Giriraj Srivastava

Optimization of Energy Sharing in a Mixed-use Neighbourhood

Master's thesis in Sustainable Architecture
Supervisor: Luca Finocchiaro
Co-Supervisor: Alessandro Nocente

February 2021

Master's thesis

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HIGHLIGHTS

- Minimum neighbourhood NEC is achieved when area of typology with least NEC is maximized
- Maximum neighbourhood PLS is achieved when area of typology with highest NEC is maximized
- Optimum scenario with minimum NEC and maximum PLS cannot be achieved without compromise
- The methodology used in the study is replicable for optimization of neighbourhood plans in different contexts

Keywords: *peak load shaving; energy sharing; mixed-use neighbourhood; GHG emissions*

HØYDEPUNKTER

- Man oppnår laveste nabolags netto energiforbruk når området for bygningstypen med laveste netto energiforbruk er høyest
- Man oppnår høyeste nabolags peak load shaving når området for bygningstypen med høyeste netto energiforbruk er høyest
- For å få et nabolag med optimal områdefordeling av bygningstype-ne, må man gå på kompromiss mellom laveste netto energiforbruk og høyest peak load shaving
- Metodikken som er brukt i forskningen kan replikeres for optimali-sering av nabolagsplaner i forskjellige sammenhenger

Nøkkelord: *peak load shaving; energideling; flerbruks nabolag; klimagassutslip*

ABSTRACT

Peak load shaving and energy flexibility of modern neighbourhoods show a great potential to reduce GHG emissions, grid capacity, and energy prices. However, research on planning of urban neighbourhoods to optimize these criteria are very limited. This study investigates the energy sharing potential of a hypothetical neighbourhood to maximize the PLS and minimize the NEC, by proposing a methodology to calculate and analyse the hourly energy consumption and production of different building typologies with varying built-up area. The optimization of NEC and PLS are carried out individually through single parameter optimization and then a qualitative scale is used for multi-objective optimization of both, NEC and PLS with both given equal importance. A south-facing section of the OEN building proposed model is simplified into a polygon form and used as a base model to simulate residential, office and retail typologies. The study demonstrates that both, neighbourhood NEC and PLS potential are inversely proportional to the area of the typology with minimum NEC. That is, the NEC of neighbourhood decreases with increase in area of typology with minimum NEC, and PLS potential of neighbourhood increases with increase in area of typology with maximum NEC. As the goal of the study is to minimize the neighbourhood NEC and maximize the PLS, it is observed that a well-informed compromise has to be made. The multi-objective optimization results show that a neighbourhood with 10% residential, 40% office and 50% retail is the optimum compromise. The methodology proposed in the study can be used for planning phase of neighbourhoods to optimize the program area distribution in order to reduce NEC and increase the PLS of the neighbourhood.

SAMMENDRAG

Peak load shaving og energifleksibilitet i moderne nabolag kan redusere klimagassutslippene, nettkapasitet og energipris i stor grad. Likevel er det gjort lite forskning rundt optimalisering av peak load shaving og energifleksibilitet i urban planlegging. Denne masteroppgaven undersøker muligheter for energideling i et hypotetisk nabolag for å maksimere peak load shaving and minimere netto energiforbruk. Oppgaven viser en metodikk for å beregne og analysere energibehovet og produksjonen for hver time på årlig basis for forskjellige bygningstyper og bruttoarealer. Netto energiforbruk og peak load shaving er optimalisert, først individuelt, og deretter sammen via kvalitativ analyse av begge parameter. OEN bygningen i Ammerud, Oslo er brukt som case-studie. En sydvendt seksjon av bygningen ble forenklet til en polygonform og ble brukt for å simulere energibehovet av boliger, kontorer og butikklokaler bygningstyper. Masteroppgaven viser at både netto energiforbruk og peak load shaving er omvendt proporsjonal med areal av bygningstypen med laveste netto energiforbruk. Det betyr at nabolags netto energiforbruk reduseres med økning i arealet av bygningstypen med laveste netto energiforbruk, og nabolagsmulighet for peak load shaving øker med økning i arealet av bygningstypen med høyeste netto energiforbruk. Formålet med oppgaven var å minimere netto energiforbruk og maksimere peak load shaving samtidig. Det er observert at man må gå på kompromiss for å gjøre dette. Resultatet viser at et nabolag med 10% boliger, 40% kontorer, og 50% butikklokaler er det mest optimale. Metodikken foreslått i denne oppgaven kan bli brukt for å optimalisere områdefordelingen av forskjellige bygningstyper i nabolagsplaner for å redusere netto energiforbruk og øke peak load shaving.

ACKNOWLEDGEMENT

Writing this thesis has been a roller coaster ride and it wouldn't have been as enjoyable without the support of my friends and family. I would like to extend my heartfelt gratitude to Hans Arne, who has been my right hand ever since I moved to Norway. My family back in India has supported me my whole life. My parents, Vandana and BK Srivastava have been by my side through highs and lows, and I am ever so grateful for their endless love and support.

I also want to thank my supervisor, Luca Finocchiaro who has supported and motivated me since the beginning of my master degree. Both of us started off as novices in the field of energy sharing and flexibility. But through hours of research and learning from other experts, we both learned a lot in last few months.

Without the expert advices of Alessandro Nocente from SINTEF, it would have been impossible to create an accurate energy model and I am grateful for his time and effort.

Last but not the least, I would like to thank NTNU and its dedicated staff who have been of great help since my first day in Trondheim by not only facilitating my education but also by helping me adapt to the cultural shock that moving to Norway was.

Thank you all very much!

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LIST OF ACRONYMS

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers
BRA - Bruksareal
CFD - Computational Fluid Dynamics
DHW - Domestic Hot Water
DOE - United States Department of Energy
EPB - Energy Performance Based Demand
ESS - Energy Storage Systems
GHG - Greenhouse Gases
HVAC - Heating, Ventilation, Air-condition and Cooling
ICT - Information and Communications Technology
IPCC - Intergovernmental Panel on Climate Change
IREC - Catalonia Energy Research Institute
KPI – Key Performance Indicator
LCA - Life Cycle Analysis
NEC - Net Energy Consumption
PLS - Peak Load Shaving
PSF - Power System Flexibility
PV – Photovoltaics (Solar Panels)
UNEP - United Nations Environment Programme
ZEB - Zero Energy Buildings

1. INTRODUCTION

The IPCC in their Special Report for policy makers in 2018 stated that in order to limit global warming to 1.5°C, "rapid, far reaching and unprecedented changes" need to be implemented (IPCC, 2018). Norway has strengthened its carbon emission targets to 50-55% of 1990 levels by 2030 (Ministry of Climate and Environment, 2020). Thus, resulting in a greater need to focus on the previously unstudied sources of high GHG emissions. Around 40% of total energy consumption and 36% of total GHG emissions in EU are related to buildings, thus making them the single largest energy consumer in Europe (European Commission, 2019). The UNEP International Resource Panel suggests that natural resource extraction and processing leads to around 50% of the total GHG emissions and above 90% of biodiversity loss and water stress. Material efficiency strategies in residential buildings has potential to reduce the material cycle GHG emissions by 80-100% and material and operation GHG emissions by up to 40% in G7 countries by 2050 (UN Environment Programme, 2020). While only 52% of the population lived in the urban areas in 2011, they accounted for 71-76% of energy related GHG emissions in 2006 (IPCC, 2014). Therefore, urban areas have a great potential to reduce total GHG emissions and mitigate climate crisis.

The urban planning of neighbourhoods has a significant effect on its balance of energy consumption (Steemers, 2003). The geometry and placing of buildings in a neighbourhood affects not only its own building energy us but that of other neighbourhoods in proximity as well (Allen-Dumas et al., 2020). Urban areas have a great potential to reduce the GHG emissions resulting from building energy use, transportation, etc. through reduced peak capacity, increased flexibility, etc (Delmastro and Gargiulo, 2020; Steemers, 2003). Peak load supply is conventionally handled by addition og grid capacity like increasing the voltage capacity of grid, increasing production capacity of power plants, etc. Since this peak only lasts for a few hours in a day, it is neither economically feasible nor sustainable (Mishra and Palanisamy, 2018). For last three decades, there have been various initiatives to develop neighbourhoods sustainably through appropriate planning (Sharifi, 2016). Hachem-Vermette et. al reviewed 21 neighbourhood scale case studies and found that the neighbourhood scale is not well defined and ranged from 0.02 km2 to 4.42 km2 within 20 of the case studies based in developed countries. The program distribution varied from total residential neighbourhoods to mixed neighbourhoods with residential, office and retail buildings (Lotteau et al., 2015). The complex dynamics of neighbourhood scale makes it difficult to define a functional unit (FU). FU varies a lot between studies making them incomparable. FU to study neighbourhood scale can vary between m2 of neighbourhood, m2 of heated floor area (BRA), and m2 of total floor area (Davila, 2013; Riera Pérez and Rey, 2013; Stephan, Crawford and De Myttenaere, 2013).

1.1. Thesis Objectives

The study aims to optimize the distribution density of different building programs (residential, office and retail) in a neighbourhood scale in order to reduce the net energy demand and peak load of the shared grid. In a series of papers, Hachem-Vermette et. al found the optimum distribution of programs in a neighbourhood while focusing on a hypothetical prototype based in Calgary, Canada. In one of them, Hachem-Vermette and

Singh considered five variables viz. net energy consumption, PV electricity generation, waste-to-energy potential, and ratio of performance and net GHG emissions. Thus, making it difficult to comprehend the impact of individual variables on the program distribution (Hachem-Vermette and Singh, 2019). This study tries to resolve this research gap by not only simultaneously but also individually optimizing two variables viz. net energy consumption (NEC) and peak load shaving (PLS). The study refers to a proposed plus energy neighbourhood named OEN in Ammerud, Oslo. A section of the neighbourhood scale building is modelled and simulated for annual hourly energy consumption for different building programs, namely residential, office and retail. Different scenarios are created for different percentage of area of different programs and then analysed for impact on NEC and PLS in order to minimize NEC and maximize PLS.

1.2. Thesis Outline

The thesis is divided into 6 sections. Section 1 introduces the urgency of reduction in GHG emissions, the research gap on applicable energy sharing and flexibility in neighbourhood scale and the objectives of the thesis. Section 2 provides an overview of the electricity grids in neighbourhood scale, concept of energy sharing and flexibility, the referred case study and state-of-art of the technologies and methods applied in the thesis. Section 3 explains the methods applied by describing the referred case study and simulated model, climate, variables, and scenarios considered, and details of the model for each building program. Section 4 presents the results received from the energy simulations and shows the typical energy profiles, energy balance, etc. Section 5 consists of the analysis of the hourly energy profile of all building programs for all scenarios. In the end, Section 6 concludes the findings of the thesis and the optimum building program distribution in the proposed neighbourhood for minimum NEC and maximum PLS, both individually and combined. The section also proposes the potential of further research on the given topic.

2. BACKGROUND

This section provides a background to the technologies and methodology used in the study. The definition of the neighbourhood and grid connection considered in the study is described first. Then the concept of energy flexibility, the case study referred, and the state-of-art of the technologies and methodology used in the study is described. In the end, the previous studies done on similar subject, the research gap in the research, and how the study tries to fill this gap are discussed.

2.1. Neighbourhood

According to Schuck a neighbourhood can be defined spatially as a specific geographic area where face-to-face social interactions occur, or functionally as a set of social networks with residents sharing common values (Schuck and Rosenbaum, 2000). A neighbourhood is a complex spatial distribution of buildings which can be of the same typology or different programs as found in mixed-use neighbourhoods. Commonly, mixed-use neighbourhoods consist of residential, office, retail and restaurant type buildings, and parking lots (Gu et al., 2019). Like Tenailleau et al., a spatial definition of neighbourhood where residents spend a considerable amount of their lives and interact with each other is considered in this study (Tenailleau et al., 2015). The other definition considered here is the energy sharing network as a semi-island mode micro-grid which enables easy sharing of electricity within the boundaries of the considered neighbourhood. The definition of micro-grid is considered as given by U.S. Energy Department which states that a micro-grid is a network of interconnected energy loads and distributed energy resources within a defined boundary and acts as an individual unit which can either function along with external grid or as an island (Ton and Smith, 2012). According to Parag and Ainspan, micro-grids have great environmental, economic, and social benefits. Just in Israel, the economic benefits of micro-grid (i.e., environmental damage costs, employment multiplier effects, transmition and distribution investment costs, and greater access to reliable and resilient electricity supply) were estimated around $13 million (Parag and Ainspan, 2019).

2.2. Energy Sharing & Flexibility

The demand for Zero Energy Buildings (ZEB) is increasing by the day and thus are the number of demonstration projects and research interest in the field (Marszal et al., 2011). However, the net energy demand of the high efficiency ZEB buildings is covered by renewable energy which is usually oversized and combined with energy storage systems (ESS) to cover for the fluctuations in the renewable energy production (RE) (Cui and Xiao, 2020; Deng, Wang and Dai, 2014). The increase in installed power capacity at individual building scale has direct impacts on the cost of the overall system (Brown and Sappington, 2019). Even though the implementation of ESS can significantly reduce the energy cost, its high initial investment cost act as a barrier for the small-scale users (Bayram et al., 2015; Schoenung, 2011). This can be easily reduced by introducing energy sharing concept at neighbourhood or larger scales.

The International Energy Agency defines Power System Flexibility (PSF) as a power system's extent to which it can either modify the energy production or consumption to respond to the expected or unexpected energy fluctuations (Chandler, 2011). The main services that power supply operators must consider for grid stability are load balancing and flexibility and voltage response (Horn, 2017). The renewable energy sources can regulate the voltage response and batteries can regulate flexibility, and together they can already perform voltage and frequency response better than convention systems with a higher cost efficiency (Kaspar Knorr, 2014). The European Portal for Energy Efficiency in Buildings states that the renewable energy sources are associated with fluctuating production which increases the need for balancing the electricity grid and usage of energy storage results in higher investment costs. Thus, interconnections of energy network and demand response play a crucial role in this context (Build Up, 2020). The lack of interoperable intelligent building management systems leads to a gap between hourly energy demand and supply in the grid (Build Up, 2019). The Energy Performance of Buildings Directive has revised their requirement to develop a rating scheme for Smart Readiness Indicator of buildings which provides information on the building's interaction with their occupants and electricity grid to improve their flexibility using ICT technologies (Build Up, 2018).

Demand Response schemes provide economic profit to both end consumers and energy providers (Korkas et al., 2016). Over last few decades, several types of Demand Response have been implemented. The most common types of Demand Response techniques implemented by energy providers are Price-based programs and Incentive-based Programs. The Fixed Rate Pricing, Time of Use tariffs and Critical Peak Pricing are examples of Price-based Programs (De Rosa, Carragher and Finn, 2018; Fitzpatrick et al., 2020). The Fixed Rate Pricing schemes are popular among companies and residential units as the tariff rates do not change often but it cannot support the grid in emergency situations (Kahn, 1988). The Time of Use tariffs are based on different pricing during peak and off-peak periods (O'Connell et al., 2014). The Critical Peak Pricing is based on sudden rise in prices during times of high grid stress (Schuitema, Ryan and Aravena, 2017). The Incentive-based Programs provide direct incentives to the end user based on load reduction during requested times (D'Ettorre et al., 2019). According Pinsen and Madson, Demand Response schemes lead to effective planning and operation of energy grids and ease the integration of renewable energy sources (O'Connell et al., 2014). However, currently most of the Demand Response schemes are used for emergency assistance and response is not real-time based (Monfared et al., 2019; Wu et al., 2020). Multiple research show that pricing plans should follow some principles that ensure consumer satisfaction. The include transparency, easy implementation, economic efficiency, justice, revenue stability and payment stability (Dupont et al., 2014; Faruqui, 2012).

There are multiple binding EU-wide targets that aim on reaching at least 32% renewable energy integration by 2030 (European Parliament & Council of the European Union, 2018). EU-member states like Spain and Portugal have recently deregulated peer-to-peer energy sharing of renewable energy generation. According to Klein et al., Peer-to-peer energy sharing is a fast-emerging concept and most of the research focus on its techno-economic aspects, but the end-user engagement is not well studied (Klein, Matos and Allegretti, 2020). The energy sharing between peers in a connected grid enables prosumers to distribute their surplus renewable energy generation among other end-users instead of selling it to energy providers (Giotitsas, Pazaitis and Kostakis, 2015).

The energy flexibility and sharing potential can be found either by building simulation tools, i.e., deductively, or by use of experimental data, i.e., inductively by statistical time series analysis. Like prediction of the energy consumption of a building, predicting the energy flexibility requires detailed dynamic modelling of a building's energy systems, including technical constraints, occupancy behaviour, and boundary conditions (Junker et al., 2018).

2.3. Case Study

Syn.ikia project is an EU Horizon 2020 commissioned project which aims to develop sustainable plus energy neighbourhoods in different climates, context and markets. The project focuses on multiple sustainability aspects viz. NEC reduction, PLS, energy flexibility, energy sharing and neighbourhood scale (Syn.ikia, 2020).

The four case studies are based in Norway, The Netherlands, Austria and Spain. The case study based in Norway is the OEN neighbourhood located in Ammerud, Oslo. The project is a ring-shaped residential building consisting 146 housing units and a gross area of 12 750 m2. The building features 4 floors, a basement, pitched roof installed with PV panels, common courtyard area and integrated shading devices. The OEN neighbourhood has been designed based on extensive research on energy and GHG emission optimization. Thus, this project is used as the base case for modelling of the neighbourhood considered in this study.

2.4. State of Art

EnergyPlus™ is a "whole building energy simulation program" that can be used by engineers, architects, and researchers to simulate building energy consumption and water usage. The program can simulate building heating, cooling, ventilation, lighting and plug and process loads. The program can run integrated and simultaneous simulations for different zone settings including unconditioned and under-conditioned spaces. The program can also run energy simulations based on user-defined time steps, up to sub-hourly time steps (Building Technologies Office (DOE), N.A.). Several other building energy simulation tools like Simien developed by Program Byggerne do not provide this feature making them unsuitable for this study (ProgramByggerne, 2019). EnergyPlus is a console-based program that imports inputs and exports outputs as simplified text files. However, several comprehensive graphical user interfaces that use EnergyPlus in the background are available in the market. One such program is DesignBuilder. DesignBuilder Software Ltd is a EnergyPlus based user/interface technology that provides environmental performance of new and existing buildings. The program can either import building integrated models or can be used to create simplified energy models. The integrated performance analysis includes energy and comfort, HVAC, daylighting, CFD, BREEAM/LEED credits, etc. The program can also be combined with various plug-in to assess other parameters like LCA (DesignBuilder Software Ltd., N.A.-a).

SINTEF work-package 3 in collaboration with the EU wide Syn.ikia project has developed the Simplified Primary Energy Calculator. The authors of the tool are Jaume Salom, Meril Tamm of IREC (IREC, N.A.). The tool serves the purpose of integrated energy design by indicative fast evaluation primary energy balance and analysing of effects of several factors viz. matching factors, PV production, and primary energy conversion factors. The tool requires monthly inputs values of on-site PV generation, matching factor, heating/DHW/cooling demands, system performance factor of technical systems, etc. The tool also requires inputs for constants like use of heat pump, technical system losses, matching factor, and primary energy conversion factors for grid, PV and environmental heat. The results of the calculation can also be represented by simplified visual presentation and brief comparison between primary energy balance and the benchmarks of interest. The tool is limited to fully electric systems and can be used for two scenarios viz. Syn.ikia base case which follows ISO 52000, and Mediterranean demo case which follows requirements stated in the Spanish technical code CTE (SINTEF, N.A.). The tool defines the system boundaries used for calculation as defined by ISO 52000-2 (ISO/TR 52000-2:2017, 2017). The Figure 1 shows system boundaries of the Syn.ikia base case and the connections of electricity transfer connection system within the case. The generated electricity on-site is exported to EPBD and nEPBD uses, the remaining electricity is exported to the grid. The remainder energy is delivered by the grid which is used for EPBD uses. The overall energy exchange between grid and on-site is separated by dark brown doted line in Figure 1. The inside and outside assessment boundaries are divided by light brown doted line named "AB". The graphs representing these values are shown in Section 4. Results.

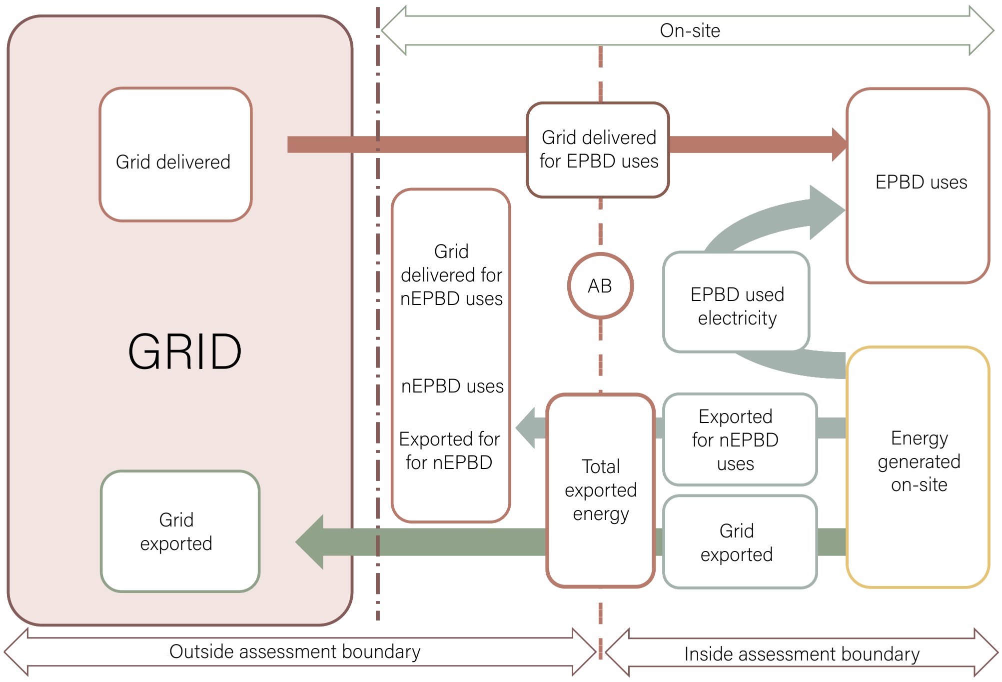


Figure 1. System Boundaries (SINTEF, N.A.).

2.5. Energy Simulations

Construction industry is highly energy intensive and majority of it is a result of operational energy usage. Due to development of computing technologies in recent years, many researchers have addressed the need for reliable modelling and simulation of building performance indicators (Ascione et al., 2020). It is well-known that building energy consumption is mainly due to heating, HVAC, lighting and DHW systems (U.S. Energy Information Administration, 2012). Advanced models and tools are required to create accurate energy models that can reliably predict building energy performance and environmental impact (Ascione et al., 2020). The intensive nature of energy consumption in building sectors makes detailed building energy modelling necessary for optimization (Hossain, 2019). The reliable tools include Energy Plus which is used in this study. In order to create accurate building energy model various inputs are required viz. geometry, building envelope, energy systems, building schedules, climate data, etc. (Farzaneh, Monfet and Forgues, 2019). Also, inter-building shading effect is a very important input generate accurate energy models as it can considerably affect the solar gains (Shaviv and Yezioro, 1997). It is essential that building designers consider the impact of external environment such as urban canyons and urban heat island effect to accurately estimate the space conditioning needs and daylighting (Li and Wong, 2007).

2.6. Literature Review

Sun et al. have proposed an energy sharing platform using a hybrid energy storage system and thermal energy storage systems to integrate power, thermal and gas systems. The authors were able to balance the fluctuations of the renewable energy by sharing the ESS among hospitality buildings (Sun et al., 2020).
Yan et al. developed a new multi-timescale cold storage system to enhance the energy flexibility in buildings. The authors proposed system provides seasonal cold storage, night-time chilled water storage, and urgent demand response. The system can reduce power imbalance in real-time, short-term and long-term time-scales. A case study conducted in Beijing showed improvement in seasonal building load factors (from 19.5% to 41.2%), and daily (from 55.7% to 72.2%). The power consumption was also reduced by 41.2% through demand response strategy (Yan et al., 2020).

Camporeale and Mercader-Moyano assessed energy flexibility of building clusters at neighbourhood-scale through a bottom-up methodology that used Geographic Information System (GIS). The KPIs of the methodology are energy demand reduction and PV production. The authors were successful at estimating the hourly load profile for heating and cooling and thermal comfort indexes for a neighbourhood in Seville, Spain. According to the authors, the methodology is adaptable to other climate zones as well (Camporeale and Mercader-Moyano, 2020).

Zhou and Zheng propose a supervised machine-learning method to predict the building load profile. The method uses multiple linear regression, support vector regression and back-propagation neural network. The authors studied multiple building energy systems viz. renewable energy, electric and thermal demands and building service systems. The study concluded that implementation of the developed hybrid controller with short-term prediction can reduce the peak power demand by 61% (Zhou and Zheng, 2020).

Several studies have also been conducted on optimization of energy pricing schemes to improve building energy flexibility. Wang et al. propose a Time of Use pricing for building energy management while aiming to optimize occupant comfort and economic aspect of power systems. The simulation results show the model can improve the economy of power system without affecting the occupant comfort (Wang et al., 2018). Tsui and Chan, and Elma et. al developed a energy management optimization method for Real-time pricing to reduce the time of peak load and generation cost of energy supplier. Elma et al. concluded that the proposed home energy management system could significantly increase the cost savings for residential prosumers and that the system can be implanted in real-world (Elma et al., 2017; Tsui and Chan, 2012).

Hachem-Vermette et al., in several studies, optimized the program distribution, efficiency and other sustainability indicators for a hypothetical neighbourhood model consisting of residential, office and retail buildings based in Calgary, Canada . In one of the studies, Hachem-Vermette and Singh attempted to optimize the program distribution for these programs while considering several variables. The building program related variables were ratios of detached houses, townhouses, apartment buildings with varying floor levels, office, retail, supermarket and school buildings. The response variables were net energy consumption, PV electricity generation, potential waste to energy generation, ratio of performance and net GHG emissions. The modelled neighbourhood was 100 hectares with 65% built up area. The energy simulations were conducted using Energy Plus along with SketchUp and TRNSYS. The PV electricity generation was calculated using Equivalent One-Diode Model. Solar-thermal collector energy generation was also calculated using TRNSYS. Waste-to-Energy potential and GHG emissions were calculated using common practices and findings of other studies. The performance parameters were optimized using elitist non-dominated sorting genetic algorithm on Matlab. A decision-making score was used to find the optimum scenario. After optimizing the hourly energy load profile, it was found that the optimum scenario was 47,5% of commercial buildings (offices and retail) and 48% residential buildings (Hachem-Vermette and Singh, 2019).

Even though the research is very well detailed and conducted, the scenarios are extremely complex due to various variables and optimization of several variables at different design stages. This results in results that are difficult to study and apply in other upcoming neighbourhood designs. Within the scope of Syn.ikia project, applicability and replicability of the neighbourhood models are significantly important. Thus, this study aims to simplify the optimization to just two parameters viz. net energy consumption (NEC) and peak load shaving (PLS) while optimizing them individually and combined. It is expected that the results of this study will be directly applicable to other cold-climatic neighbourhood scale projects.

3. METHODOLOGY

This section provides an overview of the methodology applied to achieve the goals of the study. The first step is to model a typical building, then simulate it hourly annual energy consumption for different program and in the end analyse the results. Hypothesis

3.1. Case Study

OEN project is used as the basis for modelling a typical building since multiple studies have already been conducted by Code Arkitektur AS and Erichsen & Horgen AVD to optimize the sustainability performance indicators (CODE, 2019; Erichsen & Horgen AS, N.A.). The project is planned on a site in Ammerud, Oslo where an existing Norges Hindu Kultur Senter building will be demolished. The project is owned by OBOS BBL (OBOS, N.A.). The project description is given in Section 2.3. Case Study. The project plan is shown in Figure 2. For the modelling purpose, a section in the south part of the building is chosen. The interior walls of the building are not modelled for simplification of the model and to enhance the flexibility of the usage for different program purposes. The service core is kept intact.

Figure 2. OEN project

3.2. Climate

The hypothetical neighbourhood model is based in Ammerud, Oslo. At the latitude of 59,56° North and longitude of 10,87° East, the location falls under the Köppen climate classification of Dfb which is warm summer continental climate and ASHRAE climate zone of 6A. The region is at an elevation of 17,0 m above sea level (ASL) and receives an average amount of annual precipitation of 763,0 mm. The dry bulb temperature goes beyond the comfortable of 20-24°C during June, July and August as shown in Figure 3 showing that the region is heating demand oriented. The relative humidity is high during the whole year as shown in Figure 4, but following the local regulations and trends, dehumidification is not considered in the study. The global horizontal radiation is high during Spring, Summer and Autumn months as shown in Figure 5, showing that PV production potential is high. The wind speed is high in north and south direction as shown in Figure 6, which shows that the region has potential for wind energy as well, but due to unpopularity of windmills in cities, it is not considered a practical solution and thus not studied. 59,56° North and longitude of 10,87° East, the location falls under the Köppen climate classification of Dfb which is warm summer continental climate and ASHRAE climate zone of 6A. The region is at an elevation of 17,0 m above sea level (ASL) and receives an average amount of annual precipitation of 763,0 mm. The dry bulb temperature goes beyond the comfortable of 20-24°C during June, July and August as shown in Figure 3 showing that the region is heating demand oriented. The relative humidity is high during the whole year as shown in Figure 4, but following the local regulations and trends, dehumidification is not considered in the study. The global horizontal radiation is high during Spring, Summer and Autumn months as shown in Figure 5, showing that PV production potential is high. The wind speed is high in north and south direction as shown in Figure 6, which shows that the region has potential for wind energy as well, but due to unpopularity of windmills in cities, it is not considered a practical solution and thus not studied.

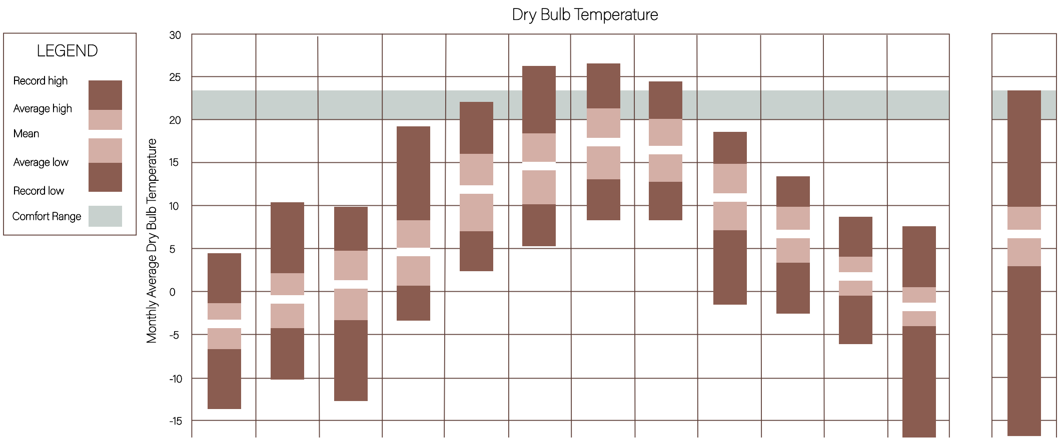


Figure 3. Monthly average dry bulb temperature

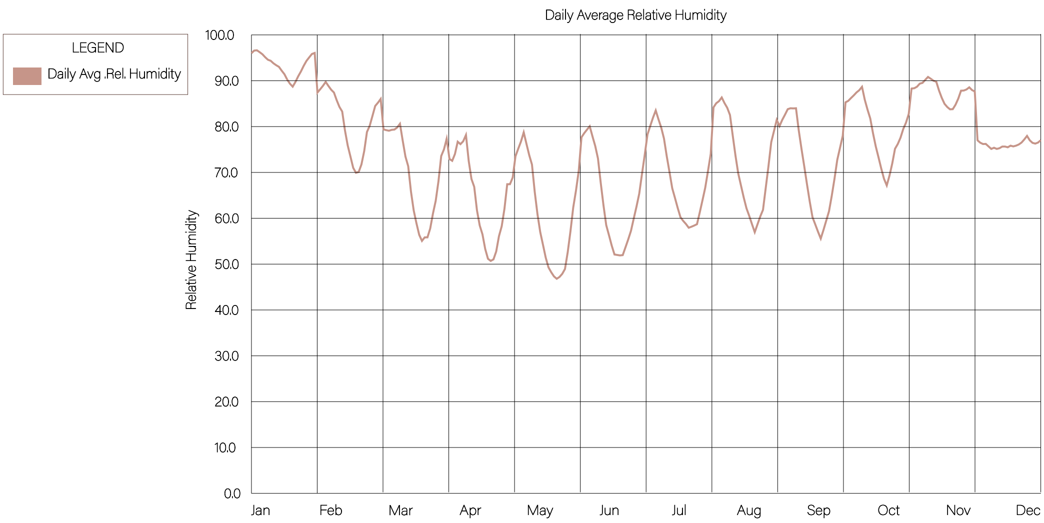


Figure 4. Daily average relative humidity

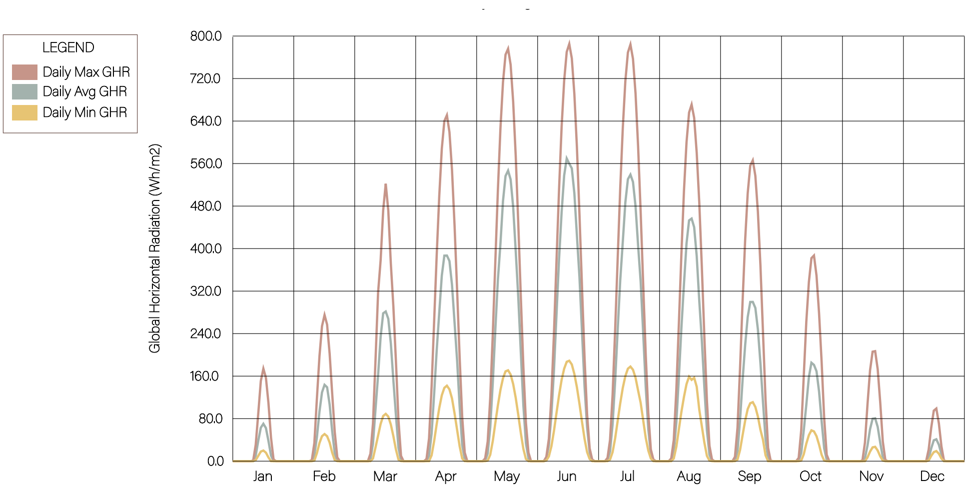


Figure 5. Monthly average global horizontal radiation

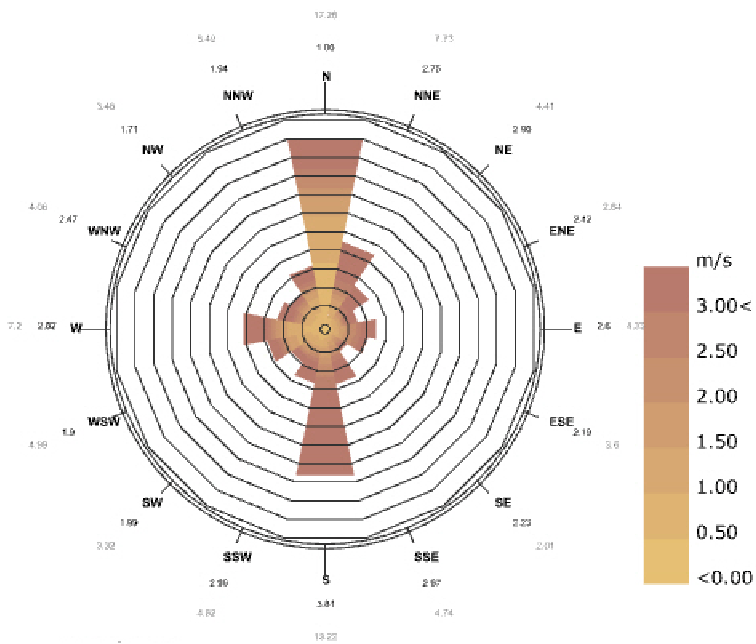


Figure 6. Annual wind rose diagram

3.3. Model Geometry

The model is design on graphical user interface of DesignBuilder. Since the building is large scale and it is expected that sections in was found through orientation sensitivity analysis that all orientations have similar energy consumption, south-facing section of the circular building was chosen for the modelling purpose. The section chosen consists of 3 apartments. The south and north facing apartments are 2-bedroom apartments and the north facing apartment is a 1-bedroom apartment as shown in Figure 7. All apartments share a one service and one circulation core. The OEN building conceptual 3D model is shown in Figure 8. The south facing section of the building was then simplified to a model with straight lines for energy modelling purpose. The concept development is shown in Figure 9. The floor plan with dimensions is shown in Figure 10. The total area and BRA of energy model are 3650,54 m2 and 3135,75 m2.

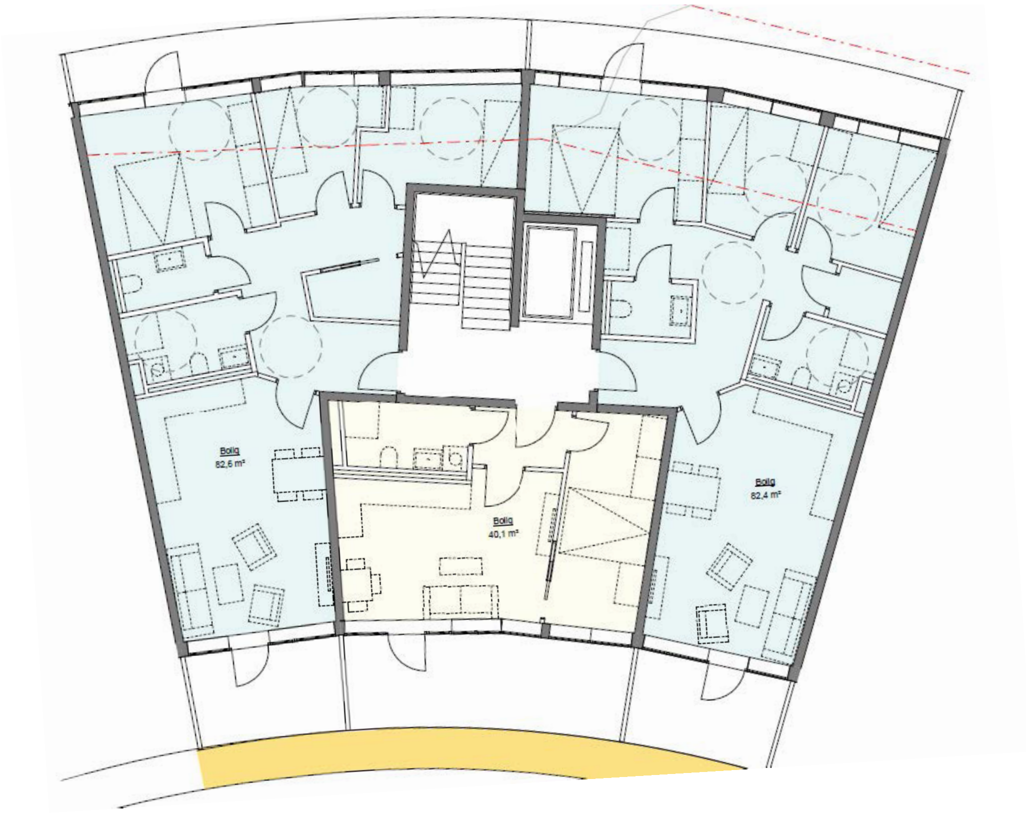


Figure 7. OEN floor plan

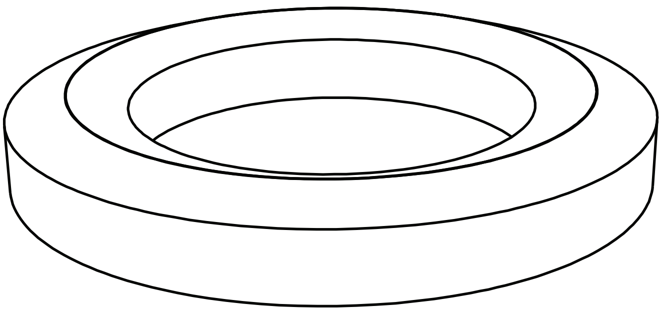


Figure 8. OEN 3D

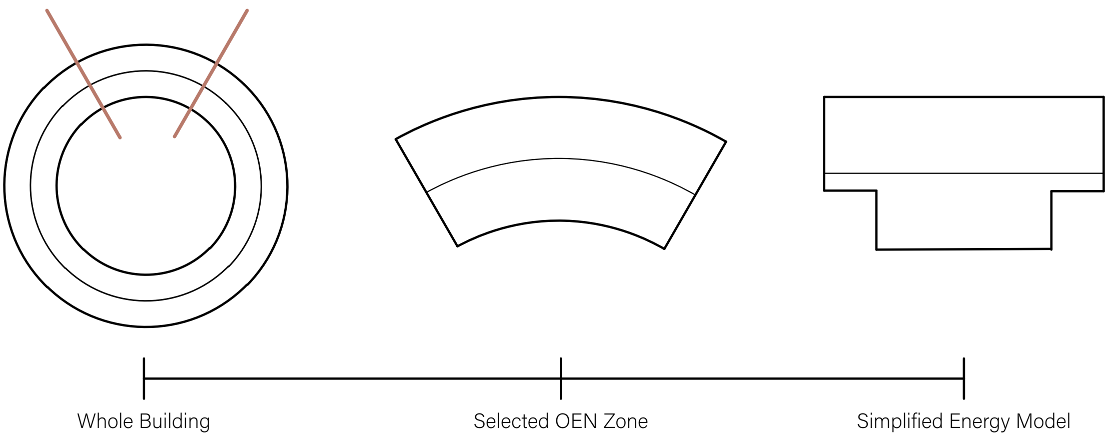


Figure 9. Concept development illustration

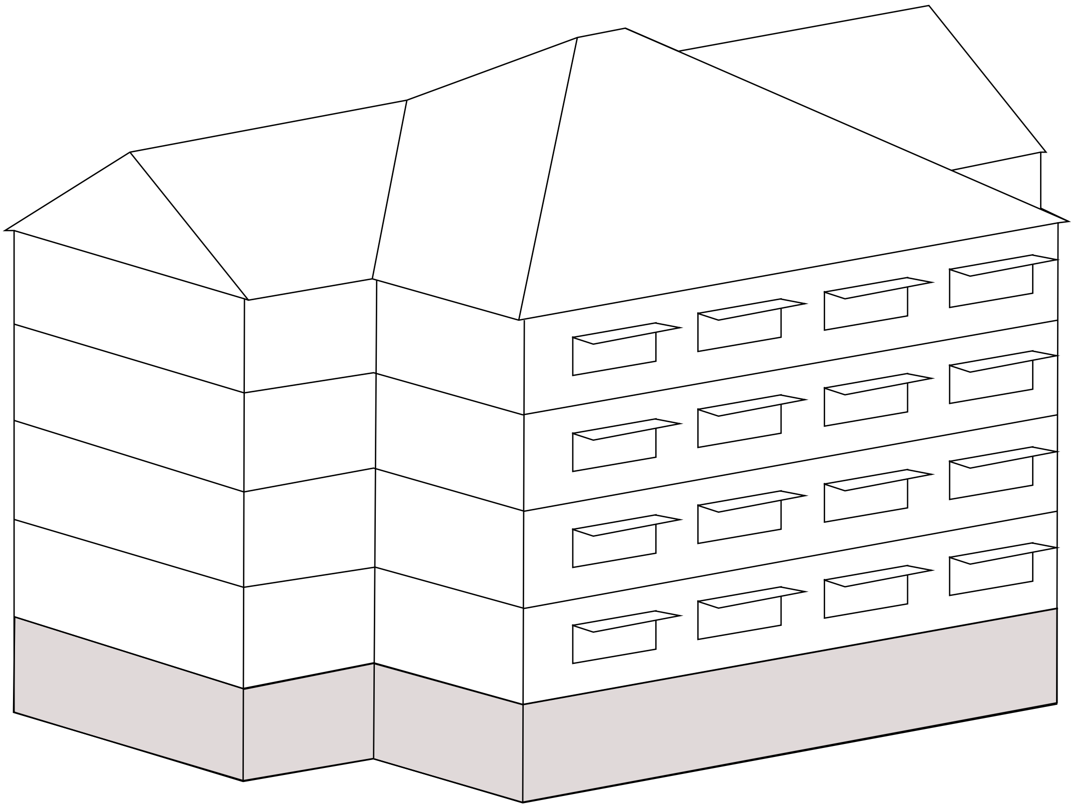


Figure 11. Simplified 3D energy model

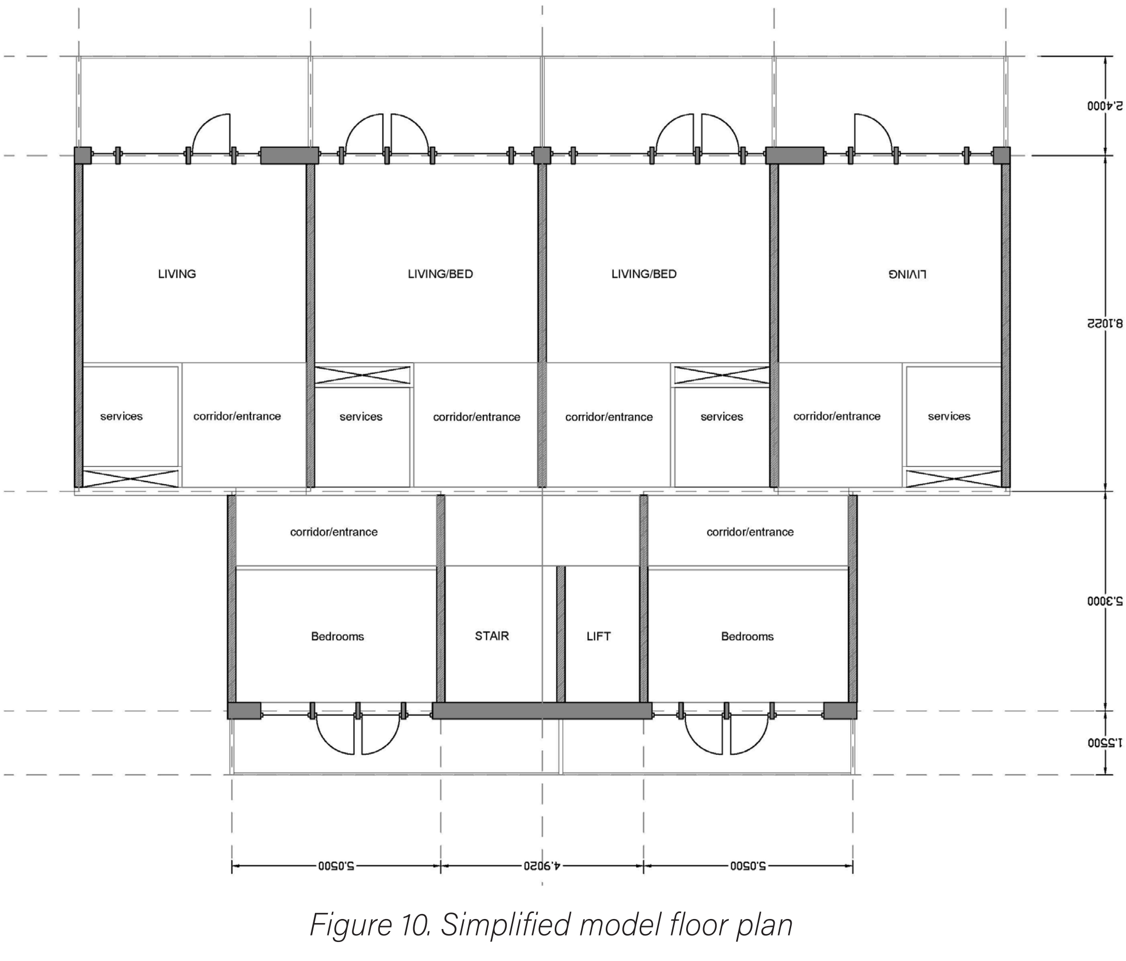


Figure 10. Simplified model floor plan

3.4. Energy Model

For energy modelling, first a base model was created as explained in Section 3.3 Model Geometry. After assigning the constants that do not vary according to the programs viz. model geometry, PVs, U-values, HVAC system and schedules, etc., the base model was used to create three different models with their respective variables viz. lighting, occupancy, HVAC schedules, internal heat gains, etc. The constants and variables assigned to the energy model have been described below. It is to be noted that the energy simulation was run with 6 timesteps per hour (10 minutes) which is the minimum recommended (DesignBuilder Software Ltd., N.A.-b). The EnergyPlus development team has used time steps of 10 and 6 minutes in previous studies (Henninger, 2013; Witte, 2004). A time-step sensitivity study concluded that time-step of 1 hr can result in energy analysis (Dos Santos and Mendes, 2006). Cesar Paulo found that time-steps larger than 10 minutes can lead serious errors in peak load energy calculations and hourly energy consumption results (Tabares-Velasco, 2013). The HVAC loops created for all typologies are shown in Appendix A.

3.4.1. Base Model Constants

A. U-values

Building Component	U-value (W/m2-K)
External Walls	0,102
Internal Walls	Adiabatic
Below Grade Walls	0,182
Pitched Roof	0,050
Core Walls	0,102
Ground Floor	0,133
Internal Floors	0,102
Windows	0,780

Table 1. Base model U-values

B. Infiltration

Infiltration Rate	0,200 ach	24/7 schedule

Table 2. Base model infiltration rate and schedule

C. PVs

30° tilted PV	15% constant efficiency

Table 3. Base model PVs specification

D. HVAC

Heating	
Setpoint (ideal average air temperature)	22°C
Set back (during unoccupied hours)	12°C
Preheating	1 hr before occupancy
System type	Radiant/convective
Maximum air supply temperature	35°C
Source	District heating

Distribution system	Water based convector
CoP (National Building Code of Finland, 2012)	4,00
Zone sizing (heat recovery not included)	Automatically met by zone equipment
Cooling	
Cooling system	Office & Retail
Setpoint (ideal average air temperature)	24°C
Set back (during unoccupied hours)	28°C
Source	GSHP with Chiller
CoP	4,50
Ventilation	
Type	Completely Mechanical
Mode	Mixed
Fresh Air	Minimum per person and area
Heat Recovery	85% efficiency
Humidity Control	
Humidifier/Dehumidifier	Off
Domestic Hot Water	
Type	District Heating with storage
Source	Waste heat generation
CoP (Stene, 2007)	0,830
Delivery temperature	65°C

Table 4. Base model HVAC specification

3.4.2. Variable Program Model Constants

A. Residential (Operation Schedules & Other Constants)

Occupancy density	0,017 people/m2 (10 pers./floor)
Clothing summer	0,50 clo
Clothing winter	1,00 clo
Comfort radiant temperature	Zone average
Fresh air	10 l/s-person
Lighting fixture	LED
Lighting power density (The Lighting Control Association, 2017)	1,95 W/m2-100 lux
Target illuminance	100 lux
Equipment Power Density	7,20 W/m2
Metabolic rate factor	1,00 (men)

Table 5. Residential model specifications

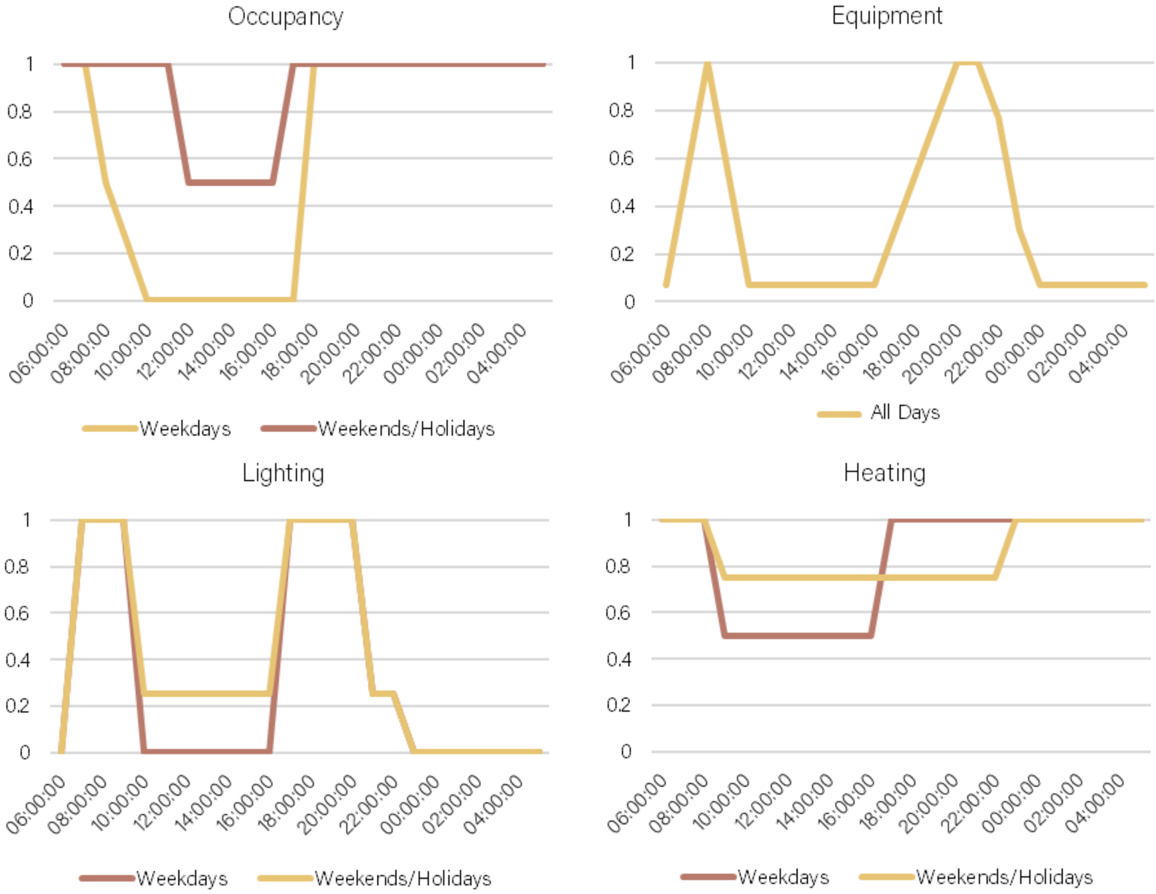


Figure 12. Residential model operation schedules

B. Office (Operation Schedules & Other Constants)

Occupancy density	0,111 people/m2 (65 pers./floor)
Clothing summer	0,50 clo
Clothing winter	1,00 clo
Comfort radiant temperature	Zone average
Fresh air	0,20 l/s-person
Lighting fixture	LED
Lighting power density	2,50 W/m2-100 lux
Target illuminance	400 lux
Computers Power Density (Pless, 2013)	3,33 W/m2
Other Equipment Power Density (Sheppy, 2014)	6,88 W/m2
Metabolic rate factor	0,90

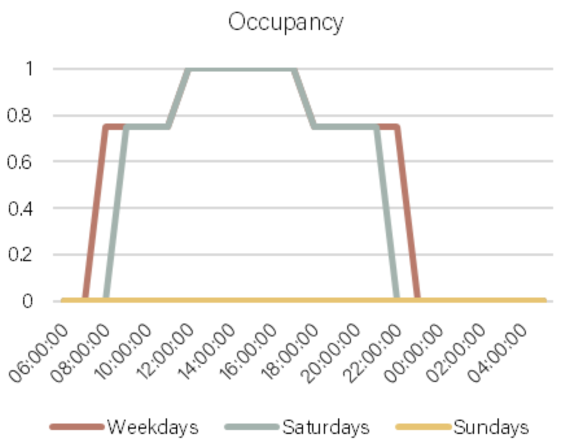
Table 6. Office model specifications

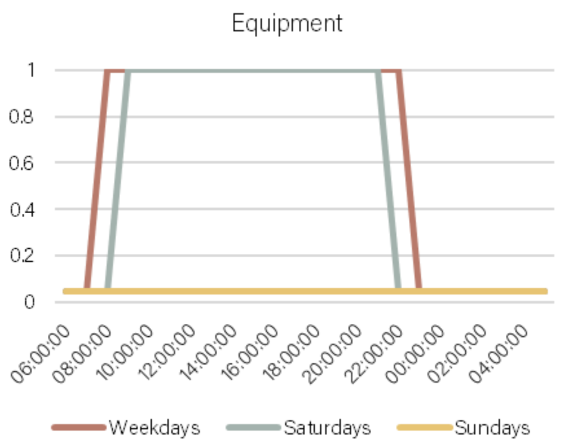
Figure 13. Office model operation schedules

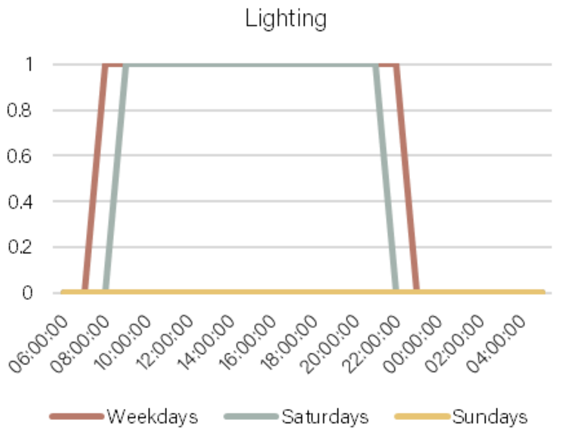
C. Retail (Operation Schedules & Other Constants)

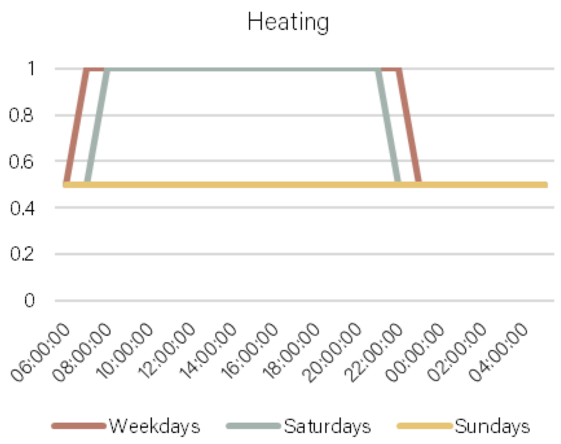
Occupancy density	0,1169 people/m2 (69 pers./floor)
Clothing summer	0,50 clo
Clothing winter	1,00 clo
Comfort radiant temperature	Zone average
Fresh air	0,08 l/s-person
Lighting fixture	LED
Lighting power density	5,00 W/m2-100 lux
Target illuminance	600 lux
Computers Power Density	0,05 W/m2
Other Equipment Power Density	5,20 W/m2
Metabolic rate factor	0,90

Table 7. Retail model specifications









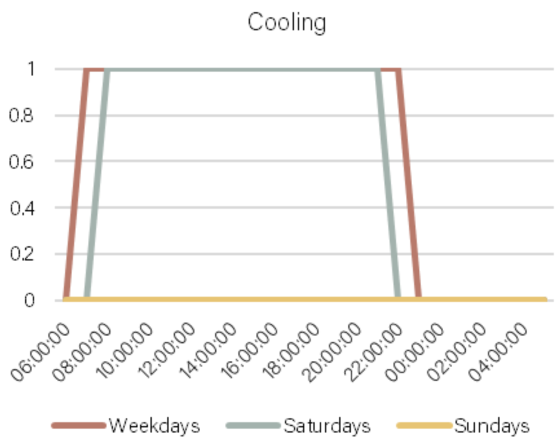


Figure 14. Retail model operation schedule

3.5. Orientation Sensitivity Analysis

The orientation of the energy model was considered to be south-north direction (0° orientation). Thus, it was necessary to analyse the sensitivity of the model for change in orientation to establish weather orientation affected the results or not. The residential model was chosen for this analysis and a 45° incremental rotation was studied. The output of the sensitivity analysis is shown in Figure 15. The classic statistical deviation analysis was conducted to calculate deviation in energy consumption of residential model with 45° change in orientation. The equation used for this calculation is shown in Equation 1. The results show that the maximum deviation of -0,22 occurs for 360° which is well within limits to be ignored. Also, this deviation is negative showing that 360° has the highest NEC.

$$\sigma_o = \frac{\dfrac{NEC_{o+1} - NEC_o}{NEC_o}}{\dfrac{O_{o+1} - O_o}{O_o}}$$

$where, \sigma = Standard\ deviation$

$and, \quad o = f[45, 90, 135, 180, 225, 270, 315, 360]$

$also, \quad \sigma_{360^\circ} = \sigma_{0^\circ}$

$Note: \quad \sigma_{0^\circ} = \infty, \text{but since } 360^\circ = 0^\circ, \sigma_{0^\circ} \text{ must be calculated for } \sigma_{360^\circ}.$

Equation 1. Standard deviation in NEC with change in orientation

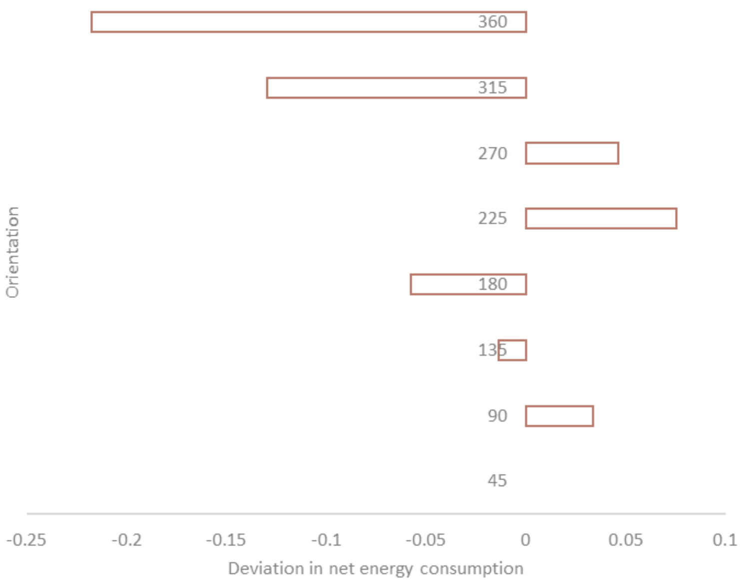


Figure 15. Sensitivity analysis for change in orientation

3.6. Scenarios & Performance Indicators

Scenarios considered and analysed in the study are shown in Table 8. A minimum cap of 10% was assumed for each building program to prevent the neighbourhood from becoming a single typology zone. The method used for scenario development is shown in Equation 2.

$$F: [0{,}1 \rightarrow 0{,}8]$$

$$i: [1 \rightarrow 36] \begin{bmatrix} F_{Res_i} & F_{Off_i} & F_{Ret_i} \\ \vdots & \ddots & \vdots \\ F_{F_{Res_i}} & F_{Off_i} & F_{Ret_i} \end{bmatrix}$$

$$where, i = scenario$$

$$F = fraction\ of\ area\ of\ respective\ program\ and\ total\ built\text{-}up\ neighbourhood\ area$$

Equation 2. Scenario development matrix

3.7. Individual & Combined Optimization

Different optimization processes were used for optimization of NEC, PLS and combined NEC and PLS. The aim of the optimization was to find the minimum NEC, maximum PLS, and best compromize between the two. These processes are explained in the paragraphs below. The NEC of each program were multiplied with their respective area fraction and then added to each other to find the total NEC for each scenario. These were then compared to each other to find the optimum scenario with minimum NEC at neighbourhood scale. The formula used for calculation of total NEC of each scenario is explained in Equation 3.

Scenarios	Residential	Office	Retail
1	0,1	0,1	0,8
2	0,1	0,2	0,7
3	0,1	0,3	0,6
4	0,1	0,4	0,5
5	0,1	0,5	0,4
6	0,1	0,6	0,3
7	0,1	0,7	0,2
8	0,1	0,8	0,1
9	0,2	0,1	0,7
10	0,2	0,2	0,6
11	0,2	0,3	0,5
12	0,2	0,4	0,4
13	0,2	0,5	0,3
14	0,2	0,6	0,2
15	0,2	0,7	0,1
16	0,3	0,1	0,6
17	0,3	0,2	0,5
18	0,3	0,3	0,4
19	0,3	0,4	0,3
20	0,3	0,5	0,2
21	0,3	0,6	0,1
22	0,4	0,1	0,5
23	0,4	0,2	0,4
24	0,4	0,3	0,3
25	0,4	0,4	0,2
26	0,4	0,5	0,1
27	0,5	0,1	0,4
28	0,5	0,2	0,3
29	0,5	0,3	0,2
30	0,5	0,4	0,1
31	0,6	0,1	0,3
32	0,6	0,2	0,2
33	0,6	0,3	0,1
34	0,7	0,1	0,2
35	0,7	0,2	0,1
36	0,8	0,1	0,1

Table 8. Fraction of each typology in all scenarios

$$Total\ NEC_i = \sum_{P=1}^{3} NEC_P . F_P$$

$where,\ Total\ NEC = Total\ Net\ Energy\ Consumption\ for\ given\ scenario$

$i = scenario\ (1 \rightarrow 36)$

$NEC = NEC\ of\ given\ program\ (P = f[Res,\ Off,\ Ret])$

$F\ =\ fraction\ of\ area\ of\ respective\ program\ and\ total\ built\text{-}up\ neighbourhood\ area$

$F: 0{,}1 \rightarrow 0{,}8$

$\sum_{P=1}^{3} f_P = 1$

Equation 3. Total NEC for each scenario

The PLS of each program were multiplied with their respective area fraction and then added to each other to find the total PLS for each scenario. These were then compared to each other to find the optimum scenario with maximum PLS at neighbourhood scale. The formula used for calculation of total PLS of each scenario is explained in Equation 4.

$$PLS_P = \sum_{d=1}^{365} (PL_d - PV_d)_P$$

$$Total\ PLS_i = \sum_{P=1}^{3} PLS_P . F_P$$

$where,\ Total\ PLS = Total\ Peak\ Load\ Shaving\ for\ given\ scenario$

$PLS = PLS\ of\ given\ program\ (P = f[Res,\ Off,\ Ret])$

$d = day\ (1 \rightarrow 365)$

$PL = Peak\ load\ of\ given\ day$

$PV = PV\ production\ at\ peak\ load\ of\ given\ day$

$i = scenario\ (1 \rightarrow 36)$

$F\ =\ fraction\ of\ area\ of\ respective\ program\ and\ total\ built\text{-}up\ neighbourhood\ area$

$F: 0{,}1 \rightarrow 0{,}8$

$\sum_{P=1}^{3} f_P = 1$

Equation 4. Total PLS for each scenario

It was found necessary to create a qualitative scale ranging from 1 to 100, in order to compare both NEC and PLS optimization. Here 100 corresponds to the best value and 1 corresponds to worst value for both NEC and PLS as shown in Figure 16. It was assumed that both have the same importance. The steps taken to find the rating are described below.

1. The scenarios were sorted from smallest to largest NEC and PLS values.
2. The value for each rating value was calculated using Equation 5.
3. The NEC and PLS values for each scenario were matched to the nearest rating value and assigned corresponding rating.
4. Finally, a curve of scenarios against rating value was plotted and optimum scenario

was plotted as shown in Figure 25.

$$Value\ for\ NEC\ rating_i = NEC_{min} + \left\{x \cdot \left(\frac{NEC_{max} - NEC_{min}}{100}\right)\right\} = y$$

$$Value\ for\ PLS\ rating_i = PLS_{min} + \left\{x \cdot \left(\frac{PLS_{max} - PLS_{min}}{100}\right)\right\} = z$$

$where, NEC\ Rating = Total\ NEC\ for\ given\ scenario$

$PLS\ Rating = Total\ PLS\ for\ given\ scenario$

$i = scenario\ (1 \rightarrow 36)$

$NEC = NEC\ of\ scenario_i$

$PLS = PLS\ of\ scenario_i$

$x: 0 \rightarrow 99$

$y: 1 \rightarrow 100$

$z: 100 \rightarrow 1$

Equation 5. Values of rating for each scenario

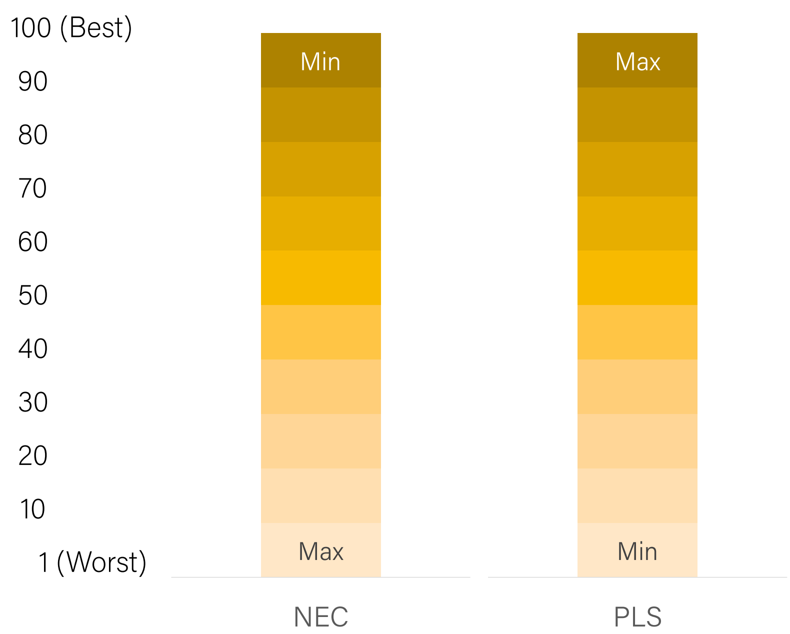


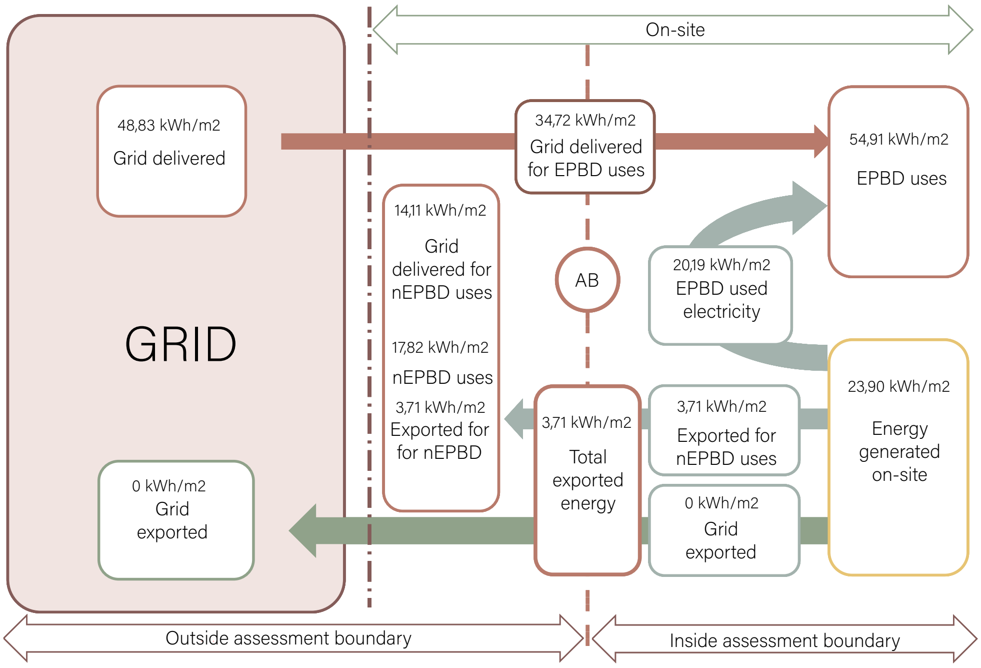
Figure 16. Qualitative chart for combined optimization

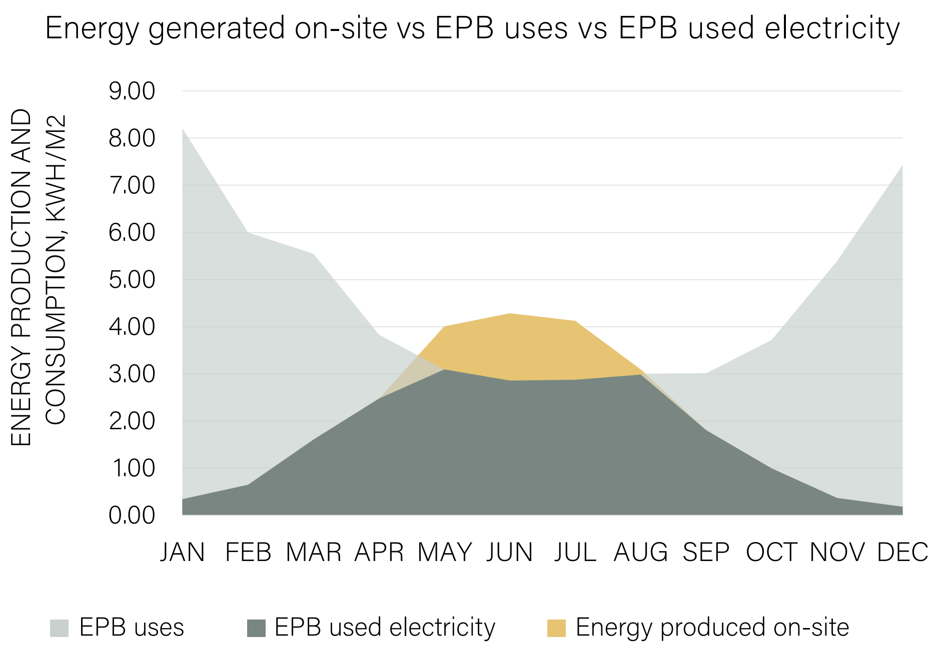
4. RESULTS

SINTEF tool developed for Syn.ikia base case (Oslo climate) was used to calculate different monthly and annual EPB and non-EPB consumptions of the building which can be compared to the monthly on-site renewable energy production and energy exported to the main external grid. The results are shown in the following sections for each building program and the values can be seen in Appendix B.

4.1. Residential Typology

The NEC per BRA for residential building typology was found to be 43,62 kWh/m2. The net district heating energy, electric lighting, electric HVAC, and other electric consumptions were found to be 13,90 kWh/m2, 32,17 kWh/m2, 3,63 kWh/m2, and 17,82 kWh/m2 respectively. The annual energy output show that the building satisfies the Passivhaus standard requirements for newly built residential buildings (Passive House Institute, 2015). The requirement of net heating energy consumption below 15 kWh/m2 or peak heating demand below 10W/m2 is also met, as peak demand is above 10 Wm2 only for 6 hrs. in the simulated year. The total energy used for domestic application are below the requirement of 60 kWh/m2. The air tightness of the envelop is below 0,6 ach per hour at 50 Pascals, and thermal comfort for maximum 10% hrs. to not exceed 25°C is also met. The results of the annual hourly simulation are shown in Figures 17 and 18.





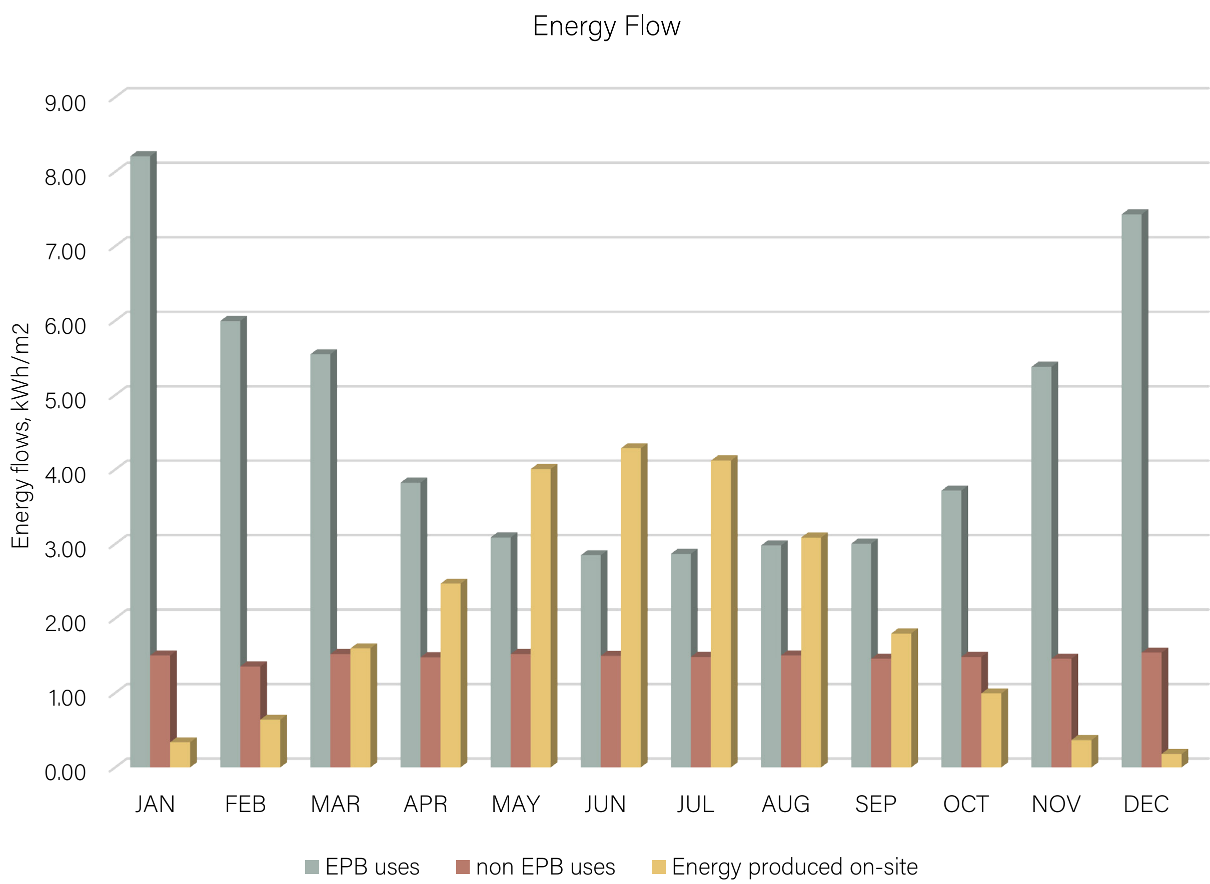


Figure 17. Compilation of energy balance figures for residential typology

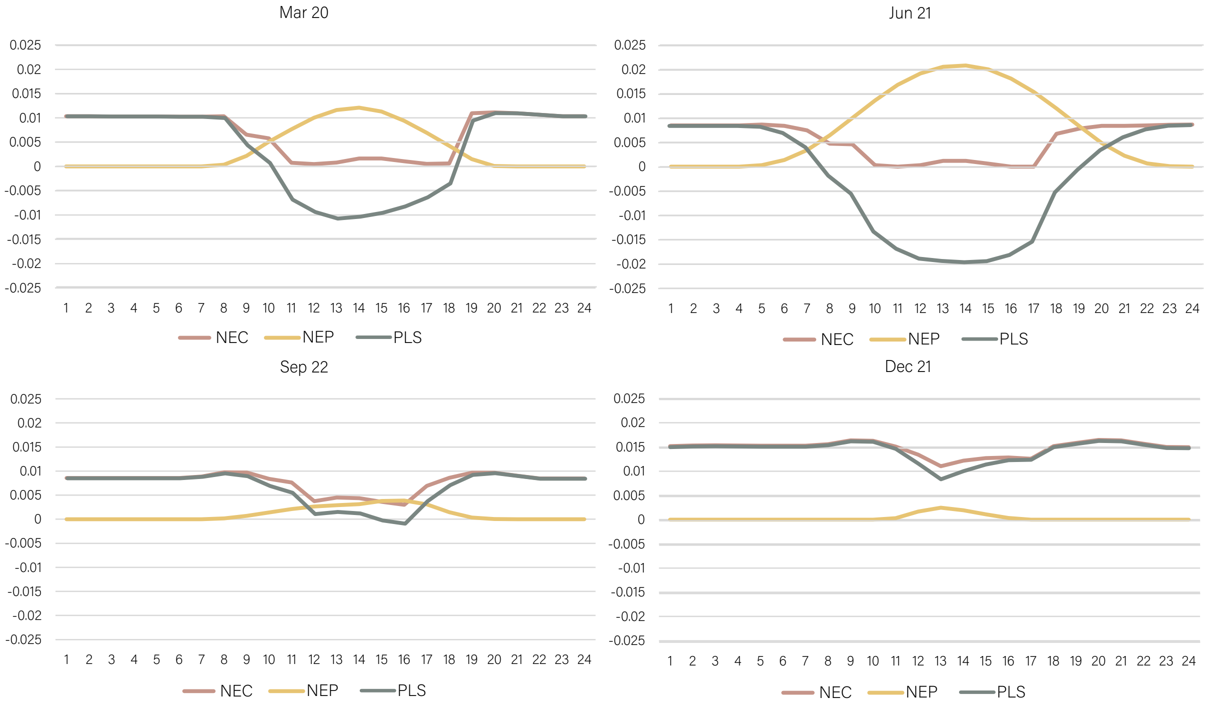
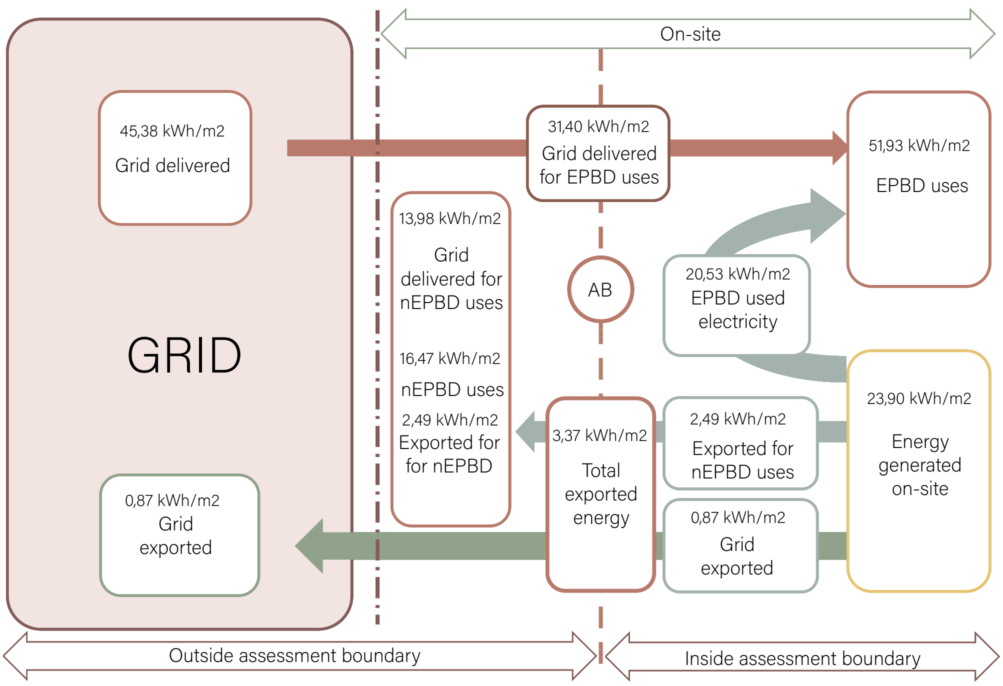
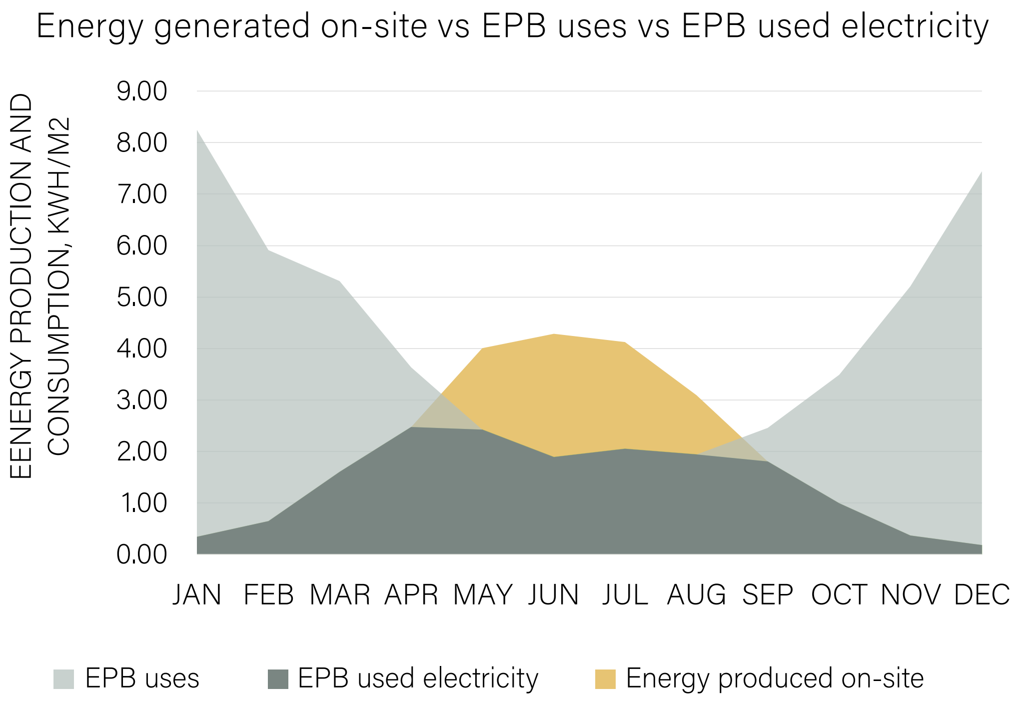


Figure 18. Compilation of peak loads figures for office typology

4.2. Office Typology

The NEC per BRA for residential building typology was found to be 39,10 kWh/m2. The net district heating energy, electric lighting, electric HVAC, and other electric consumptions were found to be 20,00 kWh/m2, 18,35 kWh/m2, 5,44 kWh/m2, and 19,21 kWh/m2 respectively. The net heating energy peak demand is above 10 Wm2 for 23 hrs. in the simulated year. The air tightness of the envelop is 0,2 ach per hour at 50 Pascals. Uncomfortable heating hours were found to be 7,83 hrs. The results of the annual hourly simulation are shown in Figures 19 and 20.





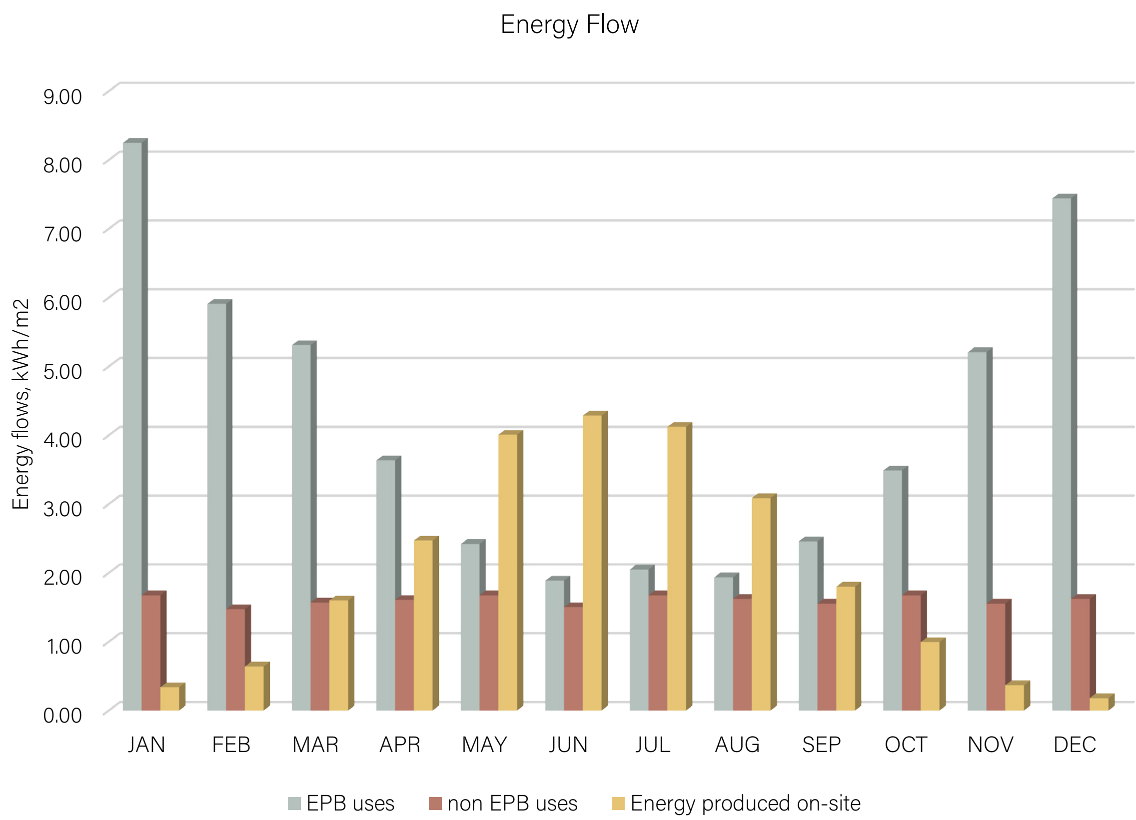


Figure 19. Compilation of energy balance figures for office typology

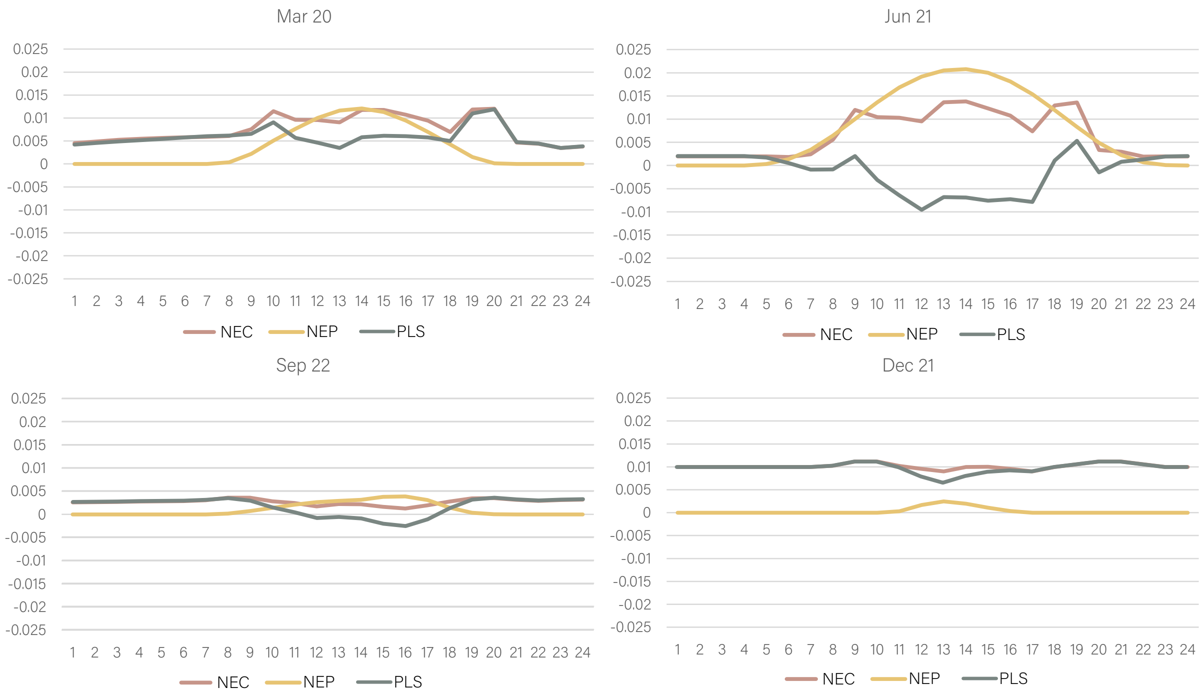
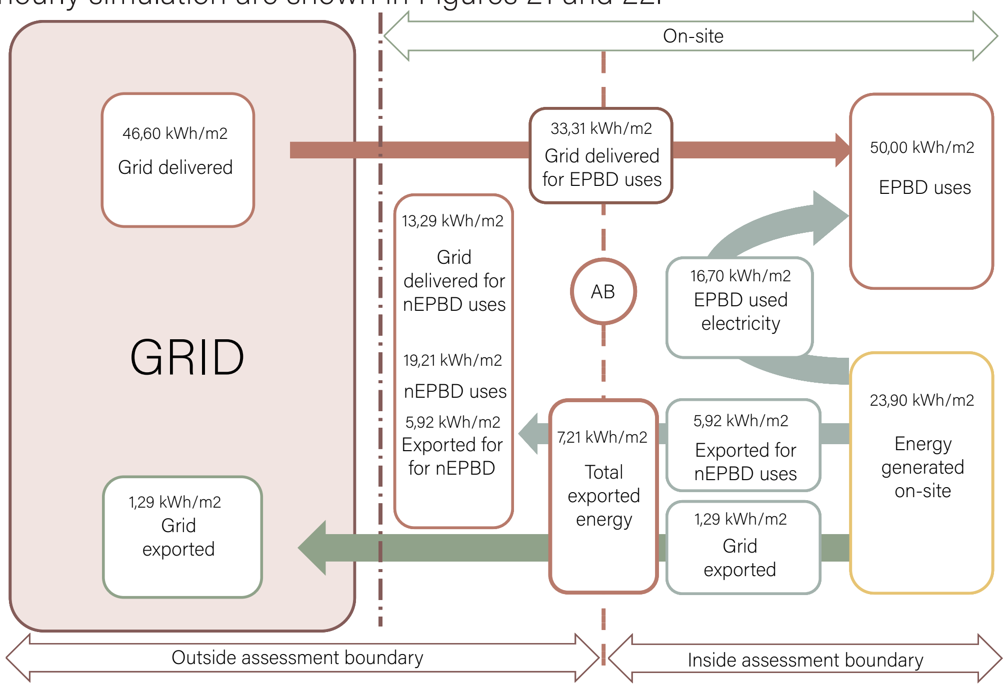


Figure 20. Compilation of peak loads figures for office typology

4.3. Retail Typology

The NEC per BRA for residential building typology was found to be 40,63 kWh/m2. The net district heating energy, electric lighting, electric HVAC, and other electric consumptions were found to be 13,00 kWh/m2, 25,56 kWh/m2, 9,49 kWh/m2, and 16,47 kWh/m2 respectively. The net heating energy peak demand is above 10 Wm2 for 9 hrs. in the simulated year. The air tightness of the envelop is 0,2 ach per hour at 50 Pascals. The results of the annual hourly simulation are shown in Figures 21 and 22.



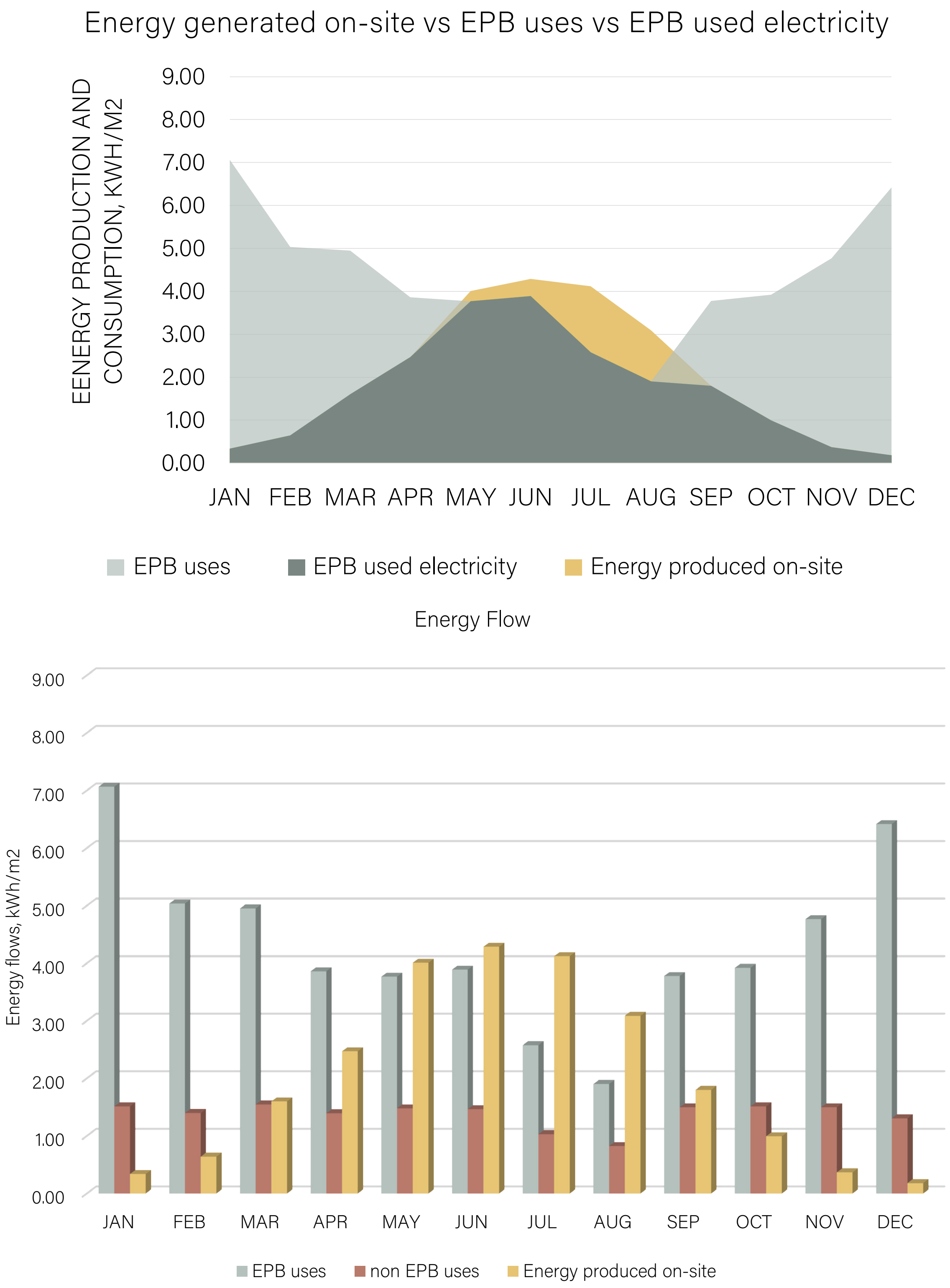


Figure 21. Compilation of energy balance figures for retail typology

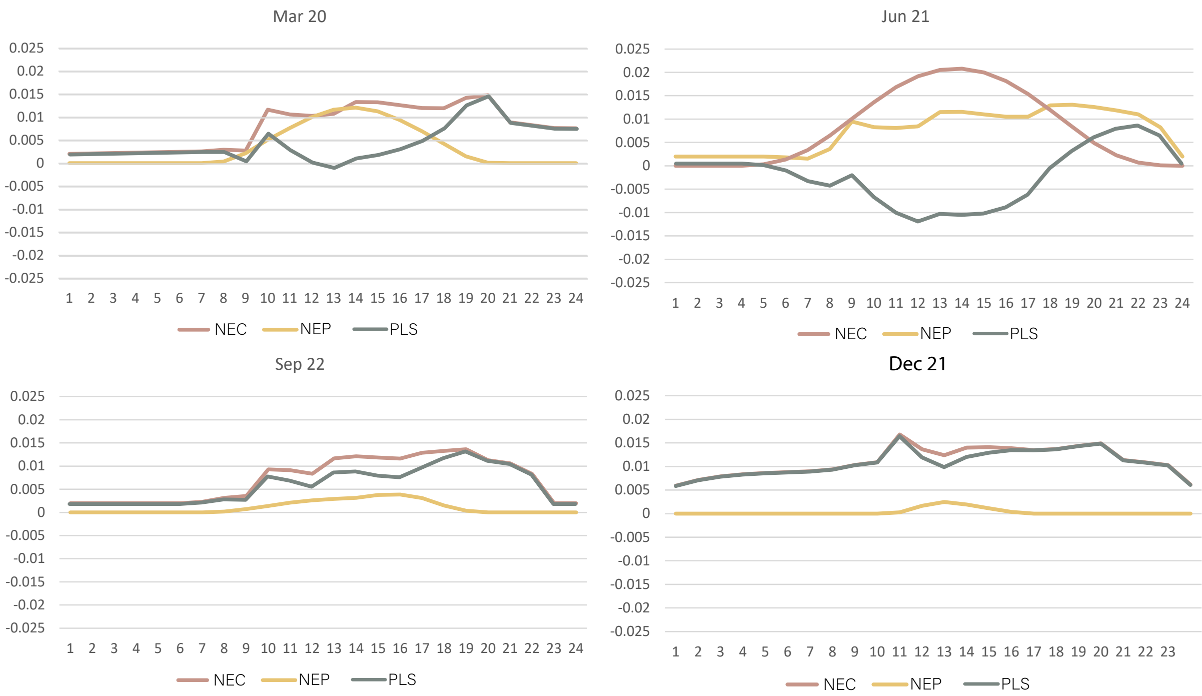


Figure 22. Compilation of peak loads figures for retail typology

5. ANALYSIS

The analysis was conducted for hourly energy consumption and production data of each scenario individually for NEC and PLS. The analysis is discussed in sections below.

5.1. NEC Optimization

The NEC for each neighbourhood scenario is shown in Figure 23. It was observed that the NEC decreases as the built-up area of the office typology increases. Similarly, NEC spikes at every scenario with least built-up area of office typology. It was also observed that the NEC vs. area composition of different typology follow a linear equation. This is true given that the total built-up area for each scenario is same. The NEC for each scenario is given in Appendix C.

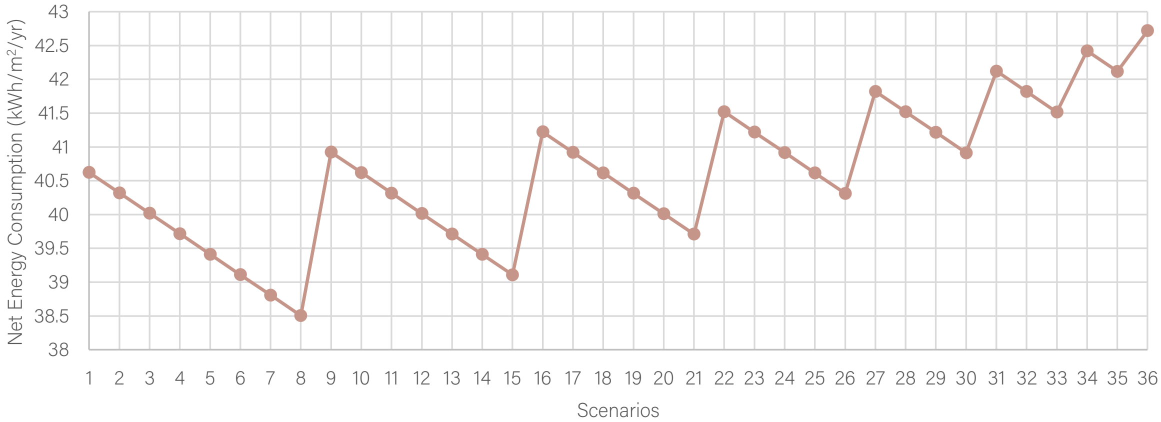


Figure 23. Optimization of NEC for all scenarios

5.2. PLS Optimization

The PLS for each neighbourhood scenario is shown in Figure 24. It was observed that the total PLS decreases as the built-up area of the office typology increases. Similarly, PLS spikes at every scenario with least built-up area of office typology. However, the PLS vs. area composition of different typology follow a linear equation with deviation. This can be said because the trend-line of the curve is linear. This is true given that the total built-up area for each scenario is same. The PLS for each scenario is given in Appendix C.

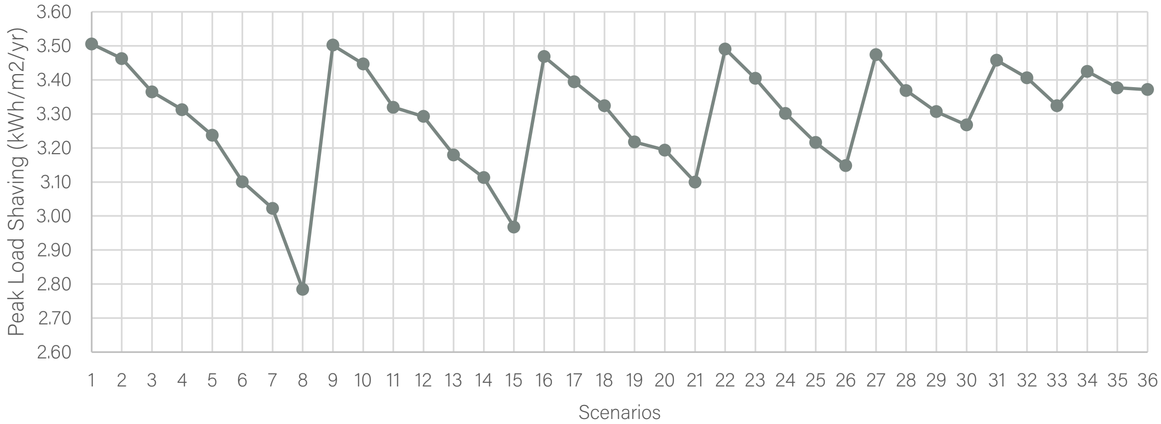


Figure 24. Optimization of PLS for all scenarios

5.3. Combined Optimization

The ranking of each scenario was plotted on scenario vs. ranking curve. Given that it was assumed that both NEC and PLS same importance, the were plotted on the same curve with each varying from 1 to 100. It was observed that while PLS follows a curve similar to Figure 25, the NEC is a mirror along ranking value 50. This is because while the maximum PLS was also the best case with a ranking of 100, but the maximum NEC was the worst case with a ranking of 1. SInce the Scenario 1 is the best for PLS optimization and Scenario 8 is the best for NEC optimization, the point at which both of these intersect is optimum compromise to optimize both NEC and PLS, given both have equal importance. The rating system can be adjust for different proportions of importance level.

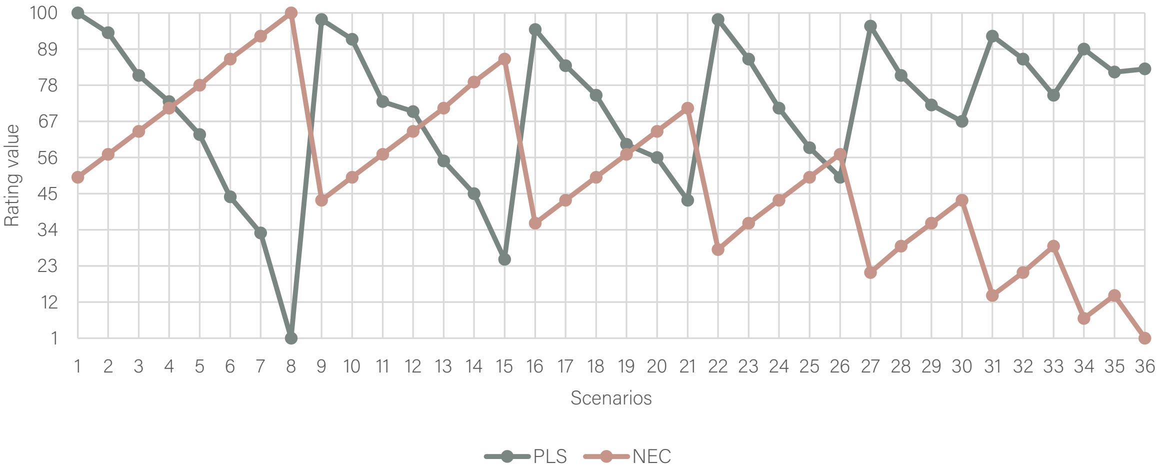


Figure 25. Combined optimizationfor all scenarios

6. CONCLUSION

The study aimed to find the optimum distribution of different building programmes in a neighbourhood in order to minimize the annual NEC and maximize the PLS for a neighbourhood of high-performance buildings. While the minimization of NEC reduces the energy demand of the neighbourhood, thus reducing the energy associated GHG emissions, the maximisation of PLS reduces the stress on grid and minimizes the need to sell produced energy to the grid at lower costs. Enough evidence was found in the literature that better informed urban planning has great potential to reduce not just the stress on the grid during peak hours but the overall GHG footprint of the neighbourhoods. However, little research has been done on optimizing the area allocated to different building programs in a neighbourhood.

The study aimed to fill this research gap by simulating 36 different neighbourhood distribution scenarios located in Ammerud, Oslo. The building programmes considered were Residential, Office and Retail. In order to ensure that all buildings were high-performing, a net-zero energy neighbourhood proposal under the pan-EU Syn.ikia project called OEN building was chosen as a case study. A south-facing section of the building was then simplified into a polygon geometry to simulate the annual hourly performance. A sensitivity analysis was also conducted to ensure that the orientation of the building did not affect the simulation results by large margin and it was found that while the deviation from the selected orientation was very low in other cases, the selected orientation had the least consumption, thus most optimum energy profile. The building model follows envelope and system efficiencies similar to those in the proposed OEN building. The residential model was found to be within the Passivhaus regulation thus substantiating its performance. The office and retail building models were modified to fit their respective operation schedules and HVAC requirements such as cooling and refrigeration for office and retail respectively. The operation schedules as discussed in Section 4, were modified to suite the average Norwegian living, work and shopping schedule.

The results of NEC optimization analysis showed that the Scenario 8 i.e., 6,5 hectare (10%) residential, 52 hectare (80%) office and 6,5 hectare (10%) retail, was the minimum for annual NEC. The results of PLS optimization analysis showed that the Scenario 1 i.e., 6,5 hectare (10%) residential, 6,5 hectare (80%) office and 52 hectare (10%) retail, was the maximum for annual PLS. The reasons behind these values are discussed in Section 6.1. Discussion. The best compromise for both reduction of NEC and enhancement of PLS was found to be the Scenario 4 i.e., 6,5 hectare (10%) residential, 26 hectare (40%) office and 32,5 hectare (50%) retail.

To conclude, it can be said that in the given context, building performance level, HVAC systems, schedule and climate, a neighbourhood with majority office buildings combined with residential and retail buildings would be most optimum scenario for minimizing NEC. Similarly, in the given context, a neighbourhood with majority retail buildings combined with residential and office buildings would be the most optimum scenario for maximizing PLS. However, it is to be note that this study should be conducted for other contexts to find the optimal distribution of building programmes in early stage urban planning projects.

6.1. Discussion

As mentioned above, the scenario with minimum NEC is with maximum office BRA. This is because office building has the least NEC reducing the total NEC of the neighbourhood. Also, as all buildings have the same morphology, orientation, and similar technical systems, all office buildings have same NEC.

Similarly, the scenario with maximum PLS is with maximum retail BRA. This is because retail building has the highest NEC which increases the potential for PLS of the neighbourhood. Also, as all buildings have the same morphology, orientation, and similar technical systems, all retail buildings have same NEC.

This would change if the modelled neighbourhood represented a more detailed and real-life neighbourhood plan which would have buildings with different morphology, orientation, technical systems and renewable energy sources creating a more complex relation between NEC and PLS.

6.2. Further Studies

Since the optimal building programme distribution heavily depends on the context of the neighbourhood, the study has a great potential for further development.

1. Different size, shape and performance levels of buildings could be chosen as a variable,
2. Mutual shading of buildings and terrain could be accounted for,
3. IET for enhanced control and sharing of energy could be studied in-depth,
4. Sharing of waste heat could be considered along-with electricity sharing,
5. Other sources of renewable energy like solar collectors and wind power could be considered,
6. Neighbourhood scale energy storage systems like thermal bank and ice thermal storage could be considered to operate neighbourhood at island mode, and
7. Building scale energy storage systems like batteries, heat storage via water accumulation, phase changing materials, etc. could be studied as well.

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APPENDIX A

HVAC loops were designed to fit the demand and supply of each typology. For residential typology, heating, DHW and ventilation units were designed. Here, the District Heating systems supplies hot water to the air handling unit (AHU), single duct VAV reheat unit, and hot water convector. DHW is provided by a electric water heater tank. The AHU consists of demand controlled ventilation valves, fixed plate heat exchanger, hot water coil unit, and supply fan. For office and retail typologies, heating, cooling, DHW and ventilation units were designed. Here, the District Heating systems supplies hot water to the (AHU), single duct VAV reheat unit, and hot water convector. The cooling systems source cooling from ground source heat pump (GSHP). The water medium GSHP connects to chiller that supplies cooling demand to AHU chilled water coil. DHW is provided by a electric water heater tank which is connected to a heat recovery system that recovers waste heat from chiller. The AHU consists of demand controlled ventilation valves, fixed plate heat exchanger, hot water coil unit, chilled water coil unit, and supply fan. The AHU also supplies to packaged terminal air conditioner at every zone level. In retail typology, the chiller is used to provide refrigeration for the smallest zone in each floor.

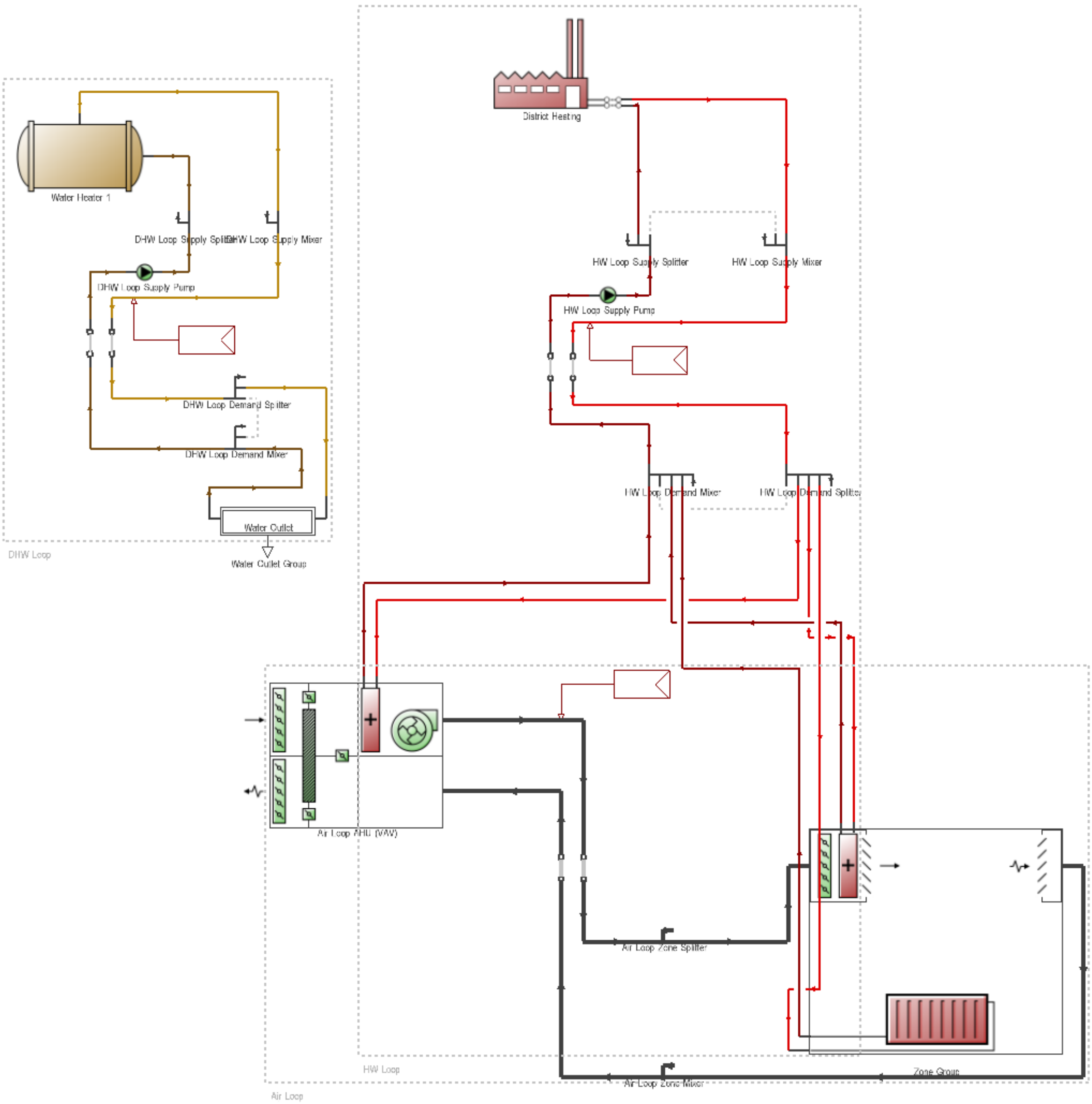

Figure 26. HVAC loop for residential typology

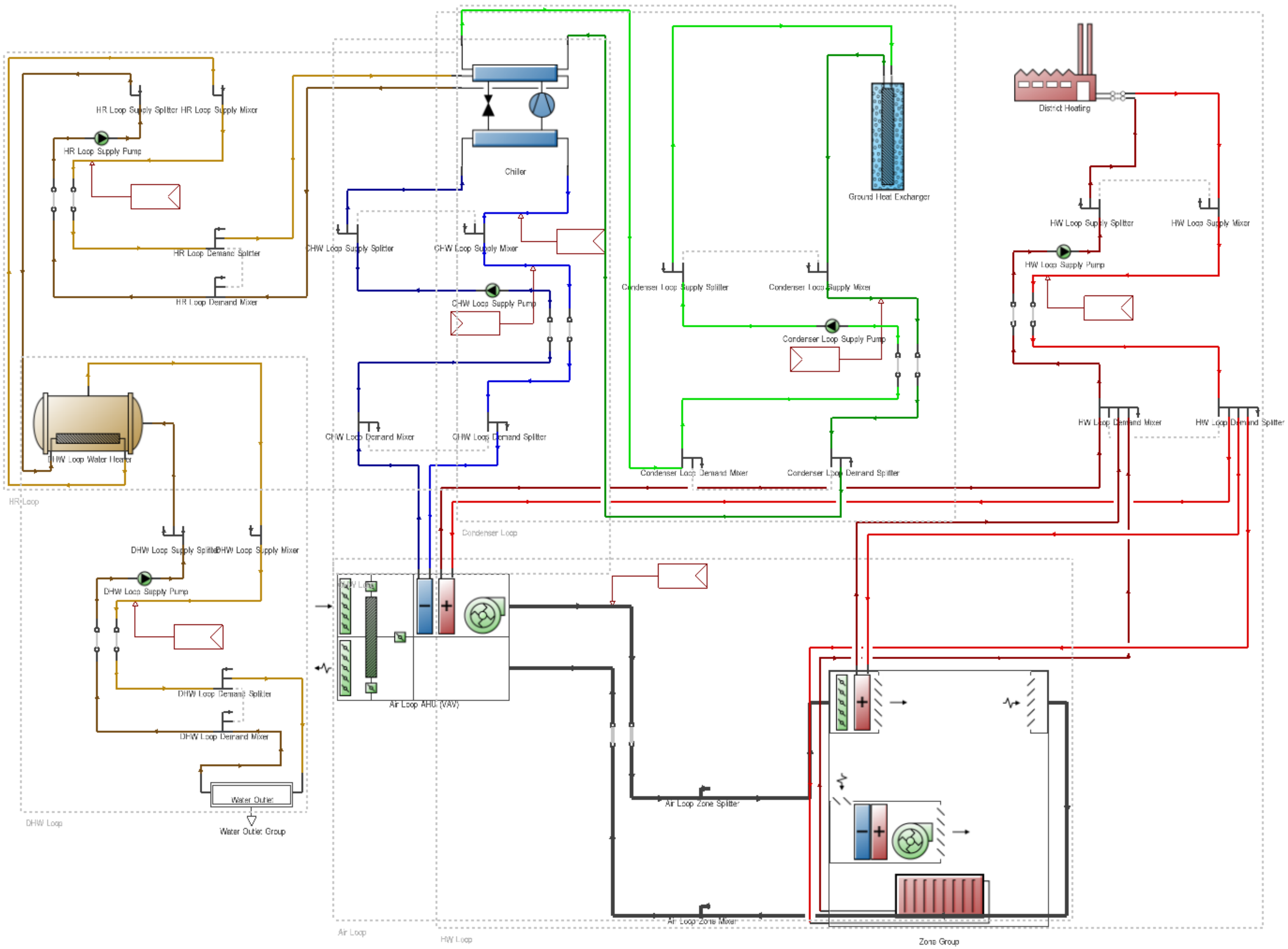

Figure 27. HVAC loop for office and retail typology

APPENDIX B

This appendix contains the raw data for each typology's total energy consumption for end use components and the monthly energy production and consumption including the transmission losses as provided by the SINTEF Simplified Primary Energy Calculator.

	Source Electricity [kWh]	Source Natural Gas [kWh]	Source Additional Fuel [kWh]	Source District Cooling [kWh]	Source District Heating [kWh]
Heating	0,00	0,00	0,00	0,00	157498,43
Cooling	0,00	0,00	0,00	0,00	0,00
Interior Lighting	319523,29	0,00	0,00	0,00	0,00
Exterior Lighting	0,00	0,00	0,00	0,00	0,00
Interior Equipment	176995,59	0,00	0,00	0,00	0,00
Exterior Equipment	0,00	0,00	0,00	0,00	0,00
Fans	35500,00	0,00	0,00	0,00	0,00
Pumps	514,41	0,00	0,00	0,00	0,00
Heat Rejection	0,00	0,00	0,00	0,00	0,00
Humidification	0,00	0,00	0,00	0,00	0,00
Heat Recovery	0,00	0,00	0,00	0,00	0,00
Water Systems	0,00	0,00	0,00	0,00	0,00
Refrigeration	0,00	0,00	0,00	0,00	0,00
Generators	0,00	0,00	0,00	0,00	0,00
Total Source Energy End Use Components	532533,29	0,00	0,00	0,00	157498,43

Table 9. Total energy consumption for end use components for residential typology

	Source Electricity [kWh]	Source Natural Gas [kWh]	Source Additional Fuel [kWh]	Source District Cooling [kWh]	Source District Heating [kWh]
Heating	2724,45	0,00	0,00	0,00	226663,25
Cooling	28343,56	0,00	0,00	0,00	0,00
Interior Lighting	182203,51	0,00	0,00	0,00	0,00
Exterior Lighting	0,00	0,00	0,00	0,00	0,00
Interior Equipment	190786,10	0,00	0,00	0,00	0,00
Exterior Equipment	0,00	0,00	0,00	0,00	0,00
Fans	21678,77	0,00	0,00	0,00	0,00
Pumps	1260,25	0,00	0,00	0,00	0,00
Heat Rejection	0,00	0,00	0,00	0,00	0,00
Humidification	0,00	0,00	0,00	0,00	0,00
Heat Recovery	0,00	0,00	0,00	0,00	0,00
Water Systems	0,00	0,00	0,00	0,00	0,00
Refrigeration	0,00	0,00	0,00	0,00	0,00
Generators	0,00	0,00	0,00	0,00	0,00
Total Source Energy End Use Components	426996,65	0,00	0,00	0,00	226663,25

Table 10 Total energy consumption for end use components for office typology

	Source Electricity [kWh]	Source Natural Gas [kWh]	Source Additional Fuel [kWh]	Source District Cooling [kWh]	Source District Heating [kWh]
Heating	0,00	0,00	0,00	0,00	147321,42
Cooling	55891,21	0,00	0,00	0,00	0,00
Interior Lighting	253862,45	0,00	0,00	0,00	0,00
Exterior Lighting	0,00	0,00	0,00	0,00	0,00
Interior Equipment	163564,77	0,00	0,00	0,00	0,00
Exterior Equipment	0,00	0,00	0,00	0,00	0,00
Fans	35968,44	0,00	0,00	0,00	0,00
Pumps	2412,26	0,00	0,00	0,00	0,00
Heat Rejection	0,00	0,00	0,00	0,00	0,00
Humidification	0,00	0,00	0,00	0,00	0,00
Heat Recovery	0,00	0,00	0,00	0,00	0,00
Water Systems	0,00	0,00	0,00	0,00	0,00
Refrigeration	0,00	0,00	0,00	0,00	0,00
Generators	0,00	0,00	0,00	0,00	0,00
Total Source Energy End Use Components	511699,13	0,00	0,00	0,00	147321,42

Table 11. Total energy consumption for end use components for retail typology

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
On-site energy production														
PV energy produced on-site	kWh/m²	0,34	0,64	1,60	2,47	4,01	4,29	4,12	3,09	1,80	1,00	0,37	0,18	23,90
Manual matching factor		0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	8,40
Technical systems														
Heating needs (el+env heat)	kWh/m²	3,72	2,35	1,82	0,66	0,11	0,00	0,00	0,00	0,01	0,42	1,72	3,09	13,90
DHW needs (el+env heat)	kWh/m²	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cooling needs (el+env heat)	kWh/m²	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SPF/COP	Heating	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	48,00
SPF/COP	DHW	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	21,60
SPF/EER	Cooling	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	66,00
EPB uses. Final consumption														
Heating, electricity	kWh/m²	1,02	0,65	0,50	0,18	0,03	0,00	0,00	0,00	0,00	0,11	0,47	0,85	3,82
DHW, electricity	kWh/m²	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cooling, electricity	kWh/m²	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Heating consumption	kWh/m²	4,09	2,59	2,01	0,72	0,12	0,00	0,00	0,00	0,02	0,46	1,90	3,40	15,29
DHW consumption	kWh/m²	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ventilation	kWh/m²	0,23	0,21	0,24	0,27	0,37	0,38	0,37	0,38	0,36	0,34	0,23	0,24	3,63
Lighting	kWh/m²	2,87	2,55	2,80	2,65	2,57	2,47	2,50	2,60	2,63	2,81	2,78	2,94	32,17
non EPB uses. Final electricity consumption														
Other	kWh/m²	1,50	1,36	1,52	1,48	1,52	1,50	1,49	1,50	1,46	1,49	1,46	1,54	17,82
Total energy prod.	kWh/m²	0,34	0,64	1,60	2,47	4,01	4,29	4,12	3,09	1,80	1,00	0,37	0,18	23,90
Total EPB uses	kWh/m²	8,21	6,00	5,55	3,83	3,09	2,85	2,87	2,98	3,01	3,72	5,38	7,43	54,91
Total nEPB uses	kWh/m²	1,50	1,36	1,52	1,48	1,52	1,50	1,49	1,50	1,46	1,49	1,46	1,54	17,82

Tabel 12. End use component monthly energy production and consumption for residential typology

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
On-site energy production														
PV energy produced on-site	kWh/m²	0,34	0,64	1,60	2,47	4,01	4,29	4,12	3,09	1,80	1,00	0,37	0,18	23,90
Manual matching factor		0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	8,40
Technical systems														
Heating needs (el+env heat)	kWh/m²	4,59	3,18	2,61	1,34	0,31	0,01	0,00	0,00	0,26	1,09	2,60	4,01	20,00
DHW needs (el+env heat)	kWh/m²	0,04	-0,06	-0,04	0,01	0,02	0,01	0,02	-0,06	0,13	0,02	-0,08	0,04	0,07
Cooling needs (el+env heat)	kWh/m²	0,00	0,00	0,00	0,01	0,23	0,30	0,55	0,50	0,08	0,00	0,00	0,00	1,67
SPF/COP	Heating	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	48,00
SPF/COP	DHW	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	21,60
SPF/EER	Cooling	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	66,00
EPB uses. Final consumption														
Heating, electricity	kWh/m²	1,26	0,87	0,72	0,37	0,09	0,00	0,00	0,00	0,07	0,30	0,71	1,10	5,50
DHW, electricity	kWh/m²	0,03	-0,04	-0,02	0,01	0,01	0,01	0,01	-0,03	0,08	0,01	-0,05	0,03	0,04
Cooling, electricity	kWh/m²	0,00	0,00	0,00	0,00	0,05	0,06	0,11	0,10	0,02	0,00	0,00	0,00	0,33
Heating consumption	kWh/m²	5,05	3,49	2,88	1,47	0,35	0,01	0,00	0,00	0,28	1,20	2,86	4,41	22,01
DHW consumption	kWh/m²	0,05	-0,07	-0,04	0,02	0,02	0,01	0,02	-0,06	0,14	0,02	-0,09	0,05	0,07
Ventilation	kWh/m²	0,24	0,21	0,24	0,27	0,39	0,39	0,39	0,39	0,37	0,34	0,23	0,24	3,70
Lighting	kWh/m²	1,63	1,44	1,54	1,50	1,52	1,40	1,52	1,54	1,50	1,61	1,54	1,61	18,35
non EPB uses. Final electricity consumption														
Other	kWh/m²	1,67	1,47	1,57	1,61	1,67	1,50	1,67	1,62	1,56	1,67	1,56	1,62	19,21
Total energy prod.	kWh/m²	0,34	0,64	1,60	2,47	4,01	4,29	4,12	3,09	1,80	1,00	0,37	0,18	23,90
Total EPB uses	kWh/m²	8,25	5,91	5,31	3,64	2,42	1,89	2,05	1,94	2,46	3,49	5,21	7,44	50,00
Total nEPB uses	kWh/m²	1,67	1,47	1,57	1,61	1,67	1,50	1,67	1,62	1,56	1,67	1,56	1,62	19,21

Tabel 13. End use component monthly energy production and consumption for office typology

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
On-site energy production														
PV energy produced on-site	kWh/m²	0,34	0,64	1,60	2,47	4,01	4,29	4,12	3,09	1,80	1,00	0,37	0,18	23,90
Manual matching factor		0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70	8,40
Technical systems														
Heating needs (el+env heat)	kWh/m²	3,18	1,85	1,56	0,89	0,25	0,01	0,00	0,00	0,18	0,69	1,49	2,91	13,00
DHW needs (el+env heat)	kWh/m²	0,03	0,03	0,05	0,07	0,42	0,69	0,40	0,21	0,43	0,12	0,03	0,02	2,50
Cooling needs (el+env heat)	kWh/m²	0,11	0,19	0,28	0,33	0,43	0,43	0,28	0,20	0,40	0,39	0,26	0,17	3,48
SPF/COP	Heating	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	48,00
SPF/COP	DHW	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	1,80	21,60
SPF/EER	Cooling	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	5,50	66,00
EPB uses. Final consumption														
Heating, electricity	kWh/m²	0,87	0,51	0,43	0,25	0,07	0,00	0,00	0,00	0,05	0,19	0,41	0,80	3,58
DHW, electricity	kWh/m²	0,02	0,02	0,03	0,04	0,26	0,42	0,25	0,13	0,26	0,07	0,02	0,02	1,53
Cooling, electricity	kWh/m²	0,02	0,04	0,06	0,07	0,09	0,09	0,06	0,04	0,08	0,08	0,05	0,03	0,70
Heating consumption	kWh/m²	3,49	2,03	1,72	0,98	0,27	0,01	0,00	0,00	0,19	0,76	1,64	3,20	14,30
DHW consumption	kWh/m²	0,03	0,03	0,05	0,08	0,46	0,76	0,44	0,23	0,47	0,13	0,04	0,03	2,75
Ventilation	kWh/m²	0,28	0,26	0,30	0,29	0,39	0,40	0,21	0,12	0,41	0,34	0,28	0,23	3,51
Lighting	kWh/m²	2,35	2,15	2,37	2,15	2,24	2,20	1,63	1,39	2,31	2,35	2,32	2,11	25,56
non EPB uses. Final electricity consumption														
Other	kWh/m²	1,51	1,40	1,55	1,39	1,48	1,46	1,03	0,82	1,50	1,51	1,50	1,31	16,47
Total energy prod.	kWh/m²	0,34	0,64	1,60	2,47	4,01	4,29	4,12	3,09	1,80	1,00	0,37	0,18	23,90
Total EPB uses	kWh/m²	7,07	5,04	4,95	3,86	3,77	3,89	2,58	1,90	3,78	3,92	4,77	6,42	51,93
Total nEPB uses	kWh/m²	1,51	1,40	1,55	1,39	1,48	1,46	1,03	0,82	1,50	1,51	1,50	1,31	16,47

Tabel 14. End use component monthly energy production and consumption for retail typology

APPENDIX C

The final NEC and PLS values, and their assigned ranking for each scenario are shown in Table 15.

Scenario	NEC (kWh/m2/yr)	PLS (kWh/m2/yr)	NEC Ranking	PLS Ranking
1	40,62	3,51	50	100
2	40,32	3,46	57	94
3	40,02	3,37	64	81
4	39,71	3,31	71	73
5	39,41	3,24	78	63
6	39,11	3,10	86	44
7	38,81	3,02	93	33
8	38,50	2,78	100	1
9	40,92	3,50	43	98
10	40,62	3,45	50	92
11	40,32	3,32	57	73
12	40,01	3,29	64	70
13	39,71	3,18	71	55
14	39,41	3,11	79	45
15	39,11	2,97	86	25
16	41,22	3,47	36	95
17	40,92	3,39	43	84
18	40,62	3,32	50	75
19	40,31	3,22	57	60
20	40,01	3,19	64	56
21	39,71	3,10	71	43
22	41,52	3,49	28	98
23	41,22	3,40	36	86
24	40,92	3,30	43	71
25	40,61	3,22	50	59
26	40,31	3,15	57	50
27	41,82	3,47	21	96
28	41,52	3,37	29	81
29	41,22	3,31	36	72
30	40,91	3,27	43	67
31	42,12	3,46	14	93
32	41,82	3,41	21	86
33	41,52	3,32	29	75
34	42,42	3,43	7	89
35	42,12	3,38	14	82
36	42,72	3,37	1	83

Table 15. NEC, PLS and their assigned ranking

Master's thesis

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