). Therefore, the thermal coupling between the PV cells (hottest element in a PVT collector) and the thermal absorber (and thus the HTF) is of most importance for the overall performance of a PVT collector.

Furthermore, silicon wafer-based PV technology is typically more efficient at lower module temperatures as their average temperature coefficient is around 0.35%/°C, which leads to a lower open-circuit voltage and thus a decreased electrical efficiency [2, 5].

Just as PV modules reach higher efficiencies at lower module temperatures, the solar thermal collectors do so too as the heat losses are proportional to the receiver's surface temperature. It is important to note that the operating temperature is regulated by the overall system (i.e., the temperature required at the heat storage) and not solely by the solar collector.

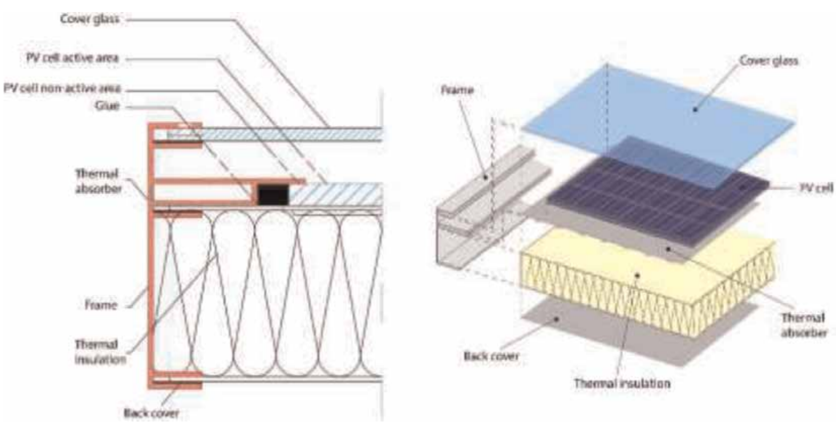

Figure 2.
Representation of an uncovered PVT collector cross-section composed by a sheet-and-tube heat exchanger and back insulation: Anti-reflective cover; front-encapsulation layer (e.g., EVA); Back-encapsulation layer (e.g., EVA); Backsheet (e.g., PVF); PV cells; thermal absorber (e.g., aluminium, copper or polymers); thermal insulation (e.g., mineral wool, polyurethane) and frame. Based on [4].

According to Lämmle [6], a solar thermal collector mean operating temperature typically ranges between 30 and 90°C. On the other hand, a PV cell typically operates at a module temperature between 30 and 60°C, which overlaps (to some extent) with a solar thermal collector mean operating temperature. This overlap in operating module and mean temperature leads to different behaviours from the PV module and the ST collector, as the ST collector has a deeper decrease in efficiency than the PV module for increasing temperatures.

Moreover, the PVT collectors do not operate at optimum efficiency for either PV or ST operation mode, which leads to a compromise between both elements. Therefore, PVT collectors operate either as *electricity* or *as heat optimum operation*, which prioritises the operating agent needs for a specific application, either giving priority to the electricity or heat generation [2]:

- *Electricity optimum operation* implies a low HTF mean temperature to lower the heat dissipation, thus enhancing the PV cell electrical efficiency.

- *Thermal optimum operation* implies higher HTF mean temperatures closer to the operation point of conventional ST collectors.

For an overall PVT collector optimum performance, it is crucial to efficiently utilise the available solar resource, therefore, it is of greatest interest to instal PVT solar collectors for better use of space.

Amongst several solar specialists, [1] consider PVT technology more complex than the available mature technologies such as PV or ST technologies. Nevertheless, PVT provides significant advantages such as the ones mentioned below.

- For the same gross are, PVT provides higher combined electrical and thermal power than a PV or ST collectors.

- The electrical production of an uncovered PVT module typically matches the electrical production of a PV module. Moreover, uncovered PVT modules can even have higher electrical outputs if operated at lower temperatures than the PV module, due to the extraction of thermal energy.

- Depending on their type, PVT collectors can produce heat for a wide range of applications.

- The ST production can be used to preheat or heat for domestic hot water (DHW). In well-designed hybrid collectors, the production can be almost as high as that of just an ST collector, 10–20% less, a reduction mainly due to the part of the irradiation that is converted to electricity.

- Thermal energy converted from either solar radiation or ambient heat can be used as a heat source for a HP. The electrical power can directly drive the circulation pumps and HP. In some cases, during summer, a fully-solar solution can be achieved when a DHW HP system can completely supply the HP consumption.

- ST energy can be stored in onsite tanks, precinct-level tanks, aquifers, ground strata and pit storage systems, which are currently much more cost-effective than electricity storage. *'This is especially true when PVT is used in combination with a*

HP that will make good use of the stored energy. The HP enables higher output temperatures enabling more compact storage solutions to be implemented. This is critical when space is limited. Larger thermal energy solutions can be accessed via district heating (DH) networks and enable the produced summer excess heat to be stored seasonally for the winter'.

- The increasing demand for cooling aids the PVT technology to disseminate has it has the potential to provide direct solutions by means of heat in absorption machines or by exposition to the night radiation phenomena (e.g., for uncovered PVT solar collectors), which cools down the HTF below ambient temperatures and therefore it can be used directly and/or stored (i.e., a compact storage example is ice storage). When coupled as a source for a HP can be recharged by an unglazed PVT collector with very high efficiencies, even during the cold heating season.

- PVT solar collectors have the potential to have no social impact, as can be comparable to both PV and ST solar collectors when incorporated into a roof or façade of a building envelope (i.e., no undesirable visual impact).

- Radiative and convective cooling also can be provided directly during the night using the thermal absorber or indirectly through a machine driven by PV electricity.

The relatively small emerging solar markets and small-scale production gives higher costs in the beginning, compared to the well-developed markets for fossil fuels. This cost disadvantage has all the time been the main barrier for both Solar PV and Solar Thermal.

A very important sometimes forgotten barrier is also proven long enough lifetimes for the new solar technologies. Many of the first concepts have failed in small things, as almost all new products, giving a bad reputation and extra costs for repair when introduced with too little product testing. For fossil energy supply the hardware stands for a much smaller fraction of the total cost and can be repaired at a lower cost per produced kWh when there is a problem. In this reliability respect, PV has had a great advantage, as it was first developed for Space applications, where the durability and reliability requirement is extreme. So, when "coming down to earth" that barrier was already solved. Only the cost was a barrier that could slowly be solved, by larger and larger markets and thereby mass production. Solar thermal has not had that kind of well-paying niche markets to the same extent and in almost all countries the subsidy systems have been an insufficient and too short term to develop a sustainable market.

For PV and solar thermal there were also niche markets in remote places without an electric grid, or for solar thermal replacing wood and oil during summer for hot water heating with low efficiency of the burners in these periods. Heat pumps have then become much more reliable in parallel and lower in cost and become a hard competitor for solar thermal (and can also compete with oil/fossil fuels). In a heat pump system, the PVT can find a niche market as one example, as it produces both heat for the cold side of the heat pump and electricity for the heat pump compressor operation. The cold side heat supply is sometimes forgotten when thinking about heat pump solutions. The heat pump still needs heat, its function is to increase the temperature of the available low temperature "free" heat to a useful level. This heat has to be inexpensive to make the whole system cost-effective. Here the PVT heat can make a nice contribution.

A further barrier for PV and solar thermal especially at higher latitudes is the annual distribution mismatch of demand versus energy production in many applications. This mismatch in demand and renewable supply is partly driven by the lack of solar radiation, causing lower outdoor temperatures and higher load in winter. In larger systems, seasonal storage in water pits can be used but in small systems, the heat losses in small thermal storage are too large for long-term storage. Phase change materials might be used then.

For PVT there is a further barrier that there has to be a reasonable match between supply and demand for both electricity and heat, to have full success. Oversizing gives longer payback times. Often too much heat is produced compared to electricity for the demand in a house, so efficient electric appliances can be extra cost-effective then. In systems where there is a need for heating a swimming pool or a borehole heat pump, the inclusion of PVT technologies could be a wise solution. Ideally, a total system view should be used when looking at PVT systems.

However, from these barriers can be concluded that several system types suit PVT technologies. It has been classified by the heating/cooling demand, as the electricity always can be consumed instantaneously or exported if too much power is produced.

- Hot water preheating systems for hotels.

- Swimming pool heating.

- PVT systems recharging Borehole/Ground Source heat pump systems to increase the Heat Pump COP and avoid undercooling of the borehole/ground. PVT can also be applied when changing to a larger heat pump in an existing ground source system.

- Air heating systems. For example, preheating of ventilation air or preheating of summer houses. Also drying of crops can be achieved. Many industry applications with large ventilation air use, like painting, can be interesting.

- Cooling by radiation to clear night sky conditions can also be used as a bonus with the same hybrid components.

1.2 PVT collector classification

According to Zondag [7], PVT collectors can be classified into four main categories according to their heat transfer medium, employed PV cell technology, collector design and their specific operating temperature.

Typically, PVT solar collectors either have air or liquid as an HTF, the latter being either water or a mixture between water and glycol (anti-freeze and anti-corrosion product) [8]. PVT air collectors are less sensitive to overheating as typically they are categorised as unglazed PVT collectors (i.e., glass cover, thus higher heat losses). On the other hand, PVT liquid collectors comprise the biggest installation share; however, they present overheating issues. Nevertheless, water (as a heating fluid) has a higher heat capacity and thermal conductivity than air [7].

The exponential increment in the efficiency of PV cells in recent decades tends to raise end users' expectations. Therefore, the system where this technology is employed is of most importance, since the specific suitability depends on electrical conversion efficiency, temperature and absorption coefficient [9]. c-Si PV cells have the highest share for both PVT and PV collectors. Mono-crystalline cells have enhanced electrical efficiency and solar absorption than polycrystalline PV cells. Thin-film technologies, which comprise CIGS and CdTe technologies, are typically characterised by their lower temperature coefficient than c-Si PV cells, thus more suitable to work under higher HTF and module temperatures. In applications such as

PVT collector, where cooling is needed at PV cell level, multi-junction (IIIV cells) solar cells are generally used for systems where high concentration is required. Therefore, this technology (IIIV cells) can be a contender for PVT solar collectors that require higher operating HTF temperatures.

Additionally, PVT collectors can be classified into two main clusters according to their design, such as flat plate and concentrating PVT collectors. Flat-plate PVT collectors can be sub-categorised into unglazed (e.g., similar aesthetics to PV modules, but without front glass cover) and glazed (e.g., similar in design to PV modules, with an additional front glass cover to decrease heat loss) PVT collectors.

Moreover, concentrating PVT collectors can be labelled due to their concentration ratio, such as low, medium and high concentration factors. Typically, low concentration PVT collectors are used as stationary (fixed collector tilt angle) solar systems. On the other hand, high concentration requires variable collector tilt angles and thus entails one or two-axis-tracking systems.

A balanced operating fluid temperature is critical to reach higher electrical and thermal efficiencies. Hence, the generality of the PVT water collectors and ST collectors can be allocated into three main groups for a wide range of applications [2]:

- Low-temperature applications for temperatures of around 27–35°C, which include swimming pool heating or spas. Typically found in unglazed PVT collectors (low thermal insulation);

- Medium-temperature applications for temperatures up to 80°C (e.g., glazed or evacuated tube collectors);

- High-temperature applications for temperatures higher than 80°C (e.g., high-efficiency flat-plate or concentrator collectors).

The temperatures of a specific system depend on the requirements of the heat supply system for DHW and space heating. Therefore, [9] allocated (in a schematic view, **Figure 3**) each PVT technology and applications per operating temperature.

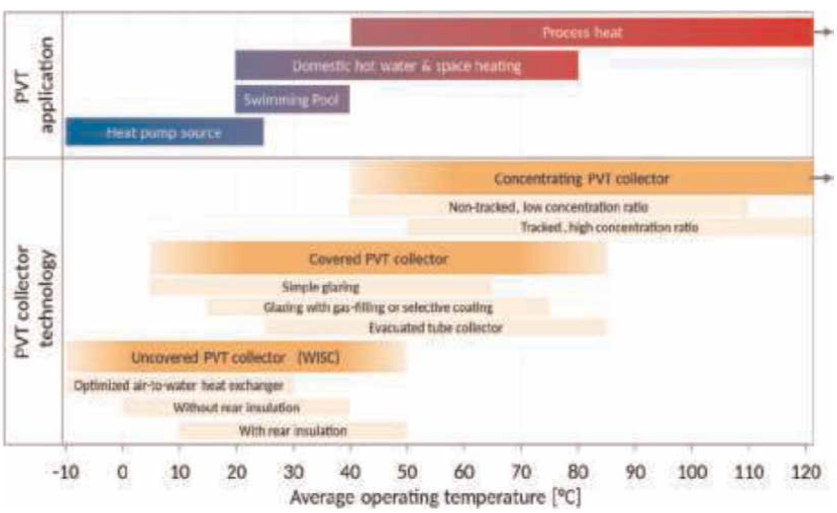

Figure 3.
Map of PVT technologies and applications per operating temperature [9].

1.3 Performance of PVT collectors

Solar radiation reaches the module at a solar irradiance, which immediately a fraction is lost to the ambient as Q_{loss} and the remaining portion empowers the PV module (Q_{el}) with a given electric efficiency (η_{el}). The accumulation of solar energy increases the temperature of the PV module and generates the thermal power of Q_{th}, depending on the fluid medium and module design, which is transferred to the thermal module through a heat transfer mechanism with a thermal efficiency of η_{th}. Finally, thermal insulation obtained by reducing and eliminating the back and sides heat losses will increase the system efficiency. The general energy equation for a simple PVT module and overall efficiency (η_{PVT}) can be defined by Eqs. (1)–(3) [10, 11].

$$\eta_{el} = \frac{Q_{el}}{G.A} \tag{1}$$

$$\eta_{th} = \frac{Q_{th}}{G.A} \tag{2}$$

$$\eta_{PVT} = \eta_{el} + \eta_{th} \tag{3}$$

Where G (W/m^2) is the solar radiation and A (m^2) is the aperture area of the module.

1.3.1 Electrical efficiency

PVT systems are two separate systems that consist of a single ST collector and a PV module, which are attached together and work simultaneously to generate electricity and thermal energy. The performance of a PVT collector is reduced when the temperature of the system rises [12]. For a separate PV module, the following Eq. (4) provides the electrical efficiency η_{el}.

$$\eta_{el} = \frac{I_{mpp}.V_{mpp}}{G.A_c} \tag{4}$$

I_{mpp} stands for the maximum power point current, V_{mpp} for the maximum power point voltage and A_c for the collector gross area in m^2 [13]. A special maximum power point tracking controller in the system assures that the PV modules operate at the best working point (I_{mpp}, V_{mpp}).

The reduction of the PV module performance with increasing temperature is given by Eq. (5), which represents the traditional linear expression for standard PV module electrical efficiency.

$$\eta_{el} = \eta_{0,el}\cdot\left[1 - \beta\left(T_c - T_{ref}\right)\right] \tag{5}$$

Where T_c is PV cell temperature, T_{ref} is reference temperature and β is the coefficient of temperature. Nevertheless, by employing flash tests in which the PV module electrical output is measured at two different temperatures for a given solar radiation flux the above mentioned-parameters can be obtained. The real temperature coefficient value depends on both PV material and T_{ref} [14–16].

1.3.2 Thermal efficiency

Based on ISO 9806: 2017 at steady-state conditions for glazed liquid heating collectors, the instantaneous efficiency η_{th} shall be calculated by statistical curve fitting, using the least-squares method, to obtain an instantaneous efficiency curve of the form presented in Eq. (6).

$$\eta_{th} = \eta_{0,th} - a_1 \frac{T_m - T_a}{G} - a_2 \frac{(T_m - T_a)^2}{G} \tag{6}$$

where T_m is the mean temperature of heat transfer fluid (°C), T_a is ambient air temperature (°C), η_{0_th} is peak collector efficiency (η_{th} at T_m-T_a = 0°C), G is hemispherical irradiance, a_1 is heat loss coefficient (W/m^2 K) and the temperature dependence of the heat loss coefficient comes as a_2 (W/m^2·K^2) [17].

1.4 PVT systems: Types, components and applications

Typically, a PVT collector operates in a solar thermal system, which affects the electrical and thermal yields substantially since its efficiency is temperature-dependent. *'The PVT system is amongst others characterized by its hydraulic layout, the sizing of storage and collector field, design temperatures of the heat supply system, and the system control'* [18].

It is crucial to create a context regarding the collector yield with its specific interaction between the collector, system components, weather, controller and user behaviour.

Lämmle et al. [18] selected four reference systems, which cover a wide range of promising applications and operating temperatures. A simplified hydraulic layout for each system with corresponding collector and storage dimensions is presented in **Figure 4**.

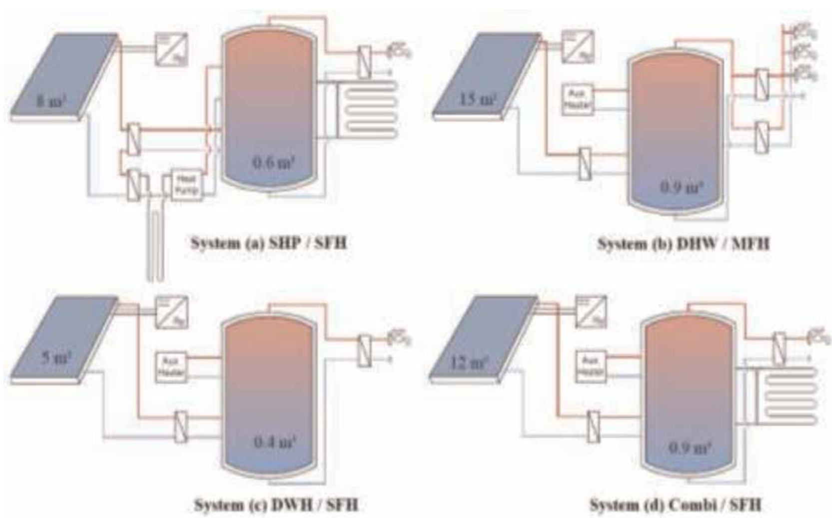

Figure 4.
System diagrams: (a) solar heat pump system in parallel/regeneration configuration in a single-family house; (b): Domestic hot water in a multi-family home; (c) domestic hot water in a single-family house, system; and (d) combi system in a single-family house [18].

System (a): A ground-coupled brine-water heat pump (HP) system incorporated into a single-family house (SFH) supplies space heat and DHW. By coupling a PVT collector to the cold side heat source of a HP or regeneration of a ground heat exchanger can potentially provide lower PVT collector temperatures and thus higher efficiencies.

System (b): A Domestic hot water (DHW) system in a multi-family house (MFH) is typically dimensioned to reach relatively low solar fraction. Therefore, the HTF is typically preheating and the overall operating collector loop temperatures are lower.

System (c): DHW system in a SFH is the classical system for solar thermal collectors and is therefore considered a promising application with a potentially big market for PVT collectors [7]. If the PVT system is not oversized compared to the load the operating temperatures can be quite low.

System (d): Combined DHW and space heating (combi) system in a SFH represent a challenge for PVT collectors due to the challenging thermal requirement efficiencies during winter, as the heat demand typically occurs with low levels of irradiance and ambient temperatures. Here avoiding oversizing is very important.

The electrical system can also be coupled with an electrical power meter, power optimizers in each PVT collector, battery storage systems and smart controllers optimising the interplay with the electricity grid.

Moreover, under the SHC-IEA Task 60 framework, a detailed representation scheme has been developed for combined electrical and thermal energy flows in PVT systems, which can be seen as an enhancement of the work developed at SHC-IEA Task 44.

In general, the system boundaries such as the final purchased energy, useful energy used in space heating, as well as system components (i.e., PVT collectors, heat pump and thermal storage) are represented and highlighted with explicit colours.

The system components are defined and highlighted as follows:

- Solar energy collectors (e.g., PV, ST and PVT collectors);
- Thermal storage (i.e., source side of the heat pump);
- Heat pump;
- Backup heater (e.g., boiler or heating rod);
- Thermal storages (i.e., sink side of the heat pump);
- Electrical storage (e.g., batteries).

Furthermore, three different system boundaries were defined as ‘left’, ‘right’ and ‘upper boundary’:

- *Left boundary*: Final purchased energy (e.g., gas or grid electricity);
- *Right boundary*: Useful energy such as DHW preparation or space heating; and final electrical energy consumption/load (e.g., residential electricity load for lighting, cooking);
- *Upper boundary*: Environmental energy sources such as the sun, ambient air or ground.

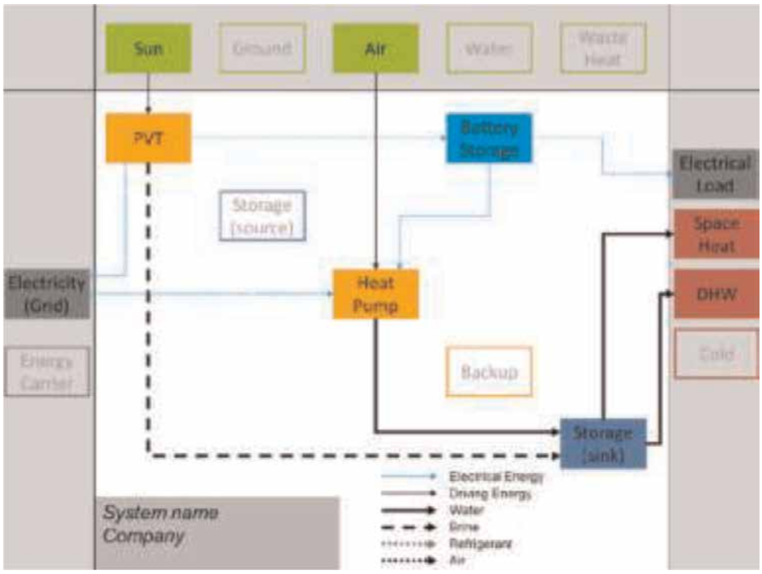

Figure 5.
System "square view" connection diagram, which comprises the system components (highlighted left) and boundaries (highlighted right) [19].

The scheme visualisation is very similar to other energy flow charts, yet it differentiates from previous ones as it has fixed boundaries, positions and colours, which are well defined by 'connection line styles'.

Within the system boundaries, different elements are highlighted (via placeholders) if they take part in the system layout/schematic. In case a specific component is not used, it is also shown in **Figure 5** without any highlight (i.e., no 'connection line styles').

The system components and boundaries have been differentiated by colours, such as Orange for Energy Converters, Blue for Thermal storages, Light Blue (colour also used for electrical energy flows) for Electrical storages, Grey for Final Energy, Green for Environmental Energy and Red for Useful Energy.

The system components are connected by arrows/lines, which represent the system energy flow. As shown in **Figure 5**, six different line styles are used for the indication of:

- Different energy carrier mediums (water, brine, refrigerant or air);
- Electrical energy or other driving energies (e.g., solar irradiation or gas).

1.5 Current state of PVT technology[1]

The past years showed that the PVT market is gaining momentum, especially in European countries, where the highest share of installed capacity of PVT collectors is located. Recently, the exponentially growing number of specialised PVT

[1] The data presented in this chapter has been acquired from the Solar Heat Worldwide report (2018, 2019 and 2020).

manufacturers that entered the European market, increased the awareness and interest in this technology, which led it to be included in the market survey developed by the Solar Heat Worldwide consortium. The report presented in both 2018 and 2019 included data from the work developed by experts in both PV and ST technologies, who are enthusiastic and share a common passion for this emerging solar technology. A market survey has been carried out under the works made by the IEA SHC Task 60 participants on "Application of PVT collectors."

By the beginning of 2019 (relative to 2018), a cornerstone had been reached of more than 1 million square meters of PVT collectors installed, in more than 25 countries.

The report developed by Weiss and Spörk-Dür [20] presents the global market developments and trends in 2019 of PVT solar collectors, in which the total area installed is around 1.167×10^6 m^2 (e.g., 675×10^3 m^2 in Europe, 281×10^3 m^2 in Asia, 134×10^3 m^2 in China and 70×10^3 m^2 for the rest of the world). Overall, it accounted for 606 MW_{th}, 208 MW_{peak} of the total installed capacity, which was provided by 31 PVT collector manufacturers and PVT system suppliers from 12 different countries.

Within the countries with the highest capacity installed, France has to date around 42%, South Korea 24%, China around 11% and Germany with roughly 10%. The market for PVT collectors registered a significant global growth of +9% on average in 2018 and 2019. This trend was also observed in the European market with a slightly higher growth rate of +14%, which corresponds to an increase of the annually new installed thermal and electrical capacity of 41 MW_{th} and 13 MW_{peak}, respectively [2].

Unglazed (also known as uncovered) water collectors are the most disseminated PVT technology with its largest market share of around 55% followed by air collectors (43%) and covered water collectors (2%). Evacuated tube collectors and low concentrator PVT play only a minor role in the total number of PVT installed capacity.

PVT technology suppliers commissioned at least 2800 new PVT systems worldwide in 2019. The number of PVT systems in operation at the end of 2019 was 25,823, of which 3296 uncovered PVT collectors were in operation, corresponding to a gross area of 667×10^3 m^2. Out of these systems, solar air (pre)heating and cooling for buildings has almost 86% of the PVT installations, trailed by DHW for single-family households with 7% and finally followed by solar combi-systems (e.g., for DHW, space heating, multifamily houses, hotels, hospitals, swimming pools, and district heating) with just 7%.

In a global context, solar air systems (i.e., including PVT air collectors) have the highest share of the PVT market, with the majority of the installations being located in the French market.

1.6 PVT collectors state of art

Previously, PVT collectors have been classified according to their design, either as flat or concentrating PVT collectors, therefore, the literature overview in the following chapter is strongly focused on the current PVT solar collector state of art.

Glazed liquid-based HTF PVT collectors aim at replacing conventional solar thermal collectors given the similarity between systems and operating temperature range. Zondag [7] expects these types of PVT collectors to overcome the challenge of temperature stability reaching higher shares of the solar market. Moreover, Zondag [7] expected that researchers would focus on temperature-protected PVT collectors with overheating protection, which was the aim of the work developed by Lämmle [6].

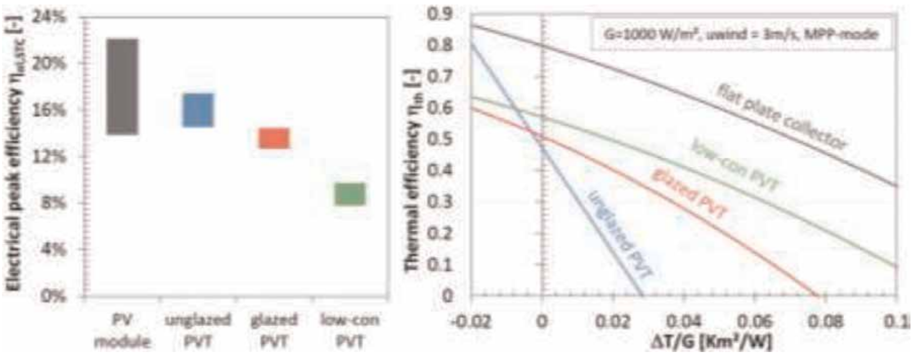

Figure 6.
Comparison of the electrical and thermal efficiency of best of market unglazed, glazed, and low-concentrating PVT collectors. Efficiency related to aperture area (provided by Manuel Lämmle and presented in [6]).

There are several commercially available concentrating PVT collectors, such as the stationary low concentrating PVT from Solarus and the line focusing PVT that was introduced by Absolicon AB and SunOyster Systems GmbH.

The motivation behind liquid-based concentrating PVT collectors is to replace the conventional thermal absorbers and at the same time decrease the amount of active PV area by applying cheaper reflectors. The reduced active PV cell area decreases the overall radiative heat losses due to the reduced hot surfaces. Stationary low concentration factor solar collectors (typically below 10 suns) do not reach temperatures higher than 120°C [9], as they do not need the use of tracking systems due to their relatively high acceptance angles [21].

Lämmle [6] made a direct comparison between ("the best PVT collectors in the market") unglazed (from MeyerBurger) and glazed (from EndeF) flat-plate PVT, low concentration (from Solarus) PVT, and a standard PV and ST module, to assess the current state of both thermal and electrical performance of the available PVT collectors. The results have been presented in the following **Figure 6**.

The thermal peak efficiencies range from 48% (for unglazed PVT) up to 53% (for the CPVT). These values fall below the 80% for standard flat plate solar thermal collectors due to simultaneous electrical generation (i.e., the fraction of incident solar radiation is directly converted into electricity), lower absorptance and higher emittance of the receivers (i.e., higher reflection losses), in most cases, a higher thermal resistance between the PV cells and the HTF.

On the other hand, both unglazed and glazed PVT collectors can compete with thin-film PV modules, but not with the high-efficiency mono-Si modules that reach around 22%.

Overall and as stated previously, a higher electrical efficiency leads to a lower thermal efficiency, which reinforces the educated "rule of thumb" that PVT collectors can either be optimised for high electrical or thermal performance.

1.7 Needs for different key actors

To establish a sustainable PVT system market there are needs for improvements on all levels. A market survey has been conducted to address the most relevant key factors for PVT technologies, where the following general needs can be pinned down as:

- Design tools for PVT systems;
- Decreased costs for PVT systems compared to separate PV and ST systems;
- Development of simple and easy to instal PVT systems;
- A complete test standard for PVT like for PV and ST;
- Teaching on all levels, also architects and installers;
- Demo systems with proven performance and reliability;
- Proven building integration designs.

Moreover, different needs for Key Actors are required from a different set of intervenients such as:

Researchers: Development of standards and planning/optimization tools for PVT systems.

Manufacturers: Development of improved PVT system types and prefabricated components for PVT systems, such as PVT panels, heat pumps, storage, etc.

Project planners, consultants, decision-makers, energy planners, property/real-state owners and construction/building contractors: Education on PVT systems and different PVT demonstration systems in different locations followed for many years to document high reliability, high performance and long lifetime of PVT systems.

Installers: Installer education on PVT systems.

1.8 The legal face of PVT solar collectors—European incentives

The PowerUp MyHouse project aims to increase the knowledge and awareness about solar energy applications and in particular about PVT technologies. The project aims to investigate the best technological applications, manufacturing, installation, measures, calculations, legislation, incentives, supports, qualifications, experiments and vocational education related to PVT.

The project has been divided into *PVT Technologies Research*, which aims to present the latest researches done in and out of the European Union (EU) related to PVT technologies. *The legal face of PVT* aims to present legal arrangements on PVT done in well-developed countries such as legislation and incentives. A *Guidebook* in which the project will test a PVT system. Finally, the *learning module on PVT* is focused on vocational training for students in RES.

The PVT technology is still very recent in commercial terms, so the existing legislation is not suitable or does not explicitly contemplate all these types of solar systems. Furthermore, there are not many references about legislation applicable to PVT technology. Thus, given the scarce information on the legal framework for PVT systems, this document addresses this issue at the level of renewable energy system (RES) systems for the production of both electricity and heating, which are widely disseminated.

For PVT systems to have a fair chance compared to PV systems, special high subsidy levels for PVT systems are suggested for the following years. It is estimated that these subsidies might generate a sustainable market for PVT and PV systems.

The O1 output from the EU project PowerUp MyHouse on PVT Technology Research—Best practices report [22] suggests several subsidy scheme principles, such as:

- The subsidy is only paid as long as the system is working and according to how high the energy production is, in €/kWh. This also promotes a sustainable aftermarket for repair and upgrade systems.
- The subsidy level is lowered year by year for new customers, according to the system cost development on the market.
- Early PVT adopters/investors get a contract with a high enough fixed subsidy (in €/kWh), stable over 10 years, to create a more predictable payback time, even when the reduction in system costs and subsidy reductions is fast for later customers.
- The energy meter should be located directly after the PVT inverter, to avoid economic uncertainties, due to local differences in self-consumption.
- If possible, add another energy meter on the thermal side, which can be used with a different lower subsidy level.
- These meter results can also be used to assure and compare system performance and assist companies.

The existing support and incentives, both for $RES_{electricity}$ and RES_{heat}, in the different countries, addressed in this document, are significantly different both in terms of amounts and in terms of the diversity of financial mechanisms. On the other hand, in some cases, there is the possibility that PVT systems are covered by the same supports as one or even both $RES_{electricity}$ and RES_{heat} systems.

In the countries of the EU, the next developments and opportunities in the renewable energy sector depend heavily on renewable energy development plans linked to the objective of reducing greenhouse gas emissions and the fulfilment of the commitments assumed under the Paris Agreement [23]. These renewable energy development plans are governed by two main regulations:

1. The EU Winter Package is a mechanism that aims at smoother the energy transition to clean energy. It defines the main goals for the EU-members for 2030, which tackle the decrease of greenhouse gas emissions, as well as energy efficiency and RES incorporation objectives. The binding goals set for the EU (directly) associated with RES are:

    a. To cut greenhouse gas emissions by 40% in relation to 1990 levels;

    b. 32% of final energy consumption to come from renewable sources;

    c. An increase in the energy efficiency of 33%.

2. The Integrated National Energy and Climate Change Plan. Following the guidelines defined in the Governance Regulation, each European country

government included specific objectives in its respective document. It appears that in some of them they seem significantly more ambitious than those defined by the EU.

In this sense and according to the Solar Thermal World most recent publication [24], the main challenges facing the PVT industrial sector are:

- Policy setting opportunities presented with the New Green Deal in the EU, in which the PVT sector has to be heard with a strong voice to be able to ensure that is not excluded from the debate, as it has been in the past, where, unfortunately, Australia still has no subsidies for RES until 2020;

- In 2020, the Renovation Wave Strategy published by the European Commission aims at improving the energy performance of buildings. It states that significant renovations can lead to noteworthy energy performance improvements up to 60%. Therefore, an opportunity to bring PVT technologies to the front and centre of this initiative by being engaged as a body in this process [25];

- Promising and emerging opportunities have been presented in the 4th Generation District Heating (4GDH) program where lower temperatures (i.e., below 100°C) are being trialled and promoted as the future choice for expanding the decarbonisation of heating and cooling. This significantly enables PVT, when coupled with HP, to play a noteworthy role in distributed and centralised solar solutions [26];

- Seasonal storage provides an opportunity for PVT based systems with the ability to monetize more of the heat generated that may otherwise be lost due to truncated thermal production (i.e., when the customers' summer PVT production exceeds thermal demand);

- The increasing interest in solar cooling can lead the PVT technologies to contribute to these low carbon solutions, by means of heating features during daytime and cooling features during night-time.

Decisively, the Recovery and Resilience Facility aims at supporting reforms and investments undertaken by the Member States, which aids the economic and social impact mitigation of the Covid-19 pandemic. Moreover, these programs tend to strengthen the European economies and societies by means of a more sustainable, resilient and better prepared economic and social structure to combat the challenges and take the opportunities of the green and digital transition.

However, for the PVT technology to grow significantly outside its market niche, amongst other necessary actions, it is recommended to take the following measures [27]:

- Players must develop clever and fair support schemes for PVT collectors and systems, present them to governments around the world, and request their implementation. After all, the PVT sector does not receive nearly as much support as the PV or solar thermal industry.

- Enlarging the knowledge of architects, planners and installers about PVT solutions. This should be helped by the fact that PVT is more efficient than just PV and is an attractive alternative to air and ground heat pumps.

Moreover, and following the previously stated incentives for solar systems, the European Union's Horizon 2020 research and innovation program leads the incentives for funding these types of solar technologies, such as the RES4BUILD, which develops RES-based solutions for decarbonising the energy use in buildings (e.g., new or renovated, tailored to their size, type and the climatic zones).

The project adopted a co-development approach, in which all the intervenients are involved in a dynamic process. Moreover, and in parallel, a full life cycle assessment (LCA) and life cycle economics (LCE) analysis are carried out, which aims at presenting the real impact of each proposed design. The diverse consortium and the dedicated exploitation tasks will connect the project with the market, paving the way for a wide application of the developed solutions.

Furthermore, the European Union's Horizon 2020 research and innovation program also provided financing for the development of PVT systems like the one presented by the RES4LIVE consortium, which adapts RES technologies, machinery and their demonstration at a large-scale on farm level. It requires supporting measures concerning spatial planning, infrastructure, different business models and market organisation, trends that are not all under control from a farmers' perspective.

The RES4LIVE project aims at fitting livestock farming with attractive costs, operational flexibility and low maintenance. The key technologies include integrated heat pumps, PVT solar collectors, PV panels, geothermal energy, electrification of on-farm machinery and biogas to be replaced by biomethane to fuel the retrofitted tractors.

Moreover, the PVT technology will be preferably installed on rooftops without occupying agricultural land. Focus on the collector mounting, piping and installation procedures to reach standardised solutions for livestock farming through (1) reducing the PVT system installations costs by more than 40%, and (2) by simplifying the installation process, to be handled by non-specialised technicians.

2. Conclusions

Due to the combination of both PV and ST technologies in the same gross area, PVT technologies employ the benefits of cooling the PV cells, thus increasing their overall efficiency, and thus using this excess heat to increase the HTF temperature of a solar thermal system.

Cabral [2] showed that PVT technologies have the potential to be a viable solution to compete with isolated systems such as PV and ST solar collectors if a significant reduction in manufacturing cost is achieved, coupled with an increased energy production performance. Therefore, its success is intensely linked to the capacity of the PVT industry/researchers to scale down its current system cost and complexity in a way that can shorten the cost/performance gap between both PV and ST technologies. PV and ST technologies have several decades of constant development; especially the PV industry with an exponential performance increment and constant decrease in material costs has been registered in the past decades.

Additionally, a bifacial PVT receiver comprising PV cells, which are high emitters, could potentially be equipped with a selective surface (i.e., between the PV cells) to increase the thermal energy yield through higher thermal efficiency.

The global production of silicon-crystalline-based PV modules typically entails a significant consumption of fossil fuels, which increases the dependence on non-RES sources. Conversely, the production of PVT collectors requires less energy. Other ways to increase useful thermal power at higher temperatures might rely on low-emissivity coatings either on top/bottom of solar glass covers or on top of the receiver core.

However, further studies are required to reduce reflectance and absorptance losses in the coatings. On the other hand, limited suitable highly transparent low-emissivity coatings are commercially available, which might limit a wider deployment of low-emissivity coatings in PVT collectors.

Furthermore, PVT technologies, in theory, allow the end-user to benefit from both feed-in tariffs and renewable heat incentives (RHI), due to the simultaneous production of electricity and heat. For DHW systems, in the UK, PVT technologies only benefit from the feed-in tariffs. However, for non-DHW systems, PVT technologies benefit from both incentives, which decreases the payback time.

In addition, the financial attractiveness concerning manufacturing and indirect costs can be improved by providing complete solar solutions with pre-configured packages of PVT collectors and auxiliary heating systems that facilitate the end user's decision. Moreover, the architectonic integration of PVT technologies into the building envelope offers a combined solution for both electricity and heat production while requiring less installation area.

An operational PVT system falls short in heat production when compared with a separate PV + ST system, which produces the majority of heat for DHW in the summer months. Whereas, in the winter months, when the required amount of DHW is not met, a backup system is required such as a heating component (i.e., boiler). This issue is also seen in ST systems, thus PVT technologies by also supplying electricity are on the verge of potentially being competitive, as PVTs are, at the core, ST collectors that can produce electricity from the same gross area. Therefore, it makes the future of PVT technology strictly reliant on the future of ST technologies, which rely on energy efficiency, durability and reliability aspects of a collector development.

The current global transformation of energy systems based on fossil fuels to RE systems lies predominantly on a high share of electrical power generation. The aim of reaching the required share of heating and cooling via power generation by the end of this century seems unrealistic with today's progress, which will require sustainable solutions such as ST and therefore PVT collectors.

The electrical storage trend is already ongoing through electrical batteries; nonetheless, heat tends to be easier, cheaper and environmentally friendlier to store than electricity, as it already gave real proof of its maturity and efficient reliability. In this way, PVT technologies have an opportunity to increase their market share, not neglecting permanent developments, both in terms of performance and in terms of cost reduction.

The high share of greenhouse gas emissions in the heat sector requires severe and methodical decarbonisation by a balanced technology mix, in which ST and PVT technologies must be considered, as it is crucial to achieve the already proposed goals in several environmental agreements.

Acknowledgements

The author would like to express his gratitude to the funding authorities that supported this work with funding, such as

- Department of Building Engineering, Energy Systems and Sustainability Science of the University of Gävle.

- European Union Horizon 2020 research and innovation program.

- Eureka Eurostars.

- Swedish Foundation for International Cooperation in Research and Higher Education.

Furthermore, the author would like to appreciate the support and knowledge exchange from both Prof. Dr. Björn O. Karlsson and Dr. João Gomes.

Acronyms and abbreviations

BTES	Borehole thermal energy storage
BTES	Building thermal energy storage
CdTe	Cadmium telluride
CPVT	Concentrating Photovoltaic-Thermal
CIGS	Copper indium gallium selenide
c-Si	Crystalline silicon
DHW	Domestic hot water
EU	European Union
EVA	Ethylene-vinyl acetate
HP	Heat pump
HTF	Heat Transfer Cooling Fluid
LCA	Life cycle assessment
LCE	Life cycle economics
MFH	Multi-family house
PV	Photovoltaic
PVT	Photovoltaic-thermal
PV + ST	Photovoltaic and solar thermal system combination
RE	Renewable energy
RES	Renewable energy systems
RHI	Renewable heat incentives
SFH	Single-family house
SDH	Solar district heating
ST	Solar thermal

Appendices and nomenclature

t_c	Cell temperature [°C]
β	Coefficient of temperature [°C/%]
A_c	Collector gross area [m^2]
I_{mpp}	Current maximum power point [A]
η_{el}	Electrical efficiency [%]
a_1	First-order heat loss coefficient at (tm—ta) = 0 [W/m^2 K]
η_{opt}	Optical efficiency [%]

η_{PVT}	PVT overall efficiency
T_{ref}	Reference temperature [°C]
G	Solar irradiance (global) [W/m^2]
a_2	Temperature dependence of heat loss coefficient [W/m^2 K^2]
$\eta_{opt,theo.}$	Theoretical optical efficiency [%]
η_{th}	Thermal efficiency [%]
Q_{th}	Thermal power [W]
V_{mpp}	Voltage maximum power point [V]

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Chapter 7

Energy Audit of Two Multifamily Buildings and Economic Evaluation of Possible Improvements

Alireza Bahrami, Arman Ameen and Henry Nkweto

Abstract

The energy use of buildings is gradually increasing, which is due to economic growth and an increase in population. Several studies have indicated that the implementation of energy-saving measures (ESMs) such as thermal insulation results in more energy saving; however, most ESMs are not economically viable. This chapter outlines ESMs using the IDA ICE computer software. The evaluation of the energy performance of two multifamily buildings is conducted, and possible ESMs are suggested such as thermal insulation, changing windows, installing a new air handling unit, installing a heat exchanger in showers, improving thermal bridges, replacing lighting bulbs, increasing external insulation plus temperature reduction, and changing schedules for air discharge control. The economic feasibility of these suggestions is assessed using the life cycle cost analysis to determine their economic viability. This involves the determination of the life cycle cost and life cycle cost saving to decide the best option. The most important factor in determining life cycle cost saving is the modified uniform present value. The addition of the attic insulation, installing a heat exchanger in showers, replacing lighting bulbs, and changing schedules meet the economic requirement within a feasible time frame.

Keywords: energy audit, energy-saving measure, economic analysis, life cycle cost, life cycle cost saving, energy efficiency, IDA ICE, multifamily buildings

1. Introduction

Energy plays an important role in economic growth and other daily humans' activities. Global energy use is mainly supplied from fossil fuels such as oil, gas, and coal. This accounts for 80% of the total energy use worldwide. The share of fossil fuels includes 33% of crude oil, 27% of coal, 22% of natural gas, and 18% of other sources [1]. Fossil fuels are not useful energy resources owing to their limited availability and impact on climate. In recent years, energy prices are increasing. This is due to the gradual increase in economic and population growth. To reduce this impact, the United Nations has considered essential measures through Paris Agreement to combat climate change. The central aim of the agreement is to strengthen the global response to climate change by keeping the temperature rise below 2°C [2].

Global energy use is mainly divided into three sectors which include industry, transportation, and residential and service buildings. Both the industry and building sectors show a gradual increase when compared with transport [3]. The increased environmental awareness and energy analysis of buildings are the tools that would drive the design of buildings with low environmental impact and energy use.

Buildings are made of enclosure that separates the internal environment from the external. Energy is used for lighting, cooking, running appliances, thermal comfort, and many other applications in buildings. Energy use in the building sector is rapidly growing. This may cause a serious environmental problem [4] in Sweden and a challenge for the European Union's (EU) directions. The energy used by buildings is approximately 40% of the total energy in the EU [5]. To reduce this, the EU proposed a directive on the energy performance of buildings, and this was implemented in 2006. The main purpose of the directive is to improve the total energy efficiency of buildings. This includes new and existing buildings.

In the EU, energy use of buildings is becoming the fastest-growing sector. Energy is needed for various purposes which include thermal comfort, lighting, cooking, etc. The need for energy saving is of great significance especially considering the fluctuation in energy prices, and the population and economic growth [6]. In this study, Doukas et al. evaluated the decision-making process for selecting energy-saving measures (ESMs). The systematic approach was integrated based on key areas of energy management systems of buildings such as load, demand, and user requirements.

An energy investigation was carried out on a multifamily building in Sweden [7]. There a simulation of the building was conducted by using IDA ICE. The results included various ESMs and analysis of the individual measure elaborated that the building had the potential to reduce the energy by 50%. This would further reduce CO_2 emissions by more than 43.3%.

Air leakages through building elements can result in a change in temperature [8]. The research performed in [8] presented a critical review of the use of the infrared thermography (IRT) survey in the building energy audit. IRT identifies leakages and thermal bridges. It was indicated that after identifying the leakages when used together with the blower door method in a building and then applying retrofitting measures, they would result in substantial energy reduction for the building.

An energy audit conducted in [9] using IDA ICE demonstrated that lowering indoor temperature could provide advantages when reducing energy use. However, lowering the indoor temperature should be combined with the insulation of the external wall. This retrofitting as a package could achieve a 53.3% reduction in the total energy delivered.

Studies [10, 11] reported that one of the biggest wastes of energy was caused by inefficient lighting. Moreover, lighting accounts for a great part of the total energy use in buildings. Using energy-efficient lights with demand and proper daylighting controls could help reduce electrical demand. This would contribute to visual comfort and green building development. Furthermore, it was illustrated that LED lighting systems reduced total power use by up to 21.9% [10]. However, in most apartments, human behavior and switching on/off depending on the need played an important role in selecting a more efficient light.

The energy audit carried out on a Swedish multifamily building using IDA ICE presented a change in the overall heat energy demand for ventilation when demand control was used [9]. This resulted in an approximately 50% reduction in the annual heating demand. Several studies [12, 13] suggested that when a heat recovery system was utilized in buildings, it was done by the air handling unit (AHU) which recovered heat from the exhaust air.

The selection of ESMs depends on the capital investment and benefit achieved after the implementation of ESMs. Various economic analysis methods can be utilized to evaluate the economic viability of each ESM [8]. However, there are various ways to analyze the economic feasibility of ESMs generated from an energy audit. Several studies [7, 8] employed life cycle cost to assess the profitability of ESMs. Life cycle cost consists of investment, energy, and maintenance costs. According to [7], when assessing which ESM is the most profitable, the outcomes are achieved when the life cycle cost is lower than the life cycle saving.

It is also important to link ESMs to environmental urban transition and urban building energy conservation [14] since reducing energy usage in buildings in urban area contributes greatly to a sustainable and environmental urban transition.

This chapter focuses on the energy audit of two multifamily buildings owned by the company Älvkarlebyhus AB located in Skutskär, Sweden. Also, some ESMs are proposed for these buildings such as thermal insulation, changing windows, installing a new AHU, installing a heat exchanger in showers, improving thermal bridges, replacing lighting bulbs, increasing external insulation plus temperature reduction, and changing schedules for air discharge control. These ESMs have also been promoted in research [15–17]. The life cycle costs of these proposed ESMs are analyzed and discussed.

2. Materials and methods

The following approach was adopted in this research. Firstly, the research involved ventilation measurements and data collection of the actual building. This includes the design plans of the buildings, site, materials, ventilation systems, energy use for hot water, and energy bills. This was further used as the input in IDA ICE for the simulation and validation of the base models. Lastly, an IR-thermal camera was utilized to detect leakages.

2.1 Field study objects

The study was conducted on two buildings owned by the housing company named Älvkarlebyhus AB located in Skutskär, Sweden. The company is publicly owned. The company is taking ESMs to decrease the energy use in these two multifamily buildings. The buildings are Centralgatan 14 and Tebogatan 5 which were constructed in 1968. Centralgatan 14 is both a residential and service building. It has five business shops on the first floor and sixteen apartments on the others. While Tebogatan 5 is a residential building with eighteen apartments. Heat is supplied by the district heating (DH) company Bionär AB, while electricity is supplied by Vattenfall AB. Centralgatan 14, Tebogatan 5, and Tebogatan 6 share one central heating system. The total heating energy demand for all the buildings is 710.082 MWh/year obtained from the invoices. According to the financial accountant of the company, the energy demand for each building is obtained from the ratio 2:2:1, respectively, as recommended by the DH company. The buildings of this study are displayed in **Figures 1** and **2**.

Figure 1.
Studied building, Tebogatan 5.

Figure 2.
Studied building, Centralgatan 14.

2.2 Field measurements

The measurements were done in Centralgatan 14 and Tebogatan 5. Ventilation flow rates were measured using electronic instruments. Two sets of instruments were utilized which were the hot wire anemometer (VelociCalc Plus 8386, TSI incorporated Ltd.) and hood (Testo 420, Swena flow air hood). The airflow hood is an electronic air instrument that was used for air volume measurement passing through the mechanically ventilated duct (uncertainty ±6% l/s) [7]. The hot wire anemometer measured the speed per second (uncertainty ±0.1 m/s). **Figure 3** illustrates the measuring instruments employed for the field measurements.

2.3 Inspection of thermal bridges and leakages

To identify the thermal bridges and leakages in the buildings, an IR camera (Thermal CAM S60, FLIR Systems) was used. This is because the air infiltration in

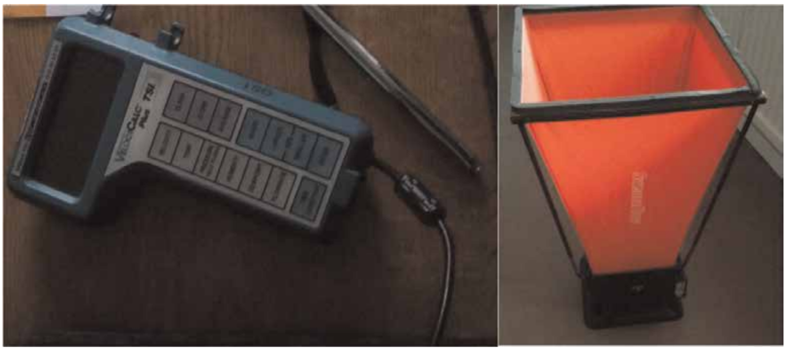

Figure 3.
Ventilation measuring devices; thermo-anemometer (TSI) on the left side and airflow hood on the right side.

buildings cannot be seen by visual inspection in most cases. Therefore, special equipment is needed to detect them. The IR-thermal camera is a fast and reliable tool to identify leakages in buildings [15]. The inspection of thermal bridges and leakages was conducted which demonstrated that the leakages were distributed on the buildings' envelopes exposed to the external environment. **Figures 4** and **5** indicate examples of IR thermography pictures collected during the inspection.

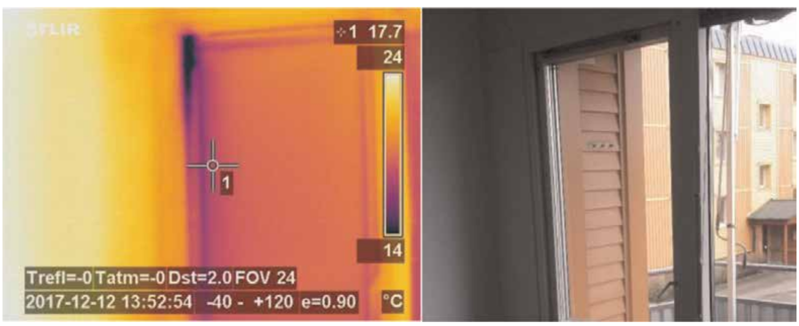

Figure 4.
IR-thermography picture showing thermal bridges around the window in Centralgatan 14.

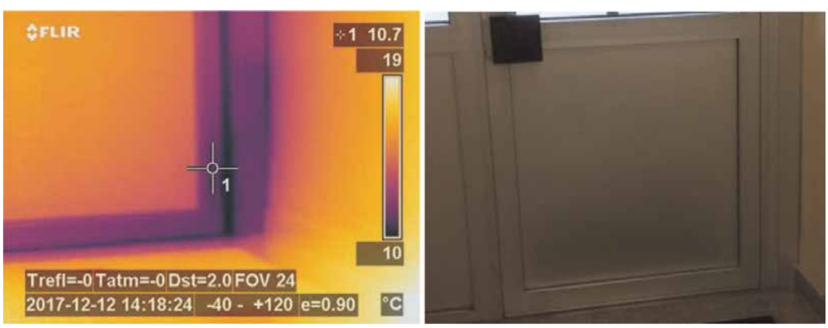

Figure 5.
IR-thermography picture showing thermal bridges around the entrance of Centralgatan 14.

2.4 IDA ICE simulation models

The models for Centralgatan 14 and Tebogatan 5 were built in the IDA ICE simulation software. IDA ICE is an important computer tool for the simulation and optimization of buildings' energy use [9]. The process of modeling involved importing the architectural drawings of each level of the buildings. Then, the zones representing each apartment within the buildings were created. The required information about the buildings was taken from the drawings. This included the dimension of the buildings, the size of the windows, the height of the buildings, and other required inputs. Söderhamn's (Sweden) weather file was utilized in the software. Then, the boundary conditions which were needed to be adopted in the software were building materials, lights and equipment, air leakage areas, ventilations, occupants of the buildings, weather data, indoor and outdoor temperatures, and the ventilation system and the temperature in corridors. **Figures 6** and **7** display the base models created in IDA ICE for Tebogatan 5 and Centralgatan 14, respectively.

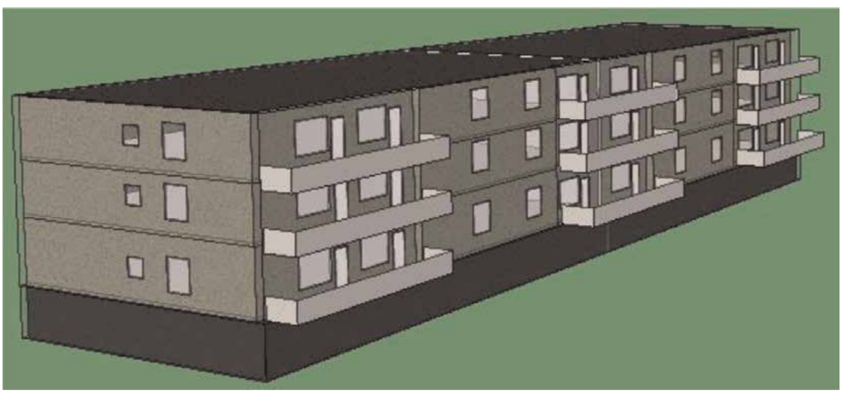

Figure 6.
IDA ICE model created for Tebogatan 5.

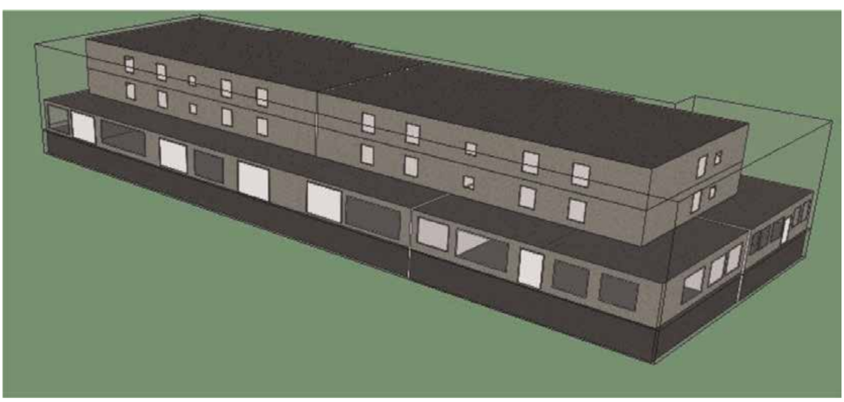

Figure 7.
IDA ICE model created for Centralgatan 14.

2.5 Parameters of buildings materials

Table 1 lists the materials that were used as the input to the models of Tebogatan 5 and Centralgatan 14. Apart from the wall surface, windows consisted of wood, covering the areas between windows and the surrounding surface.

2.6 Other input parameters

Other input parameters considered for the models are explained here.

2.6.1 Ventilation system

The base model was developed using a mechanical exhaust ventilation system for Tebogatan 5. Centralgatan 14 has both a supply and exhaust unit with a heat exchanger for the shops and a mechanical exhaust ventilation unit for the apartments. In the exhaust type of ventilation system, no supply is required. In this system, the air was entering through adjustable slots located on top of the windows.

2.6.2 Temperature and air infiltration of buildings

The room temperature of the models was set at 20°C. The air infiltration rate was taken as 0.36 $l/(s.m^2)$ at 50 Pa.

2.6.3 Ground properties

The ground specification was modeled using ISO standard 13,370. The basement floor was taken as 200 mm concrete, and the ground layer outside the basement was assumed by default values having a ground layer of 0.1 m.

Structural elements	Material	Thickness (mm)	U-value ($W/m^2 \cdot K$)
External walls	Gypsum	9.5	0.33
	Concrete	200	
	Mineral wool	150	
Roof	Lightweight concrete	150	0.18
	Attic insulation	180	
	Air gap	200	
	Wood	20	
Floor	Concrete	150	3.17
	Floor coating	5	
Internal wall	Lightweight concrete	200	0.85
External wall for basement	Concrete	200	0.33
	Insulation	100	

Table 1.
Materials of buildings.

2.6.4 Internal gains and masses

The occupancy, lighting system, and equipment are among the sources of internal gain in a building. The activity levels in the created zones were assumed as 1MET, and the number of people in each apartment was determined using SVEBY standard: 1rk = 1.42, 2rk = 1.63, 3rk = 2.18, 4rk = 2.79, and 5rk = 3.51. Therefore, it involved counting the number of bedrooms creating a zone, and depicting the number from the standard to set it as the input to the model. The occupancy was assumed to use the apartments 14 hours/day. The lighting and equipment used electricity, and 70% of that energy was converted to heat. In addition, occupants contributed to the internal heat gain.

The portion of stairs and the internal mass was assumed as an area of 2.72 m^2 per stair height with the heat transfer coefficient of 1.7 W/m·K of concrete.

2.6.5 Heating and cooling systems

Each apartment was modeled using the existing ideal heaters in the modeling software, and no cooling system was present. The heating system was provided by DH and supplied to the buildings.

2.6.6 Assumptions

- The hot water consumption was assumed as 25 kWh/m^2 floor area [18].
- The electricity used in the apartment was also taken as 30 kWh/m^2 floor area [18].
- 4 kWh/m^2 year was added as an extra heat loss due to the opening of windows [18].
- From the produced heat, 25% was from lighting and 70% was from the equipment. These were derived from the Swedish household electricity use [3] assuming that the operating loads related to the periods were neglected when occupants were not in the buildings.
- The reduction of solar radiation due to the internal shading was modeled by reducing the g-value of the windows by 70% [18].
- The thermal bridges and the DH losses were considered typical.
- The U-value for the windows was assumed as 1.9 W/m^2·K with triple pane glazing, solar heat gain value of 0.68, and solar transmittance value of 0.6.

2.7 Economic analysis

After proposing ESMs, an economic evaluation was carried out on the measures taken. This was performed to ensure that savings were at least greater than the investments. Life cycle costs were determined using the equation of the net present value (NPV), Eq. (1). NPV is generally used to calculate the cost when it is evenly distributed during *n* years. It takes into account the parameter *r* as the interest rate and *p* as the estimated rate of the increase in energy prices. Therefore, the net interest rate between the real interest rate and real energy price, *f*, is expressed as in Eq. (2) which is utilized in NPV, Eq. (1) [7]:

$$NPV = \frac{(1+f)^n - 1}{f(1+f)^n} \tag{1}$$

$$f = \frac{r-p}{1+p} \tag{2}$$

3. Results and discussion

The results obtained from the analysis are represented and discussed in this section.

3.1 Validity of base models

Based on the simulation results, the total heating loads for Tebogatan 5 and Centralgatan 14 were 263.2 MWh/year and 301.2 MWh/year, respectively. The results from the models are summarized in **Table 2**. They were compared with the real value of the total consumption of 284 MWh/year for heating and domestic hot water of both buildings. The reference value for the heating demand was obtained from the calculations (**Table 2**). This consisted of domestic hot water and the energy used for zone heating. The table also gives the total electricity demand in a year for both buildings. As can be seen from the table, the percentages of the errors between the reference values of the real buildings and the simulation results were acceptable which validated the modeling results with good accuracy.

Building	Energy source	Reference value (MWh/year)	Simulation result (MWh/year)	Error (%)
Tebogatan 5	DH	284	263.2	−7.9
	Electricity	22.9	23.5	+2.6
Centralgatan 14	DH	284	301.2	+5.7
	Electricity	32.9	31	−5.8

Table 2.
Comparison of base models with reference values.

3.2 Energy balance

Energy balance is one of the most important parts of the verified base models. It allows identifying the influence of each part of the buildings contributing to high losses to the buildings. It is also the key factor in implementing retrofitting measures. **Figures 8** and **9** display the energy balances of the base models. They allow for the identification of the specific areas required to reduce heat losses. They illustrate that

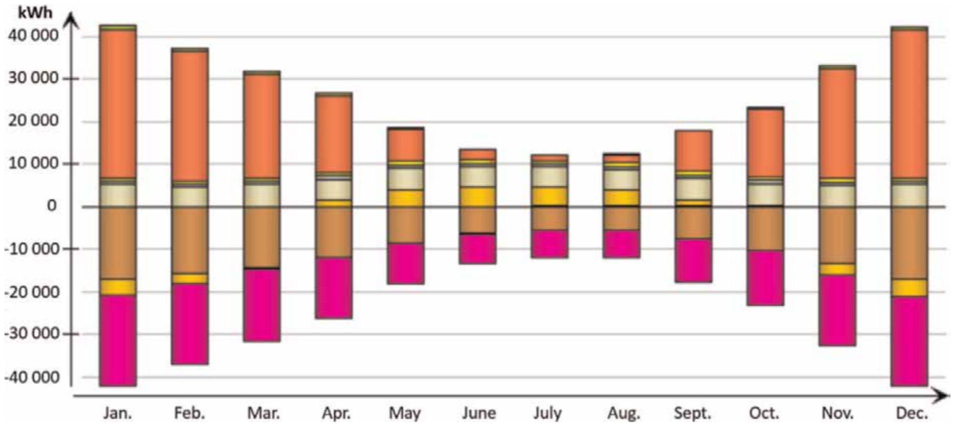

Figure 8.
Energy balance for Tebogatan 5.

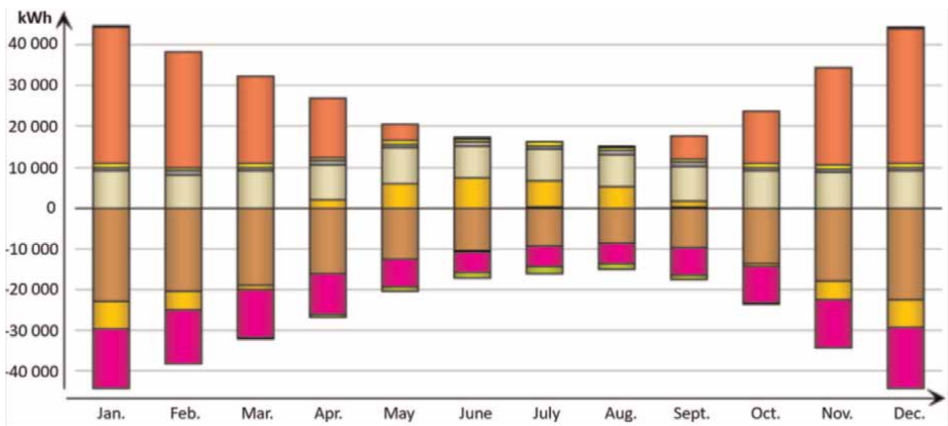

Figure 9.
Energy balance for Centralgatan 14.

higher losses were caused by the buildings' envelopes. In addition, the heat was lost through the air created by the ventilation system. It was needed to improve the insulation of the buildings' envelopes to reduce the high energy losses.

3.3 Transmission loses

Heat losses are transferred from buildings through different parts. **Figures 10** and **11** illustrate huge transmission losses through the buildings' envelopes, especially through the walls, windows, and roof. Thermal bridges such as balconies slabs also contributed to the additional heat losses. From the energy balance of both buildings, it was observed that the largest share of heat losses was due to the buildings' envelopes and thermal bridges. Apart from the transmission losses taking up the largest heat losses, some additional heat losses were contributed by the air infiltration of the buildings. Identifying the air infiltration of the buildings required the combination of

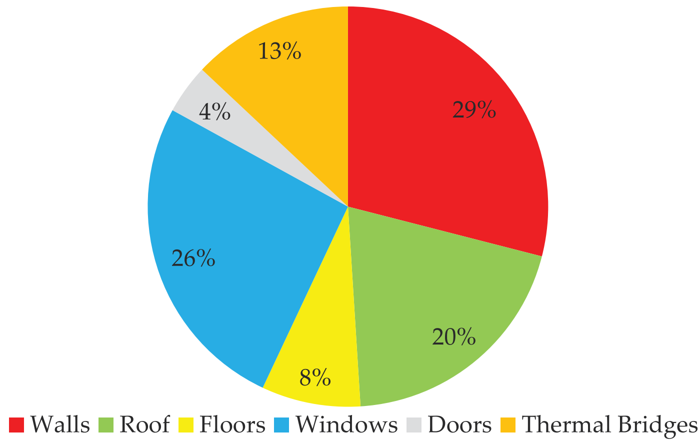

Figure 10.
Transmission losses for Tebogatan 5.

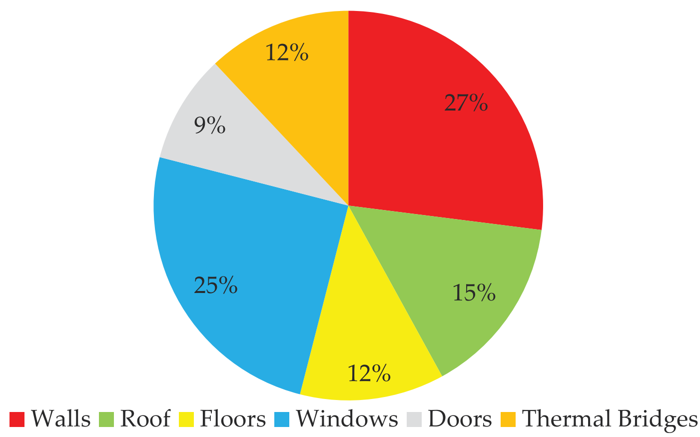

Figure 11.
Transmission losses for Centralgatan 14.

the IR-thermal camera and blower door method. In the study, as observed on the IR-thermal camera, the result demonstrated that thermal bridges were concentrated on the joints formed by the external walls and doors. Implementing retrofits is an effective solution that can promote energy saving. Therefore, various ESMs were needed to reduce heat transmission losses through the buildings and to optimize energy use.

3.4 Energy-saving measures (ESMs)

The energy performance was evaluated to improve the overall energy efficiency of the buildings. Several ESMs were proposed to optimize the energy use of both buildings. They included thermal insulation (increasing both external wall and attic insulations), changing windows, installing a new AHU, installing a heat exchanger in showers, improving thermal bridges, replacing lighting bulbs, increasing external insulation plus temperature reduction, and changing schedules for air discharge control.

3.4.1 Scenarios A_1 and A_2: thermal insulation

The addition of external insulation to buildings results in high energy savings. It reduces the flow of heat out of buildings and promotes energy saving of buildings [6]. Thermal insulation was added to the external walls and roof to provide an effective ESM that reduced the overall heat loss of the buildings [19]. On both buildings' models, 200 mm mineral wool insulation (0.036 W/m·K) was added to the external surface. The results indicated a decrease in the energy use for heating in both buildings. The net saving of energy by adding 200 mm of external insulation was 10% for both Centralgatan 14 and Tebogatan 5. To reduce the heat loss through the roof, attic insulation was utilized with a thermal conductivity of 0.036 W/m.K and a thickness of 200 mm. The net energy saving for the heating energy demand was achieved at 6% for Centralgatan 14 and 7% for Tebogatan 5. These energy savings are listed in **Table 3**.

ESMs	DH energy saving (%)	
	Centralgatan 14	Tebogatan 5
External insulation	10	10
Attic insulation	6	7

Table 3.
Energy saving when thermal insulation was implemented.

3.4.2 Scenario B: changing windows

The windows were changed by replacing them with a lower U-value (U = 0.85 W/m^2·K). The energy saving for the heating energy demand after replacing the windows was 10% for Centralgatan 14 and 7% for Tebogatan 5, as presented in **Table 4**. The net losses through the windows were reduced.

ESMs	DH energy saving (%)	
	Centralgatan 14	Tebogatan 5
Replacing windows with U = 0.85 W/m^2·K	10	7

Table 4.
Energy saving when windows with U = 0.85 W/m^2·K were erected.

3.4.3 Scenario C: installing a new air handling unit

Various control systems are employed in the AHU. The base model utilized constant air volume (CAV) on the mechanical exhaust system. This system requires high flow rates and higher energy for heating. This system was replaced with a standard AHU having variable air volume (VAV) with temperature control and a heat recovery exchanger with an efficiency of 85%. This is more appropriate for achieving good thermal comfort as well as reducing energy usage in buildings. The net energy savings of heating energy demand was 30% for Centralgatan 14 and 34% for Tebogatan 5 when compared with the base models. **Table 5** summarizes the percentages of energy saving by installing a new AHU.

ESMs	DH energy saving (%)	
	Centralgatan 14	Tebogatan 5
Installing a new AHU	30	34

Table 5.
Energy saving by installing a new AHU.

3.4.4 Scenario D: installing a heat exchanger in showers

The installation of a heat exchanger in the showers resulted in reduced hot water use by 20%. When this was implemented, the heating energy demand was reduced and led to a net saving of 5% for Centralgatan 14 and 6% for Tebogatan 5 (**Table 6**).

ESMs	DH energy saving (%)	
	Centralgatan 14	Tebogatan 5
Installing a heat exchanger in showers	5	6

Table 6.
Energy saving by installing a heat exchanger in showers.

3.4.5 Scenario E: improving thermal bridges

The presence of thermal bridges in buildings' envelopes affects the energy use and thermal comfort of occupants. To reduce the typical leakages displayed in **Figures 4** and **5**, it was required to change external windows and doors to the ones with low thermal bridges. Thermal bridges are parts of the buildings' envelopes that have a major effect on thermal performance [20]. When the thermal bridges were improved, the energy demand for the zone heating was reduced with a net saving of 5% for Centralgatan 14 and 3% for Tebogatan 5 compared with the base models, as indicated in **Table 7**. The comfort of the buildings remained the same as the base models.

ESMs	DH energy saving (%)	
	Centralgatan 14	Tebogatan 5
Improving thermal bridges	5	3

Table 7.
Energy saving by improving thermal bridges.

3.4.6 Scenario F: replacing lighting bulbs

The lighting bulbs utilized in the buildings were fluorescent and candescent based on the site visits. The average power rating for the lamps is 60 W in the apartments. To improve the efficiency of the buildings' lighting systems, the lighting bulbs should be upgraded to energy-saving bulbs. When this was replaced by 20 W LED lighting with the same luminous flux, it would lead to an electrical energy saving of 21.3% for Tebogatan 5 and 24.2% for Centralgatan 14 (**Table 8**). Using LED bulbs resulted in a

ESMs	Electricity energy saving (%)	
	Centralgatan 14	Tebogatan 5
Replacing lighting bulbs (LED)	24.2	21.3

Table 8.
Energy saving by replacing lighting bulbs.

small increase in the heat demand for both buildings. However, the amount of energy savings obtained from implementing this ESM was higher when compared with the heat demand.

3.4.7 Scenario G: increasing external insulation plus temperature reduction

The indoor temperature was lowered by 2–18°C. Maintaining the energy balance for the buildings needed increasing the external insulation to 200 mm. The total energy saving was 20% for Centralgatan 14 and 21% for Tebogatan 5 compared with the base models. This energy saving is reported in **Table 9**. The change was the result of reduced heating value for the zones, while the domestic hot water remained the same. Though, this ESM had a high impact on thermal comfort.

ESMs	DH energy saving (%)	
	Centralgatan 14	Tebogatan 5
Increasing external insulation plus temperature reduction	20	21

Table 9.
Net energy saving by external insulation plus temperature reduction.

3.4.8 Scenario H: changing schedules for air discharge control

The schedule for the air discharge control is different from VAV because it works on the demand control principle. Air is extracted depending on the demand inside the buildings. The schedule was changed during the period when the demand was low. The supply of heating energy demand was reduced because of the reduced heat generated. Therefore, running the ventilation system when it is not required, results in high energy use. When the schedules were integrated into the air discharge control, it led to a heat energy saving of 14% for Centralgatan 14 and 12% for Tebogatan 5. These percentages of energy saving are provided in **Table 10**.

ESMs	DH energy saving (%)	
	Centralgatan 14	Tebogatan 5
Changing schedules for air discharge control	14	12

Table 10.
Energy saving by changing schedules for air discharge control.

3.5 Summary of ESMs and possible outcomes

Table 11 summarizes the energy savings when the mentioned ESMs were implemented.

Analysis scenarios	ESMs	Energy savings (MWh/year)	
		Centralgatan 14	Tebogatan 5
A_1	Adding 200 mm external insulation	28.3	21.4
A_2	Adding 200 mm attic insulation	16.19	14.5
B	Replacing windows with less U value (U = 0.85 W/m^2·K)	26.8	16.42
C	Installing a new AHU (with VAV plus temperature control)	82.7	74.6
D	Installing a heat exchanger in showers (reduced hot water)	15.2	13.06
E	Improving thermal bridges	12.99	6.77
F	Replacing lighting bulbs	7.51	5
G	Increasing external insulation plus temperature reduction	55.84	46.3
H	Changing schedules for AHU control	40.0	26.1

Table 11.
ESMs and possible energy savings.

3.6 Thermal comfort for base models

IDA ICE integrates many standards which include ISO 7730 for computing the thermal comfort of buildings. From the analysis of the base models, the predicted percentage of dissatisfied (PPD) index was 9% for the base model of Centralgatan 14 and 14% for Tebogatan 5. This is within the acceptable standard of EN 15251. When the operative temperature was above 27°C, the percentage of hours was 3% for Centralgatan 14 and 1% for Tebogatan 5. **Table 12** illustrates PPDs for the base models.

Buildings	PPD (%)
Centralgatan 14	9
Tebogatan 5	14

Table 12.
PPD for base models.

3.6.1 Effect of ESMs on thermal comfort

Using the proposed ESMs in the base models to improve the energy efficiency of the buildings led to changes in thermal comfort. The PPD of the base models was increased depending on the implemented ESMs. When it was compared with the EN ISO 7730 which states that the acceptable thermal dissatisfaction in buildings should be smaller than 15%, various measures were therefore within the limit.

ESMs introduced in the models resulted in substantial energy savings for the buildings. The use of these measures had less impact on thermal comfort, apart from the combined effect of adding the external insulation plus lowering the indoor temperature. The combined effect of adding the external insulation plus lowering indoor temperature affected the thermal comfort considerably. The percentage

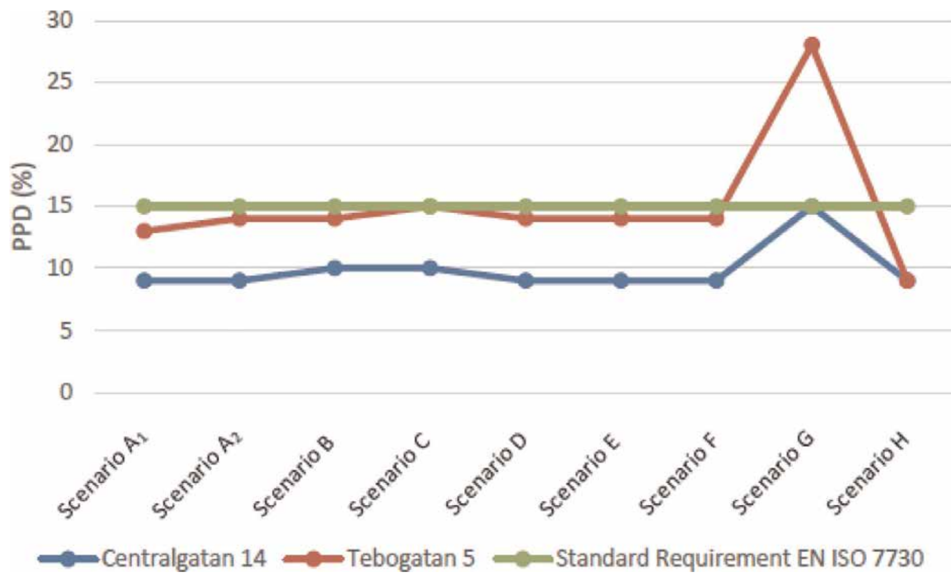

Figure 12.
Thermal comforts after implementation of each ESM and their comparison with the standard requirement.

of the total occupant hours with thermal dissatisfaction increased from 8% to 15% in Centralgatan 14, and from 8% to 28% in Tebogatan 5. This occurred when the external insulation was increased by 200 mm plus lowering the temperature by 2°C.

The percentage of occupants with thermal dissatisfaction was reduced to 13% as compared with 14% of the base model when the external insulation was added for Tebogatan 5, while it remained the same (9%) for Centralgatan 14. However, when the operative temperature was above 27°C, the percentage of hours was increased from 3% to 8% for Centralgatan 14, whilst it remained the same (1%) for Tebogatan 5.

Reducing the U-value to 0.85 $W/m^2{\cdot}K$ for the windows led to PPD remaining the same as the base models, 14% for Tebogatan 5, but it was increased from 9% to 10% for Centralgatan 14. When the operative temperature was above 27°C, the percentage of hours was increased from 3% to 5% for Centralgatan 14.

When AHU with VAV plus temperature control was used for both buildings, the percentage of the total occupant hours with thermal dissatisfaction was increased by 1% for both buildings. However, the percentage of hours, when the operative temperature was above 27°C in the worst zone, was increased from 1% to 2% for Tebogatan 5. **Figure 12** depicts the summary of the thermal results after implementing each ESM in the base models.

3.7 Economic feasibility of ESMs

The implementation of ESMs largely depends on capital, and it should be analyzed in such a way that the investment could be viable. Therefore, it is important to optimize energy use by improving areas with huge heat loss. In the base models, the heat was mainly lost through walls, windows, and thermal bridges of roofs and floors. After implementing ESMs, it was important to carry out the economic feasibility of ESMs. Life cycle cost determines the most cost-effective approach from a series of alternative ESMs.

The life cycle analysis was done based on Eq. (3). This equation is the modified uniform present value (NPV. Factor) which is obtained by modifying NPV [21]:

$$\text{Modified uniform present value } (NPV.Factor) = \frac{(1+r-p)^n - 1}{(r-p)(1+r-p)^n} \tag{3}$$

where p is the estimated rate of increase in either electricity or DH, and r is the interest rate.

Tables 13 and **14** provide life cycle costs achieved for both buildings and indicate which ESMs are economically viable. Despite high energy savings by implementing certain ESMs, the results demonstrated that some ESMs were not economically viable. This was because of higher life cycle costs compared with their life cycle savings. ESMs that were not viable for both buildings include adding 200 mm external insulation, replacing windows with less U-value, installing a new AHU, improving thermal bridges, and increasing external insulation plus temperature reduction. However, according to the tables, adding 200 mm attic insulation, installing a new heat

ESMs	Energy saving (MWh/year)	Life cycle cost (SEK)	Life cycle saving (SEK)	Working life (years)	Is this a good investment?
Scenario A_1	28.3	3.68×10^6	5.76×10^5	40	No
Scenario A_2	16.19	1.2×10^5	3.31×10^5	40	Yes
Scenario B	26.8	1.545×10^6	4.28×10^5	30	No
Scenario C	82.7	1.15×10^6	9.25×10^5	20	No
Scenario D	15.2	1.15×10^5	1.31×10^5	15	Yes
Scenario E	12.99	4.4×10^5	7.8×10^4	20	No
Scenario F	7.51	2.13×10^4	2.52×10^4	4	Yes
Scenario G	55.84	3.68×10^6	1.137×10^6	40	No
Scenario H	40.0	1.08×10^5	4.477×10^5	20	Yes

Table 13.
Results of life cycle cost analysis for Centralgatan 14.

ESMs	Energy saving (MWh/year)	Life cycle cost (SEK)	Life cycle saving (SEK)	Working life (years)	Is this a good investment?
Scenario A_1	21.4	2.822×10^6	4.36×10^5	40	No
Scenario A_2	14.5	6.092×10^4	2.95×10^5	40	Yes
Scenario B	16.41	1.035×10^6	2.63×10^5	30	No
Scenario C	74.6	9.5×10^5	8.34×10^5	20	No
Scenario D	13.06	9×10^4	1.12×10^5	10	Yes
Scenario E	6.77	5.056×10^5	7.57×10^5	15	No
Scenario F	5	1.6×10^4	1.67×10^4	15	Yes
Scenario G	46.3	2.822×10^6	1×10^6	40	No
Scenario H	26.1	5.4×10^4	2.92×10^5	20	Yes

Table 14.
Results of life cycle cost analysis for Tebogatan 5.

exchanger in showers, replacing lighting bulbs, and changing schedules for both buildings represented economical ESMs. This was thanks to lower life cycle costs than life cycle savings.

4. Conclusions

The buildings' envelopes and thermal bridges greatly affected the energy performance of the buildings. Most of the heat losses in the buildings occurred through them. To analyze the buildings' performance, various ESMs were studied to demonstrate how the energy efficiency of the buildings would be improved. The addition of thermal insulation, changing windows, installing an AHU, installing a heat exchanger in the showers, improving thermal bridges, and changing air discharge schedules could improve the energy performance of the buildings. The suggested ESMs affected the buildings' energy performance positively. All the implemented ESMs contributed to energy saving for the buildings, but their economic feasibility depended on the economic aspect of their life cycle. This was based on the investment cost and life cycle savings of ESMs. The amount of energy reduction from ESMs varied; the combination of external insulation plus temperature reduction had the highest impact on the energy reduction of the buildings. However, from the individual ESM, the highest energy reduction was recorded from the analysis of installing a new AHU, and this reflected the importance of ventilation with a heat recovery system in the buildings. The economically viable ESMs included the addition of attic insulation, installing a heat exchanger in the showers, replacing lighting bulbs, and changing the schedules for AHU control.

This study links ESMs in existing buildings to urban sustainable development and energy efficiency in buildings. Since many buildings are old, they do not meet the requirements of being energy efficient according to the latest building codes or contributing to urban sustainability, however, this can be bridged with the implementation of ESMs.

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Section 3

Resilient and Environmental Buildings – Central for Urban Transitions

Chapter 8

Viewpoints on Environmental Assessment of Building Certification Method – Miljöbyggnad

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Abstract

Production, management, use, and end-of-life of buildings has a large impact on climate change. Therefore, environmental targets are set to lower the greenhouse gas (GHG) emissions from the building sector. To reach these targets building regulation and voluntary environmental assessment methods (EAMs) that evaluate and certify the building's environmental impact are put forward as tools to push the building sector towards lower GHG emissions. In Sweden, building design is governed by building regulations and the dominant EAM is 'Miljöbyggnad' (MB) ("Environmental building"). Today, more than 1900 buildings have been certified by MB and it has influenced the building and property sector. In this chapter the potential impact MB and the linked Swedish building regulations have on building performance, energy use and GHG emissions, will be reviewed and discussed. The analysis investigates several of the MB's indicators, evaluate to what degree EAMs can influence the design of the building and the energy system to lower the energy use and GHG emissions based on material choices. The analysis presents important aspects that may influence the design of the building and its energy system and what challenges and possibilities the indicators, criteria and regulations can have on buildings and climate change. In addition, some modification and suggestion for improvements are presented.

Keywords: environmental assessment of buildings, GHG emissions, indoor environment, Miljöbyggnad, energy, environmental impacts

1. Introduction

Buildings are a major source of environmental impact, such as greenhouse gas (GHG) emissions, and use large amounts of energy and natural resources. Building construction and operation account for 36% of global final energy use and of 39% of energy related GHG emissions [1]. Awareness of the threat of a climate crisis and its recognition in global Sustainable Development Goals, and in European and national political targets, has increased the pressure to do necessary measures to reduce anthropogenic GHG emissions. The importance of decreasing the impact from building and construction industry has also been highlighted. Apart from legislation, taxation and benefit packages, environmental assessment methods can be considered as a voluntary neoliberal way to work with environmental governance [2]. They may also influence legislation. For example, the Swedish EAM Miljöbyggnad (MB) has inspired a new legislation regarding mandatory climate declaration for all new buildings in Sweden which is mandatory from January 2021 [3]. It is therefore of great importance how the environmental assessment tools content, indicators and criteria guide building design and decision-making in the building sector.

In Sweden, the most commonly used system for environmental certification of buildings is Miljöbyggnad (MB), translated to English “Environmental building”. MB was developed as a joint project between Swedish government, companies in the building and construction sector, several municipalities, insurance companies and academia, as a voluntary environmental rating tool to assess all new buildings in Sweden [4]. This still influences its characteristics. More than 1900 buildings are certified with MB [5]. Environmental certification is a third-party verification that a building meets the environmental certification criteria that the system address. Sweden’s largest organization for sustainable community building, Sweden Green Building Council (SGBC) owns and develops the system, and performs certifications [5]. MB certifies both new and existing/renovated buildings of different kinds: such as detached and semi-detached houses, blocks of flats and most types of commercial and public buildings (here called non-residential buildings), encompassing hotels, offices, restaurants, healthcare buildings, schools, kindergartens, and sport centers. MB analyzes and evaluates fifteen different indicators for new buildings. The processes for MB certification include registration of the project, pre-notification, application, review, clarification, and certification and in addition, requires reporting and verification of results with follow up inspections within three years after completion and certification, and then reporting back on maintained performance every fifth year to prolong the gained certification grade.

Each indicator can achieve Bronze, Silver or Gold grade. To achieve Gold grade, the building should have enhanced environmental performance and measurements or questionnaires should be made to guarantee the enhanced building performance and indoor climate levels [5]. If any of the indicators are classified Bronze, there is no possibility to achieve the total grade Gold.

The 15 indicators (16 indicators for existing buildings) are clustered into the areas *Energy*, *Indoor Environment* and *Material*. The final building grade calculated by aggregating the 15 indicators into 12 aspects, and then into the 3 areas, and finally into the building grade. This is described in the manual for MB [5]. An example of the grading and aggregation of the MB 3.0-certified pre-school Almgården in Gävle is shown in **Table 1**.

The aim of this this book chapter is to reflect some viewpoints about the MB’s potential impact on energy use, GHG emissions and effect on building performance. By analyzing and investigating nine of MB’s 15 indicators, it is studied to what degree MB may influence the design of buildings, the energy system and lower the GHG emissions. The analysis focuses on whether the certification system influences the design of the building and its energy system as intended and what challenges and possibilities the indicators, criteria and linked regulations can have on buildings and GHG emissions. The nine indicators that affect the GHG emissions the most in the areas Energy, Indoor environment and Material were identified and have been

			Indicator	Aspect	Area	Building
Energy	1	Heat power demand	SILVER	BRONZE	SILVER	SILVER
	2	Solar heat load	BRONZE			
	3	Energy use	GOLD	GOLD		
	4	Share of renewable energy	SILVER	SILVER		
Indoor Environment	5	Noise	SILVER	SILVER	SILVER	
	6	Radon	SILVER	SILVER		
	7	Ventilation	SILVER			
	8	Moisture safety	SILVER	SILVER		
	9	Thermal climate, winter	SILVER	BRONZE		
	10	Thermal climate, summer	BRONZE			
	11	Daylight	BRONZE	BRONZE		
	12	Legionella	SILVER	SILVER		
Material	13	Logbook of building material	SILVER	SILVER	SILVER	
	14	Phasing out the hazardous material	SILVER	SILVER		
	15	Building structure and the foundations climate impact	BRONZE	BRONZE		

Table 1.
Example of how indicator grades are valued and aggregated to a final building grade for a certified building, Almgården pre-school, Gävle, Sweden.

studied. Their potential impact on GHG emissions and building design will be presented and discussed.

The method used in the project is primarily a study of the MB manual and literature linked to the subject. The authors have had regular workshops to discuss the documents and literature and a reference group of five people from both building industry and academia with knowledge regarding MB, energy and environmental issues related to buildings have had input to the process. Some certified planned and built buildings have also been analyzed separately.

2. Energy aspects

2.1 Background regarding the aspect energy

In order to have an understanding for why four indicators are included in the Energy area, a brief overview of Sweden's energy system, building stock energy performance and energy supply/distribution are presented below. The four indicators within the energy area are: Heat power demand, Solar thermal load, Energy use and Renewable energy.

Sweden's use of energy is divided among the industry, the transportation, and the residential and tertiary sectors. The latter accounts for approximately 40% of Sweden's energy use, namely 147 TWh in 2018. Shares that sum up to this number are residences 59%, public service 11% and service businesses 21%, the building construction sector 3% and remaining 6% owing to agriculture, forestry and fishing [6].

Building type	Share of total heat supply [%]	Share of DH supply [%]	Share of building type heated by DH [%]	Specific energy demand [kWh/(m^2•a)]	Specific energy demand (DH heated) [kWh/(m^2•a)]
Detached	40	12	17	107	138
Multi-family	33	52	90	140	143
Non-residential	27	36	77	127	149

Table 2.
Average final specific energy demand for space heat and domestic hot water preparation in 2016 [7].

More than half of this energy is used for space and domestic hot water (DHW) heating; 54% in 2018 [6]. For this reason, the building stock should confine energy use, the rate at which energy is used (power), from which sources and its quality. **Table 2** displays statistics on space and DHW heating for various buildings. A large share of multifamily and non-residential buildings is heated with district heating (DH) whereas detached buildings are predominantly heated with electricity (direct and/or various heat pump types). **Table 2** does not include facility electricity (electricity for pumps, fans, certain common lighting, elevators, etc.). Nor is household and office/business electricity, which by default are calculated as 30 kWh/(m^2•a) [8] and 50 kWh/(m^2•a) [9], respectively.

It is important to differentiate energy carriers, primarily electricity and DH in view of when the power demand of the building stock is high due to issues during cold weather. Even if Sweden per capita is an extreme electricity consumer, electricity is generated using energy sources with low or moderate GHG emissions. For example, 160 TWh electricity were produced in 2019, from hydropower 39%, nuclear 39%, wind 12%, and the remaining 9% from combined heat and power (CHP) plants serving electricity to industry and society [6]. There is a growing demand for cooling energy, especially for non-residential buildings.

Electricity involves problems with power or capacity shortage. *Power shortage* occurs when demand is higher than supply on a national level. Several combined factors contribute to power shortage [10]:

- It is cold in the whole country;
- Wind generates little power since cold weather seldom are windy;
- Nuclear power does not produce as predicted or is being phased out;
- Drought leaves hydropower dams with low water levels;
- Imported electricity is limited due to low overproduction in neighboring countries or grid links to those countries are not in operation;
- Reserve power sources do not deliver enough power;
- Grid shortage of capacity in Sweden (see below).

Shortage of capacity implies power shortage in local areas, especially in expanding cities. Distribution cables from northern regions with great hydropower production to population-dense southern regions are today inadequate. Though supplied electricity has been constant since the 1980s, expanding urban and diminishing rural areas have changed the consumer landscape [6]. Transitions in society increase electricity use, for example from oil burner boilers to heat pumps [6], increased number of electric vehicles, establishment of data centers, etc. [10]. Main and local networks are reaching capacity limits.

DH can come from burning fuels, incineration and/or waste/residual heat from the industry with the purpose of heating buildings (or for industrial applications). DH can also come from a CHP plant, which produces thermal and electric power for the local community, with very high thermal efficiency. CHP delivers most power when outdoor temperatures plummet. Cold periods involve burning fuels with high energy content, such as costly renewable types (such as tall oil) or fossil fuels, which are being phased out due to high GHG emissions. In view of MB, every new building will increase the pressure on energy generation, grids and networks. Renovation of old buildings often reduce thermal energy requirement, but will in turn often imply increased use of electricity for this purpose. Therefore, power requirements, which are not explicitly expressed in Swedish Building Regulations (BBR), are important in MB and consequently reduce the increase of GHG emissions. From a future community development perspective, minimized electricity consumption should be rewarded.

2.2 Heat power demand

One of the indicators in MB assesses the heat power demand during winter. When outdoor temperatures drop, heat demand of the building stock increases, which implies that energy systems must use fossil and/or expensive renewable fuels. The purpose of this indicator is according to MB, translated to *Heat power demand,* to encourage buildings that have low space heating demand during the coldest winter period. The demand is seemingly set equivalent to heat losses by transmission, ventilation and air leakage at Design Winter Outdoor Temperature (DVUT) [11], divided by the building envelope area (unit W/m^2, A_{env}), given no solar irradiation and internal heat gains in the building. DVUT is available for cities in Sweden and dependent on the thermal time constant of the building (time constants corresponding to 24 hours to 12 days) in accordance to SS-EN ISO 15927-5 [12]. **Table 3** shows score criteria. F_{geo} is a geographic factor stated in the building regulations [13], which is 1 for the Stockholm region, larger for Northern regions and lower in Southern regions.

These two calculation methods are suggested by MB:

- The building's heat loss coefficient (with unit W/K) and time constant are calculated to assess DVUT. The heat demand comes from multiplying the heat loss coefficient with the difference between design indoor temperature and DVUT, divided by the envelope area.

Building type	Bronze	Silver	Gold
Residential	$\leq 25 \cdot F_{geo}$	$\leq 20 \cdot F_{geo}$	$\leq 15 \cdot F_{geo}$
Non-residential	$\leq 30 \cdot F_{geo}$	$\leq 24 \cdot F_{geo}$	$\leq 18 \cdot F_{geo}$

Table 3.
Indicator 1, heat power demand limits, related to envelope area [W/m²] [5].

- The heating demand can be simulated with a building energy simulation software, where solar and internal heat gains are set to zero, while the building is ventilated as if it were occupied. The climate file is that of a typical reference year for the location. Space heating demand is divided by the envelope area.

Verification is done in two ways: either with the energy signature of the building (measured supplied power versus outdoor temperature) or making a more exact calculation by using actual/measured values as input in the model used to predict the power demand.

The idea of limiting thermal power losses through transmission, ventilation and air leakage is encouraging, since this requirement is not explicitly stated in BBR, aside from criterion on maximum installed electricity power for space heating and an average area-weighted U-value of the envelope. It is also an aspect which is becoming increasingly important due to the energy systems problems with power and capacity shortage, and for limiting increased GHG emissions that new buildings entails. However, calculation procedures evaluation criterions can be doubted for several reasons, described below.

The definition of the indicator creates uncertainties. While it is called *Heat power demand*, the defining equation is based on heat losses. This may be true if all forms of heat gains are set to zero, but buildings usually have a base load which could be considered, especially when ventilations systems are on (i.e., has the presence of occupancy). Also, there is an erroneous definition when compressor energy of exhaust air heat pump is included as a form of heat recovery.

Another aspect is that the building's heat loss coefficient is normalized by division with the envelope area. The compactness of a building, measured with the Heat Loss Form Factor (HKFF is the ratio between envelope and heated floor area), affects heat losses. A compact building with low HKFF, reduces losses. Normalization with envelope area allows less energy-efficient buildings to fulfill the criteria, in contrast to reducing losses on basis of heated floor area. Moreover, envelope area can be complicated to calculate for buildings with complex facades. But this could perhaps be one way to avoid that the indicator drives building design towards buildings with low ceiling heights and low slab/intermediate floor thicknesses, such as made of wood instead of concrete.

The geographic factor F_{geo} is included in the criteria to consider the location of the building (see **Table 3**). The geographic factor comes from building regulations [13] for adjusting *energy* requirement depending on location varying between 0.8 in the south and up to 1.9 in the north. The reference value in which F_{geo} is equal to 1.0 is for Stockholm. However, energy and power demand for a location are not necessarily proportional. Kiruna in the north has the F_{geo} value of 1.9, meaning that a similar building situated in Kiruna or Stockholm will have an annual space heating requirement with the ratio of 1.9/1.0, implying that the building has the same heat loss coefficient at both sites. Now, if the space heat losses are calculated on basis of design indoor temperature 21°C and DVUT (assuming a time constant of 1 day) for Stockholm and Kiruna, −15.5 and − 30.0°C respectively, a ratio of 1.4 is obtained; Kiruna obviously has higher heat losses. So far, the heat loss coefficient ratio for the buildings is 1 (implying that the cost of building construction is the same), while noting that the ratios between energy and power demand are not the same.

If a heat demand criterion is set the same at the two sites, the heat loss coefficient ratio of 0.72 (= 1/1.4) is obtained, indicating that buildings in the north must primarily have increased insulation thicknesses (thus reducing energy losses, too). The introduction of F_{geo} (based on energy) in MB criteria for power demand changes these ratios. To fulfill the criterion, the heat loss coefficient ratio becomes 1.36 (= 1.9•0.72), indicating that buildings in northern Sweden meet this indicator criterion easier than buildings in the south. This may seem unfair, but it is noteworthy that the south is much more densely populated and the north is the big producer of hydropower and bio mass, with larger access to primarily electricity power.

The relationship between DVUT and the time constant of the building comes from SS-EN ISO 15927-5 [12]. Yet, the theories behind the standards have not been documented in a scientific way: the authors have not been able to find reports, peer-reviewed articles etc. on the topic. Nor has research been carried out to test and validate these concepts. Same criticism has been forwarded in view of building simulation tools standards [14]. Some inconsistencies can be noted: In order for heat to be stored and retrieved from building components, the indoor temperature must be able to fluctuate. However, calculation routines prescribe the use of a design indoor temperature that should be no lower than 21°C. Meanwhile, the time constant of the building is related to the response of the building subjected to a constant cold outdoor temperature, if the heating system is shut off, and the indoor temperature drops to approximately 63% of the temperature difference between the indoor and outdoor temperatures. It is questionable if the design of buildings with different time constants, in the same location, exposed to the same weather, can be verified, for example by measuring power supply versus outdoor temperature. Neither DVUT nor the time constant are measurable entities. This poses problems for verification, where a proposed method is the so-called energy signature. DVUT also appears in the winter thermal comfort indicator assessment.

Another weakness is that the typical climate of a location used in the indicator criteria is the "average" weather that was measured between 1981 and 2010. This climate format has substituted normal reference climate, based on 1961–1990, owing to climate changes. These climate files are based on previous historical 30 years of data. Given that an energy simulation of the building must be done (see Section 2.4), the same building model can be used for thermal power assessment. Today, this can be performed with the typical climate year, given that the internal and solar gains are set to zero, but it is not clear if this typical climate file contains design outdoor temperatures. Yet, certified buildings will be exposed to a future climate. Accordingly, predictive simulations should consider future weather exposure; not mean values of historic climate. A proposal is that extreme winter and summer conditions be projected in a design reference climate for designing future building heating and cooling power demand. The importance of using different climate files for various purposes is discussed by Petersen [15].

2.3 Solar thermal load

The purpose is to reward buildings that are designed to limit excessive indoor temperatures and reduce space-cooling requirement during the summer (see **Table 4**). The solar thermal load (STL) is defined as the solar energy that is transmitted through the window and contributes to heating/overheating of the room, based on the unit W/m^2 (here, floor area of the considered room/zone).

Building type	Bronze	Silver	Gold
Residential	≤ 38	≤ 29	≤ 18
Non-residential	≤ 40	≤ 32	≤ 22

Table 4.
Indicator 2, solar thermal load limits based on zone floor area [W/m^2] [5].

Calculations are performed on facades that are oriented to the east, west and/or south. Active/movable shading devices should be activated. An important part of the assessment is to estimate the solar heat gain factor g_{sys} for windows and shading devices, as well as occupant behavior (such as when using curtains). It is important to choose the most critical rooms where occupants stay more than temporarily. Analyzed rooms shall correspond to more than 20% of A_{temp} (total floor area in spaces heated to more than 10°C). Shading from surrounding buildings and vegetation must be considered.

A simplified method in MB is utilized unless more detailed simulation tools are available. STL is for rooms with window in one orientation, assuming solar irradiation 800 W/m^2 onto vertical surface, calculated according to Eq. (1):

$$STL = 800 \cdot g_{sys} \cdot \frac{A_{glass}}{A_{room}} \tag{1}$$

A_{glass} is glazed area and A_{room} is the floor area of the room. In the event that the room has windows in two orientations, Eq. (2) is used (supposing 560 W/m^2 solar intensity) where *S or E or W* depicts glazing area to the south, east or west:

$$STL = 560 \cdot g_{sys} \cdot \frac{A_{glass} \cdot S \text{ or } E \text{ or } W}{A_{room}} + 560 \cdot g_{sys} \cdot \frac{A_{glass} \cdot S \text{ or } E \text{ or } W}{A_{room}} \tag{2}$$

Depending on results from the two STL-equations, the highest value should be chosen for evaluation of reward according to **Table 4**.

This indicator has the aim of reducing solar loads primarily through passive means. It is closely linked to Indicator 10 *Thermal climate in summer*. Though this rating is quantified as heat load, it is only a part of space cooling demand. Yet, an annual building energy simulation must be performed (see Section 2.4), in which the space cooling energy demand is simulated. Internal heat gains are suggestively a larger problem when it comes to creating cooling demand and is not addressed in this indicator – thus questioning the weighting of this indicator in comparison to the other three within the energy area.

As previously mentioned, buildings should be designed in view of future climate projections. Though the solar intensity will probably remain unchanged in the future [15], the outdoor temperature will rise. This will significantly increase cooling requirement. The authors suggest that this indicator focus more on space cooling requirement, also considering internal heat gains, cool recovery from exhaust air, minimizing solar heat gains (as now) and have calculations based on projected future heat waves. Though energy implications are included in Indicator 3 *Energy use*, this indicator should combine attempts to reduce solar and internal heat gains. An option is to exclude it, or integrate it with Indicator 10 *Thermal climate in summer* addresses STL issues, see Section 3.3. As of today, this indicator has the same weighted importance as the other three energy indicators – and should probably not.

2.4 Energy use

Swedish regulations have historically understood that by decreasing energy losses, supply needs will be reduced. Requirements on building envelope component U-values and heat recovery from exhaust ventilation, rendered reduced supplied thermal power demand and thermal energy use. Building regulations have previously been based on the concept of specific energy use (i.e., purchased energy). In being an EU member state, building regulations have harmonized with EU formats using the concept of primary energy. In essence, the basis for the primary energy number (EP_{pet}) is specific energy use entities, multiplied by a weight factor (not primary energy factor) for each energy carrier, according to the building regulations, see Eq. (3).

$$EP_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{E_{sh,i}}{F_{geo}} + E_{sc,i} + E_{DHW,i} + E_{fe,i}\right) \cdot WF_i}{A_{temp}} \quad (3)$$

where.
$E_{sh,i}$ is space heating energy from energy carrier i [kWh/a];
$E_{sc,i}$ is space cooling energy from energy carrier i [kWh/a];
$E_{DHW,i}$ is domestic hot water heating from energy carrier i [kWh/a]
$E_{fe,i}$ is facility energy from energy carrier i [kWh/a];
WF_i is weight factor for energy carrier i [1].

The weighting factors are for building regulations imposed in 2020 as follows: electricity 1.8; DH 0.7; district cooling 0.6; solid, liquid or gaseous biofuels 0.6; fossil oil 1.8 and fossil gas 1.8 [13].

The upper limits for detached houses are 90–100 kWh/(m^2•a) depending on size, 75 kWh/(m^2•a) for multi-family buildings and 70 kWh/(m^2•a) for non-residential buildings. The limits may be increased if the activities within the building require enhanced ventilation rates (for hygienic and health reasons). There are also limitations on maximum electricity power for heating purposes and mean envelope U-values (0.30, 0.40 and 0.5 W/(m^2•K)), respectively for the building types. **Table 5** displays MB's reward criterions.

Energy use of new buildings has to be predicted with a whole-building energy simulation software that calculates time step of one hour or less, using a typical year climate file for the location. The monitoring plan in **Table 5** requires sub-metering so that space heating, heating of ventilation air, DHW heating, space cooling, facility energy (electricity) and in non-residential buildings the business/service activity electricity can be determined. Monitored values must be normalized for comparison and verification with BBR requirements.

Building type	Bronze	Silver	Gold
Residential	≤ BBR's requirement validated with measured energy use. A monitoring plan. Management routines for energy use follow-up.	Bronze + ≤ 80% of BBR's requirement validated with measured energy use	Bronze + ≤ 70% of BBR's requirement validated with measured energy use
Non-residential	≤ BBR's requirement validated with measured energy use. A monitoring plan. Management routines for energy use follow-up.	Bronze + ≤ 70% of BBR's requirement validated with measured energy use	Bronze + ≤ 60% of BBR's requirement validated with measured energy use

Table 5.
Indicator 3, energy use requirements [kWh/(m^2 a)] [5].

In the process of harmonizing building regulations to EU formulations, Swedish regulations had to impose criterions in terms of primary energy and derive a definition of Nearly Zero Energy Buildings (nZEB). The weighting factors (see Eq. (3)) were introduced in BBR 25 in 2017 and have undergone changes until BBR 29 in 2020. These can be seen as partially politically determined as they do not fully reflect differences in primary energy of energy sources. This is partly due to disagreements on how to calculate primary energy factors in district heating and cooling, from bio energy from forest residuals, waste to energy and free cooling (also to discourage direct use of fossil energy, oil and fossil gas were assigned factors equal to electricity). A stated aim has also been to derive values which are more "technological neutral" and "cost optimal" [16].

The relationship between BBR's weighting factors for electricity and district heating (1.8/0.7 = 2.6) "coincides" with Boverket's outmoded experience of average seasonal coefficients of performance (SCOP) for heat pumps, though with the ambition to be technology neutral. However, this value is considerably lower than the design SCOP's of most modern heat pumps. Below, an example of a real building is presented to illustrate how the building regulations influences how much primary energy is potentially available for space heating, depending on choice of heating system.

For Strömsbro school in Gävle, BBR 29 [11] sets a nominal maximum value for EP_{pet} 70 kWh/(m^2•a) (see Eq. 3), with adjustments for increased ventilation which are omitted in this case. The following energy use parameters are prescribed (note that a factor called MBN is introduced here, which quantifies the percentage of BBR value needed to get a reward, see **Table 5**):

$E_{DHW.i}/A_{temp}$ = 6.0 kWh/(m^2•a) DHW heating requirement;

$E_{fe.el}/A_{temp}$ = 11.1 kWh/(m^2•a) facility electricity;

$E_{sc.il}/A_{temp}$ = 0 kWh/(m^2•a) space cooling (low summer activity);

MBL MBs levels, 1 = Bronze, 0.7 = Silver and 0.6 = Gold;

F_{geo} = 1.1 for Gävle.

Eq. (3) can be rewritten for DH (Eq. (4)) and heat pump (Eq. (5)) heated building. The heat pump efficiency is estimated by varying three *SCOPs* (set to 3, 4 or 5). The three values can reflect different company products, different technologies (for example ground source or ambient air source heat pumps). Since the heat pumps also heat DHW at higher temperatures, the value of *SCOP* has been reduced with 0.5 units. Eqs. (4) and (5) establish available space heating requirement that is left, given the prescribed values for other variables expressed above.

For DH, the maximum allowable space heating energy use is expressed as:

$$\frac{E_{sh,\mathrm{DH}}}{A_{temp}} = \frac{\left(EP_{pet} \cdot MBL - \frac{E_{DHW,\mathrm{DH}}}{A_{temp}} \cdot 0.7 - \frac{E_{fe,el}}{A_{temp}} \cdot 1.8\right) \cdot 1.1}{0.7} \tag{4}$$

For heat pumps, the remaining energy use for fulfilling requirement is as follows:

$$\frac{E_{SH,\mathrm{HP}}}{A_{temp}} = \frac{\left(EP_{pet} \cdot MBL - \frac{E_{DHW,\mathrm{HP}}}{A_{temp} \cdot (SCOP - 0.5)} \cdot 1.8 - \frac{E_{fe,el}}{A_{temp}} \cdot 1.8\right) \cdot 1.1 \cdot SCOP}{1.8} \tag{5}$$

Results in **Table 6** indicate that it is easier to fulfill energy requirement limits with an efficient heat pump than DH. This implies that heat pump heated buildings can

Energy carrier	BRONZE [kWh/(m²•a)]	SILVER [kWh/(m²•a)]	GOLD [kWh/(m²•a)]
District heating	72.0	39.0	28.0
HP SCOP = 3	83.8	45.3	32.5
HP SCOP = 4	114.7	63.4	46.3
HP SCOP = 5	145.5	81.3	60.0

Table 6.
Available energy use for space heating for a kindergarten in Gävle, given that other energy entities are prescribed, heated by DH or heat pump (HP) with SCOP = 3, 4 and 5, respectively [5].

fulfill energy requirements with low insulation levels in the envelope and/or ventilation and air infiltration losses. However, this problem does not come from MB – this indicator is directly based on BBR's calculation methods and weighing factors. As long as this bias exists in BBR, it will be reflected in MB, unless MB sets more stringent requirements than BBR. However, it should be noted that other limitations in BBR restrict supplied energy (such as the envelopes average U-value and electricity use for heating purposes).

2.5 Share of renewable energy

The purpose of Indictor 4 *Share of renewable energy* is to reward buildings that request and use energy from renewable sources. The share of renewable energy used during one year is evaluated and results from the energy use simulations (Indicator 3) are used as input. Analysis is performed on building energy use (heating, cooling and management/facility energy) and for non-residential buildings, the business/activity energy, too (electricity). Household energy/electricity may be included in the case of residential buildings. Climate compensation energy is excluded.

The provided tool categorizes energy source in three categories as follows:

- *Category 1*, renewable energy from flow resources: Solar energy from solar collectors or photovoltaic cells; wind and hydropower; residual heat which if unused would be lost and cannot be used within its own process or product.

- *Category 2*, renewables from fonds resources: biomass; fuels with organic origin.

- *Category 3*, non-renewable energy: Energy originating from natural gas, oil, peat, nuclear (uranium); fuels with fossil origins, such as fossil plastic in waste; energy of unknown origins.

Criterions for rewards are presented in **Table 7** and instructions state some definitions. These are, coarsely summed up, as follows:

Gold requires *locally* generated and *new* renewable energy from flow sources as in Category 1 and considers only the energy that is used within the building. The term *new* is not clearly defined, but could be interpreted as coming from newly or planned built renewable energy sources. For cooling energy, electricity or district cooling energy should be categorized according to origin.

The energies origin for electricity from the grid is classified according to Energimarknadsinspektionen's (the Swedish Energy Market Inspectorate) guarantee of origin. Electricity originating from solar-, hydro- and wind power are renewable and flowing. The Nordic residual mix is the produced electricity that is not sold with

Building type	Bronze	Silver	Gold
Residential and non-residential	> 50% of used energy is renewable. Guarantee of origin of electricity and allocated DH is accepted.	Alternative 1: > 75% of used energy is renewable whereof >10% is from flow sources. Alternative 2: > 80% of used energy is renewable. For both alternatives: electricity has guarantee of origin and third-party review of allocated DH is accepted.	> 80% of used energy is renewable, whereof >5% is from local flow source and used in the building. Electricity has guarantee of origin and third-party review of allocated DH is accepted.

Table 7.
Indicator 4, requirements on shares of renewable energy [%] [5].

guaranteed renewable origin. The Swedish Energy Market Inspectorate provides annual information on its shares.

The origin of the energy that is supplied by the specific DH system is classified depending on fuel mix. Only the origin is assessed; not technical solutions or equipment in neither building nor DH system. Allocated DH shall be checked by an environmental auditor. The energy supplier shall guarantee that it will be available for at least three years. Consequences of the residual's constituents are accounted, i.e., DH which is not sold with guaranteed origins. For Silver and Gold, allocation and residual must be reviewed by a third party. For heat pumps in the DH system, energy supplied to heat pumps, excluding electricity, will be allocated in Category 1. Electricity to heat pumps are allocated depending on origin. Energy with unknown origin is classified as non-renewable (category 3) and electricity as Nordic residual mix.

Origin-labeled or allocated energy is verified with contracts, invoices, etc. Solar collectors or photovoltaics can be verified with photo or as-built documents. The intentions of awarding the use of renewable energy and specifically to encourage establishment of new renewable production units, is appropriate, such that energy use of new buildings will not burden the existing energy production systems. If origins of electricity will result in expanding electricity from renewable sources can on the other hand be discussed. As long as not all the renewable electricity produced is bought with green certifications it will not have much influence over the energy production.

The three categories could also be discussed from an environmental point of view. Should a more differentiated categorization represent the actual environmental impact from different energy sources be more appropriate, transparent and meaningful? Both life cycle assessment data for different energy sources and the energy efficiency in the energy production process could be included. The differences between different systems can be very large. For example, the lifecycle estimates of GHG emissions from wind power and coal is 10 gCO_2e/kWh vs. 1050 gCO_2e/kWh [17]. Variations can also be large between the environmental loads from the same type of energy generator depending on the source. For example, photovoltaic panels (PV panels) can have very different GHG emission impact if produced with coal in China or with the Swedish energy mix in Sweden.

3. Indoor environment aspects

Eight indicators related to the indoor environment are included in MB; Noise, Radon, Ventilation, Moisture safety, Thermal climate in winter, Thermal climate in summer, Daylight and Legionella [5]. The focus in this part is the ventilation, thermal comfort and daylight.

Several of the environmental indicators have a synergy and affect each other as well as energy indicators. For instance, ventilation can affect the indicators for energy (both the heating load and energy use), radon content inside the building, thermal comfort both in summer and winter, the noise level (due to the running fan and ducting networks in the ventilation system) and the logbook of the material (choice of environmentally friendly material for the ventilation system). Therefore, the ventilation system is a decisive indicator for the total grading of the MB assessment.

3.1 Ventilation

In a building, the ventilation system has the role of regulating and ensuring optimal indoor air quality and good thermal comfort. In terms of air quality, the uncertainty is greater when it comes to people's experience than for the thermal climate. However, there is no doubt that the quality of the indoor air is of great importance for comfort, health and performance. The balance between air quality and thermal comfort depends on a number of factors, which includes thermal regulation, control of internal and external sources of pollutants, air change rate, air distribution system, residents' activities and preferences, and reasonable operation and maintenance of the building system [18]. Guidelines for good indoor air quality have over the years often specified the highest acceptable levels of a wide range of airborne pollutants, such as dust content, CO_2, volatile organic compounds, microorganisms. However, very few unambiguous correlations have been found between pollution levels and symptom outcomes for the low-dose range to which people in non-industrial premises are usually exposed. For human-generating pollutants (so-called bio effluents), CO_2 content is often used as an indicator. Studies show that for larger populations, the number of dissatisfied users is 14% if all people are exposed to a CO_2 content of 800 ppm [19].

The ventilation indicator in MB assesses the building's ventilation solution and the purpose of the indicator is to reward buildings with good air quality. For ventilation, there are both minimum flow requirements as well as CO_2 level limits in MB. In residential buildings, the focus is on minimum flow rate and in non-residential buildings, both flow rate and air quality (CO_2 levels) are emphasized.

In new residential buildings, the minimum requirement is providing at least 0.35 l/sm^2 (A_{temp}) outdoor fresh air by the ventilation system. In non-residential buildings, 7 l/s per person should be added and to get higher grades. For Silver and Gold, CO_2 level should not exceed 1000 and 900 ppm respectively, except for temporary occasions. If the ceiling height in non-residential buildings is more than 3 m, smaller flow rates can be accepted if the CO_2 levels are within the accepted limits. In addition, the 1000 ppm CO_2 limits is per room and for the number of occupants the room is designed for [5]. The grading criteria for indicator of ventilation is shown in **Table 8**.

In addition, for the ventilation of wet rooms such as kitchen, bathroom, washroom and toilet, the minimum exhaust flow is 10 l/s. Moreover, for kitchens, there should be a minimum 10 l/s flow with at least 75% capture efficiency for the air pollutions and contaminants emitted during cooking and food preparation. The capture efficiency limits require efficient ventilation hoods equipped with carbon filters or other type of filters, which in turn may lead to larger fans with higher power and energy use. Thus, it will be more challenging to get a higher grade for the ventilation indicator and at the same time get higher grades for energy indicators.

Indicator 7	BRONZE	SILVER	GOLD
Residential building	Fresh outdoor flow rate ≥ 0.35 l/s·m^2 A_{temp}	Bronze +	Silver +
	Building care-taking routines for control of air quality.	Exhaust flow in kitchen according to **Table 3**.	Exhaust flow in kitchen according to **Table 3**
			Approved questionnaire or measurement.
Non-residential buildings	Fresh outdoor flow rate ≥ 7 l/s and person +0.35 l/s·m^2 A_{temp}. Building care-taking routines for control of air quality.	Bronze + CO2 concentration in the room should not exceed 1000 ppm except in very temporarily occasions	Silver + Alternative 1: Approved questionnaire. Alternative 2: Locally measured ventilation index ≥90% in the occupied room Alternative 3: CO2 concentration in the room should not exceed 900 ppm except in very temporarily occasions.

Table 8.
The grading criteria for Indicator 7 ventilation [5].

According to **Table 8**, in order to get Gold, the criteria for Silver must be fulfilled and a questionnaire should be provided among the building users or to have measurement of ventilation index. This additional criterion is important and well-suited since specifying required ventilation rates cannot guarantee an adequately low exposure to indoor pollutants. Guidelines by The Swedish Work Environment Authority address the important question of efficient air distribution. In addition, dissatisfaction with the quality of the indoor air cannot only be explained by incorrect ventilation, but also by the fact that the activities in the building/room could have changed after the design.

Ventilation index is a measure on how well the interior is ventilated and is defined according to Eq. 6 below:

$$\varepsilon c = (Ce - Ci)/(Csp - Ci) \cdot 100\ (\%) \tag{6}$$

Csp = set-point value of the average pollutant concentration in the occupied zone, ppm or mg·m^{-3}.

Ci = pollution concentration in the supply air, ppm or mg·m^{-3}.

Ce = pollution concentration in the exhaust air, ppm or mg·m^{-3}.

εc = the ventilation index or ventilation effectiveness for contaminant removal.

Ventilation index is 1.0 for perfect mixing condition because the concentration in the exhaust is the same as in the whole occupied zone. Ventilation index below 0.9 indicates ill-functioning air distribution in the room such as short-cuts and stagnation zones. To be able to get Gold for the ventilation indicator, the measured ventilation index should be more than 90% in the occupied zone. Alternatively, for the non-residential buildings, the measured CO_2 levels should be below 900 ppm. As many building energy simulation programs assume a well-mixed condition, which is not the case for stratified systems, it is suggested to prioritize measurements. Stratified ventilation is a concept that often creates high ventilation effectiveness (ventilation index over 1.0) and good indoor air quality [20–23]. There are many different air distribution strategies creating stratified conditions, such as impinging jet ventilation, displacement ventilation and confluent jet ventilation. These systems have the potential to create better air quality that mixing ventilation or the same level of air quality as mixing ventilation but with lower air flow rates and hence energy use [24–26]. Personalized ventilation systems have even higher effectiveness with the possibility to achieve ventilation effectiveness above 3 [27].

The recommended/minimum air flow rates given in the European standard EN 16798.1 [28] and MB assume complete mixing in the room. For non-residential buildings ventilation rates could be adjusted by the ventilation effectiveness in accordance with the European Standard EN 16798–3 [29] if the air distribution differs from complete mixing. However, this is not allowed in MB, which is one weakness.

Ventilation unit or the air-handling unit affects the electricity load and the heating power demand (due to possible heating coils). The deciding parameters are the operation schedule, the specific fan power (SFP), flow rates and heat recovery. To guarantee an acceptable indoor air quality it is not possible to compromise on the ventilation requirements. However, a time-controlled ventilation system is more efficient and can save energy together with heat recovery from the exhaust airflow. Thus, effective and energy efficient ventilation systems (with low SFPs and higher heat exchanger efficiencies) are essential in order to get higher grades for MB indicators. To remove the contaminants and pollutants from the interior, it is also important to get the filters cleaned and have it instructed in the building care-taking schedule. Such routines and instructions can be implemented in the compulsory ventilation control protocol (OVK) of the building [30].

Uncontrolled ventilation through air leakages is not included in the indicator. Air leakage influences ventilation and stands for a part of transmission losses and affect the heating power indicator as well as the total energy use [31, 32]. Building air tightness is not directly defined in the Swedish building regulation codes and it is not specified in this indicator. It can also increase the heating power demand and building energy use. Thermal comfort especially during winter can be affected due to possible draft and unwanted cold airflow from outdoor connected leakage and openings to occupancy zone. Therefore, it is suggested to add airtightness as a separate indicator, expecting minimum air tightness for newly and modern building and rewarding airtight building. An airtight building can decrease the energy use throughout the year while maintaining the thermal comfort level. In addition, it is suggested to perform airtightness measurement during the building process so that the possible leakage can be detected and get fixed with the minimum costs. This should be implemented in the regulations and criteria so that it can be verified and followed later on. Air leakage does also affect the ventilation designed flow and pressures and there is not any guide or recommendations on that. An indicator for air tightness, which can be merged with the indicator for ventilation into one aspect for ventilation would therefore be appropriate.

In addition, possibilities of airing, i.e. opening external doors and windows is important to occasionally introduce extra fresh air. This is considered for ventilation of bathrooms. However, it can be also considered for the main occupancy rooms. Airing is used also as a cooling method to adjust the inside temperature and in this case, it saves cooling energy; however, in the heating season, airing will increase the energy use by at least 4 kWh/m^2 and year [8, 9].

3.2 Thermal climate in winter

Thermal climate in winter, indicator 9 in MB, is essential in cold climates like in Sweden, and linked to the indicator *Heat power demand.* The assessment in MB is based on the predicted percentage of dissatisfied (PPD) index with DVUT. PPD is an estimation of the occupants' dissatisfaction of the thermal climate. Generally, PPD should be kept below 20% and there is always a minimum 5% PPD, i.e. there are at least 5% of the occupants who feel dissatisfied in an occupied room ASHRAE 55 and ISO 7730 [33, 34]. In the thermal comfort calculation, the so-called operative temperature, is approximately an average between the room air and the internal surfaces temperatures in the room. For PPD calculation, the operative temperature should be calculated for a point in the occupied room that has the highest risk for thermal discomfort. Such position can be 1.0 m away from the largest window and between 0.6–1.7 m over the floor. Moreover, the occupants clothing insulation (clo) and the metabolic rate (metabolic equivalent of task, met) affect the PPD. It can be considered, as 1.0 clo (a person with T-shirt and trousers) and 1.2 met (for a sitting person) if not detailed information is available. Building energy simulation programs such as IDA-ICE, EnergyPlus and DesignBuilder can be used for PPD calculations.

To get the Bronze grade, the PPD should be less than 15% with DVUT, and building care-taking routines should be provided to control the thermal climate and thermal comfort in winters. The routine should include the function of the heating system, control measurement of the temperature, user questionnaire or manuals to fix the issues leading to possible complaints (regarding the thermal comfort). The PPD should be calculated for a critical room located on a top floor with steady occupants the PPD can be calculated for several rooms and the critical rooms with highest PPD numbers can be chosen to fulfill the criteria.

For Silver grade, the PPD should be less than 10% with DVUT and for Gold, a questionnaire or measurement should be provided. The questionnaire and measurement are done during a year with its specific weather, however, PPD is calculated within the design temperature, DVUT. The weather during the measurement year might be quite different from a normal year, and this would affect the thermal comfort results.

A building has the capacity to store heat and release it when it gets colder, thus it affects the choice the DVUT within the same climate, i.e., a heavier building can withstand more temperature variations than a building with less thermal mass. For calculation of DVUT the building thermal mass is considered as one day and night (24 hours) and without the heating gain from solar and the internal loads (occupants, devices and lighting). Thus, it has been considered a worst scenario, i.e., the building is considered light and one of the reasons is that the thermal comfort should be measured in individual rooms (with lower thermal mass in compare with the whole building) and not for the whole building.

Unwanted cold air movement is called downdraft and might worsen the thermal comfort especially during winter. Air speed is specified and measured in the occupancy zone, 0.5 m inside of wall/window. In the simulation models, it is considered as 0.15 m/s for air speeds in the occupied room, but temporarily, there might be higher air speeds for instance if the person is sitting too close to a window with downdraft especially during colder periods. This will also lead to an increase in PPD and thermal dissatisfaction, however, it is difficult to simulate draft and more detailed CFD simulations would be needed.

3.3 Thermal climate in summer

Thermal climate in summer is decided based on the PPD index in a critical warm and sunny day. The assessments can be based on indicator 2, solar heat load together with the building management routines. For Bronze, Silver and Gold grades, the PPD should be less than 20, 15 and 10% with the most critical conditions, respectively. To get Silver, the building should be equipped with openable windows and doors (in residential buildings) and to get Gold, questionnaire or measurement should be provided [5].

For building without cooling facilities, the grading for the thermal climate in summer is referred to indicator 2, which is about reducing solar heat loads during the summer. For buildings without cooling system, the critical room should have internal loads (occupants, appliances and lighting) below 20 W/m^2. The PPD should be calculated for a critical room located on a top floor with steady occupancy; the PPD can be calculated for several rooms and the critical rooms with highest PPD numbers can be chosen to fulfill the criteria.

Having smaller windows would lead to less solar heat gain during summer and improve the grade for indicator 10. However, the smaller window size would also decrease the received daylight, which makes it more challenging to get enough daylight. In addition, it will decrease the building's purchased heating energy during winter and hence benefit indicator 3, the energy use. There might be a balance between the window size and the related indicators for solar heat gain, energy use, thermal climate and daylight. Research studies have shown that, the building equipped with modern windows (lower U-values and transmission losses as well as higher visible light transmittance) can have higher window areas and still fulfilling the criteria for both solar heat gain, thermal comfort and daylight requirements [35]. Also airing possibilities should be limited to the time when the indoor temperature is lower than the outdoor. For instance, in case of heat waves, it is better to have the windows closed during the daytime and instead, if possible, have them opened during the night, when it is cooler, i.e. night cooling ventilation [36].

One problem and weakness with the requirements for Gold is that the questionnaires and measurements are done during a specific summer with its specific weather, whereas, calculations are performed using historical weather data (normal year based on 1981–2010). This means that the fulfillment of Gold depends much on how warm the hottest day, in relation to the normal year, have been for the specific summer the measurements or questionnaires have been performed. Therefore, it is also suggested for the design and calculation of indicator Thermal climate in summer to use more extreme summer conditions than the typical year based on 1981–2010.

3.4 Daylight

The windows in the building, their location, size, light transmission factor and U-value, have a large impact on the daylight condition, the solar heat load, energy use and indoor comfort discussed earlier. They also influence the indoor light quality in the building, which affect the people using the building. Human eyes have evolved in sunlight and therefore responds much better to it than artificial light. In addition, it can be troublesome for people to work in a room without windows with no awareness of the weather and contact with the outdoors. We spend around 80–90% of our lives within buildings and numerous research studies have demonstrated and indicated that glazing has profound implications in terms of human health, happiness and productivity [37–40], and in northern countries lack of daylight can lead to Seasonal Affective Disorder (SAD), a syndrome characterized by recurrent depressions that occur annually at the same time each year which is affected by access to daylight [41].

In MB, indicator *Daylight* demands that the interior of the building should be provided with acceptable access to daylight. The daylight access is assessed by calculation of window to floor ratio, simulation of the daylight factor (DF). For some buildings, sales halls and halls, daylight is assessed by calculation of the percentage of the outlook area. For non-residential buildings, building caretaking routines should be also provided. The requirements are minimum DF of 0.8% for Bronze, 1.0% for Silver and 1.3% for Gold. The DF, is a measure of the luminosity indoors in relation to the outdoors with a standard gray sky, according to CIE Overcast Sky in ISO 15469: 2004 [42]. For simulation, it is required to know the window's glass size, location, light transmittance, reflection, floor area and room geometry, distance and height of surrounding buildings, exterior shadings, fixed screens, etc. The surrounding buildings and planned buildings according to the municipality's detailed plan should be also considered in the simulation.

Percentage of outlook area (with view to the outside) can be applied for workplaces in sales halls and halls (rooms with high ceilings that are intended for, e.g. sports, warehouses, trade fairs, light industry and logistics) and associated facilities that are only used temporarily. Then the proportion of view area (outlook area) is defined as being able to look out with 5° or more indoors at a height of 1.5 m, both horizontally and vertically. Floor area where these conditions are met is defined as the view area or outlook area and is expressed as a proportion of the whole floor surface.

Daylight affects the total energy use in a building as the penetrated light into the building will turn into heat and increase the internal gain. This will lead to a decrease of heating demand in the heating season and increase in the cooling demand in the cooling season. The heated parts inside the building will get higher temperatures, and in addition, the air around the floor areas will be warmed up and create plumes which also affect the thermal comfort especially during the summer season. The same phenomena might improve the thermal comfort during the winter period.

Increased glazing area will lead to more daylight. However, the transmission losses through the windows will also be increased. Thus, there is a trade-off between the glazing area (which transmit the daylight) and the total energy use, thermal comfort and solar thermal load. The buildings equipped with new modern windowpanes with lower U-values and transmission losses as well as higher visible light transmittance, can have higher glazing areas, providing more daylight with acceptable thermal comfort during summer and at the same time keeping the energy use low [35]. Obviously, this comes with the penalty of higher initial cost of the windows.

The criteria in MB regarding daylight can be difficult to reach if designing and building a thick/deep building were the rooms are deeper than 6 m. Even though median DF can be used as indicator, it can be difficult to compensate the lack of daylight in the rooms with light areas closer to the windows. Getting enough daylight can also be a problem for tall buildings located in dense and highly populated city districts with narrow streets. Alternatively, if large balconies are blocking light from the sky. In addition, for residential building, some rooms such as bedrooms are protected so that the interior cannot be viewed from the neighbors and the privacy can be obtained. In such cases, if there are surrounding buildings, it will be challenging to receive enough daylight especially for rooms located in the lower floor levels.

It can therefore be discussed if it could be possible to adjust the indicator and focus on daylight demand in the rooms where there is less demand of privacy and accept lower DF in other rooms. Then rooms where people spend most of their awake time at home, like the dining or living rooms, would have to meet high DF criteria. A total median or medium DF in a whole apartment could also be another way to make the indicator more flexible. However, a risk could be that rooms with very poor DF conditions would be designed and built. The occupants view on the daylight could also be asked via questionnaires, especially in the rooms with low DF levels.

Internationally, there are examples that the limit values for sufficient amount of daylight are set differently depending on room and building function as opposed to the static approach, which is used in MB [43]. The indicator could also develop to use more dynamic daylight performance metrics that consider the quantity and character of daily and seasonal variations of daylight for a given building site [44]. Today the criteria are the same for a building independent if it is located in the northern and southern Sweden. Hence, one should consider implementing a more dynamic approach for daylight in MB.

4. Material aspects

In the material area, indicator 15 *The structure and foundations climate impact*, is a new indicator in MB added in v3.0 year 2017 [45], where the GHG emissions from main building structure is taken into consideration. Embodied GHG emissions is the amount of CO_2e emitted to produce a material, product, or building. As the embodied GHG emissions of buildings are responsible for a large proportion of the environmental impact from buildings with a relative importance of 20–50% of the life cycle GHG emissions [46], this indicator can be of great importance. It can help to shift the focus in the buildings sector from efficiency in operation towards a life cycle perspective, which is necessary according to several studies that have demonstrated the importance of the embodied GHG emission [47]. The aim of indicator 15 stated by SGBC is to increase the knowledge of the load bearing horizontal and vertical structures climate impact, increase demand and supply of EPDs, and reward measures that reduce the environmental impact of the load bearing structures [5]. Included in the indicator's calculation are the GHG emissions from the first life cycle stages of the building products (Stage A1-A4 according to EN 15978, **Figure 1**) [48] that are used in the main structure, (the loadbearing vertical and horizontal structures) and the foundation down to the drainage layer.

For the grade Silver and Gold, emissions from transports (Stage A4) are included as well as a requirement that a certain part of the life cycle analysis data comes from EPDs (Environmental Product Declarations). Gold rating requires proving of reduction of GHG emissions by at least 10% lower than the Silver level for the already chosen building design, frame and foundation. This can be done, for example, through changes of material choice, dimensions or quantities in the load-bearing structure.

4.1 No absolute criteria for embodied greenhouse gas emissions

When analyzing what impact the indicator has on greenhouse gas (GHG) emissions and energy use, there are a number of issues that can be discussed. To start with the indicator in general, it does not have absolute criteria with a specific absolute level

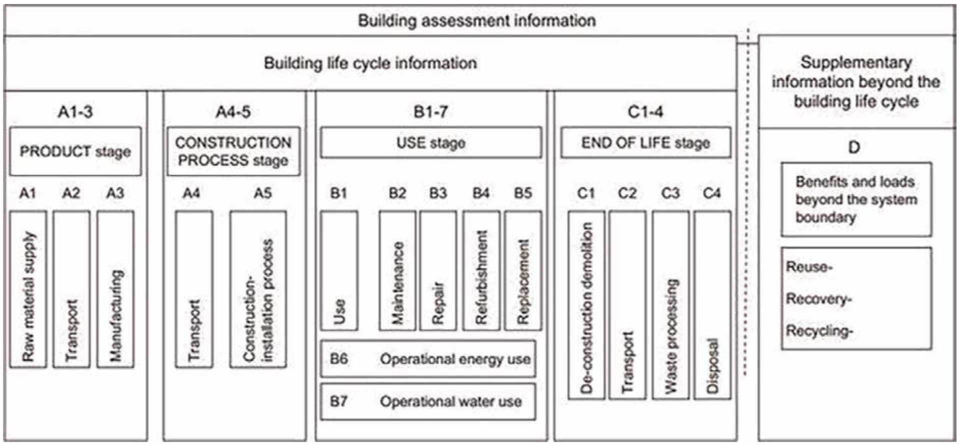

Figure 1.
Building's life cycle stages according to EN 15978 (2011) [48].

of emissions that the building has to meet. This makes it difficult to compare the environmental performance of different buildings. However, for the Gold level is a relative decrease of 10% required. This type of relative criteria that credit an improvement compared to a reference building, is similar to indicators used in the American EAM LEED (Leadership in Energy and Environmental Design) [49] and the British BREEAM (Building Research Establishment Environmental Assessment Method) [50]. Moreover, the decrease is calculated relative to an optional pre-design that can be designed as a worst case scenario with high levels of embodied GHG emissions. Other research show that the GHG emissions from buildings can vary a lot, between 165 and 665 kg CO_2e/m^2 for residential buildings and 355–580 kg CO_2e/m^2 for office buildings (first quartile and third quartile) [46]. Therefore, 10% lower GHG emissions than a building with high levels of embodied GHG emissions can still be much higher than the average levels of embodied GHG emissions. At the same time it is difficult to set more absolute targets or criteria as there are many aspects of the design of a building that influence the choice of material and the amount of material needed in the load-bearing structure. The same reason makes it difficult to have a reference building or reference GHG emissions to measure the buildings performance against.

Moreover, for Bronze, only generic data may be used which will not promote choosing materials with lower environmental impact within a product or material group. For Silver and Gold, it is different. Then at least 50% vs. 70% of the climate impact for the production of the building materials need to be based on product-specific EPDs. Then specific products or materials can be promoted. A variety of parameters and methodological choices influence LCA and EPDs. The embodied GHG levels in the generic data used in LCA tools used for the MB assessment is therefore of great importance. Values can vary a lot making the choice of used data important [51]. For example, the median of embodied carbon per kg concrete is equal to 0.19 kg CO_2e/kg, and has rather small variability of outcomes, (the interquartile range varies between 0.14 and 0.28 kg CO_2e/kg), and the interquartile range of structural steel can vary between 1.7 and 2.8 kg CO_2e/kg, with total variation ranging from 0.34 to 4.55 kg CO_2e/kg [52]. The chosen generic embodied GHG emission data for steel can thus influence if the material is perceived as a more environmental material in comparison to another material with an EPD and what the buildings absolute calculated embodied GHG emissions will be.

4.2 The impact of the system boundary

As mentioned before, buildings embodied GHG emissions represent a large proportion of a buildings total life cycle emissions. In indicator 15, part of this embodied GHG emissions are included as only the load-bearing structure belonging to the frame is accounted for (here meaning load-bearing walls, pillars, beams, floors and foundation down to the drainage layer). Other parts of the building are not included, such as the building envelope or entire internal or external walls. Nor is technical equipment or finishing materials included.

Other studies indicate that variations regarding the embodied GHG for only the structure can be 200–350 $kgCO_2e/m^2$ and for the whole building 600–850 kg CO_2e/m^2 [53]. Thus, the embodied GHG in the structure can, according to this data, represent between 25 and 40% of the buildings total embodied GHG emissions. The embodied GHG emissions from a building can also be influenced by the building's geographical contexts, climate zones and building type [46].

Another system boundary aspect is that all life cycle stages are not included; only stages A1-A4. Other life cycle phases such as maintenance, replacements or end of life, which deals with an uncertain future, are excluded. This is in line with the Cradle-to-Gate approach which is one of the three different life cycle models for buildings system boundary that EN 15978 proposes [54], which is used in EPDs. The other ones are Cradle-to-Grave, which also include buildings use phase and end of life impacts, and Cradle-to-Cradle which include potential benefits of reuse, recovery and/or recycling potentials. One consequence of MBs limited life cycle perspective is that material aspects linked to the future that may influence the environmental impact of a material during the use phase from a 50 to 100 year perspective are not taken into consideration. The benefits with long lasting products with low maintenance and replacement rate are thus not getting any credits. There is therefore a risk that suboptimizations are made. On the other hand is it not possible to have exact data beforehand regarding future management, refurbishments, service and end of life procedures. If not including future lifecycle stages in some way, the indicator does not differentiate between materials that are recyclable and non-recyclable. It is not clear how the environmental impact of recycled and reused products, or the potential benefits with reusing, or recycling the material should be calculated. For the generic data in the tool, materials with recycled content is not an option.

Another issue very close to the system boundary aspect is the room for variations in results when calculating the amount of materials that are included in the load bearing structure. Variations can be based on how detailed the structure is dimensioned, and the marginal regarding loads that has been used, as well as the detailing in calculation, for example if it is based on a BIM model or if it is based on general data linked to square meters of slabs, walls, etc. Variations in how A_{temp} is measured can also influence the results. If a building has a large garage, storage in the attic, or installation/service room for ventilation equipment that is heated above 10°C, it will be included as part of the A_{temp}. The number of square meters in A_{temp} will then increase and lower the calculated GHG emissions from the structure per square meter. This is the effect even though the amount of useable floor area in the building is the same as for a similar building without the same additional areas.

4.3 The environmental impact of using environmental product declarations

MB clearly states that it wants to promote the use of EPDs, which contain reliable and verifiable LCA-based information as a way to promote more specific and accurate LCA data for used materials. EPDs are in one way essential if wanting to compare and assess construction products environmental performance [55]. It is one way to get the building industry aware of the environmental impact from building products. However, there is no clear cause-effect relationship between environmental impact and use of EPD documented materials compared to materials lacking EPD. On one hand, companies doing EPDs will become aware of the GHG emissions and the EPD can also be an incentive motivating producers to develop and retailers to sell products with lower GHG emissions [56] which may promote development of products with lower embodied GHG emissions. On the other hand, local materials or reused materials produced by small and medium-sized enterprises (SMEs), local companies, or new startups might not have the economic power or see economic reasons for doing EPDs. They could then be outcompeted by other materials and larger companies who are able to put in the necessary investment in doing an EPD, which according to surveys are 13,000–41,000 USD and includes a workload of 22–44 person-days [56]. This can be a substantial cost for SMEs.

4.4 Inclusion of greenhouse gas emissions from transport

To achieve silver or gold Indicator 15 also demands documentation of transport of building material and products with generic information of GHG emissions from trucks, trains, boats and airplanes. This criteria has the potential to make building companies aware of the impact transportation distance and way of transport has on the GHG emissions. However, there are no criteria levels for total emissions from transport and there are no differentiation made between different fuels, even though there is a large difference in emissions from trucks with fossil fuels, bio-fuels or electricity as fuel and also between electric trains and trains using fossil fuels. These differences would be appropriate to include in such a calculation. If this is not included, the indicator will not push the industry towards using transportation methods with low emitting fuels.

4.5 Embodied greenhouse gas emissions benchmarks – next step

With the current situation, Indicator 15 has no direct measurable impact on the lowering the embodied GHG emissions from buildings. The 10% reduction criteria for Gold could give some effect. However, the impact is dependent on what construction material that is used for the optional pre-design building that is improved. Moreover, to understand if this 10% reduction is enough for lowering the GHG emissions from the building structure, one has to look at how much the GHG emission levels for buildings need to be decreased and set benchmarks for buildings. Creating benchmarks is difficult and could be one reason why MB at this stage not has any absolute criteria regarding embodied GHG emissions. Benchmarks can be set in different ways. These can be based on a relative improvement of conventional buildings average GHG emissions. As more and more LCA studies are conducted, this type of data will increase and become more available, but there have already [57] been attempts to create benchmarks. The Swedish certification system NollCO_2 or the Swiss SIA 2040 [58] are established benchmarks, which could be used. For example NollCO_2 demands a reduction in energy use and GHG emissions from building materials (phase A1-A5) in comparison with calculated project specific reference building based on parameters for building materials and systems. Furthermore, measures to reach net zero through balancing the remaining GHG emissions are demanded [57]. Different types of reference buildings have different GHG emission criteria levels and the specific projects receives a project-specific limit value that is approximately 30% lower than the baseline, which is expressed in kgCO_2e/m^2 BTA. This varies between 140 and 312 kgCO_2e/m^2 depending on type of building, layout and design [59]. The Swiss SIA 2040 benchmark is based on the German Environment Agency goal of reducing GHG emissions to 1 t CO_2e per capita per year by the year 2050 [60] to be able to achieve the target of staying below a global temperature increase of "well below 2 °C". Benchmarks for GHG emissions from buildings represent 36% of these GHG emissions, i.e. 360 kg CO_2e per capita per year. To follow the Swiss SIA with benchmarks with GHG emissions per capita the number of square meters per capita also needs to be decided upon. What would then be a reasonable level number of square meter per capita and for future GHG emission targets for buildings? As an example, four Swedish buildings that have been MB certified had embodied GHG emissions between 110 and 305 kg CO_2e/A_{temp}. It is forecasted that there is a need to build 592,000 new homes until 2029 in Sweden [61], i.e. 65,778 homes per year, for a population that was 10.3 million inhabitants 2020 and is estimated to reach 11 million in 2029 [61]. If each home is 50 m^2 this would result in 0.3 m^2 new housing per year per inhabitant and 35–97 kg CO2e/ year per inhabitant in GHG emissions from the load bearing structure of these houses if built as the certified buildings. If compared to the Swiss SIA carbon benchmarks, GHG emissions from structure of new housing would represent 10–20% of the total GHG emission budget per inhabitant in Sweden. Working with lowering the embodied GHG emissions from building is thus an important issue. Especially in countries like Sweden where the GHG emissions from the average district heating and the Nordic electricity mix is comparably low (0.059 kg CO_2e/kWh [62] vs. 0.090 kg CO_2e/kWh [63], keeping in mind that MB and forthcoming mandatory climate declaration of buildings consider only phases A1-A5.

How and on what level the GHG benchmarks for buildings should be set has not been elaborated on more in this study. However, it can be concluded that to have ambitious and effective climate mitigation targets, it is necessary to develop clear targets that are transparent and consider both embodied GHG emissions and operational GHG emissions. This would be the next step for MB indicator 15 - to ensure that the impact influence building design to lower the buildings embodied GHG emissions. Despite the fact that indicator 15 does not have any benchmark levels at the moment, several certified buildings have only reached the Bronze level. The reason behind this is not clear. If they were searching for a total Gold score, they would have needed to have Silver on this indicator. If fixed benchmarks with GHG emission criteria would be welcomed or not by the buildings sector is difficult to know, but it is not promising when the indicators without benchmarks are not reached.

5. Concluding discussion

This study has scrutinized nine of the indicators with the strongest link to GHG emissions in the Swedish environmental assessment tool MB. It has highlighted a number of things with the indicators that influence what aspects of building that are assessed and has a potential to also influence the GHG emissions, building design and choice of building systems. It clarifies the strong link MB has to the Swedish energy regulations and how both MBs' and BBRs' energy aspects are linked to the national energy system.

In general, MBs certification system is highly appreciated covering different aspects of the energy use, indoor environment as well as the material choice of the building. The follow-up inspection (within three years after the built/renovation) verify the gained certification grade and guarantee sustainable choices and good performance. Therefore, MB is an effective system with a comprehensive view on environmental assessment of buildings. However, a few limitations with the indicators and how the criteria drive sustainable building design have been identified. To improve the assessment criteria and make it even more handy and applicable the most important conclusions are here presented for the areas Energy, Indoor environment and Material:

Conclusions regarding energy-related indicators:

- The power demand of buildings addressed in MB is important to limit peak demand related emissions. Analysis of quantification methods and the criterions conclude that the unit for quantification, space heat losses divided by envelope area, may lead to less energy efficient building design; design outdoor temperatures or climate files for simulation should be based on future climate projections. The criterions set by MB involve energy factors, which do not reflect power demand.

- The solar thermal load assessment serves to reduce cooling demand. The major criticism is whether or not STL should be allocated in junction with the summer thermal comfort indicator instead of in the energy area. Introduction of a cooling demand indicator as a whole (considering solar thermal, internal heat loads and climate changes) is more justified.

- Energy use is completely based on BBR procedures, which is an advantage in the design and building permit processes. However, BBR criteria, hence MB's criteria, are dependent on weighting factors to assess primary energy use. These are not primary energy factors. Instead of leading to neutrality among heating systems types, results are biased and may lead to increased emissions since characteristics of local energy systems are not considered. The question is linked to the indicator *Share of renewable energy.* MB could suggest its own weight factors to avoid biases in BBR.

Conclusions regarding the indoor climate indicators:

- To guarantee an acceptable indoor air quality, it is not possible to compromise on the ventilation requirements in MB. Effective and energy efficient ventilation systems (with low SFPs and higher heat exchanger efficiencies and scheduled use based on the actual demand) are essential in order to get higher grades for MB indicators. For non-residential buildings, it is suggested that ventilation rates could be adjusted by the ventilation effectiveness in accordance with European Standard to incite energy-efficient air distribution systems.

- A separate indicator for air tightness is suggested. It affects draft, thermal comfort, heat power demand and energy use. Expecting minimum air tightness for newly and modern building and rewarding airtight buildings could be an indicator merged with the indicator for ventilation. Airtightness measurements during the building process and after completion could be demanded to detect and fix possible air leakages.

- To assure good thermal comfort, it is suggested that performed modeling and simulations are also made with representative weather for the specific location. The thermal comfort criteria in MB is based on PPD, calculated within the design temperature, DVUT, which is based on a 30-year period, available for 1981–2010. The weather during the measurement year might be quite different from a normal year, and this would affect the thermal comfort results. This yields in general for other indicators and for the calculation and simulation of the energy and thermal comfort.

The most important conclusions regarding the material indicator are:

- The actual effect of the indicator on building design, GHG emissions and the environment can be questioned when the indicator does not include absolute criteria that demand a measurable reduction of the embodied GHG emissions.

- There is a large part of the building that is not included in the LCA as it is not part of the load-bearing structure, and there are life cycle stages that not are considered. Therefore, the indicators lose the possibility to reduce GHG emissions from many building parts and do not encourage building with recyclable material or material with low environmental impact from a longer life cycle perspective.

- Next step to assure the indicator pushes buildings to lower embodied GHG emissions would be to set some type of benchmarks for maximum embodied GHG emissions.

Moreover, a clearer distinction between local environmental aspects, which mainly concern local environment, health, and quality aspects, versus global environmental aspect would be welcomed. It would make the existing conflict between environmental quality and environmental loads, which affect building design, environmental assessment tools, and environmental decision-making in general, more visible.

MB is a certification system that pushes building design and the building sector towards more environmental and high-quality buildings. However, the indicators and criteria seam to beset to improve conventional buildings. To reach the environmental targets in the building and property sector, especially regarding GHG emissions, and make the urban transition that is necessary the indicators and criteria levels need to be adopted more towards these environmental targets.

Acknowledgements

The comments and fruitful discussions with Agneta Persson, Andreas Hagnell, Eje Sandberg, Jonas Gräslund and Mauritz Glaumann are deeply appreciated.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

Funding of the study by the Swedish Energy Agency, E2B2 program, is greatly acknowledged (Dnr: 2018–016216).

Abbreviations

A_{temp}	Floor area that is heated above 10°C
A_{env}	Building envelope area
BBR	Boverket's Building Regulations
BIM	Building information modeling
CFD	Computational fluid dynamics
CHP	Combined heat and power plant
CO_2e	Carbon dioxide equivalent
DF	Daylight factor
DH	District heating
DHW	Domestic hot water
DVUT	Design winter outdoor temperature
EPD	Environmental product declaration
EP_{pet}	Primary energy number
F_{geo}	Geographic factor according to BBR
GHG	Green house gases
g_{sys}	Solar heat gain coefficient for windows and shading devices
HLKK	Heat loss form factor
HP	Heat pump
LCA	Life cycle assessment
MB	Miljöbyggnad
PPD	Predicted percentage of dissatisfied
SAD	Seasonal Affective Disorder
SCOP	Seasonal coefficient of performance
SFP	Specific fan power
SGBC	Sweden Green Building Council
STL	Summer thermal load
USD	US Dollars

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Chapter 9

Climate Change and Extreme Wind Events: Overview and Perspectives for a Resilient Built Environment

Sofia Pastori and Enrico Sergio Mazzucchelli

Abstract

The frequency and intensity of extreme weather events have increased in the last few years. Buildings resiliency against natural hazards (hurricanes, flooding, wildfires, etc.) is fundamental for the adaptation to climate change, however it is hardly included in their design. Buildings exposed to extreme climate conditions may become drivers of vulnerability, rather than providing shelter for users, leading to human and economic losses. The building stock assessment appears to be quite detailed about seismic vulnerability and energy demand related to climate change, but not towards other hazardous events, such as extreme winds. Furthermore, climate data provided by current standards and used for building design need to be seriously reconsidered, since they no longer represent the real weather variables. During windstorms, the main threats are mainly due to the detaching and flying of materials and elements from buildings and urban furniture. The chapter deals with the effects and consequences of strong wind events on the built heritage and calls for an urban transition to create resilient and safe environments for the people. An overview of the current standards related to building design against wind is presented, and mitigation and adaptation strategies are proposed to respond to current and future climate threats.

Keywords: urban sustainable development, built environment, building resilience, climate change, windstorm

1. Introduction

Adaptation to climate change is today recognised as a global issue, as also acknowledged by COP 26 [1] and COP 27 [2]. The number of extreme weather events has increased by more than 250% in the period between 1980 and 2013, and this upward trend is continuing [3, 4].

The world is experiencing huge pressure on living conditions and an increase in damage to assets and asset value due to extreme weather events, most of all in coastal areas, where most of the world's population lives. Moreover, the inertia of the climatic system is such that no matter how great the emissions reductions that may be achieved by 2050, the average temperature will be 1.5–2°C higher compared to the preindustrial era, and there will be a significant increase in the frequency of extreme climate events [3]. In fact, the expected impacts of climate change, including sea level rise, heat waves, droughts, and storms, will increasingly affect the built environment, economic activities and society itself (**Table 1**). Recent research [4] predicts that, by 2050, 1.6 billion people living in urban environments will be regularly exposed to extremely high temperatures and over 800 million people will be affected by sea level rise and coastal flooding.

Climate change effects call for an urban transition to create safe and resilient urban environments that can face the present environmental challenges, extreme wind events included. In this regard, a comprehensive urban transition should consider adaptation and mitigation strategies for the built environment.

Climate risks affect all aspects of a building: the structure, use, accessibility, provision of services and the safety, health and well-being of its occupants. Buildings strongly exposed to extreme climate conditions may become drivers of vulnerability, rather than providing shelter, leading to both human and economic losses [3–5]. Poor, ill-planned and over-crowded settlements face the highest risk from climate change. During the past two decades, almost 90% of deaths due to storms took place in lower-income countries, though they endured only a quarter of total storms [6]. Climate-related hazards, such as windstorms, forest fires, heavy rain and floods lead to the growing necessity for buildings to be resilient to extreme and unpredictable weather conditions. Therefore, the increased frequency, intensity and impact of extreme weather events call for resilient buildings and urban environments, designed for protection against physical damages and failures. This leads to the need for an accurate analysis of the characteristics and vulnerabilities of the built heritage as well.

Resilient buildings need to face many challenges in many combinations (hurricanes and high wind resistance, wildfire events, etc.) but today their design hardly includes these aspects. Also, for what concerns the building stock assessment generally appears to be quite detailed about seismic vulnerability and energy demands related to climate change, but not towards other hazardous events, such as extreme wind events. Furthermore, climate data provided by the standards and used for building design need to be seriously reconsidered, since they no longer represent the real weather variables [7]. The adaptation of buildings to climate change requires the development of a culture of risk management and the improvement of resilience, beyond the requirements provided by regulations [3].

Climate hazards	Chronic	Acute
Temperature	Temperature rises Freeze-thaw cycles Permafrost thawing Air quality degradation	Heatwaves Extreme cold Urban heat islands Wildfires
Wind	Wind patterns	Storms Tornadoes
Water	Sea level rise Thunderstorms	Drought Floods Coastal submersion
Land	Coastal erosion	Subsidence Landslides
Biodiversity	Species migration and loss	

Table 1.
Direct and indirect risks due to climate hazards.

The present article deals with the effects and consequences of strong wind events on the built environment. The risks related to such climatic hazards regarding the urban environment, the existing standards and the buildings' vulnerability assessment are discussed. Furthermore, a design methodology and examples of resilient buildings are presented.

The research included a first phase consisting in the state of the art analysis and review of actual standards, considering those areas already affected by strong wind events. This allowed us to define a methodology for resilient building envelope design, involving risk analysis and the definition of design guidelines.

2. The rise of extreme wind events

In the last few years, both intensity and frequency of extreme natural hazards have been increasing [8]. These events cause relevant damage to the environment, buildings and people, especially when they occur in countries not used to them, such as Europe. In 2019, strong winds caused 38% of the recorded injuries and 16% of the recorded fatalities caused by extreme weather in Europe [9].

During powerful storms and cyclones, the major risks are not only related to the high wind pressures but mainly to the impact at high speed of flying debris on buildings [10]. The flying objects can damage the building envelope and its content, eventually causing wind-driven water infiltration, producing potential significant losses of people and goods [11, 12].

The increasing risk of wind-induced damages should raise the awareness of designers, constructors, building managers, building owners and authorities on the importance of a careful building envelope design to resist the rising wind loads due to climate change. The increased frequency and severity of extreme weather events are causing more and more damage and even higher repair costs.

Storm speeds are projected to increase due to climate change in the second half of the 21st century, accompanied by an increase in frequency [13]. However accurate predictions on future storm intensity and frequency are not easy, since the forecast models used have many issues related to the lack of accurate observational data set against which to validate them [14].

Not only wind intensity but also frequency may negatively affect the built environment, subjecting building envelopes and urban elements to cyclic stress.

Despite the relevance of the topic, very few investigations have been conducted [15]. Wind has been investigated extensively to prevent the failure of the major building elements, therefore, several Codes and standards have been developed. Besides this, attention must be paid to building components and urban furniture, which can be vulnerable elements when subjected to strong wind.

Several measures to mitigate the wind effects on the built environment have been already implemented in areas prone to hurricanes, typhoons and tornadoes (i.e.: Florida, Hong Kong, Japan, Australia, etc.). Their major goal is to prevent damage to people and properties due to windborne flying debris, by adopting two sets of actions:

- mitigation, reducing the flying debris phenomenon by improving the resistance of urban and building elements to wind;

- adaptation, setting design guidelines and testing methodologies to ensure the resistance of the building envelope against possible impacts.

Figure 1.
Medicane on South Italy and Greece (left) and tornado in Venice (right) [16].

In Europe, instead, there are still no requirements concerning the consequences of windborne flying debris, since in the past such events were considered so exceptional to not represent a recurrent threat. However, several European countries experienced an increased number of tornadoes and extra-tropical cyclones in the last years, including multiple so-called medicanes (Mediterranean hurricanes) in southern European countries (**Figure 1**).

Different levels of performance must be required by the standards depending on the building function: lower performances for common buildings and more demanding ones for strategic structures (hospitals, emergency services, schools, etc.), which must act as shelters and/or operational buildings in case of need.

3. Existing standards for building design under wind action

Although climate projections can be used to understand the extreme events that are expected to occur in the future, the legislation on urban planning does not currently consider future climate risks [3].

In Europe, the design of the envelope under wind actions follows Eurocode 1 [17], but extreme load configurations, including natural events, are considered only marginally. For some extraordinary meteorological phenomena that happened in the past, it was noticed that the maximum design values were lower than the actual wind speeds. Anyway, building envelopes may show a critical behaviour already under wind speed below the maximum values predicted by the Eurocode, due to an inaccurate design of technical details.

Currently, the country with the widest and most developed legislation in this regard are the United States. US Building Code ASCE 7-16 [18] provides a map of different areas according to the usual wind speed and the probability of developing hurricanes. The standard also recognises the protocols established by ASTM E 1886 [19] and ASTM E 1996 [20] as reference tests on glazed building elements hit by hurricanes or tornadoes. These standards involve the execution of two different tests on full-scale mock-ups to analyse the combined action of wind pressure and flying debris impact on the construction systems. During the impact tests, the missiles are shot by a compressed air cannon against the specimens (**Figure 2**). The mass and velocity of the test missiles vary according to the building's level of importance and its geographical location. Three missile types are allowed:

Figure 2.
Impact test on a glazed façade mock-up using a large wooden missile, according to ASTM E 1886 and ASTM E 1996.

- small missile, a solid steel sphere with a mass of 2 g, a nominal diameter of 8 mm and an impact speed between 40% and 85% of the base wind speed (provided by the ASCE/SIX 7);

- large missile, a wooden element with a mass between 910 and 6800 g, a length between 525 and 4000 mm and an impact speed between 10% and 55% of the base wind speed (provided by the ASCE/SIX 7);

- other missiles, another item with mass, size, shape and impact velocity determined as a function of the base wind speed, calculated by engineering analysis.

The standard impact points include the centre and the edges of the specimen. In case of successful impact tests, the specimens are subjected to pressure cycles according to the design wind speed, provided by the building codes. A total of 4500 positive and 4500 negative pressure cycles are performed and the duration of each cycle is 1–3 seconds. Also, the voluntary standard AAMA 506-16 [21] is based on ASTM E 1886 and ASTM E 1996, and it requires the control of other parameters, such as temperature, during the test. Instead, no standard tests are defined for the opaque envelope.

The Australian and New Zealand design Code AS/NZS 1170.2 [22] requires doors, windows and façade cladding systems to withstand the impact produced by:

- a wooden element with a mass of 4 kg and a cross-section of 100x50 mm, launched at a speed equal to 40% of the base wind speed for horizontal trajectories and 10% for vertical ones;

- a steel sphere with an 8 mm diameter and a mass of 2 g, launched at a speed equal to 40% of the base wind speed for horizontal trajectories and 30% for vertical ones.

The test methodology and acceptance criteria for the effects produced by wind-borne debris on opaque and transparent building envelopes are provided by the technical Note N.4 [23]. AS/NZS 1170 is the most stringent standard with respect to impact velocities. However, it does not require façade testing under positive/negative pressure cycles. Furthermore, it prescribes that the building envelope must resist flying debris impacts only up to 25 m of height from the ground.

At the international level, tests for certifying the resistance of glazed products to tornadoes are regulated by ISO 16932 [24], which is based on ASTM. As for the United States, there are no protocols for testing opaque envelope elements.

Finally, in Asian countries, only few standards provide prescriptions for the construction of resilient building envelopes, despite the high frequency of extreme phenomena. In Japan, for example, the standard JIS R 3109 [25] refers to the international Standard ISO 16932.

4. Assessment of the environmental vulnerability

Flying debris during wind events is mainly due to the detaching of materials and pieces from buildings, structures, and urban furniture, such as roof tiles, façade elements, antennas, etc. Therefore, wind can cause direct damages (i.e. failure or detachment from the 'source building' of elements under wind load actions) and indirect damages (i.e. impact of windborne flying debris on other buildings). Hence, each building can be both source and target for flying debris (**Figure 3**).

The risks related to the environmental context are highly variable according to the levels of vulnerability that characterise the environment [26]. For this reason, the assessment of the local vulnerability level is fundamental [27]. First, the urban heat island contributes to creating a microclimate, which can worsen the consequences of local weather events [28, 29]. Then, the presence of old/historical buildings, but also

Figure 3.
The environment assessment is essential to identify the possible risks and the elements that can fail in case of strong winds, becoming flying debris.

buildings refurbished using new technologies, which are weak with respect to strong wind loads, could affect the vulnerability of the area.

In order to improve the resilience of the built environment, it is fundamental to strengthen the resistance against wind not only considering the already completed building but also its behaviour during the construction/renovation process, when the elements' resistance usually does not meet the final design performance.

The damage caused by windborne debris is a complex function of the wind conditions, the aerodynamic characteristics of the debris, the point of release, the type of impact and the strength of the structure impacted. The dispersion of windborne debris is related to several factors, including the variability of the wind speed, the turbulent flow field created by buildings and other structures, the fixing type and quality of the elements on the structure [30]. For example, a roofing tile securely fixed may stay in place during a hurricane until the wind reaches its maximum speed, when it will be carried away for a considerable distance and, consequently, hit a target building. On the other hand, if it had been less securely fastened, it may have detached from the roof during a weaker wind gust and it would have fallen to ground more quickly and closer to the source building.

As noted by Baker [31] in his theoretical analysis, small changes in initial conditions can completely change the whole character of a flight path. The removal of one roof tile can start to lift a neighbour one or can expose a neighbouring tile to higher wind loads. Hence, if one tile breaks free, those around it are likely to follow. If the first tile is immediately carried clear of the structure, then the subsequent path will primarily depend on the wind speed and direction at that time, which could easily be different from that which prevails when the next tile breaks free. Therefore, even if the tiles originate from a similar location, they may be dispersed by the variability in wind speed and direction (**Figure 4**).

Wind pressure acting on a building envelope depends on wind speed, characteristics of the surrounding environment and shape of the building itself. In particular, the parameters to be considered are:

- ground characteristics, since the smoother the terrain, the greater the wind speed;

- orography, which considers the presence of surface reliefs (hills, cliffs, etc.). Abrupt changes in topography cause wind to speed up;

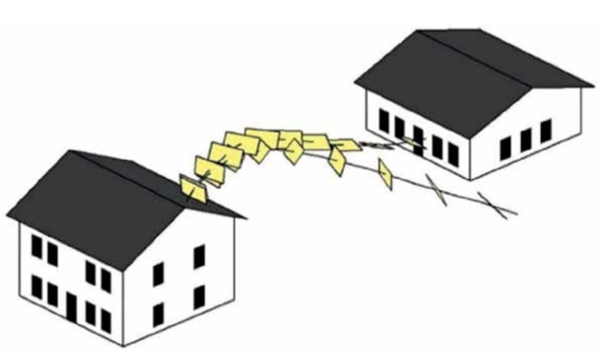

Figure 4.
Example of probabilistic wind-borne debris trajectories of a typical roof-sheathing panel with identical initial conditions [32].

- height and proximity of the surrounding buildings, which influence the pressure distribution. A building located in a densely populated city is shielded from the surrounding structures, while a building located near the sea or in open countryside is totally exposed to the surrounding weather conditions;

- base wind speed, defined by the standards as a function of the geographical area and the altitude above sea level. As the speed increases, the pressures grow exponentially;

- wind direction, which determines the arrangement of positive and negative pressure areas;

- building height, since the wind speed increases with the height above the ground. Therefore, the taller the building, the higher the speed and the wind load;

- building shape, irregularities in the geometry (such as recesses, overhangs and changes in inclination) can cause localised turbulence. These cause punctual acceleration phenomena with a consequent increase in the intensity of the wind load.

During extreme wind phenomena, the pressures acting on the building envelope can exceed the maximum design values, and the action of flying debris coming from the surrounding environment can be added to these actions. If flying debris reaches high speeds (and consequently high kinetic energy), it can damage and break the components of the building envelope (mainly transparent façades and windows, but also some types of light dry-assembled opaque façades, walls, etc.).

The main consequences deriving from these disruptive actions are:

- increase in internal pressure and new redistribution of loads on internal and external elements. The downwind façade is subjected to higher pressures than the design ones and it can be damaged, or it can even collapse. Also, pressures acting on the internal walls become much higher than that considered for their design;

- water penetration through openings and breaks in the building envelope, pushed by the pressure difference between inside and outside.

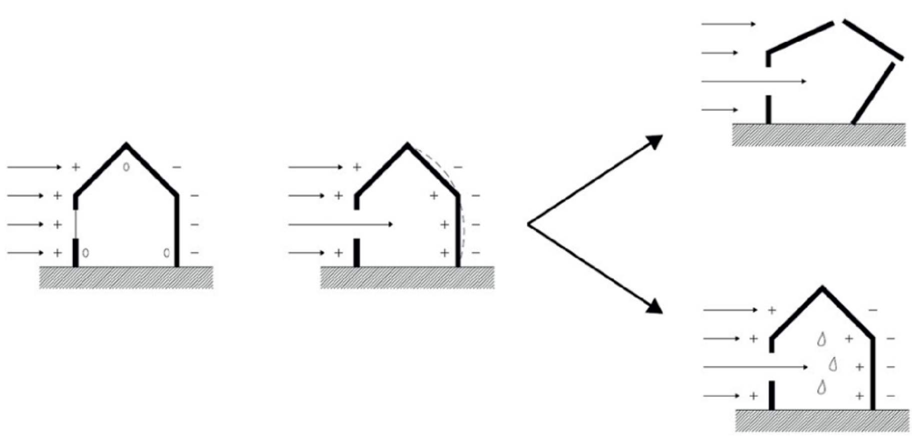

Figure 5.
Schematic of internal pressure condition in case of wind infiltration inside a building [10].

The breaking of even a small window due to a flying debris impact is typically sufficient to cause full pressurisation inside a building. When a building becomes fully pressurised, the loads applied to the exterior walls and roof are significantly increased if compared to the designed ones. The build-up of high internal pressure can blow down interior partitions and blow ceiling boards out of their support grid. Furthermore, water penetration can cause further damage to the building's content (**Figure 5**).

5. Design methodology for resilient building envelopes

Wind-induced damages are often related to the buildings' construction quality. Failures can affect building structures; however, the worst consequences are usually concentrated on façades and roofs. Nevertheless, ensuring that the entire building envelope is not damaged during extreme events requires design strategies that could be uneconomical. The sporadic occurrence of these phenomena does not justify the adoption of specific design solutions on a large scale. Therefore, it is necessary to define an analysis methodology that allows designers to collect the necessary information to establish the level of risk related to a specific case study, with respect to exposure to extreme winds and flying debris effects on it. In case of high-risk levels, the buildings that must remain always in operation and subject to higher wind pressures and the impact of more damaging debris must be identified and design strategies must be specifically planned.

An assessment methodology for resilient building envelopes design, for new and existing interventions, is proposed and discussed in this paragraph (**Figure 6**). The first analysis to carry out concerns the wind conditions at the project site, both in terms of average speed and prevailing direction, given by the standards and/or from a climatic database. The data included in the Codes represent an average of historical records, they do not provide information on the wind characteristics during exceptional events that occurred in the past. For this reason, it is also necessary to analyse the wind values recorded in the last decades to evaluate whether these are in line with the values given by the standards.

The second analysis involves the collection of information regarding buildings and urban spaces located within a radius of 200 m from the considered building. It is necessary to evaluate:

- the geometric characteristics and the construction technologies;
- the conditions and level of maintenance of the nearby buildings;
- the urban furniture located in the surrounding areas, such as in parks, streets and uncultivated and abandoned spaces.

Based on the information collected, it is possible to identify the potential windborne debris that might hit the target building in case of extreme wind phenomena, which might be considered in wind engineering analysis for an integrated design.

The assessment of the possible impact effects on the building envelope is then carried out based on the potential debris, the building characteristics and function (which determines its social and economic importance). The results of the analysis should meet the requirements in terms of building safety, serviceability, durability and robustness. Safety is the most important issue during the design, and it shall be strictly guaranteed. Serviceability and durability are fundamental as well. Hence, designers are supposed to minimise the risk of out-of-service and maintenance costs during the service life.

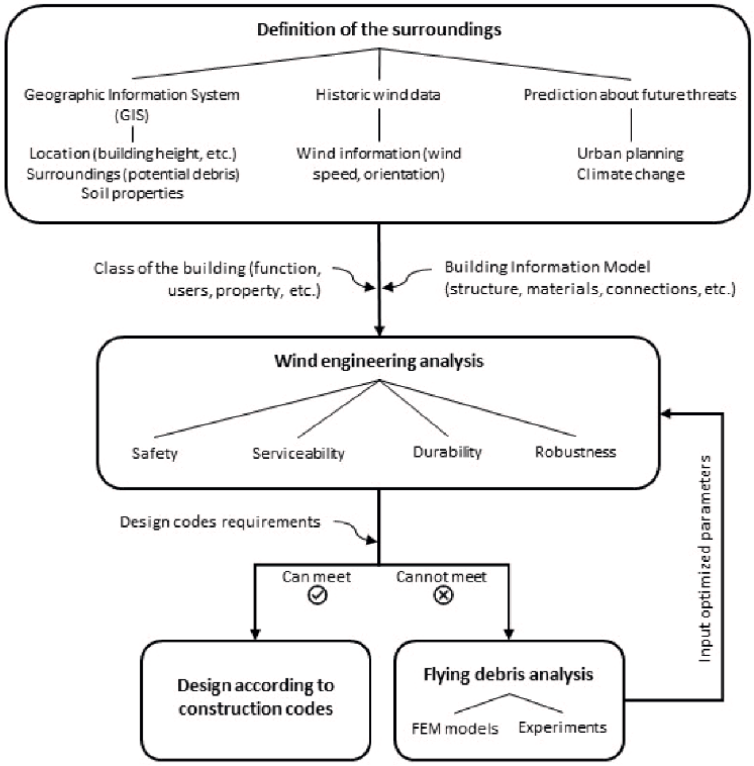

Figure 6.
Proposed methodology for resilient building envelope design.

In case the requirements provided by the available construction standards are not considered appropriate, a building design optimization process should be considered. Once obtained, the optimised parameters could be used as a guideline for re-designing the whole building envelope. In this case, the design of the technical details should be defined after specific experimental tests, as well as finite element modelling. Impact tests might also be performed, while data including the impact velocity and impactor characteristics (material, geometry, etc.) are collected. This information plays a significant role in the definition of the necessary equipment to be arranged for the verification of the building envelope's effectiveness against flying debris protection. To perform this kind of impact test on façades, it is necessary to set up specific testing equipment. In fact, compared to existing tests conducted using missiles, the projectile to be shot on the façade might have different sizes, materials, weights, and impact speeds. The test aims to verify the façade solution's effectiveness in withstanding the impact of wind-borne objects, which have been previously identified as a potential danger under extreme wind conditions (**Figure 6**).

6. Examples of resilient building and urban environment design

The risks deriving from extreme wind events, such as tornadoes or hurricanes, cannot be eliminated completely, but specific design strategies can be used to mitigate their effects. Adequate building resistance to wind actions can only be achieved with good design, construction and maintenance. A significant deficiency of any of these three elements could compromise the performance of the entire building [33].

When envelope failures occur only in specific areas of the building envelope (i.e., corners, changes in building geometry and inclination, etc.), the causes are usually related to the underestimation of the wind pressure acting on their surface. Otherwise, scattered failures are mainly related to the impact of windborne debris or to the effect of interference due to the presence of other buildings.

In this paragraph, some considerations and recommendations about resilient envelope design are presented and discussed.

For what concerns opaque façades, although some failures of massive brick walls have been observed after cyclones and hurricanes, the construction systems most subject to damage are the dry-assembled ones. In recent years, there has been an increase in the use of dry construction technologies, which allow higher flexibility, lightness, fast installation and waste reduction. Dry cladding systems are composed of the combination of different materials and layers, which allow them to achieve increased or higher energy performance compared to traditional technologies to optimise the thickness, masses and time of installation and to simplify the connection and interfaces among the various components (**Figure 7**).

Dry stratified vertical walls, although without any structural function, must be able to resist positive and negative wind pressures to avoid their collapse. Therefore, the wall substructure must be adequately fixed to the structural support and adequately stiffened by decreasing the distance between mullions, or by adding intermediate transoms. Finally, it might be useful to integrate a double panel fixed to the external side of the substructure, using concrete-based panels reinforced with a fibreglass mesh instead of classic plasterboard panels.

In case of ETICS (External Thermal Insulation Composite Systems) applied on dry walls, in addition to damage and perforation of the insulation layer by flying debris, common failures concern the detachment of the external coating from the insulation, the separation of the insulation from the rear panel of the dry-wall (e.g., concrete-based or plasterboard panels) and of the latter from the wall substructure. In the worst cases, it is also possible to detect the partial failure of the substructure (**Figure 8**).

Considering ventilated façades, failures can involve the cladding panels, the substructure, or the connections of the panels to the substructure. The finishing panels are the most vulnerable components since they are the most exposed and stressed by wind

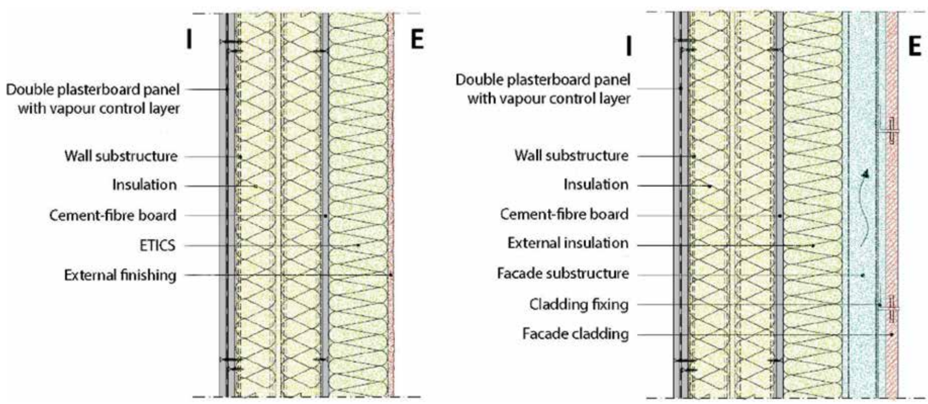

Figure 7.
Example of ETICS and ventilated façade system applied on a dry-technology wall.

Figure 8.
Detachment of the plasterboard panel from the wall substructure in Pensacola (Florida) [34].

actions. The substructure components are calculated according to the expected state of stress and the maximum service limit displacement. Moreover, the substructure should be provided with adequate reinforcements in all the areas that can be subjected to particularly high stresses (for example, the building corners). The impact of flying debris on the façade can cause damage, above all, to the finishing slabs (**Figure 9**). The most critical points are generally the centre of the slab and the anchoring areas, where failures might be more likely due to the concentration of stresses. The resistance of the system can be increased in several ways, including the reduction of the size of the slabs, the increase of the slab thickness and of the number of fixings for each slab; the reduction of the distance between the substructure elements and the fixing brackets and the increase of the metal substructure thickness. Also, the use of ductile materials for the finishing slabs (e.g. metal panels) can ensure better behaviour against non-penetrating flying debris than fragile materials. The size and anchor type of the cladding are relevant since the panels might detach from the substructure, causing trouble to the people outside and damage to the buildings.

The fixing typology might allow the substitution of each module independently in case of damage. Attention is to be paid to the action of wind inside the cavity. In fact, the wind can enter through the façade openings, joints or broken panels, stressing the anchors and tearing the cladding away. The anchors of the façade should be tested under cyclic loads, as well as under localised impacts, to evaluate their mechanical resistance.

Concerning flying debris impact, transparent façades are the most critical part of the building envelope. Glass breakage is particularly insidious, since it causes an

Figure 9.
Extensive damage due to wind action and flying debris to the opaque and transparent façade of the Hyatt regency hotel (New Orleans) [8].

increase in the internal pressure due to wind infiltration into the building, compromising the envelope's watertightness as well (**Figure 10**). There are mainly two ways to improve glass façades behaviour:

- increase the resistance of the façade components;
- introduce external shielding systems acting as façade protection.

The use of float glass should be avoided, while the use of laminated glass is preferred. In fact, in case of breakage, the plastic interlayer keeps the glass pieces in place, avoiding the formation of openings and damage to people and/or things. The most used interlayer is the PVB, but over the last decade, new solutions have been studied and tested, which guarantee greater resistance to the impact of flying debris in areas exposed to the danger of hurricanes. PVB reduces its elastic module to around 30°C (glass transition), decreasing its mechanical properties. In case of exposition to the sun and for higher resistance to flying debris impact, ionoplast interlayers are recommended. Moreover, for further improvement of the glazing resistance against impacts, laminated glass made by coupling float and toughened glass can be used.

However, acting only on the type of glass is not enough. In fact, it is also necessary to use adequate glass retention systems. The structural bonding technology responds better to the mechanical stresses caused by wind than mechanically retained façades. First, the sealing ensures a good response to wind suction since it is put on the whole glass perimeter. Moreover, the presence of the gaskets prevents direct contact between the glass and the frame, avoiding mechanical stresses in case of wind loads and possible glass or frame breakage. Anyway, a mechanical retention system should be integrated, acting as additional protection in case of adhesion failure. If a solution with mechanical retention is chosen, particular attention must be paid to the connection between the frame and the pressure plate.

The choice of the frame must take place according to the reliability of the system and the methods of breaking (and consequent replacement) of the glazing. From this

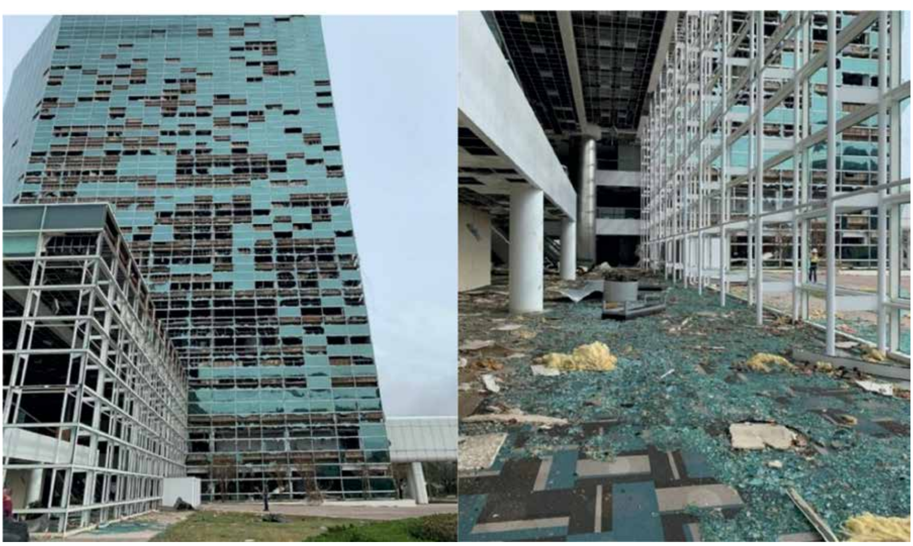

Figure 10.
Capital one tower (Louisiana) transparent façade damaged by hurricane Laura [34].

point of view, a unitized system allows easier maintenance and guarantees a higher quality of the product, since the elements are assembled off-site. An advantage of the unitized façade, compared to stick systems, is that each cell is independent of the others, allowing the substitution of a single unit in case of damage. Moreover, the façade system should integrate fixings that allow the substitution of the broken glazed part without touching the inner frame and layers. Hence, in case of glass breakage during wind events or construction phases, it is possible to change only the glazed part and fix it to the inner frame.

If a stick system is preferred, the length of the mullions must not exceed the distance between two consecutive floors and the connection between the vertical and horizontal elements must be reinforced. Stick systems show lower performance than unitized façades in case of strong wind events. This is especially because, in case of damage to the glazed or framed parts, the substitution of a large façade portion might be required. The cross-section between transoms and mullions is critical from the point of view of wind loads, thus preliminary pull-out laboratory tests should be performed on this connection. The building involves a façade portion with external louvres.

Point-fixed curtain walls are, on the other hand, to be avoided in locations subject to extreme wind events. In fact, all the functions required of a building are entrusted to glass (mechanical resistance, air and water tightness, etc.); therefore, in the event of glass failure, the entire façade fails.

Among the solutions that increase the level of protection, expensive but effective technology is the double skin façade. Normally used for purposes related to internal comfort, this solution, if properly designed, provides good protection of the indoor environment. The internal and external glazing are totally independent of each other, and they are separated by an air cavity. The outer skin must be strong enough to protect the inner one in case of extreme events. Shielding systems (with slats, fixed, adjustable, etc.) can be installed in the air gap, with the aim of regulating solar radiation and indoor daylighting. However, these systems must be able to withstand gusts of wind and the impact of flying debris, and, in case of failure of the outer skin, they should be able to close completely to form a continuous barrier to protect the innermost glazing. If not sufficiently resistant, once exposed to the external environment, the screens could become a potential source of debris.

Other protection systems are represented by external shielding, which can be permanent or can be activated in case of extreme wind events. Some examples are roller shutters, shutters or more innovative systems, such as coiled wire systems (i.e., light metal meshes, used both for decorative purposes and to improve the building's thermal performance). The presence of external sunscreens can be hazardous in case of strong wind since they can break and damage the façade itself or other parts of the building envelope. Thus, they should be fixed to the façade in an appropriate way and their substitution should be guaranteed without touching the façade module behind them.

7. Conclusions

Climate change effects call for an urban transition to create resilient urban environments that can face the present environmental challenges, such as extreme weather events. The effects produced by windstorms are often devastating, despite this the topic is still very little studied. The resilience of the building envelope to extreme phenomena is fundamental and must be achieved through careful planning and accurate design. This must consider the meteorological and environmental boundary conditions of the building site, the identification of the most critical areas of the building and the localised adoption of building technologies and strategies specific design, with the aim of minimising the risk without excessive uneconomical design.

The considerations regarding the existing standards show the current lack of regulations on the topic in Europe. Insurance companies that protect buildings in the event of extreme events are already present, but there are no design requirements concerning the building envelope resistance against the impact of windborne debris. There is an urgent need, in the European context, to introduce adequate regulations and impact test requirements in order to ensure the building's functioning after hazardous events, at least for public and strategic buildings, that may also be used as extreme-weather shelters.

A design tool must be developed for façade engineers to assess adequate airborne debris resilience of façades, based on local environment and aerodynamic simulation of debris flight in strong wind conditions. This design implementation should lead to a safe building envelope design both for new constructions and retrofit solutions. By integrating local measures for the built environment adaptation to climate change, Authorities, project developers, funders and community members can motivate and educate people, provide incentives and develop a favourable environment for the promotion and innovation of a sustainable building design and construction standards for the community resilience to climate change.

Conflict of interest

The authors declare no conflict of interest.

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Section 4

Sustainable Ventilation – Give Air to Urban Transitions

Chapter 10

Building for Sustainable Ventilation and Air Quality

Mikael Björling

Abstract

Most legislations concerning ventilation are based on perceived air quality criteria, but ventilation is also important for the health of the occupants. The perceived air quality criteria can be viewed as a pragmatic tool to achieve an adequate ventilation for precautionary health measures. From a comfort and health perspective, the ventilation rate and an efficient air distribution are both important for achieving a healthy and comfortable indoor environment. Yet, most legislative requirements focus on the ventilation rate. This is not enough, and it is recommended that legislation also address the air distribution with the same zeal. In particular, the efficient distribution of fresh air to the occupied zones or lowering the concentrations of pollutants in the occupied zones. Because there are clear links between ventilation and health, it is extremely worrying that the "energy efficiency first" principle advocated in the Energy Performance of Buildings Directive (EPBD) has led to decreasing ventilation requirements in the European Union legislations, at the same time as the objective is to aggressively tighten the envelopes of the building stock. A second consequence of EPBD is probably that many naturally ventilated buildings will be retrofitted with mechanical ventilation systems. It is not clear that this would be the more sustainable solution in the long run.

Keywords: ventilation requirements, ventilation rates, air distribution, air change rate, local mean age of air, air change efficiency, indoor air quality, EPBD, natural ventilation

1. Introduction

The purpose of buildings is to protect the occupants from a harsh outdoor climate, but also to provide a comfortable and healthy indoor environment. The latter two objectives are intimately related to building ventilation, i.e. the exchange of indoor air with outdoor air. However, 40% of the total consumption of energy resources in the European Union (EU) can be traced to building use [1]. A large part of the consumption is due to the need to condition the indoor air for the thermal comfort of the occupants, i.e. heating or cooling depending on the outdoor climate. In these situations, exchanging the conditioned indoor air for unconditioned outdoor air obviously raises the energy consumption. On the other hand, striving for more energy efficient buildings without a clear strategy for adequate ventilation is likely to lead to more

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toxic and hazardous indoor environments. In a wider perspective, the relative projected societal costs for the occupants of a building, compared to the energy use in that building, are probably nine to one [2]. Compromising public health in the name of "energy efficiency" can therefore lead to a considerable economic backlash for society. In a larger perspective, many indoor sources of pollutants in the world have been identified as major causes of premature mortality, e.g. combustion of biomass fuels for cooking, burning incense or mosquito coils and parental smoking [3, 4]. In addition, if the occupants perceive the indoor environment to be unhealthy or uncomfortable, they are likely to take actions (e.g. use air cleaners or increase ventilation flows) that will increase the energy use in buildings [5].

After the energy crisis in 1973, new and renovated buildings have been built with increasingly tighter envelopes to stop uncontrolled air exchanges through cracks and leaks in the construction and to improve energy efficiency. In 1974, the "Passivhaus"-concept combined three energy-saving measures: adequate thermal insulation, a tight envelope, and heat recovery into the idea of a building requiring no, or very little, energy use after it was built [6]. After a few serious backlashes in the early days, the building technologies used to achieve energy efficiency in nearly zero energy (NZE) buildings are currently more mature, but the efficiency of the corresponding ventilation strategies have not been given the same attention. There are several examples of inadequate ventilation in NZE buildings [7]. After the EU Energy Performance in Buildings Directive (EPBD) in 2010 [1], stipulating that all new building should meet the NZE requirements, a majority of EU ventilation experts were worried that EPBD would lead to a worse indoor air quality as compared to the current state [8].

The EPBD is an integral part of the European Green Deal: an action plan to reach a "climate neutral" EU economy [9]. The European Green Deal outlines a more sustainable path for economic and societal development to "transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy" [9]. The European Green Deal addresses many issues: a toxic-free environment; preserving and restoring ecosystems and biodiversity; circular economy; a fair, healthy and environmentally friendly food system; but much focus is devoted to an energy transition to reach zero net emissions of greenhouse gases in the EU by 2050 at the latest [9]. Zero net emissions means that there should be a balance, between the actual emissions of greenhouse gases and the absorption of greenhouse gases by nature (or other processes), in some bookkeeping system like the Emission Trading System [9, 10]. This goal of net zero emissions by 2050 will be legally binding for the member states if the proposal for an EU Climate Law is ratified [11]. Renewable energy sources as well as moving to more energy efficient and sustainable solutions play essential roles in the European Green Deal [9]. The EPBD is the result of the European Commission's resolve to "rigorously enforce legislation related to the energy performance of buildings" [9].

Another issue addressed in EPBD (and its amendments as well as in the European Green Deal) is that 85% of the present building stock in the EU is built before 2001, and most of those buildings are not considered energy efficient [12, 13]. More importantly, at the current rate of renewal (1%), 85–95% of the buildings that will be standing in 2050 are already built [9, 12, 13]. Increasing the rate of renovation of the existing building stock to NZE standard should therefore be strongly encouraged in order to reach "climate neutrality" [12]. Recently, the European Commission also proposed to triple the building renewal rate to 3% coupled with an even more aggressive renovation strategy to kick-start the EU economy after Covid-19 [14].

Adapting existing buildings to NZE are much more complex tasks than to build a NZE-building from scratch. It requires a considerable knowledge-base of old building techniques, old installations, and the consequences that may arise when NZE technologies are retrofitted to these older structures. In addition, 25% of the existing buildings are historic and will require respect for aesthetics, conservations principles and architectural craftsmanship [15]. In fact, the craftsmanship in many older buildings, although non-historic, deserve the same respect. However, the guiding principle of EPBD: "Energy efficiency first", clearly states that the energy aspect will be given a high weight in a decision conflict [14]. Even though the EPBD states that indoor environments should be healthy or that cultural heritage should be safeguarded and preserved, it is obvious that these incentives will be pushed towards the minimum legal requirements when they are in conflict with the efforts to achieve energy efficiency [12].

In the decision conflict between energy efficiency in buildings and adequate ventilation, EPBD has put an increasing pressure on governmental agencies in the member states to lower the standards for ventilation and air quality in existing building codes and ventilation regulations (see discussion in Section 2.3) [12]. From a ventilation perspective, the standards for air quality should rather become more stringent when the buildings become tighter. There is a balance between the existing ventilation regulations in a country and the air leakages in its building stock because these air leakages contribute to the indoor ventilation, albeit uncontrollably. Legislative regulations on the performance of ventilation systems are also important counter balances to the quest for energy efficiency in buildings. The pressing question is *what* must, or should, be regulated to ensure an adequate indoor environment that is comfortable and healthy for the occupants. The aim of Section 2 of this chapter is to investigate possible answers to this question and put them in a wider perspective.

Another effect, of the coming EPBD renovation wave, is probably that the number of buildings with natural ventilation systems will decrease [8]. Many of the older buildings have some kind of natural ventilation system, whereas most new buildings have mechanical ventilation systems. Because heat recovery is such an important ingredient in NZE buildings, mechanical ventilation systems will be chosen more frequently in spite of the fact that some of the energy recovered will be offset by the energy used by the fans. In a milder climate, a balanced mechanical ventilation system with heat recovery will probably save very little energy and would be costly from a life cycle perspective [16]. Fully functional older buildings with natural ventilation systems will perhaps be retrofitted with mechanical ventilation systems and lose some of their aesthetical or cultural heritage values. On the other side of the spectrum, if such a building cannot satisfy the building code regulations, it may be declared unfit for use and demolished [17]. It would naively appear that natural ventilation, where natural driving forces for air flows are used to ventilate the building, is a more sustainable solution than mechanical ventilation, where electrical energy is used to power fans that generate air flows with high pressures. While even the older natural ventilation systems have many advantages regarding occupant satisfaction, they have some difficulties to compete with the mechanical systems when it comes to predictability, controllability, and heat recovery [16, 18]. Nevertheless, natural ventilation systems are considered the more sustainable options in many research initiatives [19–22].

From this perspective, a revival of the use of natural ventilation systems, rather than the projected decline outlined above, would be desired. There are a number of new promising innovations and old, forgotten, know-how is rediscovered, e.g. wind towers, evaporative cooling, solar chimneys and box windows to name a few [23]. The thermal performances of many ancient buildings, with natural ventilation systems, are far superior to many modern buildings, with mechanical ventilation systems. The list could probably be made very long, but some selected examples are: the "baadgir" in the Dolatabaad garden in Yazd, Iran, that uses several of the mentioned techniques [24]; the Villas at Costozza, Italy, use cool air from nearby caves; the Palazzo Pitti in Florence, Italy, use the cooler air from the Boboli gardens and further cool it underground; the cloister Palazzo Marchese in Palermo, Italy, cool the air underground and augment the effect using underground rivers [23]. Natural ventilation systems thus display many good properties, but their drawbacks will prevent them from fulfilling all ventilation needs. The future of sustainable ventilation will probably be centered on optimal combinations of natural and mechanical ventilation techniques instead, i.e. hybrid ventilation systems.

While there are many good modern examples of buildings with natural and hybrid ventilation systems [21], there are at least three important hurdles to cross. One hurdle is that the local building codes and the ventilation regulations in many instances are written with mechanical ventilation systems in mind, which makes it difficult for natural ventilation systems to comply. The second hurdle is that architects and builders may consider natural ventilation systems as a more risky option than mechanical ventilation systems. Describing the low pressure systems of natural ventilation is inherently more difficult than to describe the high pressure systems of mechanical ventilation. The most diligent Computational Fluid Dynamics (CFD) description of natural ventilation can be completely transformed when occupants are moving or closing doors. To cross this hurdle, better tools for design of larger buildings with natural or hybrid ventilation are needed [16, 25]. The third hurdle is urbanization. Many effects of urbanization: pollution, "heat islands", and wind obstruction, favor the use of mechanical ventilation systems [20]. Ventilation requires the outdoor air to be healthy, otherwise it must be cleaned at a considerable cost of energy. There are many issues concerning natural ventilation to discuss, but in this chapter, there is only a brief discussion (at the end of Section 2) on the hurdles for natural ventilation systems in the local building codes and ventilation regulations.

2. Requirements for ventilation

The purpose of building ventilation is to provide a healthy and comfortable environment for the occupants. However, the human perception of the conditions that constitute a healthy and comfortable environment depends on many factors [26, 27]. The section starts with a historical perspective on the evolution of different ideas concerning the relationship between ventilation and human health and comfort. This is followed by a theoretical treatment of ventilation that hopefully will give the reader some insights into how a good ventilation system performance may be specified. The section finishes with a critical examination of how legislative regulations of ventilation are specified and some suggestions on how it may be modified to facilitate the use of natural and hybrid ventilation systems.

2.1 A short history of ventilation and health effects

The notion that "bad air" leads to health problems has a long history. The name for the disease malaria is derived from the Italian *mala aria* that literally means "bad air". The origin of the word, used in the sense that the surrounding air in wet, and swampy locations is a cause of disease, can be traced back as far as the ancient Greeks and Romans. Another word for "bad air", first used in 1655, is "miasma" that is derived from the Greek *minainein* "to pollute". In the advent of urbanization in the late eighteen hundreds, medical doctors observed that diseases were more common in the poorer areas of cities. These areas were often overcrowded and situated in unsuitable damp areas. Two battling theories were put forth: the *miasma*-theory preached that diseases were caused by locally generated emissions (or antropotoxins); the *contagium*-theory preached that diseases were caused by poisonous particles that were transferred between humans. The father of ventilation science, Max von Pettenkofer, was a front figure for the *miasma*-theory and suggested increased air flows into the dwellings to remove the locally generated emissions [28]. A leader of the *contagium*-theory (from Latin *contagio* "contact"), i.e. the father of clinical microbiology Robert Koch, instead suggested measures to limit the spread of the supposed *contagium*: isolation, quarantine, and border control [29]. The scientific battle was infected by political undertones. The latter measures were unpopular among the trade-friendly industrialists that were politically opposed to the more isolation-friendly local land owners at this time [30]. It was a heated battle, where von Pettenkofer scored some political points when he in 1892 drank a cocktail of cholera bacteria without catching the disease [31]. He was probably immune [30]. By 1900, bacteria were firmly established as the *contagium*-vehicle. It was a landslide victory to the point where most of von Pettenkofers academic contributions were practically erased. He continued to maintain that *miasma* ought to be an aiding factor in the spread of diseases, until he killed himself with a pistol head shot in 1901 [30].

Today this issue may not be altogether black or white. Ventilation and overcrowding have been shown to indirectly influence the spread of diseases [32]. It becomes difficult to conduct good scientific work when political polarization and strong emotions enter the scientific discussion. The historical lessons are not so easy to adopt, as evidenced by more recent heated scientific battles such as global warming or the present Covid-19 battles (see for example [33]).

A remaining *miasma*-related question concerned the rising sense of discomfort experienced by humans in overcrowded rooms. It was well known at the time that enclosing people in a room with very little ventilation lead to symptoms like headache, nausea and dizziness. In severe cases it could even lead to unconsciousness and death. The father of chemistry, Antoine Lavoisier, in cooperation with Laplace had demonstrated in 1783 that the cause of death could not be attributed to lack of oxygen molecules, but probably to an excess of carbon dioxide [34]. Exhaled air of humans contain approximately 44 000 ppm of metabolic CO_2 [35]. This means that the excess CO_2 in the blood cannot be expelled at exposures to CO_2 concentrations above that. Accumulation of CO_2 in the blood cause the pH to progressively decrease, and in turn this leads to a series of bodily malfunctions. Death by drowning is caused by the increasing acidity of the blood (acidosis) as the CO_2 concentration accumulates and not by too few oxygen molecules in the lungs. Exposure to 20 000 ppm CO_2 leads to headache and shortness of breath after a few hours. Exposure to 70 000–100 000 ppm CO_2 leads to unconsciousness after a few minutes. Exposure to >170 000 ppm CO_2 causes death in humans within one minute from first inhalation [36]. To illustrate how high these concentrations are: a human hermetically enclosed in a 2.5 m^3 box would probably still be barely conscious after 24 hours, assuming an exhalation rate equivalent to 0.018 $m^3\ h^{-1}$ pure CO_2 [35]. Pettenkofer had dismissed CO_2 as the cause of diseases, but had developed simple methods to measure it and suggested that the concentration of CO_2 could be used as a proxy for the supposed antropotoxins. While investigating public venues in Munich, he had found values as high as 7100 ppm CO_2 [31]. Pettenkofer noticed that human odours were clearly perceptible around 1000 ppm CO_2 (now known as the Pettenkofer number) and proposed this as a "safe" target to strive for.

The final blow to the *miasma*-theories was dealt by Carl Flügge in 1905 [37]. He devised a series of experiments enclosing humans in glass boxes. The air supply to the breathing zone and to the rest of the box could be controlled separately, as well as other parameters such as temperature and relative humidity. Among other parameters, Flügge varied the odors in the air supply, e.g. air from sewage etc. He found that only the appetite of the subjects was adversely affected, otherwise the subjects adapted to the foul smells. The only “contaminant” that had any adverse effect on the comfort of the subjects was temperature [38]. These experiments totally obliterated the contemporary ventilation philosophy and turned it on its head. There appeared to be no evidence for regulating ventilation from a chemical perspective, as long as the physical parameters (like temperature and relative humidity) were within acceptable comfort-limits. The purpose of a window quickly changed from letting fresh air in to letting heat out. However, some practitioners argued (on the basis of proven experience) that it might be wise to retain some ventilation flows into buildings [30]. It took several years before new ventilation standards were proposed [38, 39].

The need for ventilation, and the chemical perspective, slowly crept back via odor-control. The human nose is in fact very sensitive to certain indoor odors. From an evolutionary perspective, it appears to have been advantageous for humans to judge a dwelling by its smell. While the human nose may adapt, people were not comfortable with entering a room with foul smells. This angle provided an incentive for new and fruitful experiments on ventilation requirements. In 1936, Yaglou et al. [40] extended some experiments performed by Lehmberg et al. [41] the year before. They conducted a series of experiments on a group of people to determine their subjective acceptance of the perceived air quality upon entering a test chamber. By varying a number of parameters in the test chamber, Yaglou et al. demonstrated a correlation between the degree of acceptance, the pollution load, and the ventilation air flow into the test chamber. Their results were immediately, but cautiously, adopted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [38].

Figure 1 (inspired by Awbi [35]) shows a compilation of the ventilation requirements historically recommended by ASHRAE, including its predecessors [38]. The

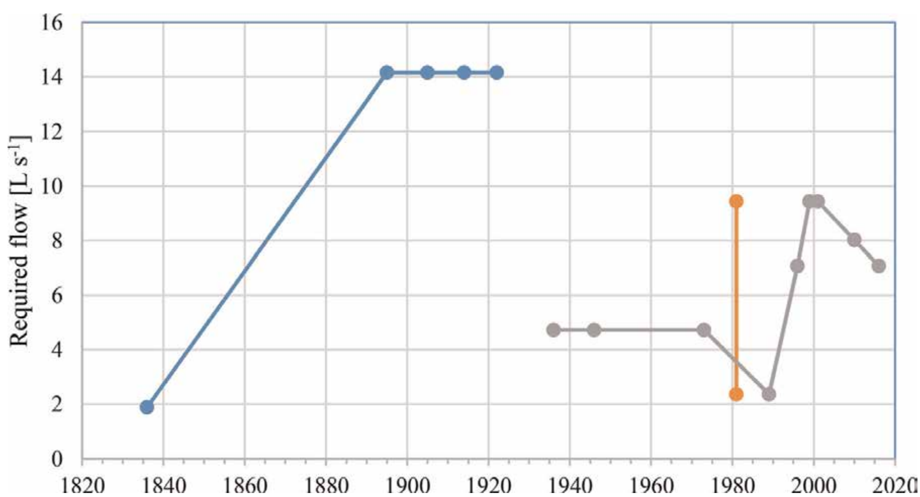

Figure 1.
Ventilation requirements recommended by ASHRAE and predecessors. From 1936 and forward (grey) the required flow per person in a standard office is shown. The earlier values (blue) are per room. The red shows the unadopted ASHRAE 62 (1981).

news of Flügge's experiments hit like a bomb when it was presented at the ASHRAE 1911-meeting [30]. All previously accepted ventilation requirements were for all practical purposes under reevaluation until 1936 [37]. (The reason why the old high ventilation requirements were maintained for some time (as shown in **Figure 1**) had to do with the fact that the previous requirements were included in many state laws [37]). Yaglou also studied the ventilation requirements in relation to environmental tobacco smoke (ETS) [42]. As non-smokers are very sensitive to any remaining smoke odor, he found that very high ventilation rates were required to reach acceptance (from them). Smoking was very common at the time. In 1965, 43% of U.S. adults were regular smokers [43]. As health concerns in U.S.A. regarding smoking and indoor ETS were starting to be officially recognized from 1964 and onwards, the question of ventilation requirements started to become a hot topic again [43]. In the ASHRAE Standard 62 (1981), two ventilation requirements for offices were proposed (shown in red in **Figure 1**). The lower one applied to offices without smokers and the higher one to offices where smoking was allowed. This was immediately perceived as a business threat by the tobacco industry. A memorandum circulated at Philip Morris concludes that adopting and enforcing this standard would at least double the maintenance costs for a workplace that allow smoking [44]. In the end, neither the American National Standards Institute (ANSI), nor the Building and Official Code Administrators adopted the 1981 standard as it was considered "controversial". Therefore, the standard was never enforced. In the next "revised" standard that was accepted by ANSI, i.e. ASHRAE 62 (1989), the lower ventilation requirement was retained and moderate smoking was allowed [44]. The tobacco industry succeeded to block the enforcement of new ASHRAE standards until 2000 [44]. The recent decreases in the recommended ventilation requirements, shown in **Figure 1**, can probably also be interpreted as energy-saving measures.

Note that the lower limit proposed in ASHRAE Standard 62 (1981) (red in **Figure 1**) essentially is a revocation to the lowest ventilation requirements proposed in 1836. The guidelines for ventilation requirements are in fact influenced by a number societal parameters. By this time a fair amount of the newer buildings were mechanically ventilated. In Sweden, mechanical ventilation was primarily used in industrial buildings before 1947, but the invention of the less noisy radial fans opened the market for ventilating other buildings [30]. When the energy crisis hit in 1973, the energy used for ventilating buildings suddenly became a liability. The lowered ventilation requirements in the standard of 1981 can therefore be understood in terms of the corresponding decrease in the energy use for the fans in mechanical ventilation and for heating (or cooling) the air supplied. The air supplied into dwellings was further reduced by efforts to reduce air leakages through the building envelope, particularly in the Nordic countries. After a while, reports of occupant discomfort started pouring in. It appeared that up to 30% of the newly built office buildings had an unusually high amount of complaints. In some cases, causal relations to ill-health could be found: e.g. in the use of new materials, moisture damage, or improperly performed building techniques [39, 45]. A large group of diffuse symptoms such as headache, fatigue, lack of concentration and irritation of the skin and mucous membranes remained unexplained. In 1984 the WHO Regional Office for Europe collectively referred to these symptoms as a new medical diagnosis: Sick Building Syndrome (SBS) [46]. The onset of constructing tighter building envelopes seemed to be a likely cause. This sparked a renewed research interest in finding the optimal ventilation requirements.

Fanger and coworkers repeated the Yaglou experiments, but with a much larger sample size in the 1980s [47]. In addition, Fanger attempted to quantify the perceived emissions from the human body and suggested a new subjective, relative unit: *olf*, the emission rate of air pollutants (bio-effluents) from a standard person (from Latin *olfactus* "smelling"). The idea of relative units related to standard people came from previous studies of thermal comfort. Fanger's standard person was characterized as a sedentary white-collar worker (or student) aged 18–30 with a hygienic standard corresponding to 0.7 baths/day and changing underwear daily. Deodorants were used by 80% and some were smokers, but the proportion is not specified. By varying the test chamber ventilation rate (q) in a cohort study of 1000 people judged by 168 "judges" (probably from the same cohort), Fanger found the following correlation (r^2 = 0.79 and valid for $q \geq 0.32$ L s^{-1} per person, or *olf*):

$$PD = 395 \cdot exp\left(-1.83 \cdot q^{0.25}\right) \quad (1)$$

where PD is the percent dissatisfied "judges", q is the ventilation rate (L s^{-1}) per person, L is liters [dm^3] and s is seconds. **Figure 2** shows the correlation curve given by Eq. (1). These results corresponded well with contemporary measurements [48]. In field studies in 15 office buildings, using a similar experimental method, Fanger et al. found that the sources of disagreeable indoor air pollutants were definitely not limited to human bio-effluents. The olf-equivalents attributed to other indoor sources were: indoor materials, 1–2 *olf*;: the mechanical ventilation system itself, 3 *olf*;: tobacco smoking, 2 *olf* [49]. These and other studies highlighted the necessity to control all indoor air pollution sources in order to reach an acceptable indoor environment in terms of perceived air quality. In a large study of school workers by Smedje et al. [27], it was also shown that their perceptions of the air quality at work were confounded by personal, psychosocial and domestic factors. In short, studying human perception is complicated by many factors and pose some challenges on experimental design.

No single factor causing SBS has yet found any consensus. Sometime after its last official document on SBS in 1995, WHO discontinued the use of SBS as a medical diagnose. A contemporary search on the homepage of WHO yields zero hits. However, that a correlation seem to exist between SBS-related issues and some ventilation parameters receives some consensus in the multidisciplinary field concerned with healthy buildings. In 2001 [50], Jan Sundell managed to convene several European principal researchers in the field to search for consensus on the connection between

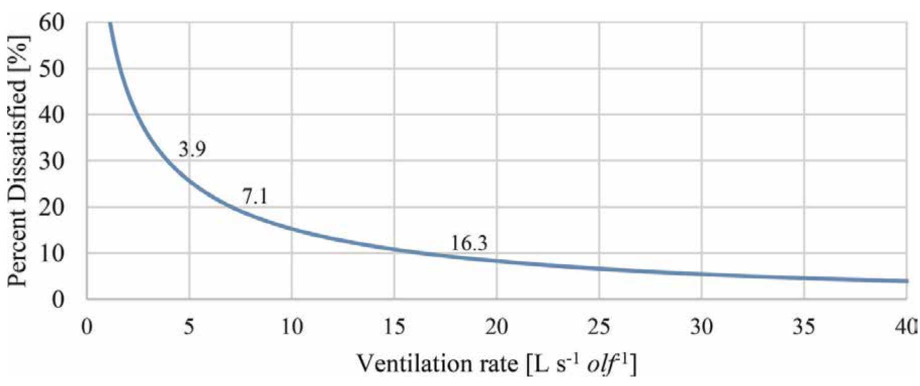

Figure 2.
Fanger's correlation between the required ventilation rate per person (or olf*) and the percent dissatisfied judges upon entering the test chamber. The numbers in the figure correspond to the required ventilation rates for the 10%, 20%, and 30% levels of the percent dissatisfied judges.*

ventilation and health. There are few well-designed studies that adequately account for all the multiple factors that are encountered when assessing indoor environments. Out of the selected 105 scientific papers in peer-reviewed journals only 30 were deemed conclusive for the question at hand. The consensus statement include the conclusions that there is:

"*a strong association between ventilation and comfort (as indicated by perceived air quality) and health (as indicated by SBS symptoms, inflammation, infections, asthma, allergy, short- term sick leave). … also indicates that there is an association between ventilation rate and productivity (as indicated by performance of office work).*" [50].

A similar exercise, with a larger geographical spread of the researchers, was initiated by Jan Sundell and Hal Levin in 2010. Many conclusions were similar, but it should be noted that the panel members were divided as to whether the association between ventilation and health outcomes (excluding SBS) was strong or simply suggestive [51]. Both studies conclude that air change rates (see Section 2.2) below 0.5 h^{-1} leads to increased infestations of house dust mites in the Nordic countries. The latter was deemed important, since there is a plausible link between exposures to the feces of house dust mites and the prevalence of asthma and allergic rhinitis [52].

This concludes the selective short history of ventilation. The idea that ventilation promotes health by removing harmful substances has been a lingering and recurring theme. The effects of indoor exposure to harmful substances are typically studied as dose–response assessments [39]. The relevant exposure dose is the *concentration* of the harmful substance in the indoor air and the responses are the measureable effects on humans. When adverse health effects are established, the exposures of those harmful substances are usually regulated or their use simply forbidden [39]. This also means that, in principle, there should be no *known* harmful substances to be removed by ventilation in the indoor environment. As will be evident in Section 2.3, most guidelines for ventilation requirements are based on perceived indoor air quality, and not health, criteria.

Nevertheless, there is a case for using ventilation as a precautionary measure to prevent adverse health effects caused by the indoor environment. There has been a significant increase in the number of chemicals never before encountered in the indoor environment, particularly in the last fifty years [43]. Today, literally thousands of chemicals are present in the indoor air (see for example [53]). Since most studies of dose–response assessments focus on one single substance at the time, the effects of mixtures of substances are largely unknown [54]. In addition, a majority of these new indoor chemicals have not been studied for health effects. When a harmful substance is forbidden, it is often substituted for new substances with (as yet) unknown health effects. In light of these *known unknowns*, it may be prudent to specify some minimum ventilation requirements as a precautionary health measure.

2.2 Some insights from the theory of ventilation

Before critically examining the existing guidelines for ventilation requirements a few theoretical explanations of the salient points are needed. Consider first the One-zone model as shown in **Figure 3a**. The flows of air supply to, and air exhaust from, the zone are equal. An air pollutant is emitted at a constant rate into the zone. The assumption for now is that the zone is fully mixed, i.e. the concentration of air pollutant is exactly the same everywhere in the zone. The validity of this assumption, and other assumptions, will be discussed below.

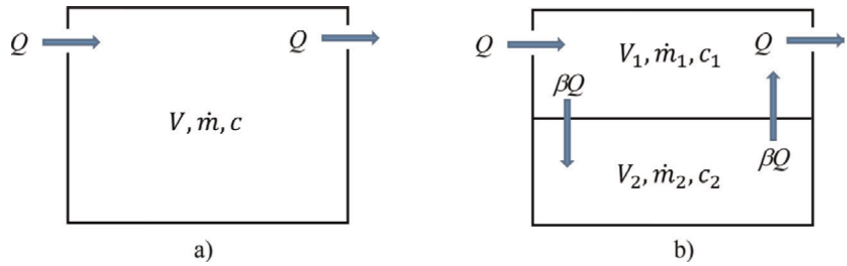

Figure 3.
Simple zone models. (a) One-zone model. (b) Two-zone model.

Assuming that the initial concentration of air pollutant is zero and no air pollutant enters via the air supply ($c_0 = c_{ext} = 0$), the mass balance equation for the air pollutant in the zone is

$$V\frac{dc_t}{dt} = \dot{m} - c_t Q \tag{2}$$

where V [m^3] is the volume of the zone, $\dot{m}$ [kg h^{-1}] is the constant emission rate of air pollutant, c_t [kg m^{-3}] is the concentration c of air pollutant in the zone at time t [h], and Q [m^3 h^{-1}] is the rate of air flow into and out of the zone. (The conversion factor between Q [m^3 h^{-1}] and q [L s^{-1}] is $Q = 3.6q$). The steady state solution of Eq. (2) is obtained when a constant equilibrium concentration is established in the fully mixed zone. Setting the left hand side to zero gives

$$c_\infty = \frac{\dot{m}}{Q} \tag{3}$$

where c_∞ is the constant equilibrium concentration at $t = \infty$. This is an important result. It appears that, given a constant emission rate of an air pollutant, it is the ventilation rate that determines the final concentration of air pollutant in the zone (i.e. the exposure to the air pollutant). However, this conclusion is only valid *provided that* the zone is completely mixed at all times.

For the case of a hermetically closed zone, i.e. when $Q = 0$ in Eq. (2), it can be solved by integration to yield

$$c_t = \frac{\dot{m}}{V}t. \tag{4}$$

Eq. (4) shows that the air pollutant concentration will increase linearly with time in a hermetically closed zone. Note that the volume of the zone (V) buffers the rate of concentration increase in the zone. The larger the volume, the slower the rate of increase of the air pollutant concentration in the zone.

Another illustrative one-zone case is obtained by allowing an initial concentration c_0 of the pollutant in the zone at $t = 0$ and assuming that $\dot{m} = c_{ext} = 0$. Solving for the concentration gives

$$c_t = c_0 e^{-(Q/V)t} = c_0 e^{-Nt} \tag{5}$$

where the hourly air change rate (ACH) for a completely mixed zone is defined as $N = Q/V$. Eq. (5) means that for any temporary emission of air pollutant in the zone, its concentration will decay exponentially with time. The rate of decay is gauged by the air change rate N. A higher air change rate means a faster decay.

The simple One-zone model of ventilation presented above has two main problems: (i) Emission sources are not evenly distributed in the zone volume. They are local and confined to surfaces, objects or humans. (ii) Complete mixing of a zone is difficult to achieve. Both points can be illustrated with a simple Two-zone model, originally proposed by Etheridge and Sandberg [55], as shown in **Figure 3b**. In the Two-zone model, emission sources are allowed to be slightly more local and the required mixing air flows are made slightly more explicit in terms of the inter-zonal air flows. Inter-zonal air flows are given as βQ, so when $\beta = 1$ the inter zonal air flows have the same magnitudes as the supply and extract air flows. For simplicity, complete mixing of both zones are assumed. The mass balance equations in each zone for the case $c_{ext} = c_{10} = c_{20} = \dot{m}_1 = 0$ becomes

$$\begin{aligned} V\frac{dc_1}{dt} &= \beta Q c_{2t} - (1+\beta) Q c_{1t} \\ V\frac{dc_2}{dt} &= \dot{m}_2 + \beta Q c_{1t} - \beta Q c_{2t} \end{aligned} \quad (6)$$

The steady state solutions for the concentrations in each zone are then

$$\begin{aligned} c_{1\infty} &= \frac{\dot{m}_2}{Q} \\ c_{2\infty} &= \frac{(1+\beta)\dot{m}_2}{\beta Q} \end{aligned} \quad (7)$$

Note that the steady state result for c_1 in Eq. (7) is the same as for the completely mixed One-zone model in Eq. (3). If nothing is known about the distribution of concentrations within the zone, the proper interpretation of steady state in Eqs. (2) and (3) is that the emitted amount equals the exhausted amount and that the accumulation of air pollutant in the zone has stopped. The interpretation that the concentration is constant in the zone is not correct. Unless, of course, complete mixing is established by other measurements. In general the concentrations are not equal, as is evident in **Figure 4** where the dimensionless quotient c_2/c_1 of the steady state

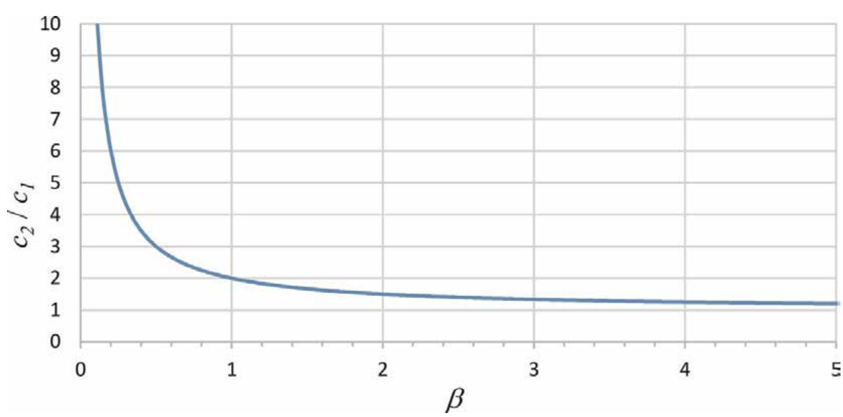

Figure 4.
Increase in the relative concentration in the lower zone (2) as a function of the interzonal flows. When β = 1 the interzonal flows are equal to the air supply.

concentrations from Eq. (7) are plotted against β. Note that c_2 approaches c_1 very slowly as β increases in **Figure 4**. In order to reach complete mixing the inter-zonal air flows must be much larger than the supply and extract flows. In experiments where complete mixing of the whole zone is important, e.g. using the decay in Eq. (5) to measure the air change rate using tracer gases, several extra fans are employed to come as close as possible to the ideal case of complete mixing. It is also clear from **Figure 4** that the concentration of air pollutant in the lower zone rises very quickly as β decreases below unity. From an exposure point of view, it is problematic that concentrations of air pollutants may differ considerably within a room when mixing is incomplete.

The special case when the fresh air from the supply flow never enters the lower zone and directly exits by the extract is called ventilation short-circuiting. In this case, β is zero and the lower zone essentially behaves as a hermetically closed zone (Eq. (4)) and the concentrations of all air pollutants emitted in the lower zone rise without bounds. To be fair, ventilation systems are designed to deliver fresh air to occupants and complete short-circuiting is rare. However, poorly designed systems do exist. One example is shown in **Figure 5**. Typical situations when short-circuiting may occur are: if inlet and exhaust devices are close to each other; if there are obstacles in the flow path of a mechanical ventilation air inlet; if the air supplied is warmer than the air in the room and the extract is near the roof.

In a more general theoretical approach, allowing for non-homogeneous concentration distributions in the zone, all possible paths of a very small package of air from the inlet to the outlet are considered (see Etheridge and Sandberg [55] for a complete treatment). A long and tortuous path for the package or air will result in a long residence time for the package within the zone, whereas a short path corresponding to a ventilation short-circuit would lead to a very short residence time. At the outlet, packages of air escaping the zone in every instance of time will represent many different residence times. At steady state, in a similar manner as in Eqs. (3) and (7),

Figure 5.
Retrofit of cooling beam (with attached light fixture) leading to a high degree of ventilation short-circuiting. Air supply device to the left and air exhaust to the right.

the distribution of residence times will converge to a constant average residence time $\langle \tau_r \rangle$ for the air packages. The average residence time can also be interpreted as an average age of the air packages exiting the zone, if the age of an air package is set to zero as it enters into the zone through the inlet. This concept of ages of air packages is useful when examining the interior of the zone.

The simple process of plug (or piston) flow illustrates the age concept well. It is the most efficient method to ventilate and is used in so called "clean rooms". The idea is to achieve a laminar flow by supplying slightly colder air from the roof and letting it fall vertically to the floor where it is extracted. Ideally, all air packages entering from the whole area of the roof fall at the same speed and reach the floor simultaneously. This means that all air packages have exactly the same residence time in the zone. It is easy to show that the residence time only depends on Q and V, regardless of the shape of the zone, and is given by

$$\langle \tau_r \rangle_{plugflow} = \frac{V}{Q} \equiv \tau_n \tag{8}$$

where the nominal time constant of the ventilation system τ_n is defined. For plug flow the average residence time is equal to the nominal time constant. Since the air packages follow the shortest route from the roof to the floor in plug flow, the nominal time constant can be interpreted as the shortest possible residence time. It is also easy to determine the local age of the air packages in the interior of the zone. It must increase linearly from age zero at the roof to an age equal to the residence time at the floor. Consider an arbitrarily small volume element within the zone. It will contain many air packages with ages that vary linearly with height. The local mean age of air $\overline{\tau}$ is defined as the average age of the air packages within the small volume element. The local mean age of air can be interpreted in terms of how well the ventilation system delivers fresh air to the volume element. As the packages of air enters the zone, they start to equilibrate by diffusion with the concentrations of contaminants in the local environment and start to become less fresh. The older the air, the less fresh it is. Now let the volume element be as small as one package of air. The average local mean age of air with respect to the entire zone must then be equal to the local mean age at half the height. Think of a process where all volume elements with a low age above the middle height can be paired with volume elements with a high age below the middle height so that their average is exactly the local mean age of air at half height giving

$$\langle \overline{\tau} \rangle_{plugflow} = \frac{\tau_n}{2} \tag{9}$$

This result can be generalized since the residence time and the local mean age of air of an arbitrary path of the air packages are related by

$$\tau_i + \tau_{rl} = \tau_r \tag{10}$$

where τ_r is the residence time of the path, τ_i is the time already spent in the interior of the zone (i.e. the local mean age of air of the air package) and τ_{rl} is the residual life time until the air package exit the zone. This is obviously valid for all paths and all air packages will eventually complete their paths to the exit. It will therefore always be possible to pair air packages (with the same residence time), so that their average local mean age is exactly half the residence time. Taking the average of all possible paths, a generally valid relation is given by

$$\langle\bar{\tau}\rangle = \frac{\langle\tau_r\rangle}{2}. \tag{11}$$

Note that the averages of the local mean age of air over all paths or over the zone space give the same results.

Since no other ventilation process can be more efficient than plug flow, the average local mean age of air for other ventilation processes cannot be lower than that for plug flow. It therefore seems natural to assign a 100% air change efficiency to plug flow and consequently define the general air change efficiency in a zone as

$$\langle\varepsilon_a\rangle = \frac{\tau_n}{2\langle\bar{\tau}\rangle} \cdot 100\%. \tag{12}$$

For the case of complete mixing, the paths of all air packages should reach any volume element within the zone with the same probability. Complete mixing may also be viewed as a process where all volume elements in the zone are instantaneously considered identical at all times. All volume elements have identical characteristics, such as the same concentrations of molecules and the same local mean age of air. Air entering through the inlet will therefore, in theory, simultaneously enter all volume elements. Within each volume element, air packages with increasing ages will continue to accumulate until the steady state is reached and the local mean age of air stays constant. In analogy, the mass balance given in Eq. (2), describes how a contaminant is accumulated in each volume element until a steady state concentration is reached. Since the mixing conditions are the same, the accumulation of ages and of concentration, respectively, follow the same time evolution. Solving for c_t in Eq. (2) gives

$$c_t = c_\infty\left(1 - e^{\frac{-Qt}{V}}\right) = c_\infty\left(1 - e^{\frac{-t}{\tau_n}}\right) \tag{13}$$

where Eqs.(3) and (8) were used. In the field of statistics, c_t/c_∞ is an example of a cumulative distribution function. By analogy, it is also the cumulative distribution function for the ages of the air packages. A probability distribution function is obtained by taking the time derivative of the cumulative distribution function. Thus, it is evident that, for a completely mixed zone, the ages of the individual air packages accumulated within a volume element at steady state are exponentially distributed according to

$$f_{\tau_i}(t) = \frac{1}{\tau_n} e^{\frac{-t}{\tau_n}} \tag{14}$$

Now the average local mean age of air for a volume element (and for the whole zone) can be evaluated to τ_n. This gives the following relations for a completely mixed system

$$\begin{aligned}\langle\bar{\tau}\rangle_{mixed} &= \tau_n,\\ \langle\tau_r\rangle_{mixed} &= 2\tau_n,\\ \langle\varepsilon_a\rangle_{mixed} &= 50\%.\end{aligned} \tag{15}$$

The average air change efficiency of a mixing ventilation system is at best 50% as compared to plug flow. In analogy with the nominal air change rate N (or ACH) being given as the inverse of the nominal time constant τ_n as

$$N = \frac{Q}{V} = \frac{1}{\tau_n}, \tag{16}$$

An effective local air exchange rate of the zone can be defined as

$$N_{eff} = \frac{1}{\langle \overline{\tau} \rangle} \tag{17}$$

where N_{eff} is the effective air exchange rate and note that the local mean age of air average is spatial and taken over the zone. It can be interpreted as the local ability of the ventilation system to dilute contaminants with fresh outdoor air in the point p. This an important property from an exposure viewpoint.

The aim of the above theoretical exercises for two mixing models is mainly to introduce the concept of local mean age of air and its properties. The fact that it is a local property that can be determined experimentally by tracer gas techniques [55] means that interior points of any ventilated zone can be characterized by it. In particular, in means that the distribution of fresh air to the occupied volumes of a zone can be tested.

The insights from this subsection can now be summarized. It has been shown that requiring a specific ventilation rate is not a guarantee for good performance of a ventilation system. The supplied air must also be distributed efficiently and this capacity should be evaluated. Possibilities for ventilation short-circuiting should be eliminated. Finally, a large zone volume can be a strategy to prevent build-up of concentrations from transient sources of air pollutants.

2.3 A critical examination of guidelines for ventilation requirements

Most of the contemporary legislative guidelines for ventilation requirements are based on criteria for perceived air quality, as concluded in Section 2.1. For more than 20 years, the basic guidelines in the U.S.A. (and also in Europe) have been based on the recommendation that no more than 20% of the occupants should be dissatisfied with the perceived indoor air quality [56]. Nevertheless, the adaptation of the human nose adds a dimension and there is a difference between the philosophy in Europe and the U.S.A on how perceived air quality should be measured. The guidelines in Europe (following Fanger et al. [49]) are based on the perceived air quality as judged by an un-adapted visitor to the room, whereas the guidelines in the U.S.A. (ASHRAE) are based on the perceived air quality by a judge that has been allowed to adapt to the room air for 15 minutes [5]. The American guidelines therefore recommend lower ventilation rates than the European guidelines at the same level of dissatisfied judges. [5]

Comparison of the work place ventilation rates required per sedentary person in **Table 1** (i.e. 7 $L{\cdot}s^{-1}$/person) with the ventilation rates given in **Figure 2**, show that The Swedish Work Environment Authority appears to follow the European philosophy in the old [57], as well as in the new, guidelines [58]. In line with the findings of Fanger et al. [49], many guidelines assume that all other indoor emissions of pollutants (e.g. from building materials and human activities, such as smoking, cleaning, and cooking) should be added to the emissions of bio-effluents from the occupants. All these emissions are lumped into a floor-area-based emission rate. The total required ventilation rate is then the sum of two contributions as shown in Eq. (18).

$$q_{tot} = n_p \cdot q_p + A \cdot q_A \tag{18}$$

where q_{tot} is the total required room ventilation rate [$L{\cdot}s^{-1}$], n_p is the number of occupants, q_p is the required ventilation rate per person [$L{\cdot}s^{-1}$/person], A is the room area [m^2], and q_A is the required ventilation rate per square meter [$L{\cdot}s^{-1}{\cdot}m^2$]. The required q_A in **Table 1** are based on a room with very low emitting materials and no smoking. The Pettenkofer number (1000 ppm CO_2) can also be recognized in the guidelines in **Table 1**. However, the lowest required q_p (4 $L{\cdot}s^{-1}$/person) from The Public Health Agency of Sweden [59] can only keep the CO_2 concentrations below 1500 ppm in most realistic scenarios [60]. The Public Health Agency of Sweden is the only government agency recommending a specified air change rate of 0.5 h^{-1} [59]. Note that the floor area based ventilation rate 0.35 $L{\cdot}s^{-1}{\cdot}m^2$ corresponds to an air change rate (N) equal to 0.5 h^{-1} if the room height is 2.5 m (a common room height in the Swedish building stock). While there are common elements between the required ventilation rates in **Table 1**, it is clear that the more generally valid recommendations from The Public Health Agency of Sweden prescribe lower ventilations rates than the recommendations from The Swedish Work Environment Authority that are valid only in nonresidential buildings.

There are mutual dependencies between the ventilation rates presently required by government agencies and the properties of the existing building stock [8]. If the building stock can be shown to cause health problems that can be traced to inadequate ventilation, then the government agencies will try to improve the situation by requiring higher ventilation rates. On the other hand, if air leakages through the building envelopes provide ample contributions to the ventilation of the building stock, in addition to the controllable ventilation rates, then the required ventilation rates need not be as stringent because the total ventilation rate will be sufficient anyway. The point here is to highlight plausible dependencies on average, even though there may be a wide spectrum of properties in the building stock. Thus, changes in the properties of the building stock will lead to changes in the ventilation requirements recommended by government agencies.

The EPBD objective to transform the building stock to NZE- buildings with tighter building envelopes should, with the above logic, lead to a more stringent requirements for ventilation rates [8]. However, as mentioned in the Introduction, the "energy efficiency first" principle in EPBD [12] pushes other incentives towards their

	FoHMFS 2014:18	**AFS 2009:2**	**AFS 2020:1**
Air supply/person	≥ 4 $L{\cdot}s^{-1}$ ≥ 7 $L{\cdot}s^{-1}$ (schools)	≥ 7 $L{\cdot}s^{-1}$	≥ 7 $L{\cdot}s^{-1}$
Air supply/m^2	≥ 0.35 $L{\cdot}s^{-1}$ + 0.35 $L{\cdot}s^{-1}$ (schools)	+ 0.35 $L{\cdot}s^{-1}$	+ 0.35 $L{\cdot}s^{-1}$
Air change rate	≥ 0.5 h^{-1}		
CO^2 concentration	Normally < 1000 ppm	Normally < 1000 ppm	Normally < 1000 ppm
Air change efficiency		≥ 40 %	≥ 40 %

Table 1.
Values are extracted from the official Swedish guidelines for ventilation requirements and air quality. FoHMFS are the ventilation guidelines issued by The Public Health Agency of Sweden. [59] AFS are the old [57] and the new guidelines (valid from 1 January, 2021) [58] issued by The Swedish Work Environment Authority. The +-sign signifies that the required air supply per m^2 must be added to the air supply per person.

Category	CEN EN 15251:2006		CEN EN 16278.1:2019	
	Expected Percent Dissatisfied [%]	**Airflow per person [L·s^{-1}/person]**	**Expected Percent Dissatisfied**	**Airflow per person L·s^{-1}/person**
I	10	10	10	10
II	**20**	7	20	7
III	30		**30**	**4**
IV	< 30	< 4	40	2.5
	Expected Percent Dissatisfied [%]	**Very low polluting building [L·s^{-1}/m^2]**	**Expected Percent Dissatisfied**	**Very low polluting building [L·s^{-1}/m^2]**
I	10	0.5	10	0.5
II	**20**	**0.35**	20	0.35
III	30		**30**	**0.2**
IV	< 30	<0.2	40	0.15

Table 2.
Values are extracted from the official European guidelines for ventilation requirements and air quality. CEN EN 15251:2006 are the old guidelines from 2006 [61] and CEN EN 16278.1:2019 are the new guidelines (valid from 8 May, 2019) [62] issued by European Committee for Standardization. The bold figures are the recommended values.

minimum legal limits when they are in conflict with the efforts to improve the energy performance of buildings. Maintaining a good indoor air quality by ventilation is such an incentive, and therefore ventilation rates will be pushed towards their minimum legal limits. As a consequence, in the coming EPBD transformation of the building stock, the minimum legally required ventilation rates play a critical role as counter-balances to prevent a decline in indoor air quality. The required ventilation rates will probably need to be increased to maintain the present levels of indoor air quality in the building stock.

It is therefore doubly worrying that the ventilation requirements in the standards on the European level recently have been lowered as shown in **Table 2**. For example, in a standard 10 m^2 office for one person, the required ventilation rate (q_{tot}) is lowered by 43% from 10.5 L·s^{-1} in the old guideline CEN-EN15251:2006 [61] to 6 L·s^{-1} in the new guideline CEN-EN16798:2019 [62]. The change corresponds to recommending 30% dissatisfied un-adapted judges in the new guidelines as compared to 20% in the old guidelines. The guidelines in the European Standards provide the “floor” upon which the legal requirements of the member countries rests. Lowering the required ventilation rates in the European Standard opens for a corresponding lowering in the legislation of the member states. While it is slightly encouraging that the Swedish legislation is unchanged at the moment, as seen in **Table 1**, it is obvious that the risk of EPBD creating unhealthy indoor environments will be augmented. The present levels of indoor air quality in the building stock risk being lowered by the combined effect of tighter building envelopes and the prospect of lower required ventilation rates.

As concluded in the previous section, simply specifying required ventilation rates cannot guarantee an adequately low exposure to indoor pollutants [63]. Legislation also need to address the air distribution. In the European Standard [62] and in the ASHRAE Standard [56], the given ventilation rates assume complete mixing in the room. Thus, they presuppose a mixing mechanical ventilation system. Other ventilation systems are accommodated by dividing with a correction factor. ASHRAE [26] proposes a correction factor called the air change effectiveness defined as $\varepsilon_I = \tau_n / \langle \bar{\tau} \rangle$ evaluated in the breathing zone [56]. For mixing ventilation this gives $\varepsilon_{I,mixed} = 1$ and for plug flow $\varepsilon_{I,plugflow} = 2$. The correction factor in the European Standard is similarly defined, but evaluated as a room average, and is called ventilation effectiveness ε_v. (The nomenclature for the correction factors is a bit confusing and may be easily mixed-up with the air change efficiency defined in Eq. (12).) If the system is not fully mixed, the correction factor is less than unity and the required ventilation rate should be correspondingly increased. If displacement or plug flow ventilation systems are used, that are more efficient than mixing ventilation, the correction factor is larger than unity and the required ventilation rates may be correspondingly decreased.

Legal ventilation requirements also address air distribution, but rephrased into requirements that newly installed ventilation should be shown to function as designed, that the ventilation rate should be sufficient, or by requiring a specified air change efficiency as in **Table 1**. I have the impression that air change efficiency is seldom tested in the field. The control of newly installed ventilation systems mostly consist of ensuring that the design ventilation flows are obtained, otherwise the ventilation system components are assumed to function with the same efficiency as in laboratory tests. However, there are a number of factors that may lower the ventilation system efficiency in a real building. Some of these factors were mentioned in connection with ventilation short-circuiting in previous section (see also **Figure 5**); ventilation systems may be very complex and design choices may have unforeseeable consequences; a ventilation designer may enter late in the planning process and may be forced to make suboptimal choices, e.g. inlets vents may end up too close to outlet vents; or occupants may tamper with the intended function of the ventilation components to minimize perceived draft. It may be prudent to verify that air is distributed with the intended efficiency in new and old ventilation installations.

The above standards clearly favor mechanical ventilation systems where ventilation rate is an easy parameter to measure. It is not that easy to measure ventilation rate for natural ventilation systems. It is more difficult to demonstrate that natural ventilation systems are in compliance with the legal requirements than it is for mechanical ventilation systems. In addition, rooms with natural ventilation systems typically have higher room heights, than rooms with mechanical ventilation systems. Naturally ventilated rooms require larger room volumes to prevent concentration build-up of transient pollution sources to offset the natural fluctuations in the ventilation rate. Historically, the introduction of mechanical ventilation systems allowed building entrepreneurs to squeeze in three floors in the same volume where previously there would be two floors in older naturally ventilated buildings [30]. Using this observation, rooms with natural ventilation are roughly estimated to be 50% larger than rooms with mechanical ventilation. If there is a legally required air change rate or a required ventilation rate per floor area (as exemplified in **Table 1**), the prescribed ventilation rates will also be 50% larger for naturally ventilated rooms, as compared to a mechanically ventilated room. This increase is probably unnecessary and it arises because the legal requirements does not consider the different ventilation strategies used in natural ventilation systems. It would be desirable that all ventilation strategies should be treated equally in the eyes of the law, with the same objective requirements for adequate indoor air quality.

If the objective of the legal regulations is to ensure that 80% of the occupants find the perceived air quality to be acceptable, as it appears to be, then it would be more fitting to simply require that less than 20% of the occupants are feeling uncomfortable. This could be tested in a questionnaire. Note that this approach is suggested in some environmental certification systems for buildings, e.g. the level GULD in Miljöbyggnad

3.1 [64]. The problem with such an approach is that other factors, than the actual air quality, may affect the outcome [27]. Alternatively, the regulations should apply specifically to the occupied zone of a room. This would lead to more balanced demands on natural ventilation systems as compared to the demands on mechanical ventilation systems. To specify concentration limits in the occupied zone would be preferable because of the direct link to exposure, but the challenge is that the human nose is very sensitive so some substances and there may be difficulties to measure such low concentrations at the present time. An indirect approach would be to specify some local ventilation parameter, such as the local mean age of air, in the occupied zone.

The fact that ventilation requirements primarily targets occupant comfort, does not mean that ventilation is irrelevant for the health of the occupants. Adverse health effects caused by exposure to indoor air pollution have been estimated to cause that approximately two million disability-adjusted lifetime years (DALYs) are lost annually, based on the population in 26 European countries. In economic terms this corresponds to a societal cost exceeding €200 billion [60]. It is very likely that the combined effect of the lower ventilation requirements and tighter building envelopes due to EPBD will increase this societal cost considerably. The prospect of turning buildings into unhealthy containers for the occupants certainly tempers my enthusiasm for the projected EPBD energy savings.

3. Conclusions

Most legislations concerning ventilation are based on perceived air quality, but ventilation is also important for the health of the occupants. Perceived air quality can be viewed as a pragmatic tool to achieve an adequate ventilation for precautionary health measures. From a perceived air quality and health perspective, the ventilation rate and an efficient air distribution are both important for achieving a healthy and comfortable indoor environment. Yet, most legislative requirements focus on the ventilation rate. This is not enough, and it is recommended that legislation also address the air distribution with equal zeal. In particular, verifying the efficient distribution of fresh air to the occupied zones or the concentrations of pollutants in the occupied zones.

Because there are clear links between ventilation and health, [3, 4, 50, 51, 60], it is extremely worrying that the "energy efficiency first" principle advocated in EPBD has led to decreasing ventilation requirements in the EU legislations, at the same time as the objective is to aggressively tighten the envelopes of the building stock. A second consequence of EPBD is probably that many naturally ventilated buildings will be retrofitted with mechanical ventilation systems. It is not clear that this would be the more sustainable solution in the long run.

Every citizen's right to a healthy indoor environment has been suggested to be a basic Human Right by WHO [65]. Adequate ventilation is at the heart of the solutions to reach this commendable goal. The mantra "build tight – ventilate right" [66] is a good one, but do not forget the second part!

Acknowledgements

The author wishes to acknowledge helpful discussions with Jan Sundell. He will be missed.

Conflict of interest

The author also works as a ventilation consultant.

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Chapter 11

Some Aspects of HVAC Design in Energy Renovation of Buildings

Taghi Karimipanah

Abstract

It is well-known fact that air conditioning systems are responsible for a significant part of all energy systems in building energy usage. In EU buildings, the building HVAC systems account for ca 50% of the energy consumed. In the U.S., air-conditioning accounts on average about 12% of residential energy expenditures. The proper choice of air distribution systems and sustainable energy sources to drive the electrical components have a vital impact to achieve the best requirements for indoor climate including, hygienical, thermal, and reasonable energy-saving goals. The building energy system components that have a considerable impact on the demand for final energy in the building are design, outdoor environment conditions, HVAC systems, water consumption, electrical appliances, indoor thermal comfort, and indoor human activities. For calculation of the energy balance in a building, we need to consider the total energy flows in and out from the building including ventilation heat losses, the perimeters transmission heat loses, solar radiation, internal heat from occupants and appliances, space and domestic water heating, air leakage, and sewage heat losses. However, it is a difficult task to handle the above time-dependent parameters therefore an energy simulation program will always be used. This chapter aims to assess the role of ventilation and air-conditioning of buildings through the sustainability approaches and some of the existing renewable energy-based methods of HVAC systems are presented. This comprehensive review has been shown that using the new air distribution systems in combination with renewable energy sources are key factors to improve the HVAC performance and move toward Nearly Zero Carbon Buildings (NZCB).

Keywords: sustainable HVAC systems, building energy systems, thermal comfort, indoor human activities, energy balance, energy saving potential, Nearly Zero Carbon Buildings (NZCB)

1. Introduction

The generation and use of energy is the largest contributor to anthropogenic CO_2 emissions and therefore the most important factor to tackle greenhouse gases and climate change issues. According to the International Energy Agency (IEA), World Energy Outlook 2010, the worldwide contribution of the building sector to the final energy demand has steadily increased to about a third of the world's final energy demand. Therefore it makes the building the most energy-intensive sector which contributes almost 30% of the anthropogenic greenhouse gas emissions. More unfortunate is that the energy use in buildings will increase to 67% by 2030. A major cause for high energy use in buildings is the demand for better thermal comfort and air quality in indoor environments. It is estimated that heating, ventilation, and air conditioning systems are responsible for almost 50% of the total energy use in buildings which is about 10-20% of the national energy use in most developed countries. To reduce global CO_2 emissions, the economic use of energy resources is of outstanding significance. The buildings sector is a significant contributor to energy-related sustainability challenges. That is why buildings should be considered as a key element to a sustainable future because of their processes of design, and construction including their operation, and all human indoor activities. Therefore, reducing energy demand in buildings can play one of the most important roles in solving these challenges. A sustainable and efficient energy supply in buildings needs the use of more energy-efficient manufacturing materials which are a part of the futures critical is to tackle the sustainability-related challenges.

It is indicated that the air conditioning systems as a considerable part of building energy systems and account for about 12% of residential energy expenditures in the U.S., and the building HVAC systems are responsible for ca 50% of the energy usage in EU buildings [1].

The air distribution systems in buildings are of vital importance to achieving the best requirements for indoor climate including, hygienical, thermal, and reasonable energy-saving goals. Yang et al. [2] in a comprehensive review article tried to describe all existed air distribution methods in which the benefits and shortcomings are treated. The air distribution systems are the main element for good ventilation systems which play a key role in creating an acceptable microclimate in the indoor environment. Thus, the development and adoption of sustainable ventilation and air conditioning systems are a viable solution to mitigate climate change and curtail carbon emissions [3].

It is worth mentioning that globalization, economic development, and population growth will be among the factors that will increase energy use worldwide in the future.

According to Gustafsson [4], solar systems, including both thermal and solar cells, can be applied to reduce the environmental impact of buildings. He also pointed out that without an input tariff for surplus electricity and government subsidies for the Central and Northern European buildings, it is still not economically feasible.

However, in the renovation of multi-family houses, the solar energy systems can reduce the total lifecycle costs (LCC) both in Southern as well in Northern European climates.

In cold climates, air heat recovery and low-temperature heating were both found to have a larger impact in colder climates. To improve the performance factor of heat pumps, low-temperature heating systems can be used, particularly when the space heating demand is relatively high concerning the hot water demand. It is worth mentioning that this chapter is based on a comprehensive review of existing literature in the research area. We tried to show that using the new air distribution systems in combination with renewable energy sources are key factors to improve the HVAC performance and move toward the EU's directives for Nearly Zero Carbon Buildings (NZCB).

2. Energy flow in buildings

Maintaining the indoor climate has a direct impact on energy usage, that is to say, the energy is used to clarify and control the indoor air quality. Danielski [5] described the main energy balance in buildings as all the energy flows to and from the building which includes:

- Transmission or conduction heat losses from building surfaces
- all internal heats from the building occupants, lightings, and appliances
- solar radiation especially from windows
- space heating and domestic water heating
- ventilation heat losses, infiltration and exfiltration air leakages
- heat losses by sewage system.

The building's components which their interaction have an impact on the demand for final energy in the building and henceforth on the whole energy system are [5]:

1. Design process
2. Outdoor environment conditions as a significant factor
3. HVAC systems
4. Total water consumption
5. electrical appliances
6. thermal comfort in the indoor environment
7. indoor human activities in the indoor environment.

However, each of the energy flows includes many variables that can vary with time, therefore an energy simulation program will always be used (see, later on about energy simulation).

2.1 Energy renovation of buildings

Gustafsson [4] stated that the building sector accounts for around 40% of the total final energy use in the EU. Therefore, the energy renovation of buildings, or increased energy efficiency through renovation, can be considered vital in the work toward the EU climate and energy goals for the year 2030. It is noted that comparing the building renovation without energy efficiency measures, the energy renovation can often reduce life-cycle costs as well as the environmental impact.

When making renovation of old apartment buildings, the improvement of ventilation is unavoidable. By using a modern and energy-saving ventilation strategy one can provide a healthy indoor environment for the occupants [6].

Randazzo et al. [7] stated that: using data for 8 industrial countries shows that when households adapt to the increasing temperature of global warming and climate change, then the electricity demand increases yearly between 35–42%. They pointed out that this is because of adapting new air condition systems and consequently the rate of poverty for the lowest-income increases as well. They also show that CDDs (the colling degree days) affect electricity expenditures and forced households to purchase and then use air conditioners. They also pointed out that households on average spend 35–42% more on electricity when they adopt air conditioning. Therefore, by recognizing the role of space cooling in energy consumption to drive up emissions, the national policy agendas should thus prioritize increasing the supply of electricity from renewable sources [7].

2.2 Energy saving potential in the building sector

The building sector is an important candidate for energy usage and presents a lot of potentials for energy saving. The population growth and desire for a better living standard are responsible for increasing energy demand. But researchers predict that there are a lot of potentials for energy saving in old and new buildings. Thus, the implementation of energy efficiency measures is calculated to result in up to 30% savings in the building sector by 2020 [8].

Many measures and methods are implemented to reduce energy use in the construction sector:

- implementation of energy-efficient renovation strategies for buildings
- stricter building regulations by taking into account modern technology,
- green building systems.

In the European Union, policies for demands on energy efficiency in buildings have been stricter according to the EU2030 goals to meet the EU's long-term 2050 greenhouse gas reduction target [9].

The above report pointed out that, the European Parliament approved the "*Directive on the Energy Performance of Buildings in 2010*" as a measure to realize this long-term potential. Thereby, all newly constructed buildings in the EU should be *nearly zero-energy buildings* (NZEB) as the directive demanded by the end of 2020. This means that all EU member states could convert existing buildings under renovation into almost energy-efficient buildings.

We may explore many energy-saving measures for this sector such as improving the building energy management, incorporating energy-efficient technology, and the awareness of energy efficiency for building occupants [10].

Residential energy consumption can be determined in two different ways, namely [11]:

1. Top-down approach: which is concerning with the building industry as an energy reduction and which does not differentiate energy consumption due to individual end uses. Top-down models determine the effect on energy consumption due to ongoing long-term changes or transitions in the housing sector, primarily to determine the need for delivery. Variables commonly used by top-down models include macroeconomic indicators (gross domestic product (GDP), employment rate, and price index), climatic conditions, housing construction/demolition levels, and estimates of appliance ownership and number of units in the housing sector.

2. Bottom-up approach: The bottom-up method covers all models that use input data from a hierarchical level that is smaller than that for the sector as a whole. Models can account for the energy consumption of individual end uses, individual houses, or groups of houses and then extrapolate to represent the region or nation based on the representative weight of the modeled sample.

The ventilation and air conditioning systems in operation are a potential energy-saving area in the building sector. This can be done by achieving thermal comfort and good health of the building occupants with minimized use of energy is the essence of HVAC systems [12].

2.3 Sustainable and well-designed air distribution systems and energy saving

Ventilation is a major player in air-conditioning and HVAC systems; therefore, it should effectively and properly be designed to save a reasonable amount of energy. The main goal of a ventilation system is to remove excess heat from the space, contaminant removal, and provide and distribute fresh air to the space.

There are two ways to ventilate occupied spaces, namely: natural ventilation and mechanical ventilation.

- Natural ventilation: The buildings are naturally ventilated via *air infiltration* and *airing*. *Air infiltration* is the airflow through adventitious leakages in the building envelope, while *airing* is the intentional air exchange through large openings like windows and doors, see Hayati [13].

- Mechanical ventilation: mechanical ventilation has also two main types, see Hesaraki and Holmberg [14]:

    - Constant air volume system (CAV): Concerning the CAV systems, supply or exhaust fans generate steady airflow to room space, the fan keeps the same power all the time. But temperature for the heating unit changes with the heating demand. For these systems, the operation cost is high because when the space is empty it is still on and uses its full capacity.

    - Variable air volume systems (VAV): The VAV systems mainly installed in school and office and the system has a relatively high initial cost and consist of more mechanical components. But its operation cost is lower than the CAV system. In a VAV system, the temperature will maintain at a certain level. Airflow is controlled by a damper and changes with heating or cooling demand. To the last, the indoor air temperature will be kept at the desired level. Therefore, the VAV system has the potential to save energy by reducing the airflow rate. Related to the variable air volume method (VAV), *Demand control ventilation* (*DCV*) is used and has the function to adjust the airflow rate with demand. Supply or exhaust airflow can vary with factors such as temperature, occupants, indoor polluting concentration, time, and relative humidity (RH). The research shows that ca 5-60% of energy can be saved with demand control [14].

The traditional air distribution and supply devices in ventilated rooms are not always able to effectively remove excess heat from the space. Therefore, chilled beams, especially the active systems, are used to achieve the desired cooling demand [15].

Yang et al. [2] explained that there are many different types of air distribution and ventilation systems which can briefly be defined as:

1. Mixing ventilation system (MV): A mixing ventilation system aims to dilute indoor pollutants by mixing. The researchers and building operators found that the effectiveness of MV is low, while energy consumption is high.

2. Diffuse ceiling ventilation system (DCV): Here, the outdoor air is supplied into the occupied zone from perforations in the suspended ceiling panels. Because of the large opening area of the supply inlet and its low mentum, the air enters the occupied zone with very low velocity and no fixed direction then the room airflow is driven by the buoyancy force generated by heat sources.

3. Displacement ventilation system (DV): The displacement ventilation has a stratification system of two-layer. One cleaner layer in the occupied zone at low velocity and the other is the upper contaminated layer close to the ceiling. The contaminants and the excess heat are displaced upwards due to the plumes rising above heat sources in the room. Its ventilation effectiveness is usually >>100%. Wall displacement units are suitable for small cooling loads (<40 W/m^2) and desired higher cooling loads are compensated by the chilled ceiling panels or chilled beams.

4. Underfloor air distribution system (UFAD): UFAD uses an underfloor supply plenum located between the structural slab and the underside of a raised floor system to deliver conditioned air to floor supply outlets.

5. Stratum ventilation system (SV): SV is an effective method that supplies air to head (breathing) level and generated sandwich airflow fields in indoor environments. SV is most suitable for small to medium-sized or zonal rooms.

6. Impinging jet ventilation system (IJV): Here the supply device is a pipe that creates a jet of air down onto the floor level with quite a high momentum (That is to say it is resembling mixing ventilation) but because of a tin layer with relatively high velocity on the floor and then the velocity decays very rapidly away from the point of impact on the floor, it will behave like a displacement system. Instead of a displacement system that works with cooling only, this method is suitable for cooling and heating. Two new research articles that describe the heating and cooling usage of the impinging jet ventilation system are shown in [16, 17].

7. Confluent jets ventilation system (CJV): Like IJV, this is also a relatively new air distribution method developed in Sweden by the author and colleagues. Confluent jets define a system of multiple round jets issue from different nozzles that after a certain distance from the supply device, the combined jets behave as a single jet. Colliding with each other, after traveling a certain distance after their exit, to form a single jet that will converge to the exit of the ventilation system.

8. Wall attached ventilation system (WAV): WAV is based on the combination of MV, DV, and impinging jet flow. The concept is the predecessor of air curtain

(jet) ventilation (ACV). The air jet with high momentum is directed downward and then reaches the floor level, impinges to corner, and then separates from the vertical wall surface and re-attaches to the floor to generate a clean air layer ("air reservoir").

9. Intermittent air-jet strategy (IAJS): This is a ventilation strategy with a rapid variation of ventilation flow rate. It works with a sinusoidal function and the flow rate is controlled within a specified range by repeatedly switching on and off the HVAC supply fan for stipulated periods. The purpose of IAJS is to create variations is to change the conditions within the room for the airflow pattern and the velocity field.

10. Protected occupied zone ventilation system (POV): This system is used to separate an indoor environment into several subzones by using low turbulent plane jets. The POV method is suitable for indoors with a protected occupied zone (POZ) like an open plan office and an isolation room. A POZ is defined as an occupied zone as a sub-zone consisting of the office personal working zone, where occupants spend most of their time indoors.

11. Personalized ventilation system (PV): The PV system is used to provide clean and cool air to the breathing zone or at least close to each occupant. It improves the inhaled air quality by delegating the occupants to optimize and control temperature, flow rate (local air velocity), and direction of the locally supplied personalized air according to their preference, and consequently to improve their thermal comfort conditions.

12. Local exhaust ventilation system (LEV): Here, the air is supplied directly to the occupants from a desk or seat unit. The occupant has access to the controls.

13. Laminar airflow (LAF)/Piston ventilation system (PiV): Here, the air is supplied vertically or horizontally across the whole room at low velocity (typically 0.2 to 0.3 m/s) and turbulence to create a piston-type flow. This is a very effective but expensive ventilation system with an extraordinarily high airflow rate (200 to 600 air changes per hour) and is only used for clean rooms and hospital operating theaters.

14. Demand-oriented ventilation system (DVO): According to Li et al. [18], when the occupants are not close to the located air terminals even for personalized ventilation (PV) the ventilation efficiency is not high. They raised a question that: can we realize the demand-oriented ventilation (DOV) for occupants wherever occupants are located? They answered that it is necessary for the operation stage that the DOV system should have the ability to know the various positions of occupants and switch the ventilation mode into the most efficient one for the scenario. An integrated theory for non-uniform indoor thermal environments should be established, based on which the design method.

It is well known that traditional HVAC systems are predesigned and operated using a fixed airflow pattern. The research conducted by Wang et al. [19] - using Adjustable Fan Network (AFN) for improving airflow pattern maneuverability - indicates that great progress has been achieved in the fundamental theory of nonuniform environment, based on which the multi-mode ventilation (MMV) system and the online identification method were proposed and shows energy-saving potential. The MMV system is generally based on the solid foundation of DOV. It is believed that with further development of this system, the DOV system can come up soon and play an important role in high-efficiency ventilation and energy saving in the future [19].

However, in real life operations of the conventional design and operation of the ventilation systems are based on the non-uniform indoor environment assumption but many calculation methods are based on a uniform airflow pattern. Thus, based on the design method, theoretical model, and control strategy of DOV an integrated theory for non-uniform indoor thermal environments should be established and developed.

As we know the ventilation is a major player in air-conditioning and HVAC systems as a whole, therefore it should effectively and properly be designed to save a reasonable amount of energy. The main goal of a ventilation system is to remove excess heat from the space, contaminant removal, and provide and distribute fresh air into space. Liang et al. [20] postulate that: ventilation which is a significant part of the HVAC system needs to be designed properly to save energy. The proper treatment of the space cooling load in the indoor environment relies on the effective use of different ventilation systems.

The ventilation energy can be reduced by the following parameters:

- Reducing room air temperature in winter and increasing it in summer. Occupants can adapt to small changes in room temperature

- Ventilation system balancing and minimizing air leakage from ducts, fans, etc.

- Heat recovery

- Demand control ventilation, e.g. using CO_2 controllers for dampers, etc.

- User control ventilation to cater to individual requirements.

It has been demonstrated by Fong et al. [21] that the use of advanced and sustainable ventilation methods like stratum ventilation (SV) and displacement ventilation (DV) systems in specific configurations can reduce the carbon emissions up to 31.7% and 23.3%, respectively. It has been concluded that with a properly designed supply air velocity and volume, location of diffusers and exhausts, the SV system has the potential to maintain better thermal comfort with a smaller vertical temperature difference, lower energy use, and better IAQ in the breathing zone [22].

Comparison of the mean air temperatures in the occupied zone confirmed that Stratum (SV) systems offered the highest cooling efficiency, followed by displacement ventilation (DV) and then mixing ventilation (MV) systems [23].

Studies involving Impinging Jet ventilation (IJ) and Confluent Jets ventilation (CJ) systems have shown that these methods of room air distribution methods are capable of providing considerably better air quality performance and at the same time require less energy than the MV system and a higher cooling capacity than DV systems, see [24–26]. In this part, the performance of systems based on the hybrid (Impinging Jet and Confluent Jets ventilation systems) method is compared with the mixing and displacement methods of air distribution, which are the most commonly used for

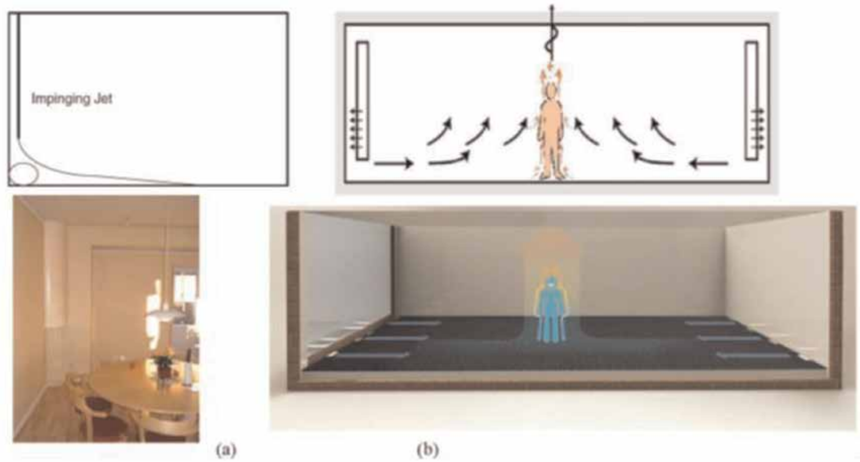

Figure 1.
Hybrid air distribution systems (HAD); (a) impinging jet; (b) confluent jets. Based on Awbi [27].

room air distribution presently. **Figure 1** shows an impinging jet supply device and confluent jets system that is called a hybrid air distribution system (HAD) [27].

Comparing with the mixing ventilation system, it is known that a displacement system is a more efficient method of air supply, but it suffers from two main problems, namely:

1. it is not capable to be used for heating mode,

2. and it has a limited penetration depth into the room which hinders that the supply airflow covers the whole floor surface.

Therefore, hybrid air distribution systems (HAD) have been developed. HAD systems combine the benefits of both MV and DV systems to use the stratification effect of the DV, the entrainment effect of MV, and to overcome the shortcomings of the DV system. Two HAD systems have recently been developed by the author of this chapter and colleagues in Sweden and the UK, that is the impinging jet ventilation (IJ) system and the confluent jets ventilation (CJ) system, see **Figure 1**. The contaminant distribution is very similar to that in a (DV) system because of the fresh air supply to the breathing zone in both the (IJ) and (CJ) methods of air distribution.

There is a need for assessing current methods of building ventilation and developing ventilation systems that are capable of providing good IAQ and energy performance to satisfy building occupants and, at the same time, meet new building energy regulations [28].

As we consider late on, the performance comparisons between the HAD air distribution systems, i.e. the imping jet and the confluent jets system, with the common mixing system show much better indoor air quality with lower ventilation energy requirement can be achieved by using the (HAD) systems of (IJ) and (CJ). One can see that the (DV) system generally performed well in cooling cases too. As we mentioned before, the (DV) system has limitations on the delivered cooling load, has less penetration depth of the DV jet in the occupied zone, and cannot be used for heating. Anyway, because of the higher supply air jet momentum, the other two systems of (IJ) and (CJ) were also shown to be used for both cooling and heating purposes, maintain good performance, providing higher cooling loads, and penetrating deeper into the room [28].

Cho et al. [29] and Karimipanah et al. [24], conducted some studies on the energy consumption of air supply processes for a ventilated rooms involving one MV (high-level) and three a wall displacement ventilation (DV), impinging jet ventilation (IJ), and confluent jets ventilation (C) which all later three were low-level supplies.

To achieve the same environmental performance for each case, the measures of energy usage were distinguished in terms of the fan power consumption and at the same time to the related airflow rate. The performance of the above-mentioned air distribution systems was compared using data from measurements in an environmental test chamber and computational fluid dynamics (CFD) simulations, see **Figure 2**.

The Air Distribution Index (ADI) concept was developed by Awbi [30], to obtain, simultaneously, the evaluation of the thermal comfort and air quality:

$$\mathrm{ADI} = \sqrt{\mathrm{N_{TC}} \times \mathrm{N_{AQ}}} \tag{1}$$

where $\mathrm{N_{TC}}$ is the Thermal Comfort Number, and $\mathrm{N_{AQ}}$ is the Air Quality Number.

Applying the Air Distribution Index (ADI) in a CFD study, compared the airflow rates for four different types of air distribution systems that are required to achieve an equal indoor environment.

The fan power (E) equation $E \propto q^3$ was used to compare the four systems. When the required air supply rate was changed to obtain an $ADI \sim 16$, as shown in **Table 1**. It was distinguished that the lowest required airflow rate (i.e. 0.025 m^3/s) was found to belong to the (CJ) system. Instead of the (IJ) system, the flow rate was slightly higher (1.4 times higher than that of CJ) which required 2.74 times more fan power compared to that of the (CJ) system. But the research showed that impinging jet (IJ) system used the fan power of ca half of that consumed by the mixing (MV) system. It was demonstrated that in comparison with the confluent jets (CJ) systems, the displacement system (DV) required a 1.1 times greater flow rate and 1.33 times higher power consumption. The results obtained for IJ and DV systems were almost similar.

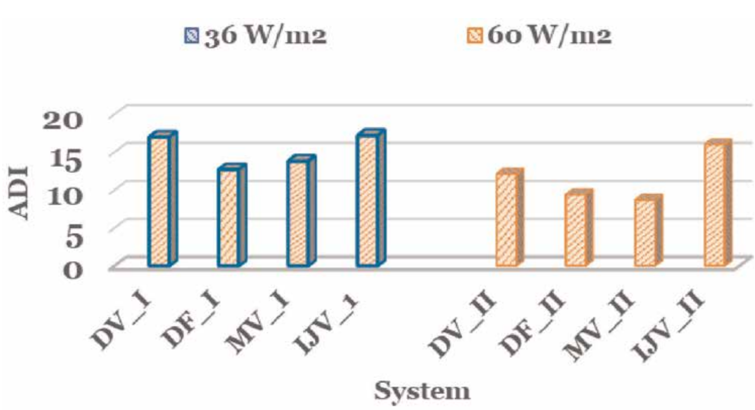

Figure 2.
The air distribution index from tests on four air distribution systems. (DV = wall displacement ventilation; DF = floor displacement ventilation; MX = mixing ventilation; IJV = impinging jet ventilation. Cases I and II refer to cooling loads of 36 and 60 W/m² respectively).

Ventilation system	ADI	Total flow-rate [m^3/s]	Fan energy usage compared to CJ
Mixing ventilation (MV)	15.5	0.045	5.83
Impinging jet ventilation (IJ)	15.7	0.035	2.74
Displacement ventilation (DV)	15.9	0.0275	1.33
Confluent jets ventilation (CJ)	16.1	0.025	1.0

Table 1.
Comparison between the fan power consumption of the ventilation systems for the same ADI (air distribution index) [24].

The results reveal that mixing ventilation requires the highest fan power and the confluent jets ventilation needs the lowest fan power to achieve nearly the same value of ADI. The following results were obtained:

- The confluent jets (CJ) air supply system performance in terms of flow rate and fan energy (power) usage was considerably higher than those of the displacement DV), the impinging jet (IJ), and the mixing ventilation systems (MV) systems.

- Compared with the confluent jets (CJ) system, it is shown that to achieve the same ADI (Air Distribution Index) a mixing system (MV) needs at least 1.8 times more flow rate and consequently, consumes 5.83 times more fan energy.

- The displacement ventilation (DV) system needs 1.33 times and an impinging jet ventilation (IJ) system uses 2.74 times the energy consumed by the confluent jets ventilation (CJ) system. As one can see in **Table 1**, both IJ and CJ systems still perform much better and need less energy than the conventional high-level supply mixing ventilation (MV) system.

- Finally, the research shows that the choice of air supply system has a major impact on energy consumption.

Figure 2 shows that the total ventilation performance of a system in terms of combined heat removal effectiveness and ventilation efficiency can be interpreted by the value of the air distribution index (ADI) it achieves. It is also shown that with the higher value of ADI (e.g. ADI > 10) the compared systems archive better performance. At the same time demonstrating that the adverse comfort conditions (no cause of draughts) were presented.

As shown on the right-hand side of **Figure 2**, the mixing ventilation (MV) can perform quite well at higher cooling loads and it is surpassed by the DV and IJ systems for both cooling loads (36 and 60 W/m^2).

The results show that although mixing ventilation can perform reasonably well at the higher cooling load, it is outperformed by the DV and IJ systems for the higher cooling loads (60 W/m^2).

In a displacement ventilation system (DV) the thermal forces are more dominant than the flow forces but in impinging ventilation systems (IJ) the flow forces are more dominant therefore the IJ system performs better (higher ADI) than the DV system [24].

As one can see from studies of Karimipanah et al. [24], see **Table 1**, the energy performance of a ventilation system is directly related to the choice of room air supply system. When choosing a proper air distribution method as a major part of the total HVAC systems, will cause large differences in the thermal and air quality effectiveness and finally the requirements of energy usage. The research also shows that the overall performance of the confluent jets air supply system is somewhat better than the displacement and impinging jets systems (both low-level supply) but superior to the mixing system (high-level supply). The confluent jets behave like the displacement and the impinging jet ventilation systems combined. The energy consumption was presented in **Table 1**.

The above-mentioned air distribution index (*ADI*) is suitable for a *uniform* thermal environment in the occupied zone, but may not be suited for cases, as in the displacement ventilation, in which a major part of thermal stratification in ventilated spaces is present. Therefore, a modified Air Distribution Index (ADI_{New}) Has been developed for a *non-uniform* environment by Awbi [27] that will be described in the following section.

The new index $(ADI)_{New}$ for non-uniform (and some unform cases as can be described late on), combines the thermal comfort and air quality numbers as follows: The proposed air distribution index ($(ADI)_{New}$) combines the thermal comfort and air quality numbers as follows [31, 32]:

$$(ADI)_{New} = \underbrace{\left[\left(1 - \frac{|S|}{3}\right) * \varepsilon_t\right]}_{N_{T.C.}} + \underbrace{\left[\left(\frac{\tau_n}{\overline{\tau_p}}\right) * \varepsilon_c\right]}_{N_{A.Q.}} \tag{2}$$

where $N_{T.C.}$ is the thermal comfort number, $N_{A.Q.}$ is the air quality number, $|S|$ is the absolute value of the average overall thermal sensation over the exposure time, ε_t is the ventilation effectiveness for heat removal, τ_n is the room time constant, $\overline{\tau_p}$ is the local mean age of air and ε_c is the ventilation effectiveness for contaminant removal. These parameters are calculated as follows:

$$\varepsilon_t = \frac{T_o - T_i}{T_m - T_i}, \varepsilon_c = \frac{C_o - C_i}{C_m - C_i}, \tau_n = \frac{1}{ACH} \tag{3}$$

the used parameters in Eq. (3) are: T_o, T_i and T_m representing the outlet temperature, the inlet temperature, and the mean temperature value in the occupied zone respectively. C_o, C_i and C_m are the concentrations of contaminants (here CO_2) at the same locations as above and ACH is the air change rate per hour for the ventilated enclosure.

The local mean age of air ($\overline{\tau_p}$) can be calculated as follows:

$$\overline{\tau_p} = \frac{1}{C(0)} \int_0^\infty C_p(t)dt \tag{4}$$

there $C(0)$ is the input of tracer gas at the beginning of the measurements which is called for the initial concentration and C_p is the gas concentration at a certain point in the room (for this case in the breathing zone).

In Eq. (2), the $(ADI)_{New}$ development follows a logic that when the thermal sensation of the occupant is neutral (i.e. $|S| = 0$). The is an ideal thermal condition, in which the thermal comfort number $N_{T.C.}$ reaches its maximum value. When $|S|$ reaches its extreme values (i.e. -3 or +3), $N_{T.C.}$ reaches its minimum value (zero). In Eq. (2) the high value of the heat removal effectiveness (ε_t) gives rise to a higher

Ventilation system	$\|S\|$	e_t	$N_{T.C.}$	t_n (hr)	$\overline{\tau_p}$ (hr)	e_c	$N_{A.Q.}$	$(ADI)_{New}$
DV	|10.17|	1.10	1.04	0.33	0.23	1.35	1.98	3.02
IJ	|0.34|	1.08	0.95	0.33	0.25	1.28	1.68	2.83
MV	|0.49|	0.97	0.81	0.33	0.40	0.93	0.76	1.57

Table 2.
Parameters for the index based on CFD simulations (airflow rate = 15 l/s and air supply temperature = 18 °C in each case), based on [26, 27].

thermal comfort number ($N_{T.C.}$) which implies that the ventilation system is efficient to remove excess heat from the occupied zone. In the same equation, both ε_c and ACH are connected to the air quality number ($N_{A.Q.}$) in $(ADI)_{New}$ which involving the contaminant removal effectiveness and consequently assessing the air distribution performance in the ventilated enclosure. Obtaining a low value for both $\overline{\tau_p}$ and ACH and a high value for the ε_c means that the ventilation system is performing well in removing contaminants and at the same time is capable of providing fresh air to the occupied zone. Consequently, the new air distribution index $(\mathrm{ADI})_{\mathrm{New}}$ presented in Eq. (2) is a unique and useful tool for the evaluation of air quality in both *uniform* or *non-uniform* thermal environments. The index is also useful for thermal comfort (based on the local comfort concept), see [32, 33].

As one can observe in Eq. (2) the calculation of $(ADI)_{New}$ the index needs both thermal comfort and air quality numbers. Almesri et al. [26], obtained the index for both mixing and displacement ventilation systems from tests in an environmental test chamber (2.78 m x 2.78 m x 2.3 m high). They used 4 males and 4 females for providing the thermal sensation data and for each test one subject was used [26]. All the tests were carried out with a supply temperature of 18°C and a total room cooling load of 21.2 W/m^2 (ventilation load of 9 W/m^2) of the floor area. The supply airflow rate was also 15 l/s which is equivalent to 3.64 l/s/m^2 floor area.

By using Eq. (3), they measured air temperature distribution in the occupied zone of the chamber to calculate ε_t. But for the calculation of ε_c and local the mean age of air ($\overline{\tau_p}$) at the breathing zone, the measured CO_2 concentrations were used. They also used the CBE thermal comfort model [34], which was also checked for accuracy with the subjects' votes, the occupants' overall thermal sensation $|S|$ was calculated. Finally, from Eq. (2) the $(ADI)_{New}$ index was obtained.

Table 2 summarized the results for the three ventilation systems. The results show that by using the above air supply conditions, the displacement ventilation system (DV) achieves higher, $(ADI)_{New}$ index, thermal comfort, and air quality numbers (NTC and NAQ) than those for the IJ and MV. The IJ system was a close second and far behind was the MV system. These simulation results and others have been given in Almesri [33] which confirmed the findings from experimental measurements in an environmental chamber using human subjects as given in Karimipanah et al. [24] and the above **Table 1**.

3. Parameters affecting the indoor environment and its energy

There are at least seven main parameters that affect the indoor environment and its energy usage are:

1. Building type
    a. Type of construction (i.e. heavy-weight, light-weight, low cost, prestigious building)
    b. Energy efficiency (degree of thermal insulation, air leakage, fabric thermal storage, night cooling, etc.)
    c. Sound insulation
    d. Level of services (very basic → highly automated).
2. Building location
    a. Urban, suburban, rural
    b. Quality of local environment (air pollution, noise pollution, etc.)
    c. External view (window sizes, glazing type, e.g. clear, tinted, number of panes, etc.).
3. Building Usage
    a. Type of activity (office work, retail business, leisure, etc.)
    b. Type of furnishing, floor covering, etc.
    c. Equipment used in the building.
4. Environmental systems
    a. Mechanical/Natural ventilation
    b. Type of air conditioning system
    c. Type of heating system
    d. Air distribution method
    e. Natural/Electrical lighting.
5. Thermal Environment
    a. Air temperature
    b. Radiant temperature
    c. Airspeed and turbulence
    d. Relative humidity.

6. Air quality

    a. Outdoor air pollution

    b. Indoor air pollution

    c. Ventilation rates

7. Degree of Control

    a. Building management system

    b. Personal environmental control (lighting, temperature, humidity, etc.)

With the renovation of the old apartment and other types of buildings, the improvement of ventilation is unavoidable to provide a healthy indoor environment for the building occupants, see Noris et al. [6].

3.1 The ways of assessing energy use in buildings

When assessing the energy use in all types of buildings, the energy-saving policies are affected by the fear of extreme climate change and consequently, the occupant's health may sometimes set aside. Wargocki and Wyon [35]. stated that: poor ventilation in buildings has negative effects on occupants' health. Sufficient ventilation for indoor climate comfort has important, especially in school buildings. They also concluded that:

- To have a better connection to real-life situations like normally functioning offices and schools, the laboratory experimental results using paid subjects should be validated by the field intervention experiments and the performance of real work should be monitored over time [35]

As stated by Bluyssen et al. [36], for the energy-efficient and well-performed building it is of vital importance that:

- It should not cause any illness for its occupants.

- It should have a high level of thermal comfort and indoor air quality for the occupants in their different activity levels.

- By taking into account available technology including life cycle energy costs, the engineers and designer should minimize the use of non-renewable energy.

- The high-quality (HQ) buildings should be designed, built, and maintained taking into account environmental, economical, and social stakes to ensure sustainable development.

The energy is used to control the indoor climate therefore large amounts of energy will be consumed to ensure a comfortable indoor climate in terms of heating or cooling demands.

Roulet [37] based on the recent European standard CEN 2006 [38] discussed two principal options for the energy rating of buildings. Firstly it is being calculated and secondly, it is measured. He called the above options as the *asset rating* and the *operational rating* which can be explained as follows:

- The asset rating: This will be based on the calculations of the energy balance of the building which was described in the former sections. This provides an assessment of the energy efficiency and performance of the building under standardized conditions which makes it possible to be compared with the retrofit process of other identical or nearly identical buildings. In this part, the energy simulation tools can be used.

- The operational rating: This will be based on the measurement of energy use and is dealing with the in-use performance of a building or in other words the practical issues. The operational rating measures can be compared with the theoretical calculations or asset rating and at the same time, they provide useful feedback to all involved partners of the building including owners, occupiers, and designers of new buildings.

4. Applications of renewable energy for HVAC systems

Historically, the severe entrance of renewable energy sources to the research area began during the oil crises in the 70:s which caused difficulties for the supply of oil products all over the world. The first UN conference about renewable energy and a sustainable global energy supply was held in Kenya's Nairobi in 1980 [39]. In the beginning, there were not any common definitions for all countries. To have a clear understanding of the above subject, in 2003, the International Energy Agency (IEA) defined renewable energy as follows: "*Renewable Energy is energy that is derived from natural processes that are replenished constantly. In its various forms, it derives directly or indirectly from the sun, or heat generated deep within the earth. Included in the definition is energy generated from solar, wind, biomass, geothermal, hydropower, and ocean energy and biofuels and hydrogen derived from renewable resources*" [40].

Nowadays, the high energy demand and at the same time struggle to mitigate the energy's environmental impact led to the following strategies [41]:

- The energy efficiency standard is one of the most popular strategies for building energy saving, which is dynamic and renewed based on the currently available technologies.

- In different countries, the "Feed-in-tariff" has successfully been applied to encourage the application of renewable energy.

However, renewable energy considers the primary energy from recurring and non-depleting indigenous resources.

It is also noted by Gungah et al. [42] that for the development of renewable energy policy and to judge whether it is successful or not, the following common criteria will be identified:

a. The institutional feasibility and extent of political support for the policy.

b. The effectiveness of renewable energy policy and the extent to which the objectives are achieved.

c. The efficiency regarding innovation with reduced costs

d. The equity and fair distribution of rents between the renewable energy developers and the state

e. The replicability and extent to which the policy can be adopted in other countries.

They also concluded that when modeling the energy policies, there should be a systemwide analysis of the new technologies being incorporated into the system and their complexities.

4.1 The environmental impact of renewable-powered HVAC

In the last decays knowing more about the renewable energy sources benefits the house owners will change to the technology that reduces the greenhouse gases and carbon footprint. However, by spending the major part of our life in confined spaces of homes and offices, it is evident that using modern HVAC systems has a significant environmental impact.

That is why the HVAC manufacturers are tackling the environmental impact and struggling to create more sustainable products for end-users. That is why energy consumption reduction for air conditioning has become an extremely urgent task.

It is reported by IPCC (Intergovernmental Panel on Climate Change) that elevating indoor temperature in summer and decreasing indoor temperature in winter are necessary means in reducing the energy consumption of air conditioners. Hence, 195 countries agreed to enhance the indoor temperature by 1.5°C for the HVAC energy reduction in the Paris Agreement. Instead of the formerly estimated 2°C, this is done to minimize devastating climate change impacts on human health and their wellbeing [43].

By switching to renewable energy sources for HVAC systems will significantly lower or even eliminate greenhouse gas emissions.

As the development of new techniques going on, the way HVAC systems operate and the impacts they have on our lives and environment are changing. For instance, the use of R-22 or Freon is not allowed for newly manufactured HVAC equipment, and the industry has largely switched to R-410A or Puron which does not damage the ozone layer.

Some examples of the new renewable technologies which are becoming more prevalent in the HVAC industry are as follows:

1. Solar-powered HVAC system: With this system the electricity obtained from solar panels is used to power heating and air conditioning units. In other words, Photovoltaic cells capture the sun's rays and convert them into electricity through solar panels, and the energy is used directly or through the grid to supply power to a building's HVAC system. In case the solar power disappears at nighttime, the HVAC systems can use both powers from the grid. Customers may then be able to use excess energy to run other electrical components of their building or even sell extra energy back to the grid.

2. Ice-powered air conditioner: By creating a clean and renewable thermal battery, ice can be produced and stored during off-peak hours - which the electricity is cheap - and then will be used to cool the building envelope.

3. Thermally-driven chillers: Instead of driving the system by electricity, these types of HVAC systems will thermally be driven by solar panels that generate heat. Then the generated heat will be converted into chilled water for cooling purposes using a double-effect absorption. In case solar power disappears at night-time, these systems can supplement with natural gas.

4. Geothermal heat pumps: The geothermal technology systems have been sophisticated over the past few decades and used in some form for more than 60 years. Even if these geothermal heat pumps are not a new technology but are also frequently used in HVAC systems. It is worth mentioning that the geothermal systems only need a small amount of electricity to run and rely on natural power resources from the earth and sun to heat and cool the buildings. Finally, the geothermal heat pump technology eliminates combustion from fossil fuels and emits no carbon dioxide. Using these types of renewables, it is now even possible to heat and cool a building Without having a bad conscience about emissions. As a renewable future of HVAC, the used technologies for heating and cooling of the buildings are changing. Consequently, with the use of renewable HVAC technologies with their increased efficiency, environmental, and health impact improvements will be achieved.

4.1.1 Renewable-powered HVAC with thermal storage

Instead of using fossil fuels-powered, the available renewable-powered energy systems for heating and cooling of residential, office, and industrial buildings are an attractive alternative to overcome the considerable effects of global warming.

Hawxhurst et al. [44] integrated onsite renewable energy and thermal storage by coupling wind and solar power generation with a control strategy that matched load demand to power generation. They used renewable energy (alone) to charge building heating and cooling thermal storage systems using an isolated microgrid. As they pointed out, the control system will be designed to charge the thermal storage systems by matching their load to the available renewable supply and these thermal stores could then be used by the building control system at a later stage to offset energy consumption from either the grid or in the case of isolated systems, batteries or generators.

Thermal energy storage devices are more reliable compared with batteries because of their long life of spans, low cost, and robust nature. There are two types of thermal storage: Cold thermal storage and hot thermal storage. The cold thermal storage is achieved by using ice and the hot thermal storage is provided by ceramic bricks. It is worth mentioning that the significant part of the end-use energy is thermal thus these storage systems account for the majority of the energy storage capability.

The first advantage of the system proposed by Hawxhurst et al. [44] is a novel control strategy that matches load demand to power generation. The system stores excess energy in robust and low-cost thermal storage devices to ultimately reduce the demand for paired, grid-connected HVAC systems. The other advantage of their strategy is that the system does have batteries to store electrical energy for the control electronics.

4.2 Strategies to eliminate the shortfalls of renewable energy sources

Due to the intermittency of renewable energy resources which cause a shortfall of these technologies, various strategies to overcome this intermittency will be used. As Anthony et al. [45] pointed out, there is a lack of sufficient energy density to serve as a practical primary energy source for the industrial sector in its current clustered form. Unless factories were built adjoining custom renewable energy farms the current energy generation density is not sufficient.

They presented a methodology to investigate the generation, transport, and storage of energy based on a "*multi-physics approach*", tied to the end-use application [45].

4.2.1 Multi-physics approach to energy generation, transport, and storage

Instead of associating energy with electricity or hydrocarbons by default, the multi-physics approach simply requires consideration of different energy generation, storage, or transfer methods, based on all available physical phenomena, and considers the end-use of the energy form.

By employing such an approach the engineers will be free from the electricity and hydrocarbon-centric, default attitude toward energy to find efficiency gains in the margins. A particular application requires an approach modification for the design of an energy system to utilize multi-physics energy storage.

It is considered that different buildings have different energy needs. Therefore, different systems would be suited to each building application. The following structured approach to tackling this problem will be summarized as, see Anthony et al. [45]:

a. Energy demands: First the lists of major energy demands of the system should be handled.

b. Reduce demand: consider the possible new technologies which are available to reduce the energy demand you listed before and modify if possible.

c. Classification: Try to classify the physical mechanism used for each process, e.g. heating, cooling, gas compression, and so on.

d. Power and Energy: Consider the sizing of the system by quantifying the power demands in Watts and the energy demands in Joules.

e. Generation: Identify appropriate energy sources, preferably to include renewable energy sources for each energy need.

f. Transport: Identify appropriate energy transport methods for this important sector.

g. Storage: Identify appropriate energy storage methods to be applied to the system.

h. Safety and Practicality: Think of a safe and practical implementation of each delivery, transport, or storage method.

i. Lifecycle Costs: Finally, calculate the cycle life const (LCC) of the system.

Generally, there are two types of air conditioning (AC) systems namely [46]:

- Centralized AC systems and

- Decentralized/Zoned AC systems.

In their study Zhou et al. [46] show that in residential buildings, at the point where the centralized feature of the system meets the decentralized feature of users' load, the problems of high energy consumption and low energy efficiency could easily occur. They also pointed out that centralized AC systems are effective and should be promoted for the urban landscape. Also for the centralized AC in residential buildings, the adjustability in each segment (users' terminal, refrigeration equipment, and distribution system) would greatly influence the energy consumption and system efficiency.

In case the spaces do not have central HVAC systems or with inefficient heating and cooling options, ductless heat pumps provide efficient and easy-to-install HVAC systems. There are some advantages for the decentralized AC systems:

- users have greater flexibility controlling the AC terminals and as a consequence, the supplied cooling energy would be reduced effectively.

- no distribution system exists in decentralized AC systems which means that the total energy consumption would not include the consumption of fans or pumps.

Zoned AC systems rely on thermostats installed in every room to provide climate control information to a central HVAC control panel and are ideal for multi-story houses with the following characteristics:

- For those living in bigger homes with multiple people

- Homes with finished attics and basements

- Homes high ceilings

- Homes large windows and,

- Homes with extra rooms that aren't often used and the days of arguing about which rooms to heat and cool.

The Zoned AC systems minimize allergen transfer better than non-zoned HVAC systems, providing relief to those sensitive to airborne allergens.

4.2.2 Liquid desiccant air conditioning system (LDAC)

Liquid desiccant air conditioning systems (LDAC) belong to existing energy-efficient and environmentally friendly air conditioning technologies [47]. LDAC systems can be driven by low-grade heat sources such as solar energy and industrial waste heat. As a potential universal scheme in practical Si solar cell applications, the self-cleaning omnidirectional nano-based light-harvesting design with hierarchically structured packaging glass can be used. Since solar power has been considered as one of the most expensive sources of renewable energy, these renewable energy sources are still covering and assisting in merely a small portion of global energy demands. For instance, Photovoltaic (PV) power generates less than 1% of total electricity supplies.

4.2.3 Solar-biomass hybrid for air conditioning system (SBAC)

Another interesting system is a solar-biomass hybrid for air conditioning (SBAC) and cooling systems which is a completely renewable energy-based system as is illustrated in **Figure 3** [48]. It is demonstrated that the first part of **Figure 3**, the control volume on the left-hand side, is a solar water heating system.

The solar water system consists of a field of solar collectors, a hot water storage tank, and a circulating pump. The second part with a three-ways motor valve (in the middle of the Figure) is a biomass gasifier-boiler. The biomass gasifier-boiler consists of an automatic up-draft gasifier and gas-fired boiler. The control volume showed on the right-hand side of the figure is an absorption air-conditioner. The absorption air-conditioner consists of an absorption chiller, fan coil unit (FCU), cooling tower, and three pumps (cooling, hot, and chilled water pumps) [48]. It will be noted that the model-based design of a renewable energy-based solar-biomass hybrid air-conditioning system uses LiBr–H_2O absorption chiller.

There are also other interesting renewable energy-based methods for HVAC systems. For instance, Wang et al. [49] presented a tri-generation system which is the combined process of heating, cooling, and power generation, see **Figure 4**. The system is using sewage treatment digestion biogas according to the principle of energy gradient utilization technology. The tri-generation system uses Lithium Bromide (LiBr) absorption cooling technology for office air conditioning, a biogas power generator and, a heating system for digestion tanks.

They developed an innovative and more efficient utilization way for using the digestion biogas from sewage treatment works. The main findings can be concluded as follows:

1. When replacing the boiler with Lithium Bromide absorption chillers, the cooling capacity produced by the chillers can be used for space air conditioning. The chiller will also be used for cooling the inlet air of the biogas generator to improve its power generation efficiency.

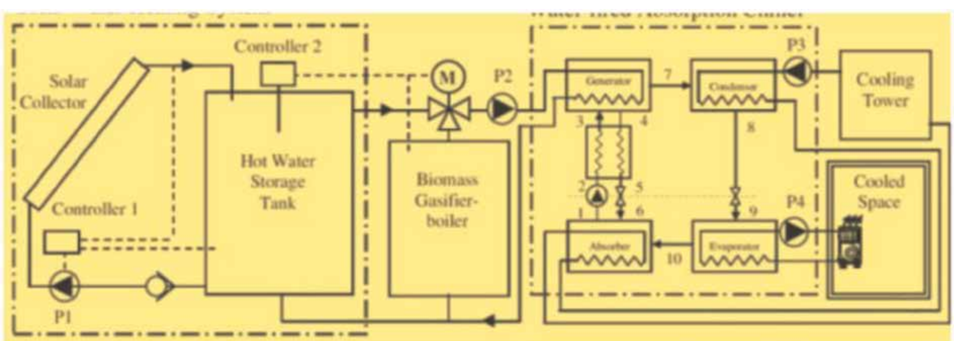

Figure 3.
Schematic diagram of the solar-biomass hybrid cooling system [48].

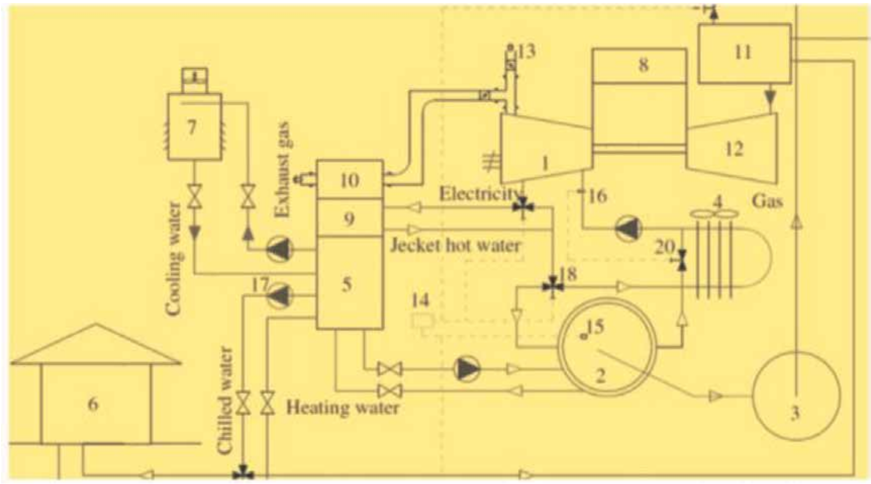

Figure 4.
Schematic diagram of the proposed tri-generation system [49]. The numbers in ***Figure 4*** *are: 1) biogas generator, 2) sludge digestion tank, 3) gasholder, 4) radiator, 5) Lithium bromide absorption chiller, 6) office building, 7) cooling tower, 8) combustor, 9) hot water generator, 10) flue gas generator, 11) inner air cooler, 12) compressor, 13) chimney damper, 14) controller, 15) temperature sensor, 16) thermometer, 17) pump, 18) three-port regulation valve, 19) valve and number 2, and 20) two-port regulation valve.*

2. It is shown that the tri-generation cycle system is very cost-effective.

3. The inconsistency of heating and cooling loads can be solved by the system and the extensive energy efficiency is much higher.

A schematic diagram of the tri-generation system is shown in **Figure 4**, which provides multi services by using a single energy source, including electricity supply, space air conditioning, and heating of sludge digestion tank or hot water supply to other users [49].

Finally, about the future of cooling and air condition systems *Fatih Birol, IEA Executive Director* indicates that: *"Growing demand for air conditioners is one of the most critical blind spots in today's energy debate. Setting higher efficiency standards for cooling is one of the easiest steps governments can take to reduce the need for new power plants, cut emissions and reduce costs at the same time"* [50].

5. Conclusions

In comparison with the total energy use in a building, the proportion of ventilation and air conditioning energy is expected to increase as the building's fabric energy performance improves. These lead to ventilation standards that recommend higher ventilation rates for improving indoor air quality (IAQ). However, there is a great global emphasis on reducing the reliance of buildings on fossil fuel energy and a move toward Nearly Zero Carbon Buildings (NZCB), the researchers are determined to develop more sustainable ways of HVAC systems. At the same time, many promising energy-efficient solutions for air distribution systems are available.

Some existed methods of sustainable HVAC systems using renewable energy resources and at the same time, some methods for overcoming the renewable energy sources intermittency and fall-down are presented. The Solar-biomass hybrid for air conditioning (SBAC) and the Liquid desiccant air conditioning systems (LDAC) belong to existing energy-efficient and environmentally friendly air conditioning technologies.

Some other examples of the new renewable technologies which are becoming more prevalent in the HVAC industry are also described:

- Solar-powered HVAC system
- Ice-powered air conditioner
- Thermally-driven chillers
- Geothermal heat pumps:

It was also described that a method, New Air Distribution Index (ADI_{New}), for evaluating the performance of air distribution systems is to introduce ventilation efficiency and energy effectiveness.

It was pointed out that reducing energy demand for heating and cooling is essential for improving the energy efficiency of a building but not at the expense of deteriorating air quality and the health of the people. The energy flows in buildings can be assessed in two ways: by calculation or by measurements. Estimation of various energy flows brings the necessary knowledge for improving energy performance [37].

Acknowledgements

The author wishes to thank the financial support of the University of Gävle for publishing costs.

Conflict of interest

The author declares no conflict of interest.

Nomenclature

ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
ACH	room air change rate per hour
ADI	Air Distribution Index
$(ADI)_{New}$	New Air Distribution Index
BEM	Building Energy Simulation
CAV	Constant air volume
CEN	Comité Européen de Normalization
CJV	Confluent jets ventilation
CO_2	carbon dioxide
CDDs	the colling degree days
C_i	contaminant concentration at the inlet (CO_2)

C_m	the mean value of contaminant concentration (CO_2)
C_o	the contaminant concentration at the outlet (CO_2)
$C(0)$	the initial concentration of a tracer gas
C_p	the gas concentration at a certain point in the room (e.g. breathing zone)
DCV	demand-controlled ventilation
DV	displacement ventilation
HVAC	Heating, ventilation, and air conditioning
HQ	high quality
IEA	International Energy Agency
IAJS	Intermittent air-jet strategy
IAQ	Indoor air quality
IJV	Impinge jet ventilation
LDAC	Liquid desiccant air conditioning systems
LAF	Laminar airflow
LEV	Local exhaust ventilation
LCC	lifecycle costs
LiBr	Lithium Bromide - the cooling medium used in absorption cooling
MV	mixing ventilation
$N_{A.Q.}$	the air quality number
$N_{T.C.}$	the thermal comfort number
NZEB	Nearly zero-energy buildings
PiV	Piston ventilation
POV	Protected occupied zone ventilation
POZ	protected occupied zone
PV	Personalized ventilation
PV	Photovoltaic
RH	relative humidity
$\|S\|$	the absolute value of the average overall thermal sensation over the exposure time
SBAC	solar-biomass hybrid for air conditioning
SV	Stratum ventilation
T_o	temperature at the outlet, °C
T_i	the temperature at the inlet, °C
T_m	the mean temperature value in the occupied zone, °C
UFAD	Underfloor air distribution
VAV	Variable air volume
WAV	Wall attached ventilation
ε_c	the ventilation effectiveness for contaminant removal
ε_t	the ventilation effectiveness for heat removal
τ_n	the room time constant
$\overline{\tau_p}$	the local mean age of air at the breathing zone

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Chapter 12

Post Covid 19: An Innovative System to Supply 100% Treated Fresh Air for Improving City Liveability

Esam Elsarrag and Mohammad Elsarraj

Abstract

Prior to COVID-19, densely occupied areas were already suspected of making employees sick. Post-COVID-19, there is an urgent need to improve air quality and ventilation standards shall change. However, any changes to ventilation must consider other negative consequences including energy and health and well-being impacts from thermal discomfort and exposure to pollutants. The need for moving away from traditional energy sources and to find alternate energy sources is undoubtedly one of the primary objectives for a sustainable progress to humankind. The design and construction of buildings in hot-humid climates requires high energy consumption typically for air conditioning due to higher thermal loads. A further increase in ventilation rates will have intensive impact in energy consumption and infrastructure loads. This chapter presents the performance of an innovative fully integrated smart ventilation system with low energy consumption. It is all in one ventilating and air conditioning system that provides efficient, cost-effective, and sustainable cooled fresh air for open or enclosed spaces whilst achieving thermal comfort. Based on the application, it consists of multistages that can dehumidify and cool the air to the required comfort level. The system has shown 50–60% reduction in energy consumption compared with conventional systems.

Keywords: Covid 19, ventilation, comfort, energy efficiency, outdoor cooling

1. Introduction

Higher ventilation rates are dictated both by better comfort requirements and by the most recent standards such as ASHRAE (62-2019) and various CIBSE guides. However, post-COVID 19 pandemics, these ventilation rates require re-consideration. People shall also maintain social distancing regulations, which impact occupied spaces both indoor and outdoor. Eventually, higher fresh air rates are required and researchers will continue to work on the additional fresh air amounts. The more outdoor air is used, the larger the cooling or heating loads required, particularly cooling loads in hot and humid regions. In addition, the uncontrol of the ventilation

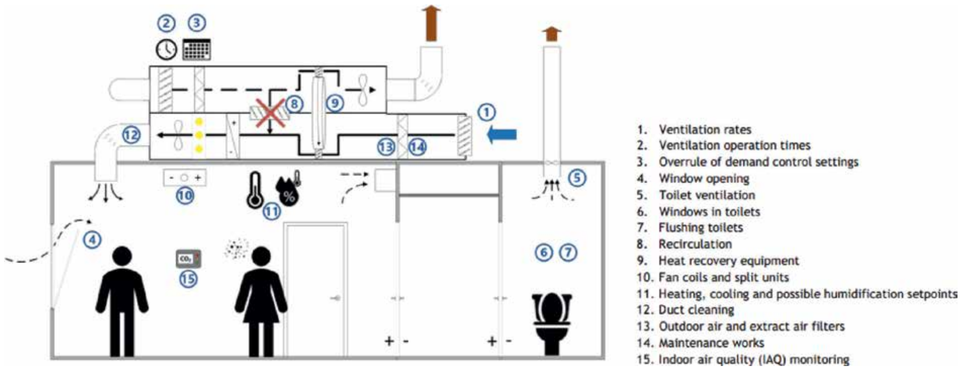

Figure 1.
Main items for building services operation [1].

air physical parameters will impact human comfort and health. For instance, the fresh air must be treated and conditioned to the desired comfort level of humidity and temperature before being supplied to the occupied spaces.

Cooling of outdoor air is usually obtained with refrigeration equipment and often in humid climates and some post-heating is required to heat the air before it is supplied to the rooms. **Figure 1** demonstrates the ventilation air mixing in a typical HVAC system. Conventional energy resources are more depleted and the energy demands of a growing global population continue to increase.

According to Fang et al. [2], individuals spend 90% of their time indoors, resulting in a significant rise in energy consumption to maintain indoor thermal comfort. The characteristics of humid tropical climates are that they are hot and humid. These climates cover a huge portion of the globe and are home to more than 33% of the world's population as stated by Bonell et al. [3]. As a result, achieving thermal comfort outside is also becoming increasingly crucial. For outdoors, however, thermal comfort is difficult to accomplish since humans are directly exposed to the environment, which is influenced by the combination of air temperature, air velocity, relative humidity and radiation fluxes. These are among the environmental parameters. Clothing insulation and metabolic rate are two human personal factors, which are also variables that influence thermal comfort.

Binarti et al. [4] noted that in these hot-humid locations, a pleasant thermal environment is difficult to establish due to the combination of high temperatures and humidity. These variables also vary and are not uniform in large outdoor spaces, which creates difficulty in monitoring and managing them to achieve thermal comfort. Wind speeds will also impair cooling techniques in hot, humid areas.

If outdoor thermal comfort is accomplished, this will increase city liveability whilst simultaneously reducing building heating and air conditioning energy usage by reducing time spent indoors. To correctly analyse the outside thermal environment, it is important to utilise appropriate outdoor thermal comfort models.

Due to the outbreak of COVID-19, it has become increasingly difficult to have many occupants in the same room inside buildings such as restaurants and cafes. Therefore, outdoor spaces must be utilised to accommodate for a larger group of people. However, in hot-humid climates thermal comfort is difficult to achieve outdoors as previously discussed. The presented ventilation system in this chapter achieves outdoor thermal comfort whilst boasting low energy consumption.

There are challenges related to intensifying energy consumption majorly by the installed air conditioners especially related to hot-humid climates (46°C dry bulb, 31°C wet bulb) due to the fact that evaporative cooling systems will certainly fail to meet the comfort criteria due to the high wet bulb temperature. Despite searing temperatures and high humidity, people will find it interesting to go to places such as markets, cultural venues and other tourist destinations if given a cool and suitable ambiance. Evaporative cooling is often used for outdoors but it will not be enough to relieve people's discomfort with the weather during the hot months. Cooling is usually obtained with refrigeration machinery, and often some post-heating is required to heat the air before it is supplied to the rooms. Conventional air conditioning systems (e.g. vapour compression systems) address these issues by cooling air below its dew point such that water vapour condenses on a cooling coil, thus removing moisture from the air.

Nevertheless, achieving thermal comfort in using fresh air in hot and humid regions is energy intensive. Countries with extreme climatic conditions impose a heavy reliance on cooling, mostly electricity-based, and thus a strong and structural dependency of a high energy resource. In hot-humid climate, the average highest outdoor temperatures during a year is 37.0°C; however, high-temperature values that exceed 46°C could be observed in summer. As illustrated by **Figure 2**, the temperature exceeds the 40°C for more than 300 hours, which anticipated to be doubled when considering hot-humid climate climate change in 2025. Air conditioning counts for more than 60% of the electricity consumption in the Gulf Region as explained by Elsarrag [5]. Moreover, this lack of responsiveness to the local climatic conditions also leads to problems of indoor air quality, user comfort and user productivity. With energy being cheaply available, the incentive for building users to save on their energy consumption is weak.

In hot-humid climates, not only the total annual energy consumption in buildings is very high, but peak demands for electricity also put a heavy burden on the infrastructures needed to respond to such demand pattern. In this context, building energy efficiency strategies can help to realise peak shaving by load reduction and load shifting.

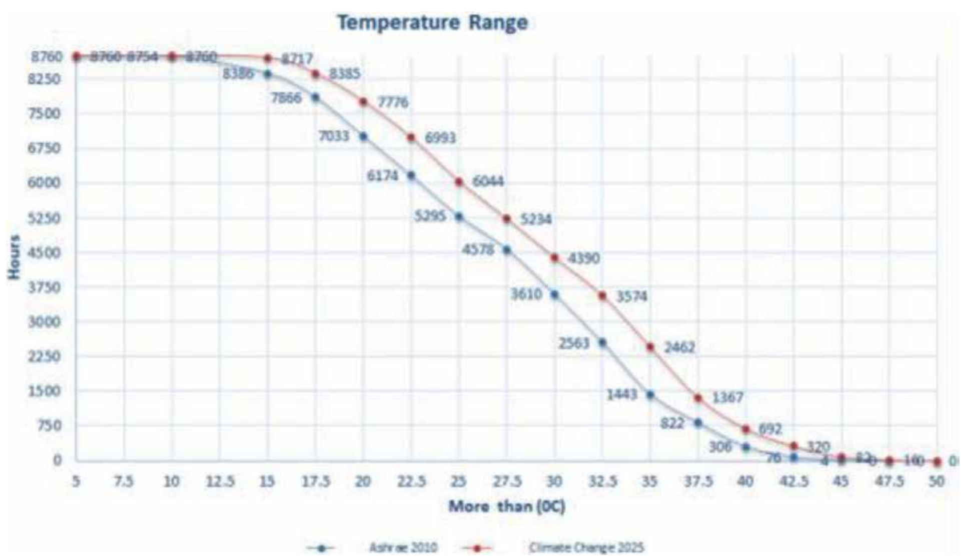

Figure 2.
Temperature range in hot-humid climate in Doha City [5].

Improving the energy efficiency measures has taken the attention of researchers in hot-humid climate in the Gulf Region. Experimental and theoretical studies were conducted recently to improve building fabric efficiency and promote enhanced indoor air quality in hot-humid climates as conducted by Elsarrag [5]. High-rise building passive design attracted researchers from different parts of the world [6–9]. In hot-humid climate, it is vital to cool and dehumidify the ventilation air before being supplied to the space. Alternative fresh air cooling and dehumidification methods to conventional refrigeration system were presented by Elsarrag [10, 11].

The use of efficient systems and effective means of control is vital to reduce the energy consumption. Several resilience cooling strategies are identified by Zhang et al. [12]. The study by Siroky et al. [13] showed that the energy saving of a building heating system by adopting controls could be reached the range of 15 to 28%. At times when ventilation and daylight cannot alone meet the needs of occupants, the building services should meet the remaining demands as simply and effectively as practicable, in harmony with the occupants and the building as a whole. An essential part of the integrated design is to ensure that the energy supply and monitoring strategy are as coherent and environmentally sustainable as possible.

Figure 3 shows about 83% of the ambient weather conditions are not in the comfort zone; therefore, the following strategies are used to design a high efficient cost effective system. Several strategies can be used to reduce the need of conventional vapour compression systems. Such strategies include the use of desiccants and evaporative cooling (direct and indirect).

In hot climates, it is desirable to reduce the ambient air temperature in order to improve comfort levels; however, in hot and humid climates (as in some Gulf countries), removal of moisture from the air (dehumidification) is almost as important as cooling [15].

Conventional air conditioning systems (e.g. vapour compression systems) address these issues by cooling air below its dew point such that water vapour condenses on

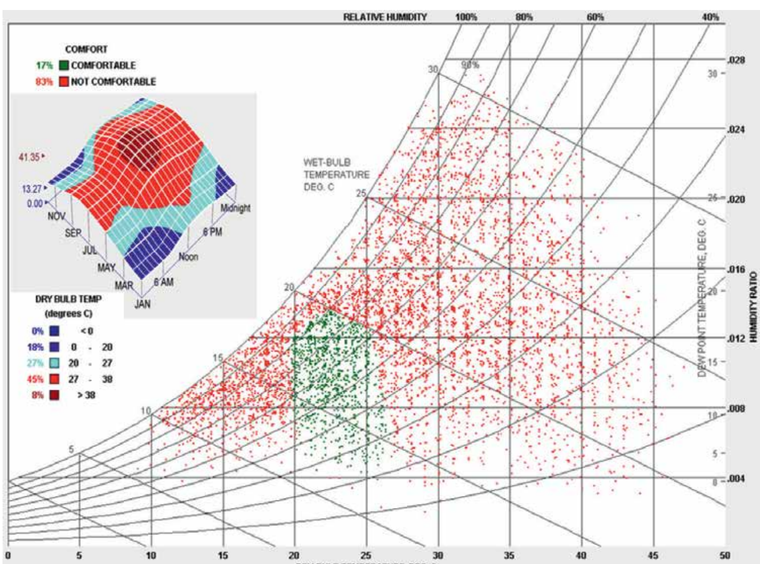

Figure 3.
Extreme weather conditions of hot-humid climate Doha City [14].

a cooling coil, thus removing moisture from the air. The dehumidified air is then reheated to the desired temperature [16]. This process of deep cooling to dew point and reheating consequently leads to higher energy requirement.

This chapter discusses the integration of the innovative and efficient fresh air cooling and filtration system that has been designed, manufactured and tested to reduce the need of vapour compression cycles and provide better liveability for urban environments.

2. System description

The innovative smart air conditioning system is a fully integrated and controlled—beCOOL Innovation—ventilating and air conditioning system that provides efficient, cost-effective and sustainable fresh air cooling for open spaces or enclosed spaces in moderate, hot or humid climates. The system can be used tool open spaces such as restaurants, coffee shops, open markets, parks, playgrounds. It can also be used to provide fresh air (ventilation air) to enclosed spaces such as offices, schools, retails. The integrated unit consists of a multistage that can dehumidify and cool the air to the required comfort level. The system utilises the condensate water. The 'all in one' HVAC system can be fully driven by renewable energy. **Figure 4** shows the proposed system that combines air filtration system, and a three-stream water temperature control system, a multistage fresh air cooling heat exchanger and water collection/makeup system. The system is integrated with a variable frequency drives and smart controls. Initially, fresh air is filtered and used to cool three water streams. The scavenging outdoor air is exhausted to the atmosphere again. The innovative heat exchanger is a compact heat exchanger that allows more than one water stream to circulate. The first water stream is so called the high grade as the water temperature is higher than the second water stream (low grade). The supply hot and/or humid air will be initially filtered, precooled by the first stage in the heat exchanger, dehumidified in the second stage and cooling enhanced in the third stage. Dry cold fresh air is then supplied to spaces. The system is installed at different facilities for testing

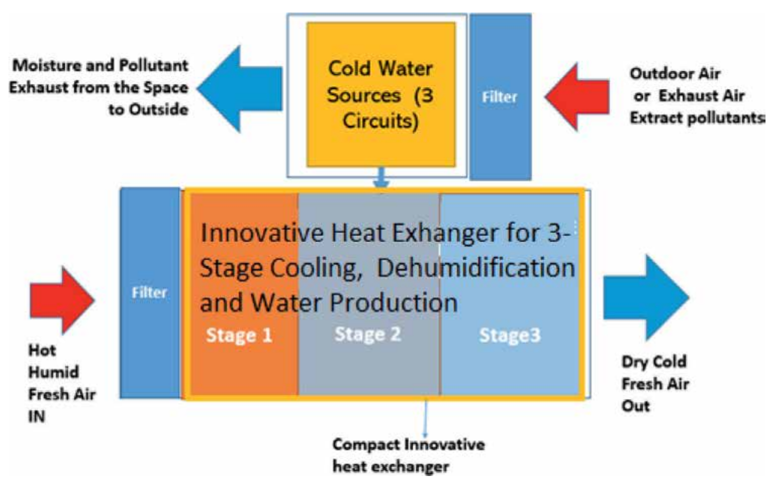

Figure 4.
The innovative system schematics.

Figure 5.
beCOOL-innovation outdoor testing setup.

in a coffee shop, residential external sitting area and industrial workshop in Doha, Qatar. The tests were conducted during the months of June and July where temperature exceeds 47°C in the afternoon and humidity exceeds the 75% at night. Several temperature and humidity sensors are used to verify the readings. At the air intake and outlet, two type of sensors were incorporated, the first is directly integrated with the beCOOL-Innovation control system and the second is connected to the cloud for monitoring and verification.

The system was placed at a coffee shop—an open sitting area as shown in **Figure 5**. The system was placed 2.5 m away from the sitting area. To maintain effective outdoor

Figure 6.
The actual beCOOL-innovation system.

cooling, the use of beCOOL-Innovation must be aligned with outdoor energy efficiency strategies to improve resilience to extreme heat in order to maintain comfortable outdoor thermal conditions during heat waves, such as the use of solar shading and wind barriers. Here, the system was placed between buildings that have shading and act as wind barriers for most of the day.

Temperature and humidity sensors were placed at the air intake of the unit (behind the unit), and the supply temperature and humidity are measured at the diffuser outlet. Air flow is measured using anemometer. The measured data were used to obtain the enthalpy of the entering and exit air, hence calculating the total cooling energy of the unit. A multimetre was used to measure the voltage and current to calculate the electrical energy. The coefficient of performance (COP) of the system is equal to the cooling energy divided by the electrical energy. Typical COP of conventional air conditioning in hot-humid climate varies between 2 and 2.5 for air-cooled direct expansion units. In this study, the COP for conventional system is considered the highest value (COP = 2.5) to ensure that energy savings are compared with the best practices for similar systems.

The temperature metre accuracy is 0.1°C and the humidity metre is 1%. Energy is measured *via* multimetre to measure both the voltage and current. The objective of the setup is to verify the theoretical performance.

Figure 6 shows the beCOOL-Innovation actual system. Jet diffusers are used to supply air to far distances.

3. Results and discussion

Figure 7 compares the theoretical monthly cooling coil load of the conventional fresh air handling unit and the beCOOL-Innovation cooling load. beCOOL-Innovation supplies 2500–3400 m3/h of treated fresh air with a considerable reduction in the cooling coil load compared with conventional. The system is designed to provide fresh air supply without assistant of any mechanical refrigeration in dry season and to provide cooling and dehumidification in humid season. The theoretical analysis showed that it will correspond to an annual cooling load reduction (cooling capacity reduction) of around 60% as shown in **Figure 8**. The overall predicted monthly

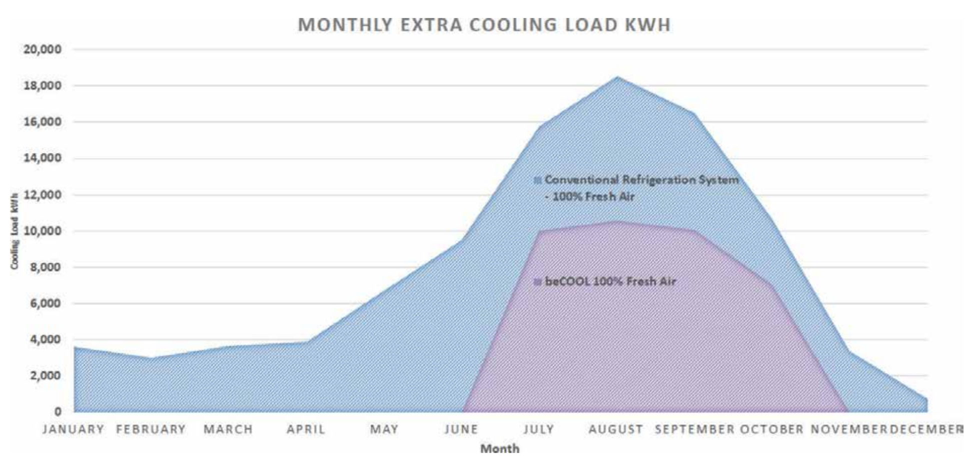

Figure 7.
Monthly cooling coil load (kWh).

and annual system electricity consumption is compared with system cooled *via* direct expansion (conventional refrigeration machine) system in **Figures 9** and **10**. beCOOL-Innovation can reduce the total annual electricity consumption by 55%. The system electricity consumption includes all power associated with unit including fans, pimps, compressors and electronics. The experimental setup results showed consistency with the theoretical analysis.

Table 1 shows the theoretical and measured results for average summer days. It can be clearly noticed that the discrepancy between the theoretical and experimental is below 8%, which provides confidence to the system design. For thermal comfort comparison, the apparent temperature analysis is used. The apparent temperature (AT) is the temperature perceived by the human body from the combined effects of ambient temperature, wind speed, humidity and solar radiation more

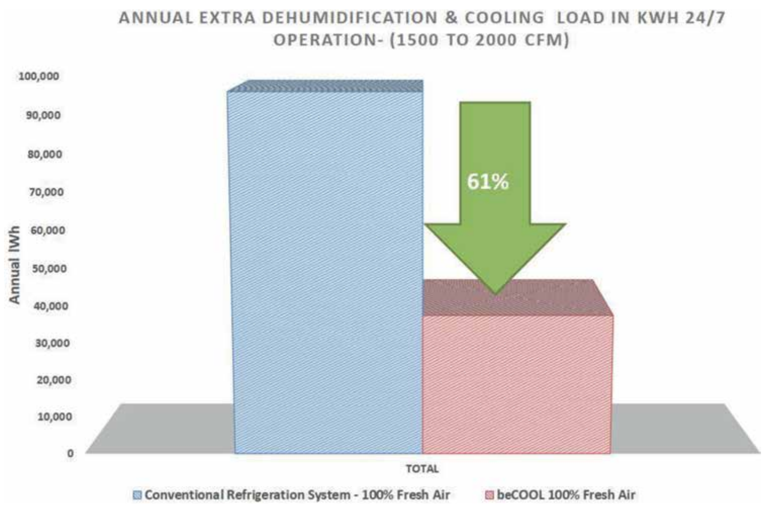

Figure 8.
Annual cooling coil load (kWh).

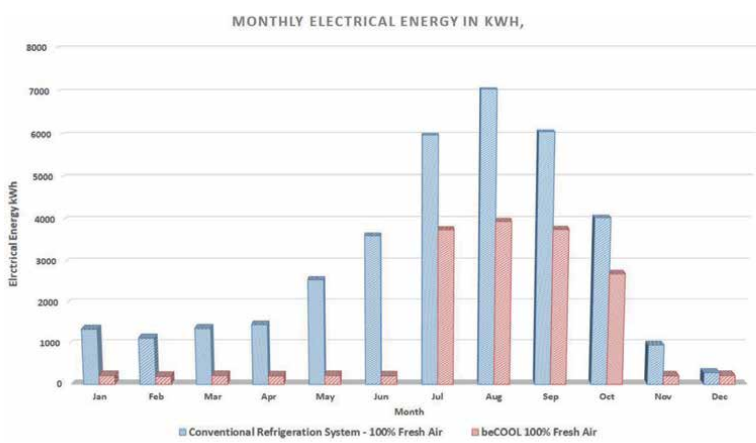

Figure 9.
Monthly system electrical energy (kWh).

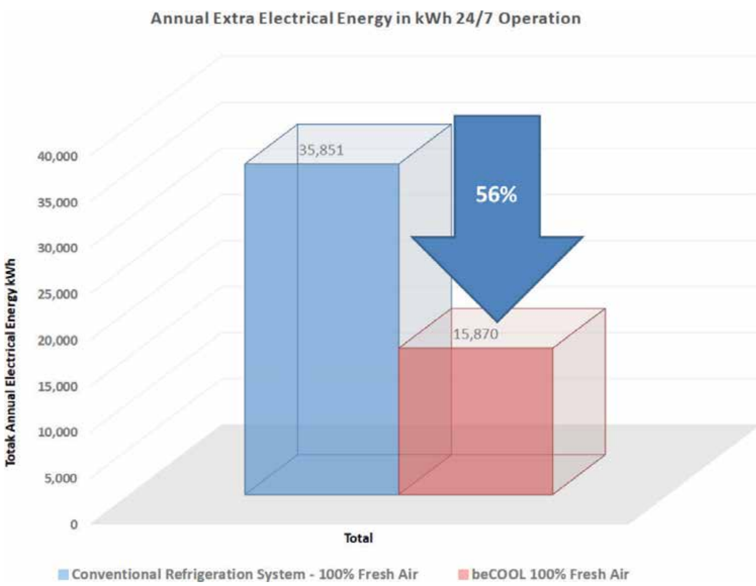

Figure 10.
Annual system electrical energy (kWh).

Ambient air temperature °C	Ambient air humidity %	Measured supply air temperature °C	Theoretical supply air temperature °C	Discrepancy
44.8	26.8%	22.4	21.4	4.7%
44.1	16.2%	15.8	14.7	7.5%
44	22.0%	18.1	17.1	5.8%
42.8	31.6%	21.8	21.5	1.4%
41.5	43.2%	23.6	23.3	1.3%
37.6	65.2%	26.8	26.3	1.9%
36.1	74.8%	28	27.5	1.8%

Table 1.
System measured vs. theoretical supply air temperature.

objectively reflecting the thermal sensations experienced by the human body than temperature alone, especially in highly humid environments [17, 18].

The apparent temperature (AT) is a suitable comfort index for climates with high temperatures and humidity. As shown in **Figure 11**, the apparent temperature at air speed for afternoon shaded is at 1 m/s air speed 50°C. If evaporative cooling is used, AT is reduced to 36.5°C. A two-stage indirect direct evaporative cooling system will reduce AT to 31.6°C. beCOOL-Innovation can reduce AT to 22.7°C at the same speed (1 m/s), which will have good impact on human comfort compared with traditional technologies.

The beCOOL-Innovation is a 100% fresh air system; therefore, the water consumption is directly related to the weather conditions. The average hourly water is found to be 10 litres/hour; however, the system produces 17.5 kW of cooling and consumes 3.4 kW electricity.

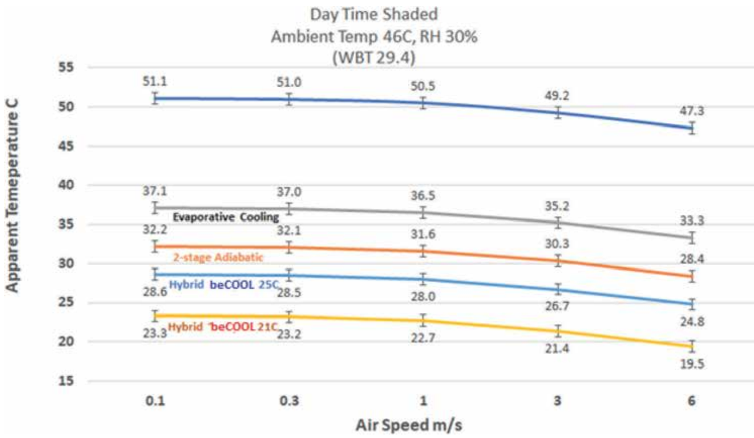

Figure 11.
Comparison of different systems on thermal comfort.

4. Conclusion

This chapter presented the drivers, challenges and the beCOOL-Innovation technology to provide efficient treated fresh air for outdoor comfort whilst reducing energy consumption especially for hot or humid climates. Outdoor comfort is vital to improve urban liveability. The system has shown 50–62% reduction in energy consumption compared with conventional refrigeration systems. The efficient cooling system can shrink clients' carbon footprints using cost-effective means. In addition to enclosed spaces, typical applications include open spaces such as stadiums and walkways, hospitals, health centres, laboratories, and greenhouses that would reduce food imports and strengthen national and regional food security. The testing results have shown less than 8% discrepancy between the theoretical and actual air supply temperatures.

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Edited by Marita Wallhagen and Mathias Cehlin

This book assembles the latest knowledge linked to urban environments and urban socio-eco-technological systems including urban, energy, transport, material, and ecosystems. Urban environments and systems affect every person's life in many ways and can have negative impacts on the local and global environment. They create value but sometimes with a high environmental cost from a lifecycle perspective. Therefore, scientists and global leaders call for an urban transition to create more urban environments and systems that are climate-positive, sustainable, and healthy, which is necessary for society to function within the planetary boundaries. This is a great challenge. Huge transformations and new ways of thinking regarding the design and co-existence of technical, social, and ecological systems are necessary to turn the present challenge into opportunities. This book, *Urban Transition - Perspectives on Urban Systems and Environments*, explores this challenge and several different topics related to possible, probable, or necessary urban transitions in the urban environment. It assembles a variety of authors who present many aspects and the latest knowledge linked to urban transitions of the urban environment and urban socio-eco-technological systems - including urban-, energy-, transport-, building- material- and eco-systems. Furthermore, the importance of urban systems and urban environments is seldom clearly linked to their impact on the environment and humans. This book examines this gap, the crucial issues relating to how urban systems influence the urban structure, and how they can be formed and designed to become more sustainable. It explores the link between the complex systems in cities, the physicality of the built environment, and the living environments for the people. The book proposes a rich garden of ideas to provoke and develop current research, debate, and new forms of practice.

ISBN 978-1-83962-414-8

Published in London, UK

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