TOWARDS A RESILIENT BUILT ENVIRONMENT: ENERGY POSITIVITY THROUGH ENERGY FLEXIBILITY AND GENERATION

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ABSTRACT

TOWARDS A RESILIENT BUILT ENVIRONMENT: ENERGY POSITIVITY THROUGH ENERGY FLEXIBILITY AND GENERATION

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The threatening impacts of climate change increase on a daily basis, pushing each sector to go under significant changes. Architecture is integral to this issue since the built environment accounts for a major portion of energy usage. Hence, a fundamental re-consideration of the relationship between energy and buildings is inevitable. Currently, most buildings are connected to electricity grids only to retrieve energy. However, through effective utilization of renewable energy sources, this connection is prone to radical changes. Buildings must be able to mitigate renewable energy generation with existing electricity energy and balance the electricity inputs and outputs, underlining the necessity of energy flexibility. This thesis aims to portray the significance of energy flexibility for energy generation and present the means of considering energy flexibility as a framework for architects to utilize as a design strategy. For this purpose, a methodology of achieving energy positivity through energy flexibility and generation is created and tested on a case study. The results show that through effective utilization of energy flexibility and generation, energy positivity is possible.

Keywords: Energy Flexibility, Renewable Energy Generation, Smart Scheduling, Building Thermal Mass

ÖZ

DAYANIKLI BİR YAPILI ÇEVREYE DOĞRU: ENERJİ ESNEKLİĞİ VE ÜRETİMİ ARACILIĞIYLA ENERJİ POZİTİFLİĞİ

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İklim değişikliğinin tehdit edici etkileri her geçen gün artmakta ve her sektörü önemli değişikliklere zorlamaktadır. Yapılı çevre enerji kullanımının büyük bir kısmını oluşturduğundan ötürü, mimari bu konuya entegre bir konumdadır. Bu nedenle, enerji ve binalar arasındaki ilişkinin temelde yeniden değerlendirilmesi kaçınılmazdır. Günümüzde, çoğu bina yalnızca enerji temin etmek için elektrik şebekelerine bağlıdır. Ancak, yenilenebilir enerji kaynaklarının etkili kullanımıyla, bu bağlantı köklü değişikliklere tabiidir. Binalar, yenilenebilir enerji üretimini mevcut elektrik enerjisiyle değerlendirilmeli ve elektrik kullanım ile üretimlerini dengeleyebilmelidir, bu da enerji esnekliğinin gerekliliğini vurgulamaktadır. Bu tez, enerji üretimi için enerji esnekliğinin önemini tasvir etmeyi ve mimarların bir tasarım stratejisi olarak kullanabilecekleri bir yöntem olarak enerji esnekliğini kullanmanın yollarını sunmayı amaçlamaktadır. Bu amaçla, enerji esnekliği ve üretimi yoluyla enerji pozitifliğine ulaşmak için bir metodoloji oluşturulmuş ve bir vaka çalışması üzerinde test edilmiştir. Sonuçlar, enerji esnekliğinin ve üretiminin etkili kullanımı yoluyla enerji pozitifliğinin mümkün olduğunu göstermektedir.

Anahtar Kelimeler: Enerji Esnekliği, Yenilenebilir Enerji Üretimi, Akıllı Programlama, Bina Isıl Kütlesi

To Better Days

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CHAPTER 1

INTRODUCTION

The ever-growing global energy demand, coupled with an upcoming shortage of fossil fuels and the accelerating effects of global warming, have led countries to mandatory exploitation of renewable energy sources (IEA, 2019). Carbon neutrality, critically emphasized in the Paris Agreement, is seen to be a mutual goal of countries (Huang & Zhai, 2021). There are two main strategies proposed by the agreement: decarbonization of the electricity grid and the electrification of transportation, heating, and industry (UNFCCC, 2015). Those strategies were again confirmed at the latter COP26 summit (UNFCCC, 2022).

Architecture, as a field, is not exempt from this discussion. On the contrary, our immediate surroundings contribute majorly to the concerns of global warming and energy crisis. The built environment accounts for approximately 40% of global energy usage. A paradigm shift governing the energy demand and consumption of buildings is therefore inevitable considering their account in energy usage (IEA, 2019). In the light of our current habitat where electricity energy is an inevitable need, architects must be in a constant search of seeking mitigation and adaptation strategies in the buildings they design.

As a fundamental means of climate mitigation, the framework of SER (sufficiency, efficiency, and renewable) was proposed by the 6th Annual Report of the Intergovernmental Panel on Climate Change (IPCC) (Puthalpet, 2022). The elements of this framework can be explained as such: 1) sufficiency refers to the delivery of building-related services in an equitable, sensible, and sustainable manner, 2) efficiency focuses on calibrating the energy consumption of a building by reducing the consumption without compromising occupant needs, and 3) renewable simply indicates the integration of renewable energy sources into building energy systems (Cai & Gou, 2024). The concerns of architecture regarding energy are growing each day, and the discussions around sustainable architecture must adapt itself to the ever-increasing stream of information that will carry our buildings into the next generation.

As the energy consumption of the built environment steadily increases, responsive actions continue to emerge and develop. The urge to change the meaning of residential housing from an unresponsive structure to an active, responsive tool have led to many improvements in the field. 'Smart Buildings' is an umbrella term that was introduced due to the growing concerns. Buckman et al. (2014) define 'Smart Buildings' as:

> *"Smart Buildings are buildings which integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at the core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction. The increased amount of information available from this wider range of sources will allow these systems to become adaptable and enable a Smart Building to prepare itself for context and change over all timescales."*

Numerous kinds of buildings, even categories of buildings, fall under this umbrella category. One of the known examples is Net Zero Energy Buildings (NZEBs) (D'Agostino & Mazzarella, 2019). Another known example is Positive Energy Buildings (PEBs) (Kumar & Cao, 2021). PEBs claim certain improvements over NZEBs, in the fields of renewable energy (on-site and off-site), reduction of carbon emissions as well as GHG emissions, reduction of building energy cost as well as overall building cost, and positive impacts on the utility grid (Kumar & Cao, 2021).

Another significant example, and a relatively new one, can be defined as Positive Energy Districts (PEDs). The Joint Programming Initiative Urban Europe (JPI Urban

Europe, 2020), managing the PED programme on behalf of the European Commision, define PEDs as:

> *"Energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and information and communication technology (ICT) systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability."*

PEDs are not to be conceived as isolated districts within the city, instead, they act as a part of the whole, contributing to mitigation and adaptation with climate change, "creating future-proof, energy-positive and climate-neutral urban living environments" (Ahlers et al., 2020).

NZEB Model	PEB Model	PED Model
• Energy trade between one building and the grid • Power generated in individual buildings can be exported	• High energy flexibility • Complex system for trading between buildings and the grid • Optimized energy performance of the building	• Optimizing assets across the district • Minimize impact on the centralized grid • Provision of flexibility across the district and to the market

Figure 1.1. Differences between NZEBs, PEBs and PEDs (Tuerk et al., 2021)

The three pillars of a PED development can be defined as "Energy Efficiency, Energy Flexibility, and Energy Generation" (Nair et al., 2024). All three of these concepts revolve around the notion of electricity usage. While considering a PED, as the initial step, energy efficiency plays a significant part via decreasing the essential loads by modulating the district towards more efficient means of energy usage. The achievement of energy efficiency can be through several means. One of the ways is the proper insulation of the building envelope, through which the heat energy is preserved indoors for longer time periods. Another means is the electrification of heating and cooling systems through equipment such as a heat pump, which results in decreased amounts of energy usage for heating and cooling purposes. Yet another example would be the usage of energy efficient household appliances, in order to lower the amount of energy devoted to electricity and lighting. Energy flexibility, as the second pillar of PEDs, helps tackling the imbalances within the distribution of electricity loads. The main aim of energy flexibility within this context is the re-distribution of electricity loads so as not to juxtapose with the hours of extreme electricity usage within a day. The last pillar of a PED, namely 'Energy Generation', contributes to supplying the remaining necessary electricity loads through locally (or off-site) generated renewable energy.

1.1 The Need for Energy Flexibility in the Built Environment

Energy flexibility should be an integral part to architectural design, due to several valid reasons. Most of the built environment needs energy flexibility practices as they are bound with an electricity grid. The more direct reasons why we need energy flexibility in our buildings are: 1) electricity grids going through a demand pressure during peak electricity usage hours, 2) renewable energy lacking in a major portion of the built environment and mostly locally generated, energy flexibility is needed in means of mitigating this electricity traffic (Lind et al., 2023). There are, however, more important reasons behind the need for energy flexibility. For a long time, sustainable architecture brought about an image of green buildings. A building with integrated green elements was simply considered sustainable. The connotations of the terms 'green' and 'sustainability', widely used in the field, became so vague as to blur the existence of sustainable architecture (Smedt, 2010). Nevertheless, greening of architecture is not composed of a set of unchangeable definitions, it should rather be considered as an evolutionary process that keeps improving itself (Tabb & Deviren, 2017). However, component-based solutions such as additions of vegetation in the building, or simple attachments of PV panels, does not qualify the building as 'sustainable' thoroughly. Simply attaching some PV panels to the building, do not suffice the need for sustainability. There is an urgent need for architects to approach this issue as a whole. For a building to be considered sustainable, it should be able to approach the electricity issue in a reactive, responsive, and generative manner. Renewable energy generation must be an integral component to the building from the start, and the energy generation should be considered in hourly or daily time resolutions to establish a more effective communication with the electricity grid. In order to achieve this, energy flexibility must be utilized as a design strategy by the architects, and as an operational practice on the occupant side.

A common definition of the term ‘Energy Flexibility’ is “the ability to adapt/manage its short-term (a few hours or a couple of days) energy demand and generation … without jeopardizing the technical capabilities of the operating systems in the building and the comfort of its occupants” (IEA, 2019). Energy flexibility is therefore one of the key components for the feasibility of the connection between the buildings and the electricity network. Through energy flexibility operations, a building can lower its energy demand during the times when the electricity grid is overcharged and shift the demand to the times when the grid operates easier. Energy flexibility further facilitates the immediate distribution and usage of renewable energy, which can mitigate the transformation procedure between renewable energy generation and the existing electricity grid.

In the light of these, here are the reasons why energy flexibility is inevitable for architects as a design strategy:

1. Currently, most of the buildings are connected to the power grid with a unidirectional link (Ahrens et al., 2021), meaning that the building takes the electricity from the grid and distributes it to the users. This is a mistaken approach as electricity is a limited source and the overuse of it significantly contributes to climate change and energy crisis. As the ‘prosumer’ buildings increase, which do not only consume but also produce electricity, buildings necessitate a bidirectional connection to the grid (Ahrens et al., 2021). Only

through energy flexibility can the balance between electricity grid and renewable energy production be sufficed.

2. The relationship between architecture and renewable energy generation, until the present day, has simply been the installment of PV panels (or other renewable energy sources). Nonetheless, the nature of renewable energy generation was poorly understood. Renewable energy generation is intermittent, and in order to maximize its benefit, **instant energy balance** must be considered. Energy flexibility makes it possible to mitigate the immediate energy production, making the building a mitigatory agent between renewable energy and electricity grid.
3. The selection of building envelope materials defines the building thermal mass from the beginning, and it is significantly challenging to modify after the building is constructed. However, building thermal mass is a critical tool for the feasibility of energy flexibility. Thus, building envelope materials must consider energy flexibility in the design stage.
4. It is possible to reach energy positivity in PEDs, according to recent studies. Nevertheless, energy autonomy (independence from the electricity grid) is yet to be discovered. Energy flexibility is a key component in means of reaching energy autonomy, as it can facilitate the optimum usage of renewable energy generation. Therefore, energy flexibility is crucial in means of carrying PEDs to the next step.

As the global threats of energy crisis and climate change increase, the buildings must adapt themselves for the incoming renewable energy generation tools, while rebuilding their unidirectional relationship with the electricity grid. Through the integration of energy flexibility, this transition procedure can smoothly proceed. Through the success of this procedure, buildings can evolve for the near future, forming habitable and resilient environments.

1.2 Problem Statement

Energy flexibility is a critical area of interest in the literature. There are a variety of studies conducted within the scope of exploring, evaluating, measuring and quantifying energy flexibility. However, a great amount of these studies focusses on a single operation. Examples include the smart scheduling of HVAC equipment to achieve energy flexibility. the relevance of building thermal mass in reaching energy flexibility, smart scheduling of household appliances, or model-predictive control mechanisms that majorly focus on the computational features of the model. Therefore, a comprehensive evaluation framework rooting from an evaluation of building thermal mass, smart scheduling of HVAC equipment and household appliances, and a comparative evaluation of flexible load profiles and potential renewable energy generation, presents a gap in the literature. Thus, the scope of this thesis is to present a thorough evaluation of energy flexibility, coupled with energy generation to test whether energy positivity is possible, and present this as a framework for the architects to utilize. Evaluating these gaps in the literature, this thesis will focus on the following research problems:

- Evaluating energy flexibility as a tool for the architects by proposing a framework that walks through three steps of analysis, for the architects to utilize in their design strategies, as this approach is missing.
- Achievement of energy flexibility is mainly discussed in the literature through separate operations. The focus is either on HVAC equipment, or household appliances, or several other partial systems. A framework binding multiple concepts together to achieve further inclusivity on energy flexibility, however, is mainly missing.
- Even though a large portion of the literature evaluate energy flexibility and energy generation together, their coupled usage within the context of reaching energy positivity is rarely considered, constituting a gap in the literature.

1.3 Aims and Objectives

This thesis focuses on evaluating the energy flexibility potential of a building, and a collaborative evaluation of it with respect to the potential renewable energy generation, presenting this scheme as a three-step framework for re-usability. In order to establish this goal, an exploratory analysis of several consecutive strategies is proposed. **The analysis evaluates the potential of (i) building thermal mass through a simulation-based method, (ii) incorporates smart scheduling on HVAC systems and (iii) incorporates smart scheduling on household appliances to establish energy flexibility through model-predictive control, and (iv) compares the flexible load profile with potential renewable energy generation to evaluate whether energy positivity is possible or not.**

Within the scope of the development of this exploratory analysis, a focus on energy positivity forms the basis of the study. Achieving energy positivity through strategic deployment of energy flexibility is one of the main concerns of the thesis. In other words, energy flexibility is evaluated together with the energy production. The relationship and collaborative functioning of the two is evaluated.

The proposed exploratory analysis is evaluated through a case study in Ankara, Turkiye. A single household within a residential district of 257 low-rise housing units was utilized in order to incarnate the effectiveness, strength and weaknesses of the framework.

The district used in the case study, namely Camlik District, has been studied under the scope of a project entitled “Auto characterization of PEDs for digital references towards iterative process optimization” (abbreviated as “PED-ACT”). The project is funded by the Scientific and Technological Research Council of Turkiye under grant number TUBITAK 122N780.

In conclusion, the aims and objectives of this thesis are:

- Presenting an exploratory analysis on achieving energy positivity through energy flexibility and energy generation in buildings.
- A comparative analysis of various strategies in achieving energy flexibility.
- Contributing on the means of energy positive development in existing buildings and building clusters through a focus on energy flexibility, and energy generation.
- Developing the establishment of energy flexibility as a three-step framework for the architects to utilize in the design procedure.

1.4 Research Questions

Through a comprehensive evaluation of the gaps in the literature illustrated in the introduction, the main research question of this thesis is formed as:

- To what extent can energy flexibility be harnessed and collaboratively utilized with energy generation in order to reach energy positivity?

In the light of the main research question, four sub-questions are formed to further support the scope of the research:

- How could a smart scheduling system of HVAC equipment with respect to heating and cooling loads contribute to achieving energy flexibility without jeopardizing occupant comfort?
- How could a smart scheduling system of household appliances help establish energy flexibility, through which appliances?
- To what extent can a flexible load distribution be compatible with energy generation and self-consumption?
- Is reaching energy positivity a realistic goal with respect to coupling energy flexibility and energy production?

1.5 Thesis Outline

The structure of this thesis is composed of five different chapters. So as to clearly express the research conducted through the thesis, the following chapters are generated in consecutive order:

Chapter 1 (Introduction)

This current chapter, namely ‘Introduction’, is intended to explain the problem statement, aims and objectives, research questions, and the contribution to the field.

Chapter 2 (Literature Review)

The literature review conducted in scope of this thesis explore the topics of renewable energy, energy flexibility, definition and properties of energy flexibility, demand side management and demand response, residential flexible loads, control strategies of energy flexibility, energy storage of thermal mass as well as batteries and electric vehicles, quantification methods of energy flexibility, flexibility function, energy flexibility and PEDs, and lastly, the state of the art and gap in the literature.

Chapter 3 (Methodology)

In this chapter, the structure of the exploratory analysis is discussed in detail. To create the framework of the analysis, first of all, a model that evaluates building thermal mass potential based on different materials is generated. Secondly, another model that iteratively simulates various HVAC schedules based on energy model inputs was created. The model takes peak electricity load hours, initial HVAC loads and schedules as input; and returns a comparative analysis of energy flexibility potentials of various schedules as an output. Subsequently, another smart scheduling model was generated for the scheduling of household appliances. Similar to the previous one, the model takes peak electricity load hours, shiftable household appliance loads and schedules as input; and returns a comparative analysis of energy flexibility potentials of various schedules. Lastly, the achieved flexible load profile is comparatively analyzed with potential renewable energy production, in order to evaluate whether energy positivity is possible, in conclusion.

Chapter 4 (Case Study)

This chapter discusses the implementation of the analysis to a case study centering a single household in Camlik District, Ankara, which is the district studied in the research project of PED-ACT. The workflow of the case study unfolds as the consecutive implementation of the strategies proposed in the framework of the analysis.

Chapter 5 (Conclusion)

In this chapter, the effectiveness, limitations and potential future work is discussed.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a comprehensive review of the existing literature on energy flexibility is conducted. The review covers the notions of basic definitions, properties of the concept, demand side management and demand response, residential flexible loads, control strategies, energy storage, quantification of energy flexibility, and energy flexibility and PEDs. The chapter is finalized by a comprehensive evaluation of the state-of-the-art situation regarding the concept and highlights the gap in the literature.

2.1 Renewable Energy

Renewable energy constituted an amount of 7% considering the energy generation in 2018. Projections regarding the place of renewable energy in overall energy generation state a total of 43% of power generation by 2030 and 63% by 2050 (IEA, 2021). The main challenge of renewable energy sources, such as wind and solar power, is the intermittent nature of their energy generation capacity. In other words, the generation of renewable energy is highly variable and vitally dependent on external conditions (IEA, 2019). Solar energy is the current leading source within the scope of building and renewable energy integration, mainly achieved through building integrated photovoltaic (BIPV) and building attached photovoltaic (BAPV), each having pros and cons regarding construction cost, technical difficulty, and environmental relations (Ding et al., 2023).

The linear energy model, in which the energy grids supply the amount of energy demand to buildings, is not subjected to a further elaborated model in which energy is generated on-site through renewable energy sources (RES), and the surplus energy is fed back to the grid after self-consumption (Cai & You, 2024). The new energy model has a pivotal role in transitioning building energy consumption through a new understanding in which energy supply does not follow the demand. Instead, energy demand considers the available supply (IEA, 2019).

2.2 Energy Flexibility

Rooting from the emergent need to reduce building energy consumption, a framework is seen as appropriate in optimizing building and energy relations. The fundamentals of this framework are: 1) reducing the energy demand of buildings by making use of energy efficiency measures and 2) fulfilling the remaining needs via renewable energy (IEA, 2019). However, renewable energy is not constant and does not supply uninterrupted energy. Therefore, it needs to be considered in integration with a grid, eventually resulting in a 'Smart Grid.' Smart grids (or Smart Energy Networks) are essentially developed to generate and distribute electricity in a smarter way, work in sync with renewable energy generation, and avoid congestion problems (IEA, 2019).

The integration of renewable energy resources into smart grids brings about a new challenge to the recent energy models: the intermittent nature of those resources. Therefore, a transitory process is necessary to bind together the energy demand from the end-user side and the energy supply from the smart grid. The fundamentals of energy flexibility are constructed to produce a response to this challenge (IEA, 2019). Considering the climbing energy prices and the aforementioned decarbonization strategies, the need to cultivate the potential of energy flexibility is deemed promising as an opportunity (Le Dréau et al., 2023). An increased distribution of energy flexibility mechanisms carries the potential to foster economic and environmental benefits (Li et al., 2022).

Energy flexibility, therefore, constitutes a significance in means of optimizing the transition between renewable energy generation and the energy grid through balancing supply and demand (Lind et al., 2023). The usage of decentralized energy generation is achieved via the proper deployment of energy flexibility. The built environment is expected to play a critical role in the development of future smart grids/energy networks (IEA, 2019).

The energy flexibility of buildings has numerous schemes of deployment. One of those frameworks includes the storage of renewable energy to enable a shift in the energy demand from times when electricity price and pressure on the grid are higher (also producing more CO2) to times when the price and the pressure are lower (producing lower amounts of CO2) (IEA, 2019). The storage of energy can take place in several items belonging to the building’s nature. Thermal mass, water tanks, or buffer tanks that work with an HVAC system are examples of the aforementioned items. Electricity can also be stored in batteries, which are integrated with a PV system, for example, or batteries of electrical vehicles (IEA, 2019).

Nevertheless, in order for the building to convey energy flexibility, there is a need for control and, therefore, controllable systems such as a heat pump, ventilation system, or cooling system. The ability to control these systems enables the charging and discharging of the stored energy at desired times (IEA, 2019). The control mechanisms vary significantly: from a simple mechanism in which a heat pump is turned on according to a certain predefined schedule to a rule-based control (RBC) mechanism (such as turning off the heat pump when a heating setpoint is reached) to further developed mechanisms such as model predictive control (MPC) mechanisms where the schedule of the heat pump is defined through a set of simulations considering the weather conditions, building envelope, indoor temperatures and occupant comfort (IEA, 2019).

A building equipped with such smart mechanisms of control is mainly referred to in the literature as a ‘Smart Building.’ Al Dakheel et al. define smart buildings by four fundamental aspects: climate response, grid response, user response, and monitoring and supervision. In other words, a smart building should be able to respond accordingly to climatic conditions, grid signals, and user inputs whilst maintaining real-time monitoring of its operation (2020).

Annex 67 Project (IEA, 2019) classifies building energy loads into three categories:

1) Shiftable loads: The loads that can be rescheduled to a different time of the day when the energy demand on the electricity grid is lower. It is possible to rearrange these loads without harming occupant comfort (IEA, 2019). Shiftable loads are also divided within themselves as shiftable profile loads (rigid energy profiles that can't be changed but can be rescheduled, such as washing machines) and shiftable volume loads (in which the energy profile is open to a certain amount of change, but the total energy demand must be met) (Ottesen and Tomasgard, 2015).
2) Non-shiftable loads: These loads can not be rescheduled, mainly because of occupant initiatives (examples include lighting, cooking, or leisure).
3) Other controllable loads: These are the types of loads that can be controlled through optimized control strategies such as thermostatic control, fan speed control, or dimming (Plaum et al., 2022).

A significant part of building loads can be shifted in time in order to provide energy flexibility by rescheduling the energy usage without jeopardizing occupant comfort. This type of flexibility can occur in building heating and cooling systems through pre-heating and pre-cooling, as well as household appliances such as washing machines, dryers, and dishwashers (IEA, 2019).

As illustrated in Figure 2.1, there are various means of deploying energy flexibility.

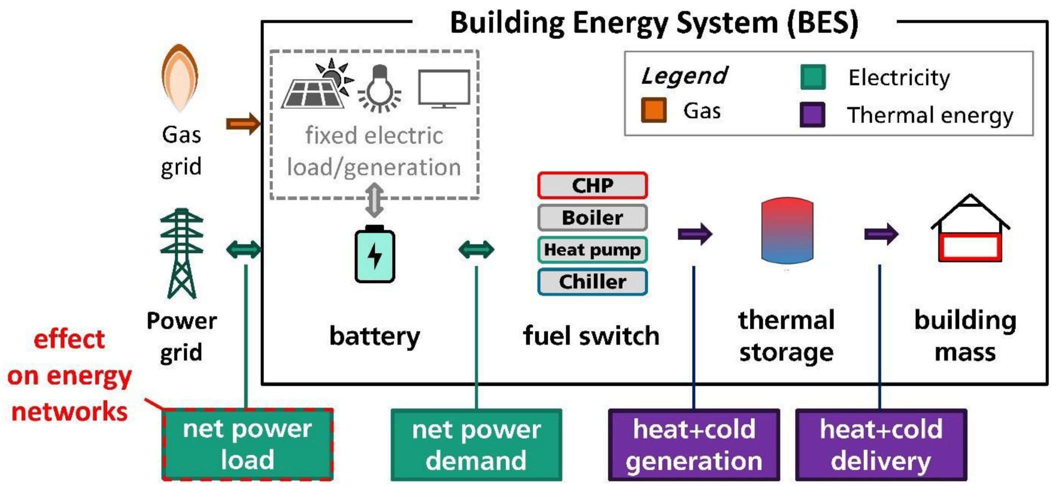

Figure 2.1. Sources for obtaining energy flexibility (Klein et al., 2017)

Energy flexibility in buildings can be obtained through building mass (utilizing the thermal capacity of the building envelope by evaluating its thermal mass), thermal storage (the energy storage outside of occupied spaces, such as water tanks), fuel switch (e.g., switching off the heat pump in times of higher pressure on the electricity grid and turning on the gas boiler), battery (as in storing the generated renewable energy), generation (through renewable energy sources), and networks (energy networks or smart grids) (IEA, 2019).

2.2.1 Definition of Energy Flexibility

In spite of the growing attention towards 'Energy Flexibility,' there is still a lack of an international, unanimous definition. The International Energy Agency (2019) examines a number of potential definitions in the literature, harmonizing the essentials of the definitions, and proposes a universal definition of the concept as:

> *"The ability to adapt/manage its short-term (a few hours or a couple of days) energy demand and generation according to local climate conditions, user needs, and energy network requirements without jeopardizing the technical capabilities of the operating systems in the building and the comfort of its*

occupants. Energy Flexibility of buildings will thus allow for DSM/load control and thereby DR based on the requirements of the surrounding energy grids."

2.2.2 Properties of Energy Flexibility

Energy flexibility, approached from a technical perspective, is simply the alterations in electricity generation or consumption, having a starting time, duration, and location in the grid (Plaum et al., 2022). Research has proposed certain terminology to illustrate the properties of energy flexibility, namely: 1) direction (up and down, generation and consumption), 2) the amount of altered electricity energy (power capacity), 3) the starting time, 4) the duration, and 5) the location (Jin et al., 2020) (Villar et al., 2018) (Eid et al., 2015).

- The directional property of energy flexibility indicates whether the flexibility source is a type of consumption or generation. The direction can be 'up' or 'down,' as well as bidirectional. Household appliances such as dishwashers and dryers have a 'down' direction as they consume energy, whereas renewable energy generation loads have an 'up' direction, meaning they produce energy. Storage equipment such as batteries of electric vehicles account for bidirectional flexibility loads, as they can both give and take energy.
- The power capacity property indicates the amount of altered energy carried out through a flexibility operation. The flexibility sources, through the combined properties of power capacity and duration, are categorized into two items: capacity type and energy type. A capacity-type source is able to be activated with high power for a shorter time, whereas an energy-type source is able to be activated with lower power for a longer time.

- The starting time property expresses the time period of delay between the start of the activation signal and the engagement time of the flexibility service.
- The location property simply describes the specific location of the flexibility source in the grid (Jin et al., 2020).

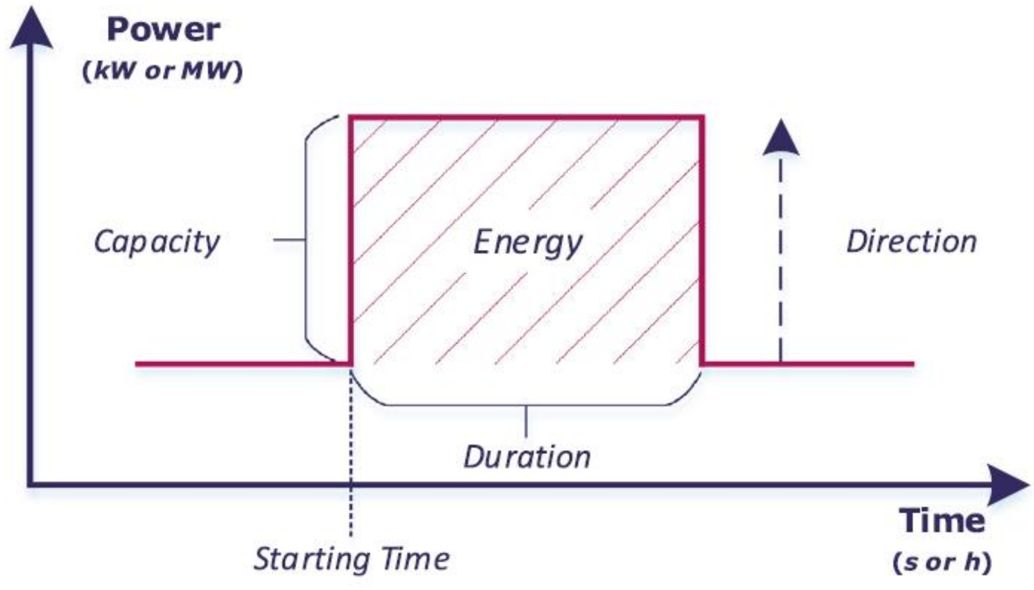

Figure 2.2. Properties of a flexibility service (Plaum et al., 2022)

2.2.3 Demand Side Management & Demand Response

The various means of establishing energy flexibility in buildings often require control mechanisms, as mentioned earlier. This can either be in the form of a direct load control or an indirect load control (Foteinaki et al., 2020). The form of control is referred to as direct when the provider directly intervenes in the energy load of the end user (Foteinaki et al., 2020). This is mainly considered 'Supply Side Management.'

A general division of energy flexibility sources can be expressed as demand-side flexibility and supply-side flexibility (Aduda et al., 2016). Supply-side flexibility is typically harnessed by the integration of power plants having various response times (the time between plant activation and power supply) into the electricity grid (Plaum et al., 2022). Supply-side flexibility is a direct form of control. On the other hand, if the form of control is indirect, incentives (usually economical or environmental) are used to convince the end-user to manage their energy load through their will (Foteinaki et al., 2020) (Lind et al., 2023). This is called ‘Demand Side Management.’

Arteconi et al. (2012) define ‘Demand Side Management’ as:

> *“The planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility’s load shape, i.e., changes in the pattern and magnitude of a utility’s load.”*

The main aim of demand-side management can be explained as balancing the centralized and decentralized electricity generation and load shifting in order to achieve peak shaving from the perspective of end-users (Dominković et al., 2018). Load shifting in this context refers to the rescheduling of the electricity load, whereas peak shaving refers to the reduction of electricity loads during peak hours of electricity usage. HVAC systems constitute a strong example in this context. The re-scheduling of HVAC systems carry significant potential for energy flexibility as HVAC systems account for a fair percentage (approximately 40%) of the building energy loads, playing a vital part in building peak demands in summer and winter (Goetzler et al., 2019).

‘Demand Response’ is another term related to demand-side management. It is defined as the adjustments of energy usage on the demand side (end-users) (Li et al., 2021). ‘Demand Response’ is a promising method that is deemed significant considering the ever-increasing local renewable inputs to the electricity grid and the worsening effects of global warming (Li et al., 2023).

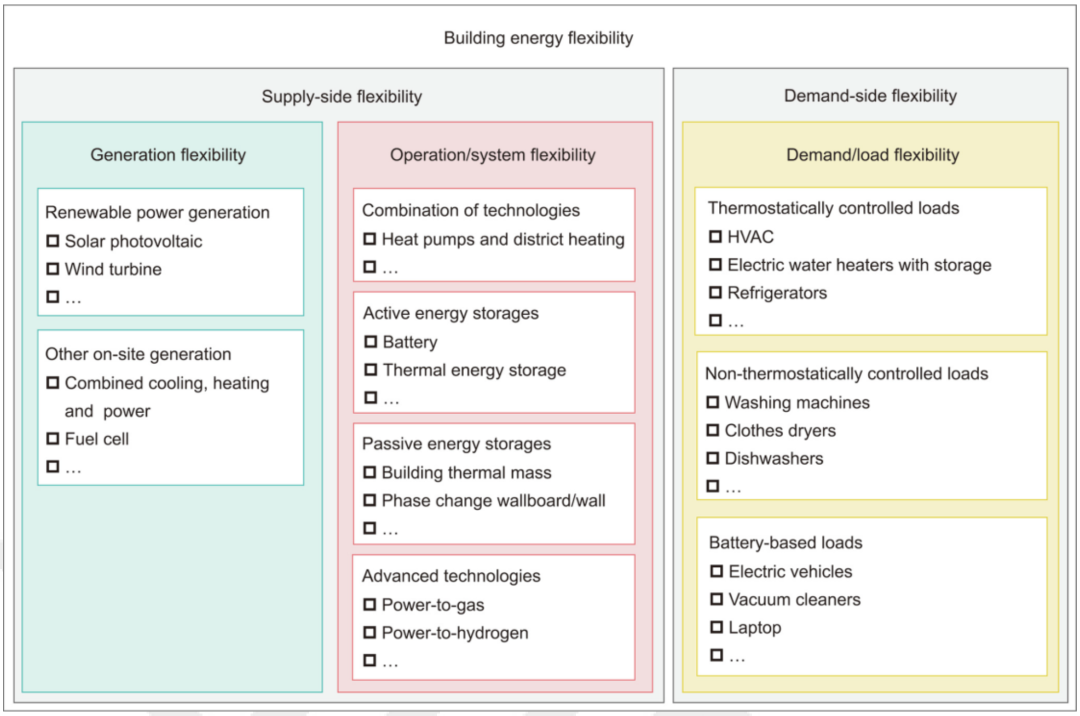

Figure 2.3. Distinction of various terms used to describe the flexibility of buildings (Luo et al., 2022)

Liu et al. (2023) categorize building demand response into three main headlines: 1) price-based response, in which dynamic pricing is utilized to alter the load profiles; 2) direct load control (DLC), through which another authority (aside from the end-user) optimizes the load profiles according to the needs of the grid and congestion solutions, and 3) transaction-based control (also referred to as market-based control), which encompasses price/incentive methods in the electricity market.

Recent developments in the fields of smart sensors, smart appliances, the Internet of Things (IoT), electric vehicles (EV), and energy storage mechanisms can help expedite energy flexibility in buildings, improving the operational management of energy supply systems (Li et al., 2021). For example, the automation of demand response has been a growing field of research in recent years. An Automated Demand Response (ADR) event can simply be described as the electric devices being turned off during peak electricity demand hours through an internal control signal (provided by the control system in the smart building) or external control via a grid operator. It can also be the case where indirect external control is supplied through incentive signals, such as the real-time price of electricity or the CO2 intensity of the system in real-time (Samad et al., 2016).

2.2.4 Residential Flexible Loads

It was previously discussed that the building energy loads are separated into three categories: Shiftable loads, non-shiftable loads, and other controllable loads (IEA, 2019). A further categorisation based on residential flexible loads is helpful in means of clearly categorizing the loads to operate on, and terminologically defining the loads for an easier understanding.

In this manner, the residential loads are characterized as storable, non-storable, shiftable, non-shiftable, curtailable and non-curtailable (He et al., 2013) (Mancini et al., 2019). Following an inclination from the most flexible to the least flexible load types; residential loads are firstly separated into storable and non-storable loads. Non-storable loads can further be categorized as shiftable and non-shiftable loads. Non-shiftable loads are then divided as curtailable and non-curtailable loads. This load type is considered as inflexible (Plaum et al., 2022).

- Storable loads: The type of loads that can be stored in electrical batteries or in the thermal inertia (e.g. the thermal mass of a building envelope). Examples include batteries, electrical vehicles, and HVAC equipment (Häring et al., 2021). The building envelope is able to store thermal energy through an improved thermal mass, or phase-changing materials that consume and spread heat energy for the purpose of altering their physical phase, through which the indoor temperature is modulated according to occupant comfort degrees.
- Shiftable loads: The type of loads that can be rescheduled to be activated earlier or later than the intended time. Washing machines, dishwashers and

dryers are examples of this type. As the time period of operation for these appliances are flexible within the day, they can be re-programmed so as not to juxtapose with peak electricity usage hours. The ability to change the timing of these loads constitutes the reason why these appliances provide shiftable loads.

- Curtailable loads: The type of loads that can not be shifted, however can be interrupted depending on adequate incentivization of end-users. Examples include room lighting, or computer usage (Plaum et al., 2022). As these are the appliances that operate based on occupant initiative, and therefore have unpredictable load profiles, incentivizing the end-users towards shifting the usage of these appliances can help curtailing these loads. The main difference between curtailable loads and shiftable loads is that shiftable loads do not interfere with occupant preferences and initiatives as curtailable loads do.

With respect to shiftable loads, Luo et al. (2022) define a framework named "flexibility window." What the authors fundamentally define is a time range within which the appliance can finish a complete cycle from start to end. In other words, the flexibility window proposes a range of hours longer than the time period needed for the appliance to start and finish working. Therefore, the electricity usage of the household appliance can be situated inside that range.

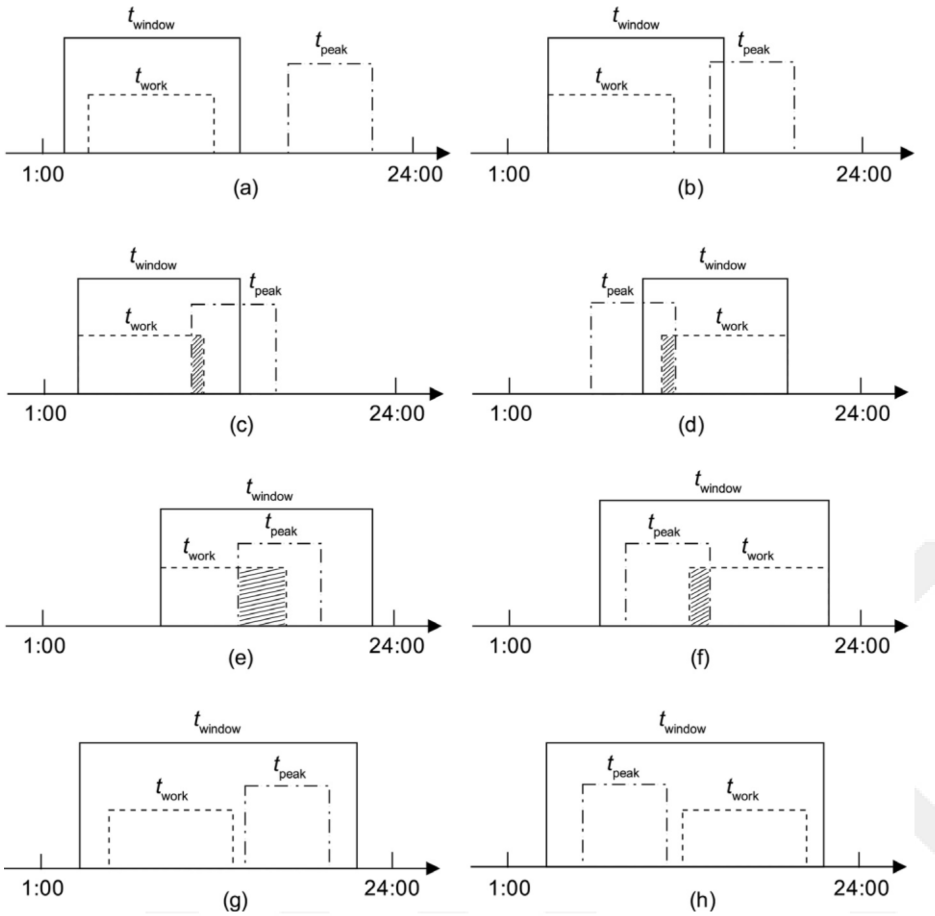

Figure 2.4. Load flexibility using flexibility window for the household appliances (Luo., 2022)

2.2.5 Control Strategies for Energy Flexibility

The preferred strategy of control can significantly alter the amount of energy flexibility provided. Model-predictive control (MPC), for example, is a relatively more recent concept that carries the potential of outperforming rule-based control (RBC) mechanisms (Liu et al., 2023).

There are three main categories of the models used in MPC mechanisms: white-box models, gray-box models, and data-driven black-box models (Liu et al., 2023).

1) White-box models: these types of models are typically based on state-space representations. They make use of mathematical equations and physical principles to model the system dynamics. As they are mostly physics-based, they require detailed parameter inputs for the precision of the model. A fundamental aspect of white-box models is that they can clearly illustrate the systems and physical and mathematical relationships of building elements (Liu et al., 2023). White-box models usually utilize simulation tools of EnergyPlus, IESVE, and TRNSYS (Besagni & Borgarello, 2018).
2) Gray-box models: These types of models are usually combinations of physical statements and empirical data. They have the potential to deliver building systems through simplified expressions. These models utilize physical systematic parameters as well as observed data to express system behavior, which makes them preferable for real-time monitoring and control mechanisms (Liu et al., 2023).
3) Black-box models: These types of models only employ empirical data without concern for definitive modeling of system dynamics. The strength of black-box models (also referred to as data-driven models) lies within complex machine-learning algorithms that utilize historical data to discover the underlying patterns and dynamics (regression models or neural networks are some popular methods). As these models can successfully cultivate nonlinear and uncertain system dynamics, they can be helpful when the parameters of systems are unknown or unclear (Liu et al., 2023).

2.3 Energy Storage

Energy flexibility firmly depends on, and functions collaboratively with energy storage. The storage of energy (either thermal or electrical) forms a strong basis for energy flexibility as it enables the flexible usage of the stored energy.

2.3.1 Thermal Mass

The thermal mass of a building has been referred to in the literature as a cost-effective solution to heating storage. It is found to be significant in transitioning the load (in other words, load shifting) from peak demand hours to off-peak hours. This operation may be helpful in several ways, such as lowering the electricity cost for the end-users, reducing CO2 emissions, or decreasing the overall energy demand (Lind et al., 2023).

Building thermal mass, however, is directly affected by the parameters of insulation level, indoor temperatures that do not jeopardize occupant comfort, and external boundary conditions. A crucial finding by the authors is that insulation level has the strongest impact on the thermal storage of a building. An increase in insulation level brings about an improvement in storage efficiency and longer periods of thermal autonomy (the period of time during which thermal comfort is maintained without any usage of heat supply) (Dominković et al., 2018) (Lind et al., 2023). The advantages of thermal energy storage are illustrated by Zhang et al. as: “(1) reduced investment and usage of peak capacity; (2) smoother operation of equipment and reduced running cost; (3) flexible load shifting to utilize non-dispatchable variable renewable energy or electricity with lower prices” (2021).

Thermal energy storage is divided into two main headlines: passive storage and active storage. Passive storage is basically achieved through the temperature differences between the building's thermal mass and indoor air. On the other hand, active storage technologies can be in the form of various types of equipment. Active storage can be integrated into HVAC systems, thermally activated building systems (TABS), or direct vicinity in buildings (e.g., borehole or aquifer) (Heier et al., 2015).

Several advantages of thermal energy storage were illustrated through a set of studies. Kensby (2017) has shown that thermal energy storage can help reduce the fluctuations of daily heat load profiles, Christensen et al. (2020) underlined that it can compensate for the growing need for fossil fuels by reducing overall heating demand, and Cai et al. (2018) has researched that it can be utilized in congestion management. Kensby (2017) further stated that building thermal mass has the potential to be a more feasible solution to energy flexibility compared with other means of storage (such as water tanks or direct vicinity in buildings) as it does not necessitate considerable investment costs.

Reynders et al. carried out an evaluation of the demand-side management potential of single-family houses heated by heat pumps. They discovered that building thermal mass could decrease the peak demand hours of electricity usage by 94% (2013). Another study carried out by Weiß et al. regarding a well-insulated Austrian building stock context has shown that more than half of the heating load in peak hours could be moved to off-peak hours (on a winter day) (2019).

As mentioned earlier, insulation level is also a critical parameter of building thermal mass. Le Dréau & Heiselberg carried out research tackling single-family housing units with different levels of insulation. The results pointed out that poorly insulated buildings have shown a much lower thermal autonomy performance. In contrast, the heating system was able to be switched off for a period longer and 24 hours for well-insulated housing units (2016). Similar research was conducted by Yang et al. for low-energy single-family houses, stating that the duration for the indoor temperature to go from 24°C to 18°C while the heating was switched off was about 43 hours (2022).

Building thermal mass is affected by certain parameters, some of which have relatively stronger impacts (Lind et al., 2023). The impact of such parameters was investigated in research carried out by Johra et al., and it was found that the insulation level of the building envelope has the strongest influence (2019). Foteinaki et al. further prove that, based on research on low-energy residential units, heat losses had a pivotal role in the amount of energy flexibility provided (2018). Another study investigating Danish single-family houses has shown that the total heat loss coefficient of the building envelope impacted thermal autonomy more importantly than thermal mass (Dominkovic et al., 2018).

2.3.2 Batteries and Electric Vehicles

Owing to the intermittent nature of renewable energy, a storage mechanism is necessary for the later usage of local energy production. Unlike unidirectional type flexible loads which may only provide flexibility through demand management, batteries act as prosumer devices as they can give and take energy, making them excellent tools for flexibility operations (Plaum et al., 2022). The battery implementation often goes hand in hand with PV installation. Coupled together, they enable on site self-consumption of locally generated energy (Ahmadiahangar et al., 2022). A framework of energy generation through PV panels and the storage of that energy by batteries is especially beneficial in means of lowering grid pressure on times of peak demand (Jankowiak et al., 2020), and mitigate the overproducing of PV panels during times with higher solar insolation (Segundo Sevilla et al., 2018).

The electric vehicles, by their nature, have a substantial difference to battery systems through their mobility. This notion can be beneficial, as well as a drawback in context (Plaum et al., 2022). On the brighter side, electric vehicles have the potential to travel between different locations of the grid. On the negative side, they may not always be present for storage utilization (Plaum et al., 2022). Overnight charging is, therefore, further evaluated in the literature (Jian et al., 2017). Electric vehicles are parked for most of the day. Therefore, they can be utilized for the purposes of demand response, on-site renewable energy usage, and peak shaving, within the presence of an aggregator (Plaum et al., 2022).

2.4 Quantification Methods of Energy Flexibility

In order to quantify energy flexibility, a rather abstract term by nature, certain properties should be established regarding the concept. Jensen et al. illustrate these properties as: “i) the time over which energy and power can be shifted or shedded; ii) the amount of energy or power that can be shifted or shedded; iii) the associated cost or efficiency loss at the building level that results from activating this flexibility.” (2017).

Further research conducted on the measurement and quantification of energy flexibility includes several other aspects of the topic. As the uncertainty of accessible energy flexibility has significant impacts on the effective implementation of demand response programs, forecasting flexibility is of utmost importance (Plaum et al., 2022). One of the methods used to forecast the number of controllable loads is referred to as load decomposition or disaggregation (Ponocko & Milanovic, 2018). Disaggregation is compartmentalized into two headlines: Non-Intrusive Load Monitoring (NILM), which makes use of a single monitoring meter (mostly a smart meter), and Intrusive Load Monitoring (ILM), which fundamentally means measuring a number of appliances locally (Ridi et al., 2014).

The studies on energy flexibility majorly focus on quantifying the concept through a framework of detailed building energy model generation, energy simulation of baseline operation and flexible operation, and comparing the two operations to achieve the quantified energy flexibility. These studies are, however, criticized by Li et al. because they lack real data to validate the model results (2023). As energy flexibility varies depending on external factors such as available resources, target objectives, and occupant behavior, real-time updates should be incorporated into the models for further precision (Li et al., 2023).

Li et al. focus on the quantification methods of energy flexibility through key performance indicators (KPIs) (2023). Key performance indicators are basically mathematical equations that can be used to quantify certain aspects of energy transition, load shifting, or peak shaving. The authors review a total of 48 KPIs emerging from 87 up-to-date and relevant papers. Appendix A contains a detailed table of those KPIs (prepared by the authors).

2.4.1 Flexibility Function

As there are numerous parameters involved, it is a challenge to characterize energy flexibility (Reynders et al., 2018). Research conducted on this notion suggests three characteristics of energy flexibility for categorization: 1) available storage capacity, 2) storage efficiency, and 3) power shifting capability expressing the dynamics of power, time period, and occupant comfort (Reynders et al., 2017). Junker et al. (2018), on the other hand, propose a further developed, dynamic method of characterization of energy flexibility through the 'Flexibility Function'. Along with their flexibility function (FF), the authors further propose a Flexibility Index (FI), which essentially measures the response of a building or a cluster of buildings to penalty signals (e.g., price/incentive or CO2 intensity). The authors evaluate a number of penalty signals for the study, which are respectively:

1) Real-time CO2. This penalty signal considers the CO2 intensity during different periods of the grid. As buildings perform energy flexibility measures by refraining from electricity usage during times with high CO2 intensity, they become emission-efficient (Junker et al., 2018).
2) Real-time price. As the buildings respond to dynamic price changes for the usage of electricity, they abstain from electricity usage during peak price hours, hence becoming cost-efficient (Junker et al., 2018).
3) Constant. Using a constant penalty is essentially meaningful in decreasing the total energy usage, thus making the building energy-efficient (Junker et al., 2018).

As inferred from former research, temporary deactivation of heating is possible without risking the thermal comfort of the occupants (Junker et al., 2018). Flexibility

Function (FF) thus focuses on heating scheduling. The authors argue that since energy flexibility is dynamic, the function should also be able to optimize dynamic alterations. In Figure 2.4., a comparison of a baseline load profile and an energy flexible load profile (utilizing flexibility function) is portrayed. The behavior of the load profile and its immediate impact on indoor temperature is clearly illustrated.

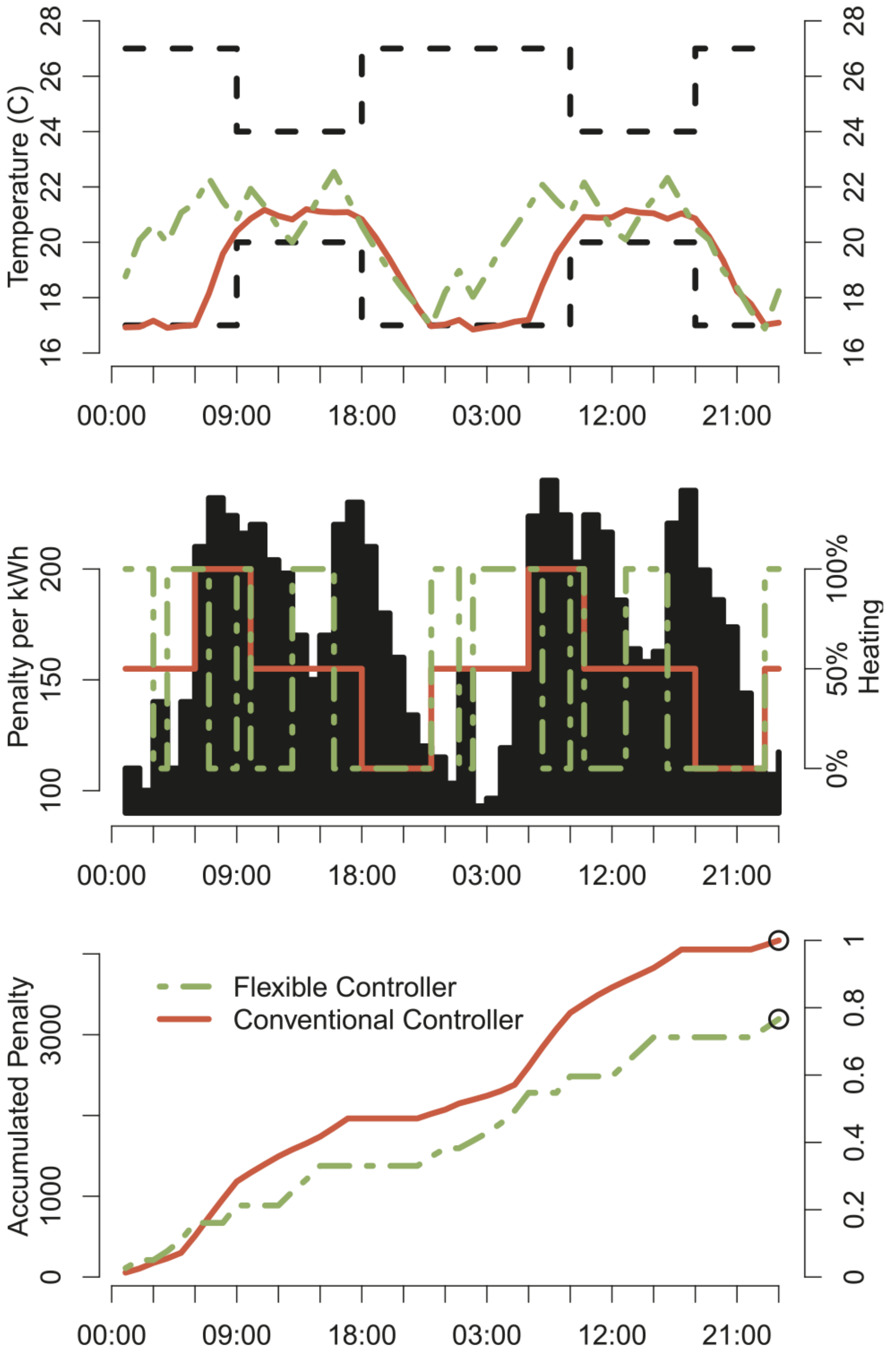

Figure 2.5. Comparing baseline and flexible load profiles (Junker et al., 2018)

In Figure 2.5, the top plot illustrates the changes in indoor temperature with a penalty-aware controller (green, dashed) and a conventional controller (red, solid). The controller can not exceed the black dashed lines. In the middle plot, the black shades indicate penalty hours, whereas the green and red lines illustrate the heating percentage and times of both controllers, respectively. Lastly, in the bottom plot, the accumulation of penalties is illustrated for both controllers (Junker et al., 2018). As inferred from the figure, the flexible controller manages to keep the indoor temperature between the desired comfort setpoints while reducing the accumulating penalty through intermittent usage of heating power, providing energy flexibility.

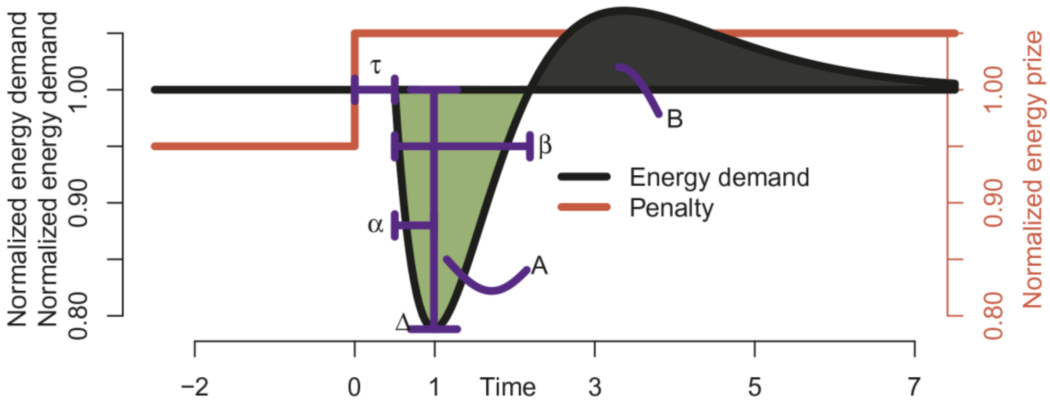

Figure 2.6. Flexibility characteristics (Junker et al., 2018)

Figure 2.6. depicts six characteristics of the flexibility function. These characteristics are, respectively (Junker et al., 2018):

1. τ (Time): The delay from adjusting the energy price and seeing an effect on the energy demand. 0.5 in the example.
2. Δ (Power): The maximum change in demand following the penalty change. 0.2 in the example.
3. α (Time): The time it takes from the start of a change in demand until it reaches the lowest level. 0.6 in the example.
4. β (Time): The total time of decreased energy demand. 2 in the example.
5. A (Energy): The total amount of decreased energy demand.

6. B (Energy): The total amount of increased energy demand (Junker et al., 2018).

2.5 Energy Flexibility and Positive Energy Districts

One of the primary pillars of PEDs, 'energy generation', is closely linked to the concept of energy flexibility. In order to increase energy generation through photovoltaic panels and self-consumption, Rinaldi et al. (2022) emphasize the need to consider the energy flexibility offered by HVAC systems, such as heat pumps and domestic hot water boilers, with the electricity energy generation through photovoltaic panels. According to Junker et al. (2018), demand-side management strategies are required to manage potential crises that may emerge when integrating instantaneous, fluctuating renewable energy generation into an electrical grid. Demand-side energy flexibility, which essentially proposes community-initiated initiatives, is firmly intertwined with the fundamental elements of PEDs within the methods and strategies of energy flexibility. This highlights the importance of energy flexibility in this regard. Given that PEDs are multi-layered systems designed to integrate renewable energy production with the current electrical grid, this evaluation is critical.

2.6 State of the Art & Gap in the Literature

The research on energy flexibility constitutes a wide range of variety. Many studies explore and evaluate energy flexibility through different kinds of buildings. Several studies are commonly situated in broader fields. Energy flexibility through thermal mass, energy flexibility via MPC controllers, and energy flexibility through smart scheduling of HVAC equipment and household appliances are a few examples of these fields.

Regarding the achievement of energy flexibility through building thermal mass or smart scheduling of the HVAC equipment, the research is widespread and comprehensive. Johra et al. (2019) conducted research on 144 dwellings in Denmark, to explore the role of thermal mass with respect to energy flexibility, and the main parameters affecting it. The results have shown that the level of insulation had the most critical effect on the flexibility of space heating. Le Dréau & Meulemans (2018) investigated five different typologies of buildings to evaluate the control of residential space heating with respect to energy flexibility. The authors have found out that activating thermal mass carries the potential of extending discharge and recharge times of space heating up to several days. Foteinaki et al. (2020) conducted research on the energy flexible behavior potential of residential buildings equipped with district heating. The outcomes proved that pre-heating was an effective solution for load shifting and peak load reduction operations, and the shifting of heating loads was achieved in all scenarios between 40% - 87%. Weiß (2020) utilized dynamic building simulation to explore the potentials of thermal load management, through four buildings in Austria. The results pointed out that thermal load management is highly dependent on heating set points and occupant comfort range. Furthermore, an increased amount of thermal mass would result in a 20-30% increase in load shifting potential. Vigna et al. (2019) model two building clusters having ‘heavy’ and ‘light’ thermal mass configurations to discover energy flexibility potential. They also model local renewable energy production through a PV system, which they utilize as a forcing factor for energy flexibility, with the aim of decreasing the heating loads not covered by renewable energy. The results have proven that through a smart set-point schedule (20°C ± 2°C with a step size of ± 5°C), a consistent reduction of 14% is possible with respect to the reference residual heating demand. Klein et al. (2017) has tested the effectiveness of four different storage options (batteries, fuel switch, water tanks, and building thermal mass) through an office building. The results have shown that the evaluated high-inertia heat emission system had significant potential in storing thermal energy.

With respect to the obtaining of energy flexibility through household appliances, there are numerous studies encompassing a wide range of digital tools and appliances. D'hulst et al. (2015), for example, conducted a quantified estimation of demand response flexibility through residential smart appliances. They utilized five appliances (washing machines, tumble dryers, dishwashers, domestic hot water buffers and electric vehicles) to measure and quantify their flexibility potential. The results showed that an average power increase of 430W at midnight, and an average decrease of 65W in the evening per household was possible. Therefore, the amount of flexibility is measured through the amount of power alteration. Tostado-Véliz et al. (2021) carried out research on the flexible operation modes of thermostatically controlled appliances. The outcomes of the study have proven that HVAC and electric water heating (EWH) equipment carried much more flexibility potential compared to the freezer, through achieving 15% and 10% energy reduction, respectively. Yamaguchi et al. (2020) explores the flexibility potential of washing machines and dryers through demand response, in the Kanto region of Japan. The results have shown that a reducible flexibility potential larger than 50 MW was possible, regarding the whole region.

Regarding the achievement of energy flexibility through model-predictive control, the research is relatively lower in amount. Arendt et al. (2019) compare a model-predictive control (MPC) algorithm using multi-objective generic algorithm to a rule-based control (RBC) strategy. The results show that the MPC method results in a reduction of ± 25% in energy consumption, proving that MPC is more beneficial in means of energy flexibility in comparison with RBC. Péan (2019) developed an MPC controller for heat pump control and evaluated the performance in comparison with traditional thermostatic control through simulation frameworks. According to the results, MPC outperforms thermostatic control by increasing the amount of cost saving and reducing the amount of CO2 emission. In another study carried out by Hu et al., a model was created that takes weather conditions, occupancy, and dynamic electricity prices into consideration. The authors found out that MPC was able to improve thermal comfort (in multi-family housings) (2019). Another research conducted by Wolisz et al. has shown that applying MPC through a self-learning model can potentially lower the energy demand by %7 compared to a rule-based control (RBC) mechanism (2020).

Even though all of these studies explicitly reveal energy flexibility potentials through various measures and perspectives, a comprehensive evaluative framework of energy flexibility through smart scheduling of both HVAC equipment and household appliances is lacking in the literature. Therefore, the scope of this thesis aims to fulfill this gap by providing a three-step evaluative framework for reaching energy flexibility potential through (i) the evaluation of building thermal mass, (ii) smart scheduling on HVAC systems and (iii) smart scheduling on household appliances. In addition to that, an inspection of potential renewable energy generation and a concern for reaching energy positivity through flexible load profiles and renewable energy generation, further enhances the study in means of providing a holistic approach towards reaching energy positivity.

CHAPTER 3

A METHOD FOR EXPLORING THE ACHIEVEMENT OF ENERGY POSITIVITY THROUGH ENERGY FLEXIBILITY AND GENERATION

This chapter is dedicated to explaining the proposed exploratory analysis in order to test whether it is possible to reach energy positivity through energy flexibility and energy generation. The methodology for the analysis was developed through a comprehensive consideration of energy flexibility applications, covering a wide range of concerns regarding load flexibility, smart scheduling, local renewable energy generation and key performance indicators for energy flexibility, with the focus being on the operational energy of the building. The method is composed of three steps. The first step is obtaining the 3D energy model, which generates a base model for the initial scenario, namely V_base, and the latter two steps add on top of this base model. This step is critical with respect to generating base heating and cooling loads, and schedules. The second step of "Energy Flexibility Operations" includes certain operations to reach energy flexibility in the building. The first step of this process is to plan a smart scheduling system for HVAC equipment for heating and cooling. The calculation for this process necessitates weather information, peak electricity hours and daily indoor (operative) temperature as an input, in order to generate alternative schedules, perform iterative simulations to determine the best combination of schedules, and define a flexible demand profile based on the final heating and cooling schedules. The latter phase in this strategy is to execute similar operations on the household appliance loads. The calculations necessitate peak electricity hours and shiftable appliance loads as input, to generate alternative schedules and return a flexible demand profile based on the final appliance schedules. Coupled together, these loads form the basis for the second scenario of V_flex, which means the incorporation of energy flexibility to the building. Last but not least importantly, the third step of "Fitting Flexible Energy Demand to

Renewable Energy" explores the coupling of energy demand and potential local renewable energy generation. This phase initially needs a calculation of potential local renewable energy generation. Following the results, a comparative analysis of energy demand and energy generation is carried out to test whether it is possible to reach energy positivity. Finally, the results are expressed through several means to complete the study. In this phase of the methodology, the version of V_flex_gen is generated, in which the renewable energy generation is incorporated.

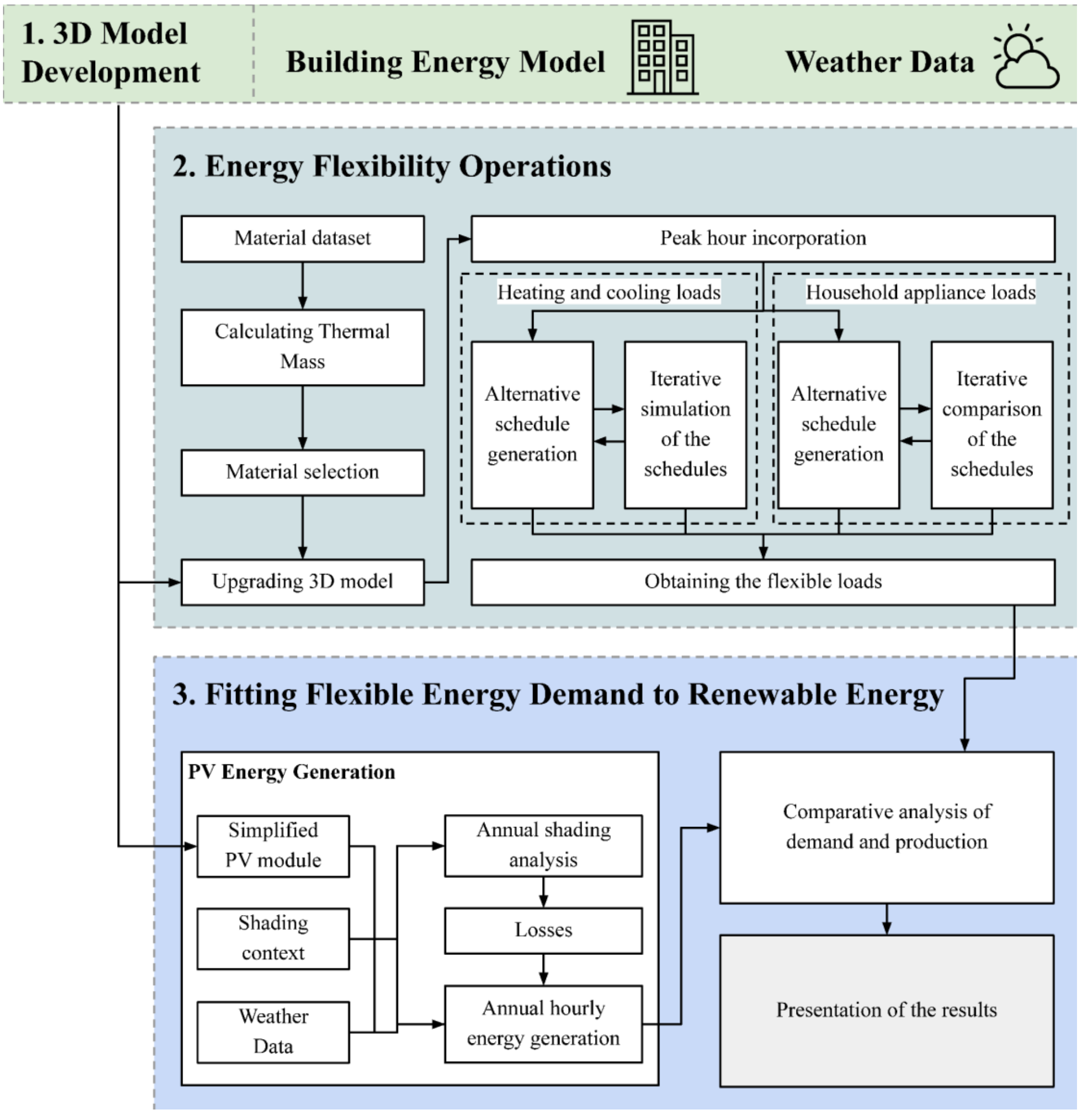

Figure 3.1. A diagrammatic representation of the proposed methodology

3.1 3D Model Development

The first step of the analysis begins by generating the initial scenario of V_base. To initiate this stage, a 3D model development is deemed necessary. 3D model development is a significant process that incorporates physical data into a digital interface, generates a digital twin of an existing building (or buildings), and calculates the energy loads such as heating, cooling, electric and lighting. The performance of 3D energy models is correlated with the quality and quantity of geometrical and technical data provided into them. Specifically for energy demand forecasting, 3D energy models are widely practiced (Liu et al., 2023). The methodology presented in this thesis necessitates a 3D dynamic simulation model and adds on top of it.

3.1.1 Simulation Based Data Generation

The results of the 3D model, with incorporated weather data, results in a realistic approximation of heating and cooling loads, as well as the schedules belonging to the housing units, forming the basis for V_base scenario.

3.2 Energy Flexibility Operations

This phase of the analysis aims to achieve energy flexibility within the household, along with the generation of the second scenario of V_flex. The phase is composed of a three-step process: an evaluation of building thermal mass potential, smart scheduling of HVAC equipment, and smart scheduling of household appliances.

3.2.1 The Operations and the Reasoning Behind Their Usage

Although there are more applications of energy flexibility, the process is narrowed down to the aforementioned three, due to several reasons. Firstly, energy flexibility through building thermal mass has been subjected to much research. Kensby (2017) proposed that building thermal mass is an effective means of storage for the feasibility of energy flexibility. Reynders et al. (2013) researched the role of thermal mass in single-family houses. Le Dréau & Heiselberg (2016) investigated single-family housing units having different insulation and building thermal mass levels, to test potential energy flexibility through thermal performance. Foteinaki et al. (2018) proved in their research that building thermal mass played a significant role in energy flexibility in preventing heat loss. Weiß et al. (2019) studied a well-insulated Austrian building stock context in order to prove the effectiveness of building thermal mass in shifting peak loads. Yang et al. (2022) conducted research regarding the thermal performance of low-energy single-family houses, in a concern for energy flexibility.

Secondly, smart scheduling of HVAC equipment is a critical strategy in the field of energy flexibility. There have been numerous studies underlining the significance of HVAC scheduling, however, the novel research of Junker et al. (2018). They propose a 'Flexibility Function' which takes a price signal (e.g. hourly electricity usage value of the power grid) as an input and arranges on/off scheduling of the HVAC equipment based on the inputs. If the price signal is ignited (e.g. power grid is overcharged), their model stops HVAC from running. Once the price signal drops (e.g. electricity usage decreases below extreme levels), the model turns HVAC back on again. The smart scheduling model in this study takes great inspiration from this study. Tomin et al. (2024) conducted research on a novel approach on the demand-response of HVAC systems using Internet of Things (IoT). Bracke et al. (2024) examines the potentials for an intelligent demand-response system using the re-schedulability of the heat pumps. Tohidi et al. (2024) propose an adaptive mechanism for the price signal generation that further enables HVAC scheduling based on a calibrated demand profile. Akbari et al. (2024) studied a novel methodology in assessing flexibility potential of a single housing using new indicators. Afroz et al. (2024) studied the energy flexibility of a commercial building with a cooling system, based on a price-responsive signal. Considering that these examples are only the recent articles, and there are many more regarding this notion, fundamentally underlines the significance of the topic within the field of energy flexibility.

Last but not least importantly, the smart scheduling of shiftable loads brings about significant energy flexibility potential. As the shiftable loads account for a fair amount of electricity usage, their re-scheduling carries the potential to establish energy flexibility without jeopardizing any occupant comfort parameter. D'hulst et al. (2015) present a quantified estimation of the energy flexibility potential of residential smart appliances through demand-response. Mohseni et al. (2017) develop an energy consumption model of household appliances for day-ahead energy management framework in order to activate time-based demand-response programs. Lezama et al. (2020) experimented on demand-response models through shifting home appliance loads using a distribution system operator (DSO). Tostado-Véliz et al. (2021) propose a home energy management model incorporating flexible operational modes of certain controllable household appliances.

Owing to the fact that these concepts are highly studied and proven to be impactful, they are selected to be explored for this study. There are more means of achieving and establishing energy flexibility rather than just the aforementioned three. Examples may include 'Automated Demand Response' (ADR) or Phase Changing Materials (PCM). However, the scope and capacity of this thesis reaches within the limits of the proposed three steps. Further inquiries regarding the other means of energy flexibility should be proposed upon this study in order to see consecutive improvement.

The initial step is an evaluation of building thermal mass. In this step, the quantification of building thermal mass is calculated by the help of the building envelope materials, and potential improvements to it by the usage of different building materials is analyzed. Whether the improvements satisfy the lower U-value limit denoted by the legislative standards is also checked in this step. Upon this, a smart scheduling system is generated for the HVAC equipment, in order to reduce the electricity loads coinciding with the peak electricity demand hours. The scheduling system essentially generates alternative heating and cooling schedules, tests whether the schedules result in indoor (operative) temperatures below the occupant comfort limit, and applies the optimal schedule which not only protects occupant comfort, but also saves electricity energy. The latter step in the process is the smart scheduling of household appliances. Following the smart scheduling operations regarding these two fields in the household, the coupling of those flexible loads helps conclude this process, resulting in the developed scenario of V_flex. The outcomes of the process are then expressed through a set of data visualizations and numeric data.

3.2.2 Evaluation of Building Thermal Mass

Building thermal mass is a feature that has a variety of influences with respect to heat exchange. While there is a variety of research on the positive impacts of building thermal mass, there are also negative aspects depending on the context. According to Reilly & Kinnane (2017), significant reductions in energy use can be facilitated through building thermal mass in hot climates with high diurnal temperature variations, as the change in the outdoor temperature is buffered by the thermal mass. However, for the cold climates in which heating is a greater concern, a high thermal mass can be a drawback instead, potentially resulting in increased energy usage, according to the authors.

In Ankara, on the other hand, critical amounts of both hot and cold time periods exist. Along with the ever-increasing temperature values, the achievement of building thermal mass is deemed necessary as it is proven to be impactful in lowering energy consumption in high temperatures (Reilly & Kinnane, 2017). Therefore, the initial step of the proposed framework consists of an evaluation of the building envelope.

According to the Turkish Standards Institution (TSE), under the regulatory framework of TS-825, the building envelope must fit certain criteria. Examples of these criteria include U-values that cannot be under a certain limit, and the thickness of insulation material.

For the calculation of the overall U-value, the following formula is used:

$$U = (d_1 \times k_1^{-1} + d_2 \times k_2^{-1} + \ldots + d_n \times k_n^{-1})^{-1} \quad (1)$$

in which *U* stands for U-value (W/m².K), *d* stands for thickness (m), and *k* stands for thermal conductivity (W/m.K). Since this method of calculation is frequently found in building physics and thermal analysis textbooks, a formal citation was not seen as necessary.

While building thermal mass is a dynamic notion that can hardly be expressed through static analyses, the main parameters influencing it are thermal conductivity, specific heat capacity and density of the building materials (Reilly & Kinnane, 2017) (Owczarek, 2019). Therefore, the formula for thermal diffusivity is a preferable indicator as it includes a calculation of all the aforementioned values:

$$\alpha = k / (p \times c_p) \quad (2)$$

in which *a* is thermal diffusivity (m^2/s), *k* is thermal conductivity (W/m.K), *p* is density (kg/m^3), and c_p is specific heat capacity (J/kg.K) (Reilly & Kinnane, 2017) (Owczarek, 2019).

With respect to these, the initial step of the analysis evaluates the U-value of the building envelope, and the amount of thermal mass that can potentially be achieved using different building materials. First, a dataset of materials and their properties is created. The features of layering order, material name, thickness, density, specific heat, and thermal conductivity are to be included in the dataset. Secondly, the overall

U-value of the building envelope, and the thermal diffusivity of all the material combinations are calculated Following that, the combination of materials having least amounts of thermal diffusivity as an output is determined. The resulting material combination is, therefore, capable of providing the highest amount of thermal mass. Lastly, the material combination can be encoded into the 3D energy model.

The initial step is to create the dataset. In order to create this dataset of various building envelope materials and their properties, a convenient data collection method is to examine material catalogs created by companies that produce building envelope materials. Many of those catalogs include technical properties of the material, they are therefore convenient. Materials and their technical properties can also be derived from the literature.

Table 3.1. illustrates the structure of the dataset and sample values.

Table 3.1 Structure of the material dataset

Layer	Material	Thickness (m)	Density (kg/m3)	Specific_Heat (J/kg·K)	Thermal_Conductivity (W/m·K) (λ)

The order of the materials ('Layer' column) is encoded as, respectively, from outside to inside. Infiltration is not included as an output for evaluation, as it is highly case-dependent and can not be measured properly. As an alternative, an average value of infiltration is encoded to the 3D energy model.

To sum up, this stage unfolds by investigating potential building materials regarding the building envelope, in order to achieve building thermal mass, while satisfying the U-values legislated through TS-825. In this step, firstly, a material dataset composed of the materials and their technical properties is created. Subsequently, the necessary combination of materials in order to establish building thermal mass while staying below the legislated U-value limits is calculated. The resulting material combination is then encoded into the 3D energy model.

3.2.3 Flexibility of Heating and Cooling Loads

The second step of this study proposes a smart scheduling system of the HVAC equipment regarding heating and cooling loads. Due to intense usage of electricity during the hours of higher demand, known as “peak hours”, the electricity grid deals with higher production of electricity, which may lead to exhaustion and potential malfunctioning issues in the grid. In order to cope with this, the electricity usage within HVAC equipment for heating and cooling applications can be manipulated. With respect to that, the calculation for this strategy necessitates peak electricity hours as input, in order to generate alternative heating and cooling schedules. Following that, the schedules are iteratively simulated. Lastly, the schedule that results in maximum energy flexibility while protecting occupant comfort, is selected; and the final demand profile is portrayed. The main purpose of the strategy is to decrease electricity usage of HVAC equipment during peak electricity hours through fluctuating on/off schedules, while ensuring the protection of occupant comfort.

Peak electricity hours are highly contextual and dependent on the local and national regulations, energy demand, energy sources and electricity grids. In the case of Turkiye, the peak hours of electricity usage encompass a time period from 17:00 to 22:00.

The smart scheduling system proposed for this thesis is highly influenced by the novel work of Junker et al. (2018). The authors present a dynamic “Flexibility Function” as mentioned in the literature review, which incorporates peak hours to a scheduling system. When the electricity usage increases, their algorithm aims to stop the HVAC equipment, and run it again when the electricity usage decreases.

The difference, however, is that their electricity usage input hourly changes, making the algorithm dynamic. In the case of Turkiye, the peak hours are pre-defined, as mentioned above. Therefore, for the calculations in this study, the peak electricity hours were regarded as from 17:00 to 22:00, and the energy consumption between these hours were aimed to be lowered by the energy flexibility operations.

The smart scheduling system proposed in this study, generates a total of 10 schedules. The initial schedule, i0, proposes to close the HVAC equipment for the entire period of peak electricity hours. The latter two alternatives, i1.1 and i1.2, propose an on/off schedule that switches every hour. The difference between the schedules is that, during peak hours, one schedule becomes the inverse of the other. Then, the alternatives of i2.1, i2.2, and i2.3 are generated. These alternatives propose schedule patterns that have two hours of 'off' and one hour of 'on' conditions. Lastly, the alternatives of i3.1, i3.2, i3.3 and i3.4 are generated. These alternatives follow a pattern that inhabits three hours of 'off' and one hour of 'on' conditions.

While i0 suggests to entirely stop the heating (or cooling) during peak hours, the i1 group follows a simple "on/off" pattern in consecutive hours. The i2 group follows an "on/off/off" pattern and the alternatives of it, and the i3 group follows an "on/off/off/off" pattern along with its alternatives.

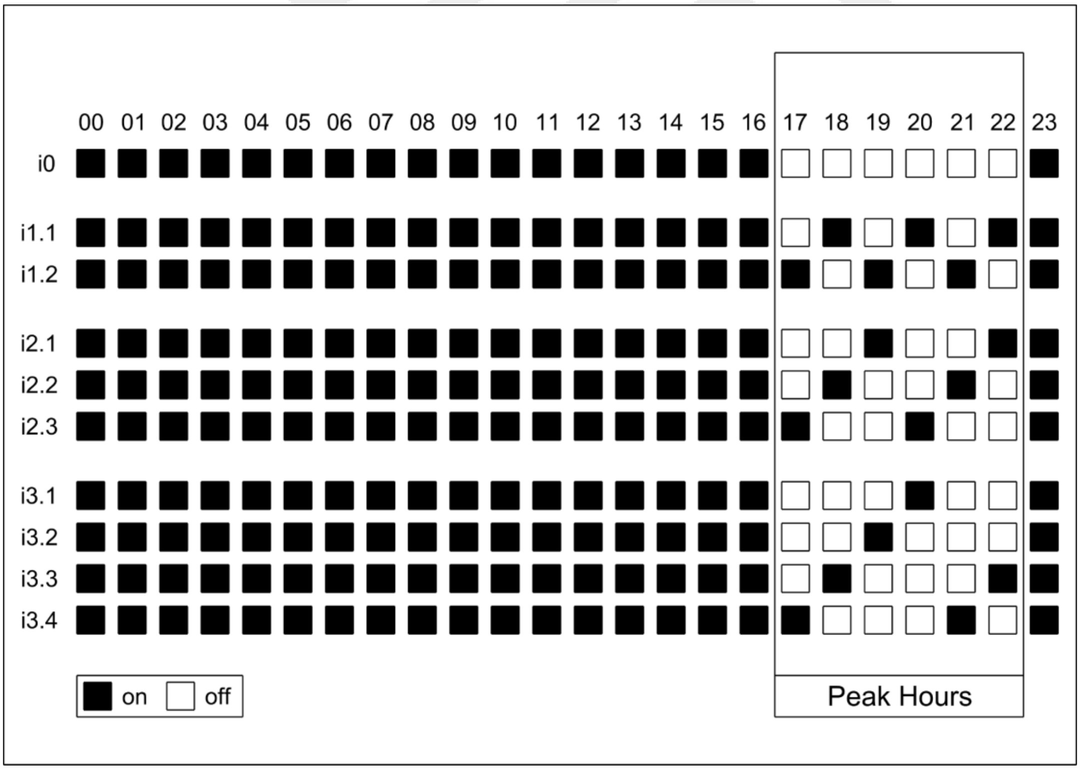

Figure 3.2. Diagrammatic expression of the schedule groups

A diagrammatic explanation of the generated schedules can be found in Figure 3.2. In order not to neglect occupant comfort, each schedule is iteratively simulated, and the results are evaluated accordingly. Upon the iterative simulations, whether the occupant comfort limit is satisfied is checked for each schedule. In case of occupant discomfort, the schedule is disregarded. Then, among the accepted schedules, the one which provides the most amount of energy flexibility is selected.

Figure 3.3 expresses the order of selection for the schedules.

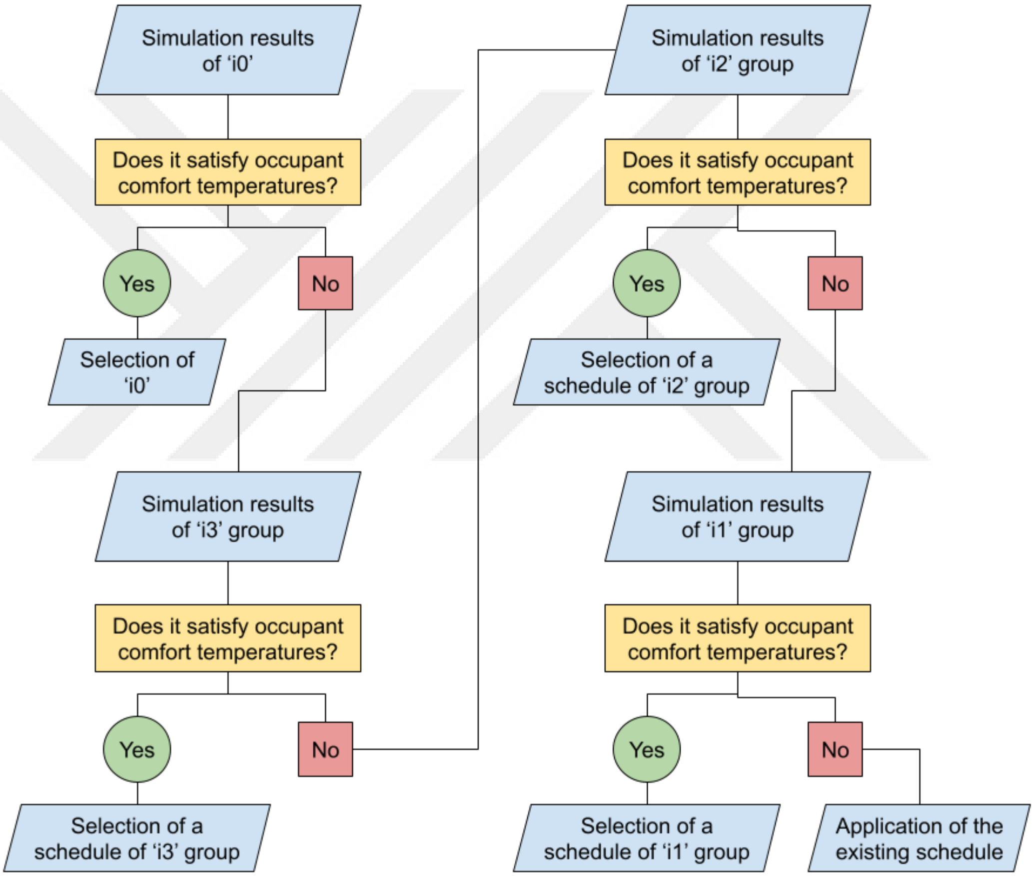

Figure 3.3. The order of selection for the schedules

Once any of the schedules are applied, the indoor (operative) temperature inevitably decreases, as the HVAC equipment would not work for a certain time period.

However, only the schedules that do not result in a decrease below occupant comfort level, are accepted and used for flexibility.

The ultimate aim of the schedules is to decrease the electricity usage of HVAC equipment during peak electricity hours. With respect to that, i0 alternative provides the best results as it proposes to close the HVAC equipment through the entire duration of peak hours. However, this alternative is predicted to neglect occupant comfort in most cases. Therefore, the second-best alternative would be the i3 group, as that group includes the most amount of 'off' hours for the HVAC equipment. Once i3 group is not applicable because of occupant comfort, i2 group is preferred, and similarly, i1 group is applied if the former does not qualify.

Upon the calculation of baseline and flexible load profiles, two key performance indicators (KPIs) are used in order to quantify the achieved flexibility. One of them is "Peak Power Reduction" (Reynders et al., 2017) (Afzalan et al., 2019) (Camporeale et al., 2017):

$$\Delta p = P_{peak\ ref} - P_{peak\ flexible} \quad (3)$$

In which Δp stands for peak power reduction, $P_{peak\ ref}$ stands for reference peak electricity load, and $P_{peak\ flexible}$ stands for the peak electricity load after energy flexibility operations.

The other KPI "Flexibility Savings Index" (Junker et al., 2018) (Azizi et al., 2020) (Salom et al., 2021) (Sergi et al. 2021) (Finck et al., 2020) (Majdalani et al., 2020) has the following formula:

$$FI = 1 - (C_{flex} / C_{base}) \quad (4)$$

in which F*I* stands for 'Flexibility Savings Index', C_{flex} stands for the cost of electricity through flexible (penalty-aware) operation, and C_{base} stands for the cost of baseline electricity (penalty-ignorant) operation.

For the calculation of the latter KPI, recent electricity prices are considered from the Republic of Turkiye Energy Market Regulatory Authority (www.epdk.gov.tr). Table 3.2 summarizes the recently announced prices for electricity.

Table 3.2 Electricity prices for 2024 (www.epdk.gov.tr)

Type of building	Morning (06:00 - 17:00) (₺/kWh)	Peak (17:00 - 22:00) (₺/kWh)	Night (22:00 - 06:00) (₺/kWh)
Residential	1.42	2.70	0.40

In their comprehensive review article, Li et al. (2023) created a table containing 48 KPI equations for the quantification of energy flexibility, guiding the KPI selection for this thesis. The selection for "Peak Power Reduction" and "Flexibility Savings Index" was made considering the relevance of the KPIs in the literature, and the number of papers (and their citation amounts) referencing the KPIs, both of which were included in the review article of the authors.

To summarize, this step encompasses a range of operations regarding the decrease of the electricity usage of HVAC equipment for heating and cooling during peak electricity hours. This is achieved through a set of calculations. First of all, the peak electricity hours are taken as input. Secondly, the peak electricity hours are utilized to generate alternative on/off schedules for the HVAC equipment. Those schedules are namely i0, i1 group (i1.1 and i1.2), i2 group (i2.1, i2.2 and i2.3) and i3 group (i3.1, i3.2, i3.3, and i3.4). The schedule that provides the most amount of energy flexibility, while not neglecting occupant comfort, is selected and applied for the achievement of energy flexibility. Finally, the energy flexibility is quantified using the KPIs of "Peak Power Reduction" and "Flexibility Savings Index".

3.2.4 Flexibility of Household Appliances

This step is composed of a set of operations that aim to lower the electricity usage in peak hours through smart scheduling of the household appliances. To achieve this, a set of calculations are made. The calculations necessitate shiftable loads (loads that can be rescheduled to be activated earlier or later than the intended time (Plaum et al., 2022); such as washing machines, dishwashers and dryers) as input, to generate alternative schedules for the rescheduling of the loads, compare the schedules to see if they accumulate at a certain time period or not, and return the final schedules to achieve energy flexibility through household appliances.

According to Luo et al. (2022), the appliance loads generated by dishwashers, washing machines and clothes dryers are shiftable loads. Some of the household appliances are not shiftable as they are highly dependent on occupant behavior (e.g. television, lighting, laptops). The advantage of utilizing dishwashers, washing machines and clothes dryers as flexible loads is that their re-scheduling does not interfere with occupant behavior as much as the loads of television, laptops, and other appliances dependent on occupant behavior. To define the appliances to be utilized in this study, 16 papers were examined (Table 3.3).

Table 3.3 Household appliances used in various papers

Author	Year	Household appliances
Luo et al.	2022	Clothes dryer, clothes washer, dishwasher, electric water heater, refrigerator
Sadat-Mohammadi et al.	2020	Clothes washer, dishwasher, electric vehicle
Fischer et al.	2020	Clothes dryer, clothes washer, dishwasher, electric vehicle, freezer, refrigerator
Mancini et al.	2020	Clothes dryer, clothes washer, dishwasher
Weiss et al.	2020	Clothes washer, dishwasher
Afzalan et al.	2019	Air conditioner, clothes dryer, clothes washer, dishwasher, electric vehicle

Table 3.3 (Con’d)

Zhai et al.	2019	Electric water heater, microwave, refrigerator, TV, washing machine
Wu et al.	2019	Absorption chiller, clothes dryer, clothes washer, dishwasher, electric vehicle
Chen et al.	2018	Air conditioner, clothes washer, dishwasher, electric vehicle, thermal storage tank
Candanedo et al.	2017	Clothes dryer, clothes washer, computer, dishwasher, freezer, refrigerator, TV
Rotger-Griful et al.	2017	Clothes dryer, clothes washer
Cetin et al.	2016	Clothes dryer, clothes washer, dishwasher, refrigerator
Salpakari et al.	2016	Clothes dryer, clothes washer, dishwasher, tumbler
D'hulst et al.	2015	Clothes dryer, clothes washer, dishwasher, electric vehicle
Brahman et al.	2015	Air conditioner, clothes dryer, clothes washer, dishwasher, electric vehicle, iron, pool pump
Chen et al.	2013	Air conditioner, clothes dryer, clothes washer, dishwasher

Hence, within the scope of this study, the appliances of clothes dryer, clothes washer, dishwasher, freezer and refrigerator will be used.

The appliance loads follow a non-predictable pattern and depend on occupant behavior regarding their schedules. The calculations, therefore, begin by taking these loads and their durations as input, along with the peak electricity hours. Following that, alternative schedules for the appliances are generated. The schedules aim to move the shiftable loads from peak electricity hours to off-peak hours. For this purpose, sunlight hours are also taken as input for the calculations. The aim is to evenly distribute the shiftable loads to the time period when renewable energy generation is ongoing, to achieve immediate consumption of locally generated renewable energy.

In spite of all the aforementioned calculations, a set of final schedules are determined for the building, concluding the achievement of energy flexibility. Through the process of appliance scheduling, the electricity load profile is expected to have a tendency towards abstaining from peak electricity hours, and escalating in off-peak hours when electricity price is lower, and the pressure in the grid is relatively decreased. Last but not least importantly, the achieved energy flexibility is also calculated in this stage, using the aforementioned KPIs of “Peak Power Reduction” and “Flexibility Savings Index”.

To conclude, this step deals with the smart scheduling of the household appliances within the exploratory analysis. In order to realize the smart scheduling, a set of calculations are executed. The calculations necessitate peak electricity hours, shiftable loads and duration periods of the household appliances as input, to generate alternative schedules for their start/end cycles. The generated schedules move the loads from peak to off-peak hours, achieving flexibility through household appliances. Finally, the achieved flexibility is quantified using the aforementioned KPI equations.

3.2.5 Coupling the Flexible Loads

This is the final step of achieving energy flexibility within the exploratory analysis. In this step, the load flexibility achieved through the smart scheduling of HVAC equipment and household appliances, are coupled to present a final flexible load distribution.

The smart scheduling of HVAC equipment helps lowering the electricity demand on the peak electricity hours. That of household appliances also contributes to the offsetting of electricity demand from peak electricity hours. When coupled together, they present a final load distribution that aims to achieve a fair amount of energy flexibility within the household. This three-step process paves the way to the next phase of the analysis, in which the demand is comparatively analyzed with potential renewable energy supply. This part of the analysis is concluded through a set of comparative data visualizations and numeric data for the V_base and V_flex scenarios.

3.3 Fitting Flexible Energy Demand to Renewable Energy

This phase of the analysis conducts a thorough exploration of local renewable energy generation potential, and a comprehensive analysis of energy demand and energy production. Through the implementation of this step, the final scenario of V_flex_gen is generated. This scenario concludes the analysis, providing critical information on whether it is possible for the building to reach energy positivity. In order to better express the results, typical winter week and typical summer week is evaluated in means of reaching energy positivity through the set of operations presented by the methodology.

3.3.1 Evaluation of Potential Renewable Energy Generation

The initial step of this phase is to evaluate the local renewable energy potential for the household. There is a wide range of options for renewable energy generation, most of which is highly contextual and dependent on various geographical factors. Nevertheless, solar energy generation through PV panels is a widespread means of local renewable energy generation. The data required for this stage is hourly local renewable energy production. Once this data is generated, the following stages can be constructed upon it.

3.3.2 Comparative Analysis of Demand and Production

In this phase of the process, the obtained data from both energy demand and energy generation, is comparatively analyzed in order to see whether energy demand can be compensated through local renewable energy generation. Given that both energy demand and energy production have intermittent and fluctuating load profiles, an evaluation of multiple temporal layers is deemed appropriate, utilizing typical winter and typical summer weeks of the year.

The renewable energy generation is fairly intermittent, as it is highly dependent on insolation hours. Therefore, renewable energy cannot be present at every hour of demand. The installment of a battery is a convenient solution to this issue. However, within the scope of this research, the action of net-metering is preferred as it does not necessitate any further installment, other than the PV panels.

3.3.3 Presentation of the Results

The last step in this process, being the presentation of the results, concludes the exploratory analysis. Through detailed expression of the final flexible loads and potential renewable energy generation, the scenario of V_flex_gen is generated. This scenario, being the last one in the analysis framework, encompasses the upgrade of renewable energy integration to the system. Along with the flexibility achievement, this scenario of V_flex_gen can express whether the household can reach energy positivity or not.

The results are presented through several charts that encompass a wide range of expression methods. The load profiles are given for both demand and supply, as well as the percentages of sufficiency or energy surplus. Furthermore, the three scenarios are comparatively illustrated to express their impacts on each other. The results further provide insight on whether the load distribution is wisely tackled or not, which may lead to a re-consideration of the previous steps.

CHAPTER 4

EVALUATING THE EXPLORATORY ANALYSIS ON A CASE STUDY

This chapter is dedicated to the application of proposed exploratory analysis on a case study. The chapter unfolds upon the generation of V_base scenarios based on the outcomes of a project under the name of “Auto characterization of PEDs for digital references towards iterative process optimization”, shortly referred to as “PED-ACT”. The project is funded by the Scientific and Technological Research Council of Turkey under grant number TUBITAK 120N780. Middle East Technical University is a partner in the project; therefore, the model is generated through the contributions of Eser Delice, Fatma Ece Gursoy, Ataberk Yilmaz, Yasin Ataberk Demir, and Cihat Ilkbahar; under the supervision of Prof. Dr. Ipek Gursel Dino and Assoc. Prof. Onur Taylan.

The development of the analysis continues with the second scenario of V_flex. This scenario is an upgraded version of the initial scenario and aims to achieve a flexible load distribution upon the achievement of energy flexibility.

The analysis is further developed upon the generation of the last scenario of V_flex_gen, which is an upgrade on the previous scenario and aims to examine whether the renewable load generation can satisfy flexible load demand or not. The analysis is concluded through a detailed expression of scenario comparisons, and end results claiming whether energy positivity is reached.

4.1 The first scenario: V_base

The initial step into evaluating the exploratory analysis is the generation of V_base scenario. For this purpose, a single household is selected from the 3D energy model generated within the scope of PED-ACT.

The energy model is generated for a gated community near METU, named 'Çamlık District'. The selected context is located at 39.885°N, 32.794°E in Ankara, Türkiye. Within the region, a typical continental climate pattern is dominant. The dry bulb temperature tends to fall below 0°C in winter and rise well above 30°C in summer months. According to the TMY file obtained through the website of Climate One Building (https://climate.onebuilding.org/), the lowest degree is 7.07°C whereas the highest is 35.3°C. The radiation levels tend to peak during the time period of June to August due to clear weather with a great amount of insolation. On the other hand, the radiation levels are the lowest within the months of December to February due to cloudy weather and less sunlight hours.

The plugins of Ladybug and Honeybee, incorporated into Grasshopper which is also a plugin of Rhino 3D modeling software, were used for the modeling process. Ladybug works with EPW files and can compute a variety of data regarding weather conditions and the impacts of them on the modeled environment, providing helpful insights for the decision-making process. Honeybee, on the other hand, is a simulation tool that combines the softwares of EnergyPlus, Radiance, Daysim and OpenStudio (Sadeghipour Roudsari M., Pak M., 2013).

The semantic data assigned to the model includes not only thermal properties of building envelope, but also heat transfer coefficients (U-values for walls, roofs, ground slabs, and windows), efficiency ratio of the heating systems in use, infiltration rate, window solar heat gain coefficient, and occupant behavior.

Table 4.1 illustrates the numerical values of semantic data provided for the model. The U-values are formed according to TS-825 standards.

Table 4.1 Semantic data for the 3D modeling (According to TS-825 standards)

		Value	Unit
U-values	Walls	0.5	W/m^2K
	Roofs	0.3	
	Ground slabs	0.45	
	Windows	2.4	
Infiltration rate		0.0001	$m^3/s\text{-}m^2$
Window SHGC		0.75	-

Each floor is modeled as one big energy zone, rather than dividing them into further rooms. ‘Zone 1’ is the living room and kitchen, ‘Zone 2’ is the bedrooms, and ‘Zone 3’ is the attic. The building models have the same parameter inputs, and only their roof geometry within the district creates a difference in their energy profile. The roof geometry alters the energy demand because of the variety of openings. The amount of sunlight (and therefore heat energy) the houses receive changes based on the openings in their roofs, which creates differences in the heating and cooling loads. Figure 4.1 illustrates the selected building for the study.

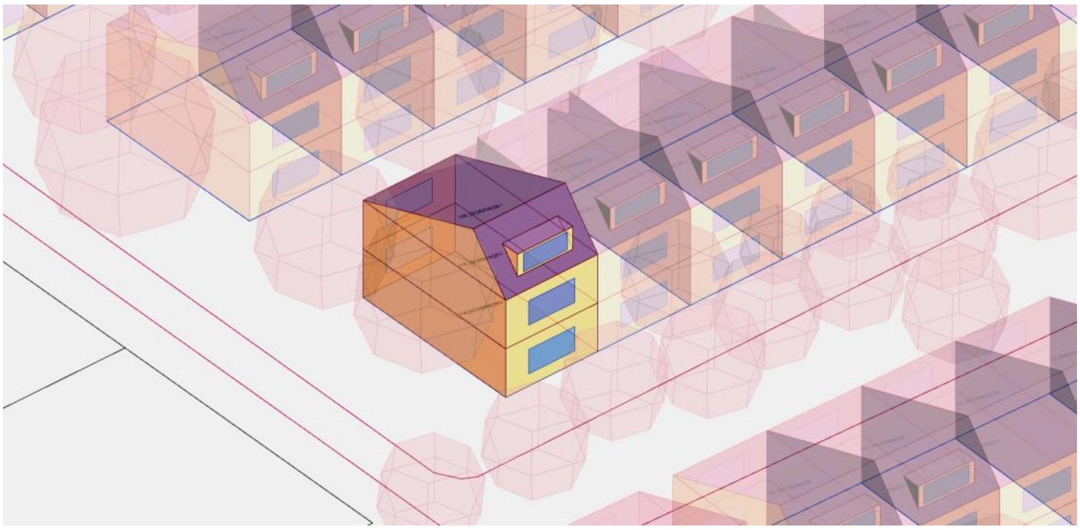

Figure 4.1. The selected building from the model

For the electrification of heating and cooling, an air-source heat pump has been integrated into the model. In comparison with the traditional natural gas boilers and air conditioners, heat pumps provide greater efficiency leading to substantial decreases in heating and cooling loads. Furthermore, through the usage of heat pump, the usage of natural gas can be eliminated.

Zone 1 is day occupied as it includes the living room and kitchen. Therefore, the heating setpoint is 22°C between 07:00 - 00:00, and 19°C between 00:00 - 07:00. Zone 2 is night occupied as it includes bedrooms, therefore the heating setpoint is kept at 19°C for all day long. As Zone 3 is the attic and it is not occupied, the heating setpoint is kept at 18°C also for all day long, since it is hardly occupied (Dino & Meral Akgül, 2019) (Zhang et al., 2011).

The cooling setpoint for Zone 1 is 24°C between 07:00 - 00:00 as it is day occupied. It is also 24°C for Zone 2 between 22:00 - 09:00 as it is night occupied. There is no cooling for Zone 3 as it is barely occupied (Dino & Meral Akgül, 2019) (Zhang et al., 2011). Figure 4.2. explains the occupancy ratio, and Figure 4.3 and 4.4 illustrates the schedules (Dino & Meral Akgül, 2019) (Zhang et al., 2011).

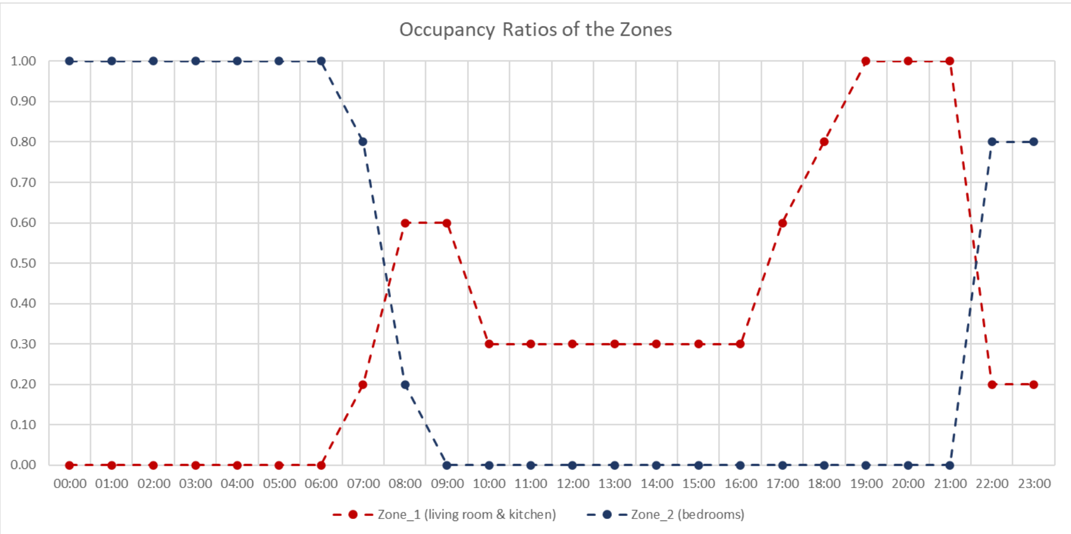

Figure 4.2. The occupancy ratios of the zones for V_base (Dino & Meral Akgül, 2019)

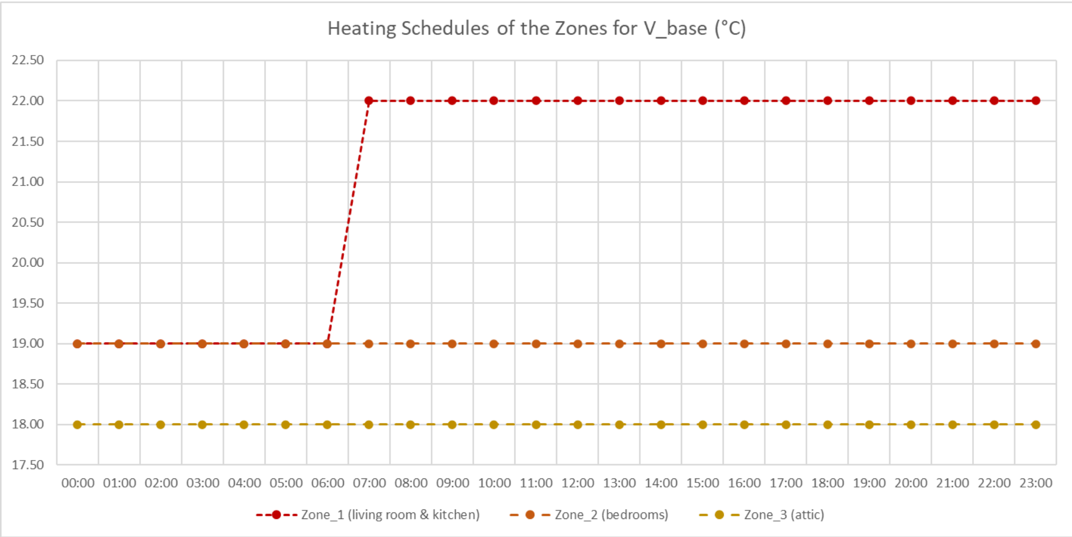

Figure 4.3. The heating schedules of the zones for V_base (°C) (Dino & Meral Akgül, 2019) (Zhang et al., 2011)

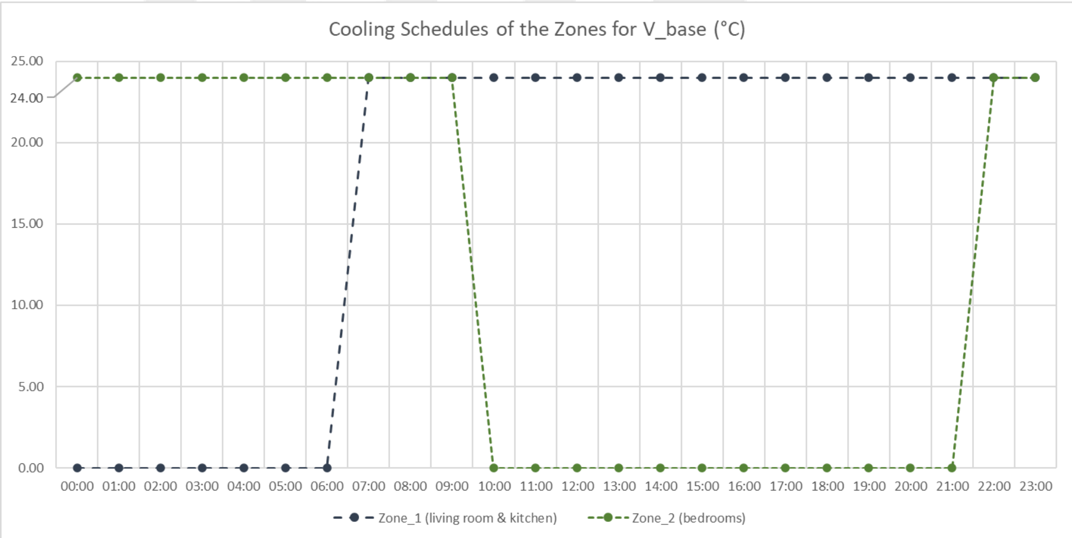

Figure 4.4. The cooling schedules of the zones for V_base (°C) (Dino & Meral Akgül, 2019) (Zhang et al., 2011)

Typical weeks are obtained from the STAT file of the EPW file in use for Ankara (Ankara.Central.171300_TMYx.2007-2021). For the validation of the EPW file, it was compared with two other EPW files (tmy_39.883_32.795_2005_2020) (ankara_central_open_meteo6). Figure 4.5 illustrates the comparison charts.

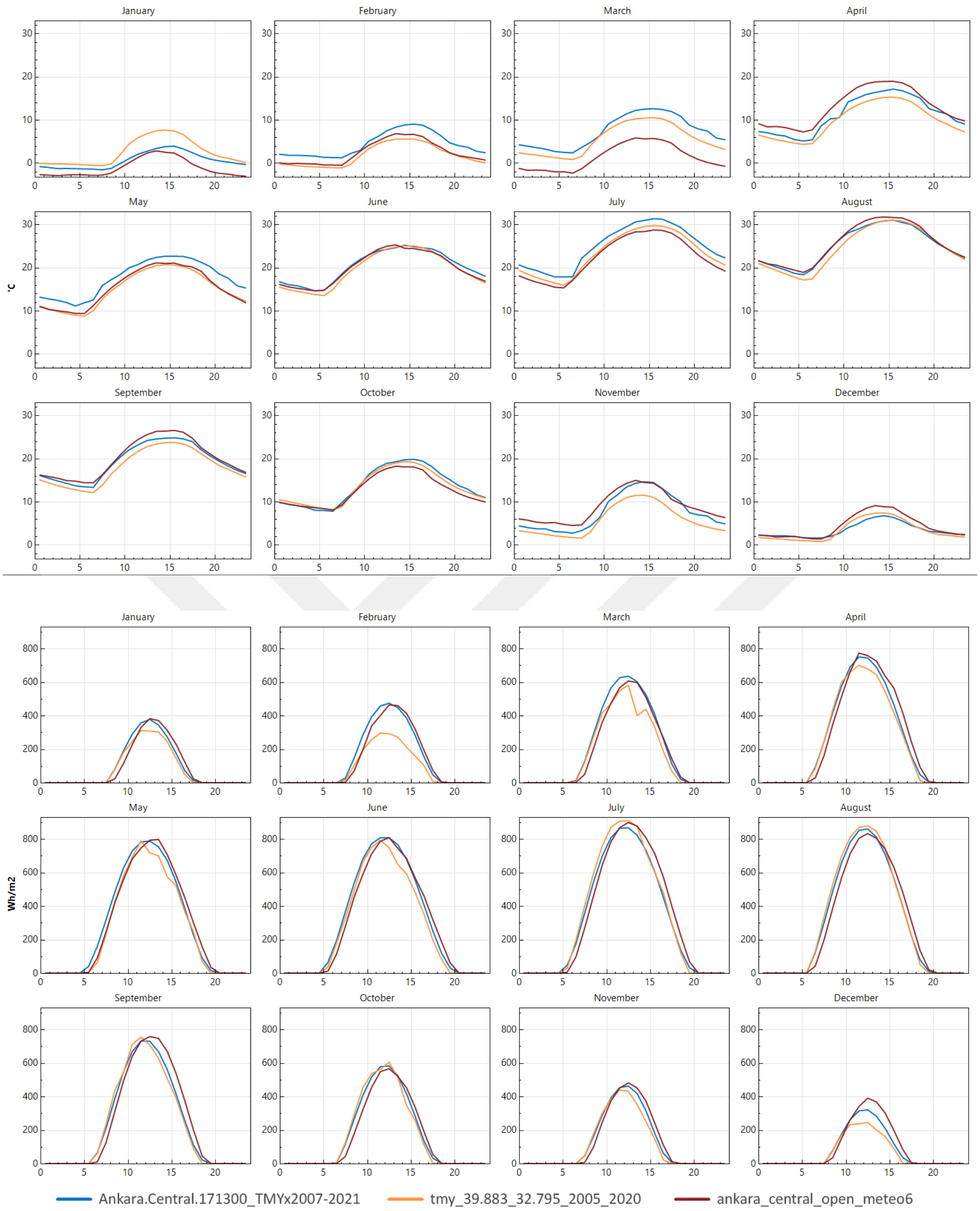

Figure 4.5. Drybulb temperature comparison (above, °C) and GHR comparison (below, W/m²).

After validating the EPW file, the typical weeks are inferred from the STAT file.

According to the results, the typical winter week dates are January 20 - January 26, whereas typical summer week dates are August 10 - August 16. Therefore, these dates will be used for typical weekdays for this study.

The dry bulb temperature values for typical winter and typical summer weeks are illustrated in Figure 4.6. The global horizontal radiation values for typical winter and typical summer weeks are illustrated in Figure 4.7.

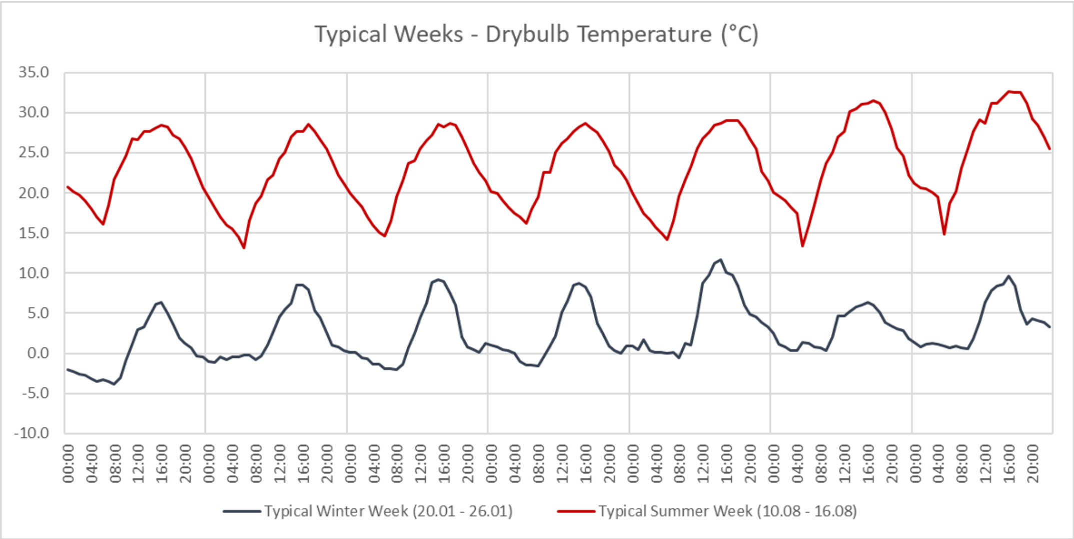

Figure 4.6. Dry bulb temperature for the typical weeks (°C)

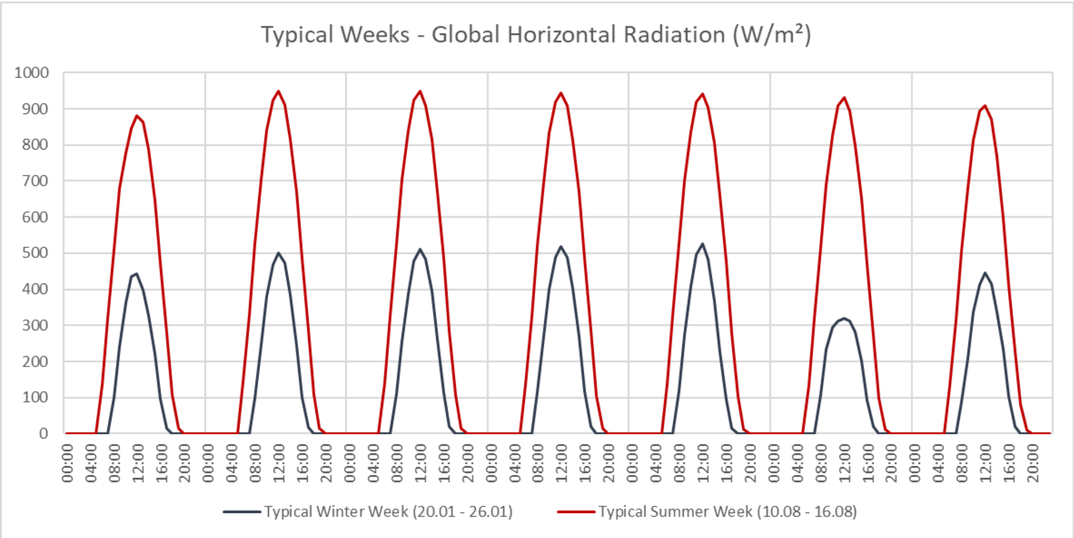

Figure 4.7. Global horizontal radiation for the typical weeks (W/m²)

In order to validate the typical winter and typical summer weeks, a comparison of average values was conducted. Figure 4.8 illustrates the comparison of average drybulb temperature values. The average value of each hour for the winter months (January, February, and December) is compared with the average value of each hour for the typical winter week. Same comparison is valid for the summer months (June, July, and August) and the typical summer week. Figure 4.9 presents a similar comparison for the GHR values.

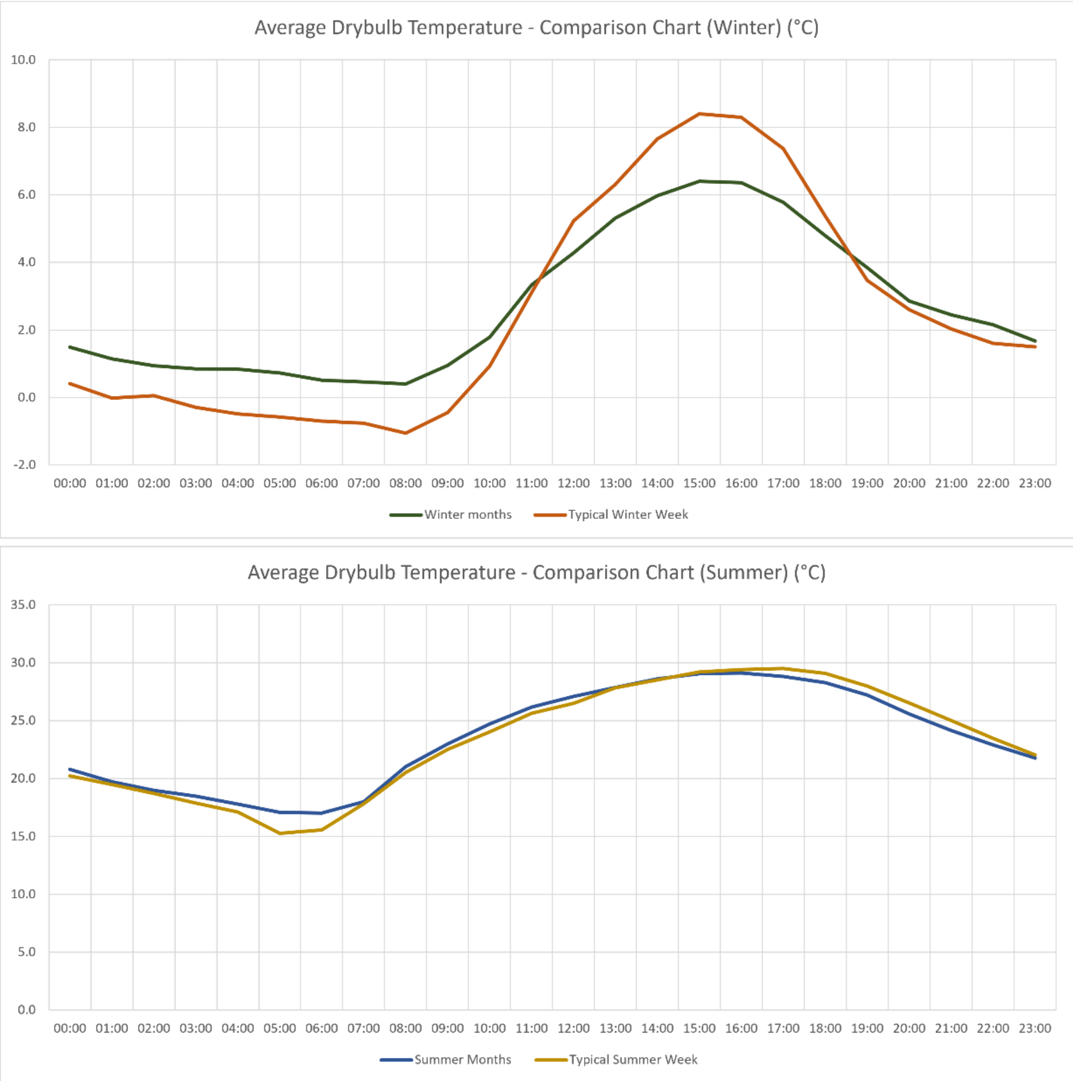

Figure 4.8. Average drybulb temperature comparison for the typical weeks

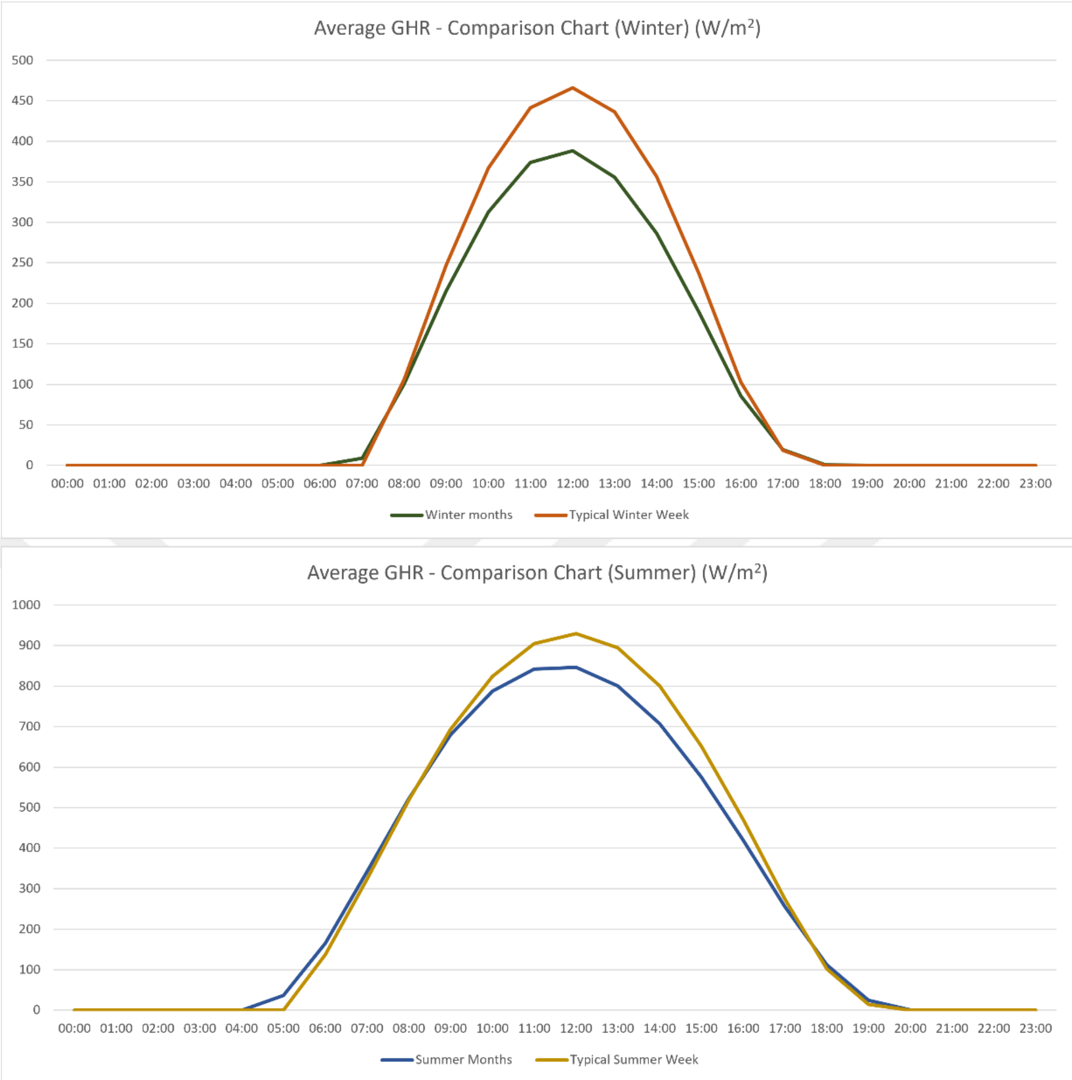

Figure 4.9. Average GHR comparison for the typical weeks

For the electricity loads other than the HVAC equipment, the software named "Load Profile Generator" was used (Pflugradt et al., 2022). This software is a tool for generating household electricity loads with various time resolutions. The tool returns an Excel file inclusive of the names, durations, start and end hours, and hourly loads of a large variety of household equipment. "Load Profile Generator" has been in a continuous improvement period since 2010, originally rooting from a PhD thesis (Pflugradt, 2016). It is fundamentally a software for generating stochastic synthetic residential load profiles. The software employs a desire-driven agent simulation for the modeling of detailed occupant behavior. The software has been used by many authors until today. To name a few; Harder et al. (2020) used it for an analysis of flexibility in electricity grids, Böckl et al. (2019) used it to generate load profiles to conduct an evaluation of sector coupling, Lovati, Zhang, et al. (2020) used it for an evaluation of peer-to-peer electricity trading, Boeckl & Kienberger (2019) used it for the size optimization of PV panels for various load profiles, and Haider & Schegner (2020) used it for an optimization analysis of EV charging patterns (Pflugradt et al., 2022).

The generated load profiles, primarily electricity and hot water, can have a wide range of time resolution options that go as low as 1 minute per se (Pflugradt et al., 2022). Therefore, the shiftable loads of clothes dryer, clothes washer, and dishwasher; along with the loads for freezer and refrigerator, are obtained from the resulting file. The lighting loads are also simulated and used for the study.

“Load Profile Generator” is a complex tool that includes many parameters to be able to estimate realistic electricity load profiles. The parameters include load types, holidays, geographic locations, climate data profiles, modeled persons, their desires and affordances, many options of household appliances, their usage patterns, and time profiles. Since all these parameters are modifiable, the tool can prepare detailed load profiles. Nevertheless, there are certain predefined sets for the ease of usage. There are “Modular Households” such as “Couple both at work”, “Family both at work, 2 children”, “Shiftworker couple” and many more. These modular households have predefined people inside them, and those people have certain desires and affordances that lead them to generate electricity loads within the household.

The calculation for this study was made for the option of “Family both at work, 2 children” scenario, to estimate the electricity loads. However, since the electricity load profiles were higher than expected, the option of “Couple both at work” was utilized instead. “Energy saving” appliances were utilized (appliances that are energy efficient). The geographical location was chosen as Turkiye, and the temperature profile of Ankara, Turkiye was used. The time resolution is hourly. The results of hourly usage data for clothes dryer, clothes washer, dishwasher, freezer, and refrigerator are used in this study, along with the lighting loads.

Table 4.2 presents the lighting and equipment loads taken from the Load Profile Generator.

Table 4.2 The loads taken from Load Profile Generator

Equipment name	Location	Type	Function	Total loads (kWh) (20.01 - 26.01)	Total loads (kWh) (10.08 - 16.08)
Clothes Dryer	Kitchen	Appliance	Cleaning	6.43	2.87
Clothes Washer	Kitchen	Appliance	Cleaning	2.39	1.50
Dishwasher	Kitchen	Appliance	Cleaning	3.00	4.19
Freezer	Kitchen	Appliance	Storage	3.00	2.98
Refrigerator	Kitchen	Appliance	Storage	1.59	1.57
Lighting	All zones	Device	Lighting	1.85	0.73

Figure 4.10 presents the load profiles of the appliances for the typical weeks. The execution ratio of clothes dryer (Miele T 8626 WP) is 3.6 times per week. The execution ratio of clothes washer (Bosch WAE 28143) is 3.3 per week, and the execution ratio of dishwasher (NEFF SD6P1F) is 3.2 per week.

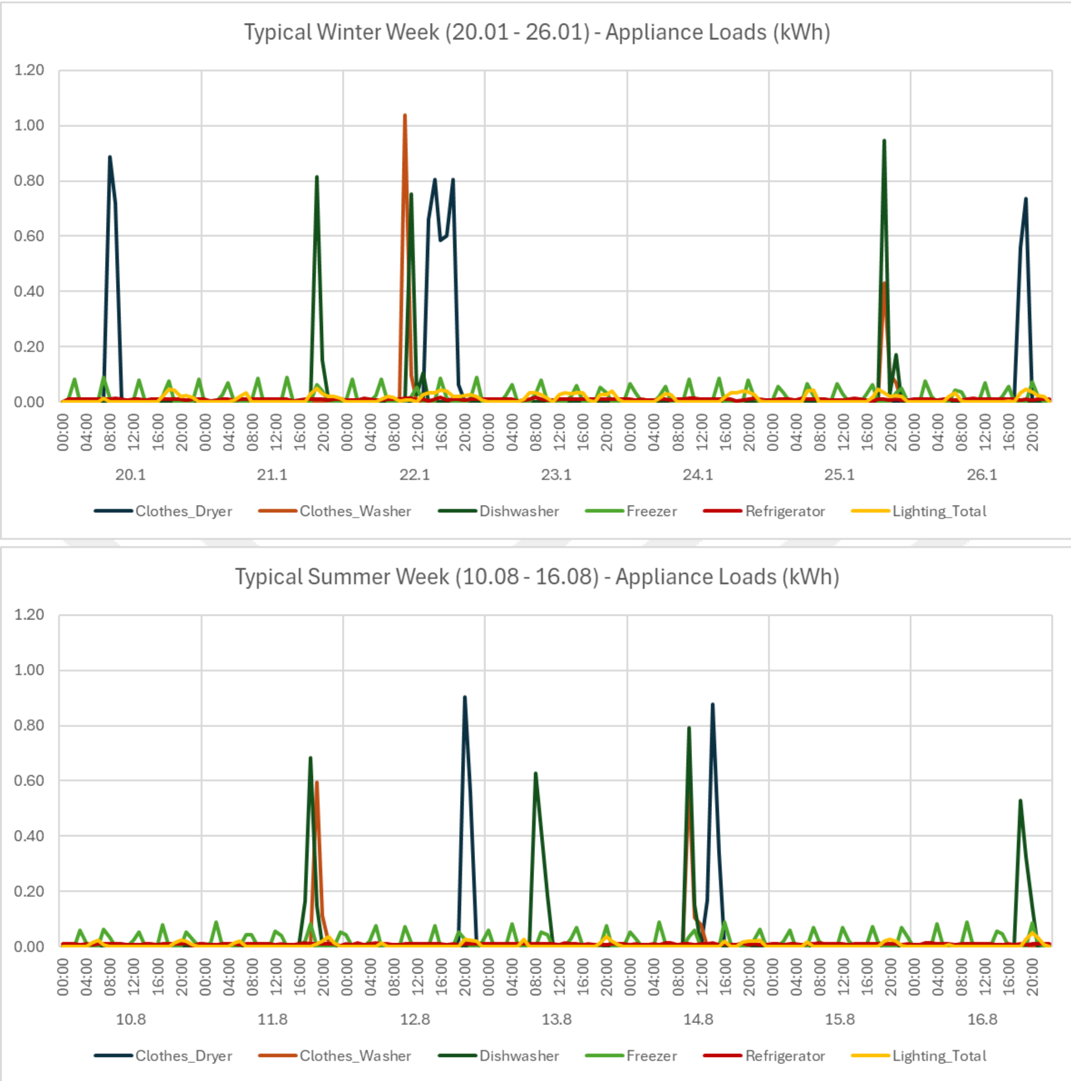

Figure 4.10. Appliance loads obtained from LPG for the typical weeks (kWh)

Figure 4.11 illustrates the simulation results of V_base for the typical winter week (20.01 - 26.01). The COP values of the heat pump for heating for this simulation, vary between 1.62 and 3.88, with an average of 2.55. Boiler efficiency is 0.87.

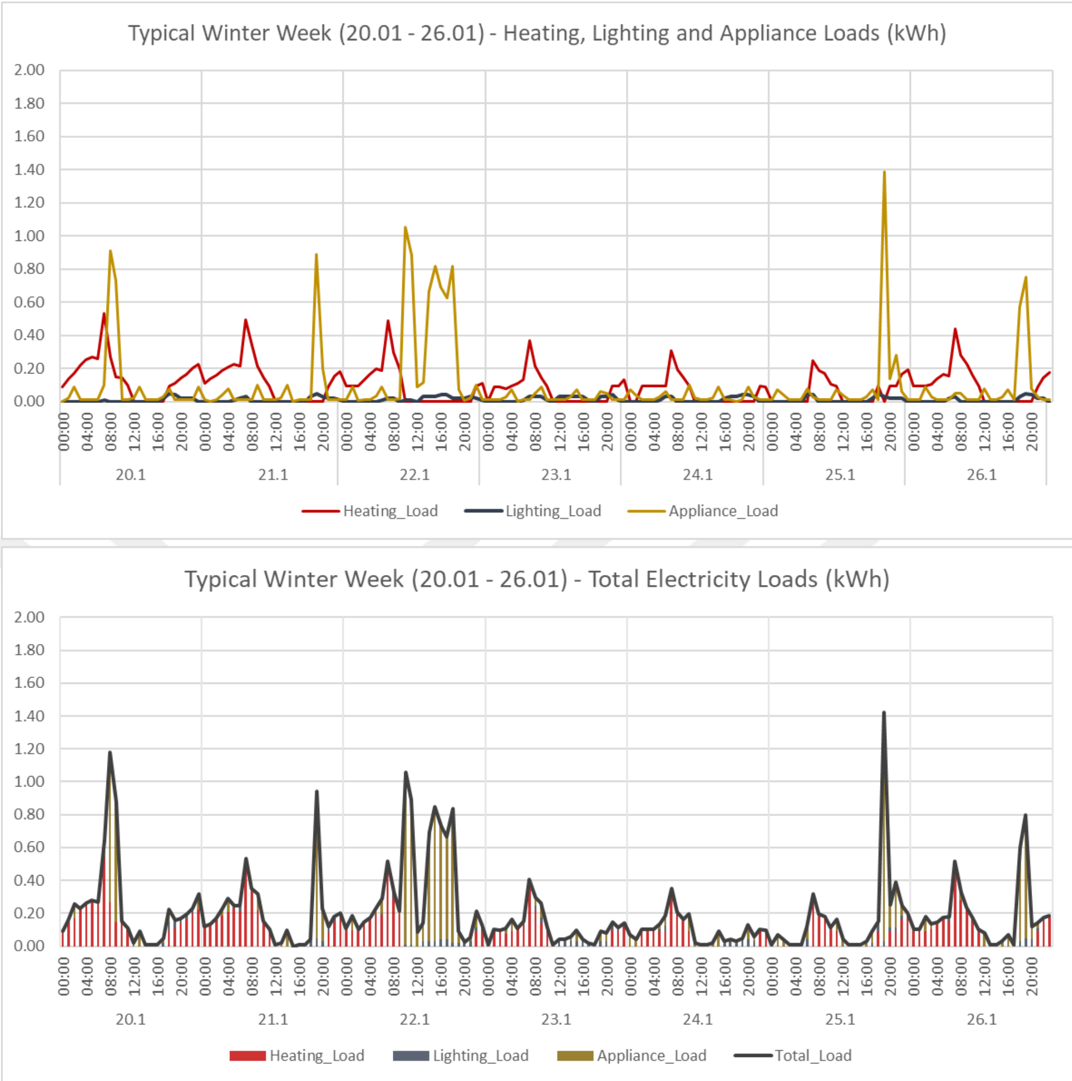

Figure 4.11. Simulation results for typical winter week for V_base

Figure 4.12 illustrates the simulation results of V_base for the typical summer week (10.08 - 16.08). The COP values of the heat pump for cooling for this simulation, vary between 2.34 and 6.26, with an average of 5.16.

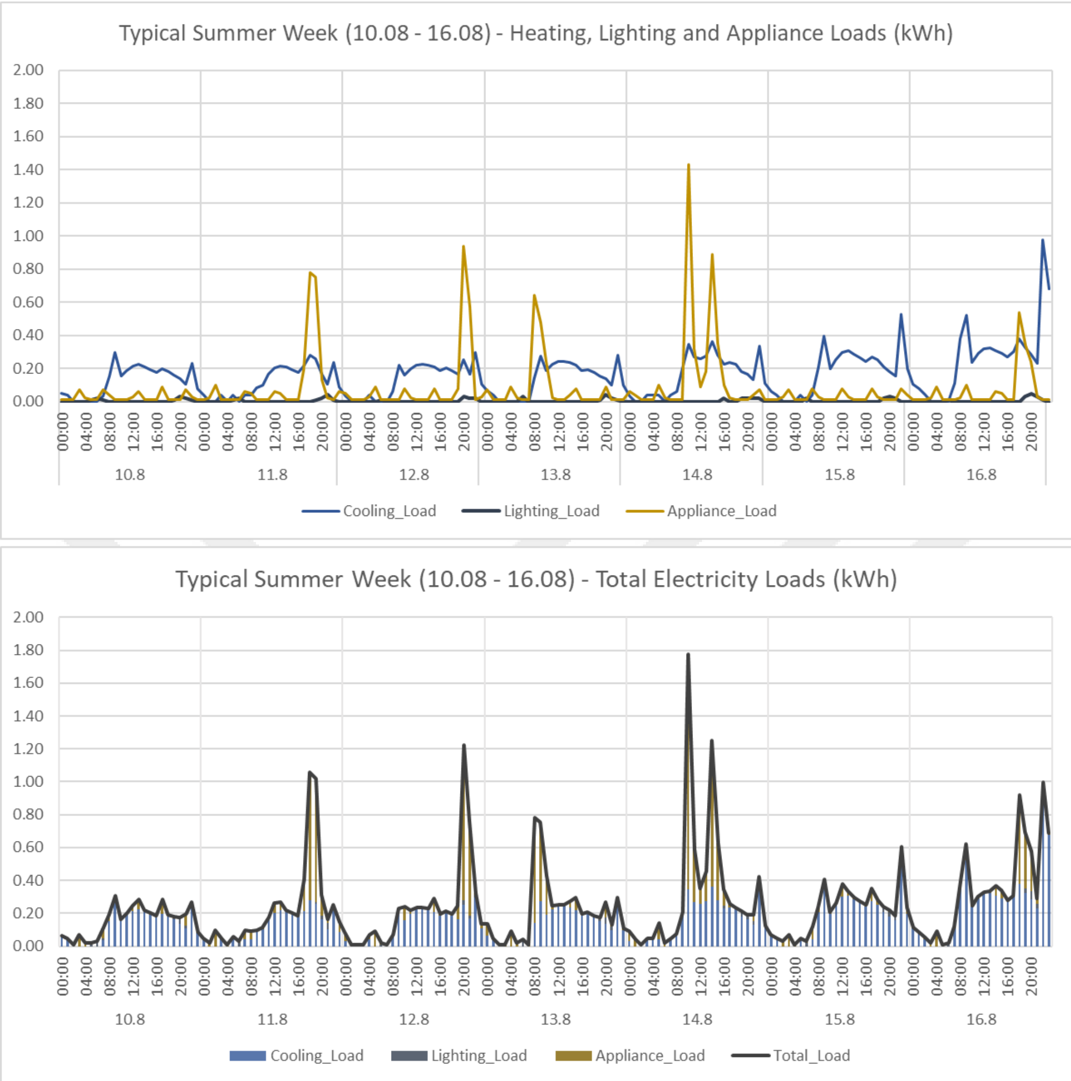

Figure 4.12. Simulation results for typical summer week for V_base

Along with the typical weeks, an annual simulation was carried out for the building. According to the results, without the usage of heat pump, the annual heating energy per square meter is 6.73 kWh/m² (boiler efficiency being 0.87), and 11.98 kWh/m² for cooling. With the usage of heat pump, the values decreased to 2.29 kWh/m² for heating and 1.56 kWh/m² for cooling. The COP values for heating vary between 0 and 4.11, with an average of 2.43. For cooling, the values have a range of 0 to 9.57, with an average of 5.79.

4.2 The second scenario: V_flex

The second scenario of V_flex aims to convert the existing electricity load profiles into flexible electricity load profiles. In order to achieve this, the three-step process explained in the methodology, is applied. The initial step is the evaluation of building thermal mass. The smart scheduling of HVAC equipment follows this step. Finally, the flexible household appliances are also put through a smart scheduling procedure, resulting in an overall flexible load distribution in the household.

4.2.1 Evaluation of Building Thermal Mass

For this step, a dataset including a variety of building materials for the building envelope construction is created. The information in the dataset is derived from the PED-ACT project database (for gypsum, EPS, and brick), and building material catalogs (for Bims and Ytong). Table 4.3 expresses the content of this dataset.

Table 4.3 The material dataset

Layer	Material	Thickness (m)	Density (kg/m3)	Specific_Heat (J/kg·K)	Thermal_Conductivity (W/m·K)
0	Gypsum_exterior	0.030	2000	840	1.600
1	EPS	0.070	22	1500	0.035
2	Brick	0.300	800	840	0.180
2	Bims	0.300	920	840	0.133
2	Ytong	0.300	600	840	0.190
3	Gypsum_interior	0.020	1200	1090	0.510

According to the database, there are three core materials to compare: Brick, Bims, and Ytong. Through the thermal diffusivity calculation by Equation (2), the material that has the least amount of thermal diffusivity is determined as ‘Bims’. The results are presented in Table 4.4.

Table 4.4 Results from the model

Layer	Material	Thickness (m)	Density (kg/m^3)	Specific_ Heat (J/kg·K)	Thermal_ Diffusivity (m^2/s)	U-value (total) (W/m^2·K)
0	Gypsum_e	0.030	2000	840	9.50×10^{-7}	0.25
1	EPS	0.070	22	1500	1.06×10^{-6}	0.25
2	Bims_f	0.250	920	840	1.70×10^{-7}	0.25
3	Gypsum_i	0.020	1200	1090	3.90×10^{-7}	0.25

According to these results, this is the combination resulting in the maximum thermal potential. The U-value is also below the limit that is legislated by TS-825; therefore, the material combination is applicable for the building envelope.

In order to validate the results, it is necessary to take simulations with all three of the core materials. However, so as to compare the impact of building thermal mass, the U-value of the building envelope should be kept the same. According to Equation (1), thermal conductivity and thickness are the two main factors that impact overall U-value. Since thermal conductivity is a fixed value, the thicknesses can be altered to reach the same U-value.

Table 4.5 presents the necessary thickness values for the core materials, to reach the same U-value in the building envelope.

Table 4.5 The thickness values

Layer	Material	U-value (total) (W/m^2·K)	Thickness (m)
2	Brick	0.25	0.32
2	Bims	0.25	0.25
2	Ytong	0.25	0.34

Figure 4.13 illustrates the indoor (operative) temperature upon the simulation of all three core materials, using the thicknesses written above.

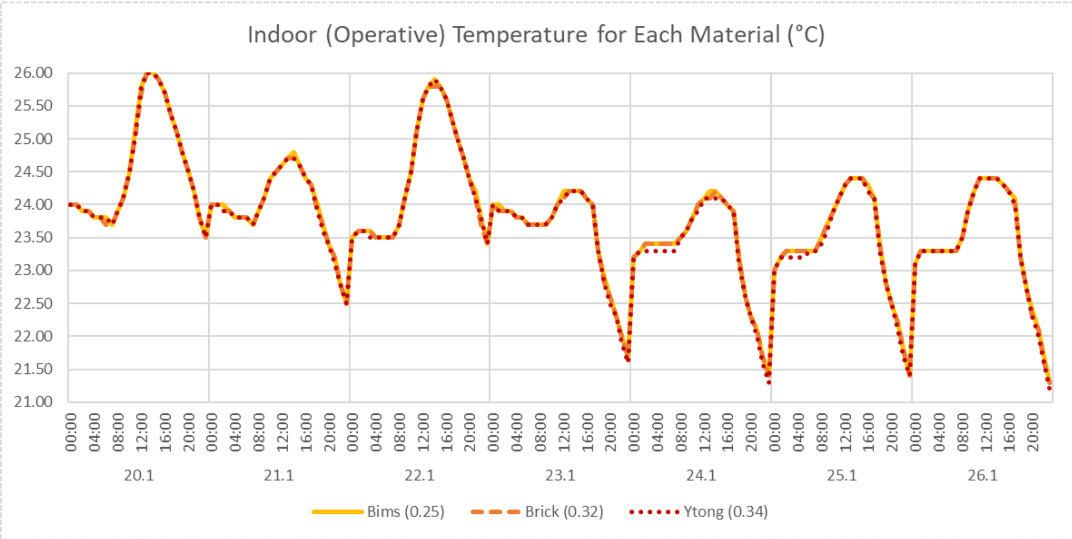

Figure 4.13. Indoor (operative) temperature for each material (°C)

For this simulation, the heating schedule is kept at a constant value for the first 18 hours of the day and closed off for the last 6 hours of the day, to observe the decrease in the indoor (operative) temperature. As inferred from the chart, The indoor operative temperature values remain almost the same upon the usage of all three core materials, with ‘Bims’ slightly performing better at a few hours.

Nevertheless, the lightest option is ‘Bims’, as it has the smallest thickness value. Therefore, for the sake of both building thermal mass and lightweightness of the building envelope, ‘Bims’ is the ideal choice as the core material.

In summary, for this stage, three building envelope materials were evaluated in means of their potential for generating thermal mass. Out of brick, bims, and ytong; bims was selected as the core material for the envelope construction. The main reason behind the selection was that the usage of bims resulted in the lowest amount of thermal diffusivity. Due to its lower value of thermal conductivity, and higher value of denisty, it was more suitable for achieving a higher amount of building thermal mass.

4.2.2 Flexibility of Heating and Cooling Loads

Upon the implementation of the former step, the smart scheduling of the heating and cooling equipment unfolds as the next step. In this phase, based on the existing heating and cooling schedules, alternative schedules (on/off schedules for the heat pump) are generated considering the peak electricity hours (17:00 - 22:00). The schedules are generated for Zone 1, as it is day occupied. The schedule generation occurs according to the patterns illustrated by Figure 3.2 in the methodology chapter.

Table 4.6 illustrates the existing baseline schedule, and the alternative heating schedules prepared for the heat pump.

Table 4.6 Alternative heating schedules for HVAC equipment (heat pump) (°C)

Time	Base	i0	i1.1	i1.2	i2.1	i2.2	i2.3	i3.1	i3.2	i3.3	i3.4
00:00	19	19	19	19	19	19	19	19	19	19	19
01:00	19	19	19	19	19	19	19	19	19	19	19
02:00	19	19	19	19	19	19	19	19	19	19	19
03:00	19	19	19	19	19	19	19	19	19	19	19
04:00	19	19	19	19	19	19	19	19	19	19	19
05:00	19	19	19	19	19	19	19	19	19	19	19
06:00	19	19	19	19	19	19	19	19	19	19	19
07:00	22	22	22	22	22	22	22	22	22	22	22
08:00	22	22	22	22	22	22	22	22	22	22	22
09:00	22	22	22	22	22	22	22	22	22	22	22
10:00	22	22	22	22	22	22	22	22	22	22	22
11:00	22	22	22	22	22	22	22	22	22	22	22
12:00	22	22	22	22	22	22	22	22	22	22	22
13:00	22	22	22	22	22	22	22	22	22	22	22
14:00	22	22	22	22	22	22	22	22	22	22	22
15:00	22	22	22	22	22	22	22	22	22	22	22
16:00	22	22	22	22	22	22	22	22	22	22	22
17:00	22	off	off	22	off	off	22	off	off	off	22
18:00	22	off	22	off	off	22	off	off	off	22	off
19:00	22	off	off	22	22	off	off	off	22	off	off
20:00	22	off	22	off	off	off	22	22	off	off	off
21:00	22	off	off	22	off	22	off	off	off	off	22
22:00	22	off	22	off	22	off	off	off	off	22	off
23:00	22	22	22	22	22	22	22	22	22	22	22

Upon the generation of the schedules, the schedules are iteratively simulated, and the alternatives that do not compromise from occupant comfort are detected. The schedules that cause an indoor (operative) temperature lower degree than 20°C are disregarded (except between 00:00 - 07:00) (Junker et al., 2018). Table 4.5 depicts which schedules are disregarded as they result in an indoor (operative) temperature decrease below 20°C, and which ones are accepted as they ensure occupant comfort. The simulations are done for the typical winter week, and the process is repeated for each day.

Table 4.7 The accepted and disregarded schedules (1: accepted, 0: disregarded)

Day	i0	i1.1	i1.2	i2.1	i2.2	i2.3	i3.1	i3.2	i3.3	i3.4
20.01	1	1	1	1	1	1	1	1	1	1
21.01	1	1	1	1	1	1	1	1	1	1
22.01	1	1	1	1	1	1	1	1	1	1
23.01	1	1	1	1	1	1	1	1	1	1
24.01	1	1	1	1	1	1	1	1	1	1
25.01	1	1	1	1	1	1	1	1	1	1
26.01	1	1	1	1	1	1	1	1	1	1

The results show that all the alternative schedules are applicable as none of them compromise occupant comfort. In this case, the optimum option is to apply i0 as the new heating schedule to Zone 1 for a flexible load profile.

Figure 4.14 illustrates a comparison of baseline vs flexible heating loads and indoor (operative) temperatures (of Zone 1) for the typical winter week, during which the schedule of i0 is used as the new heating schedule.

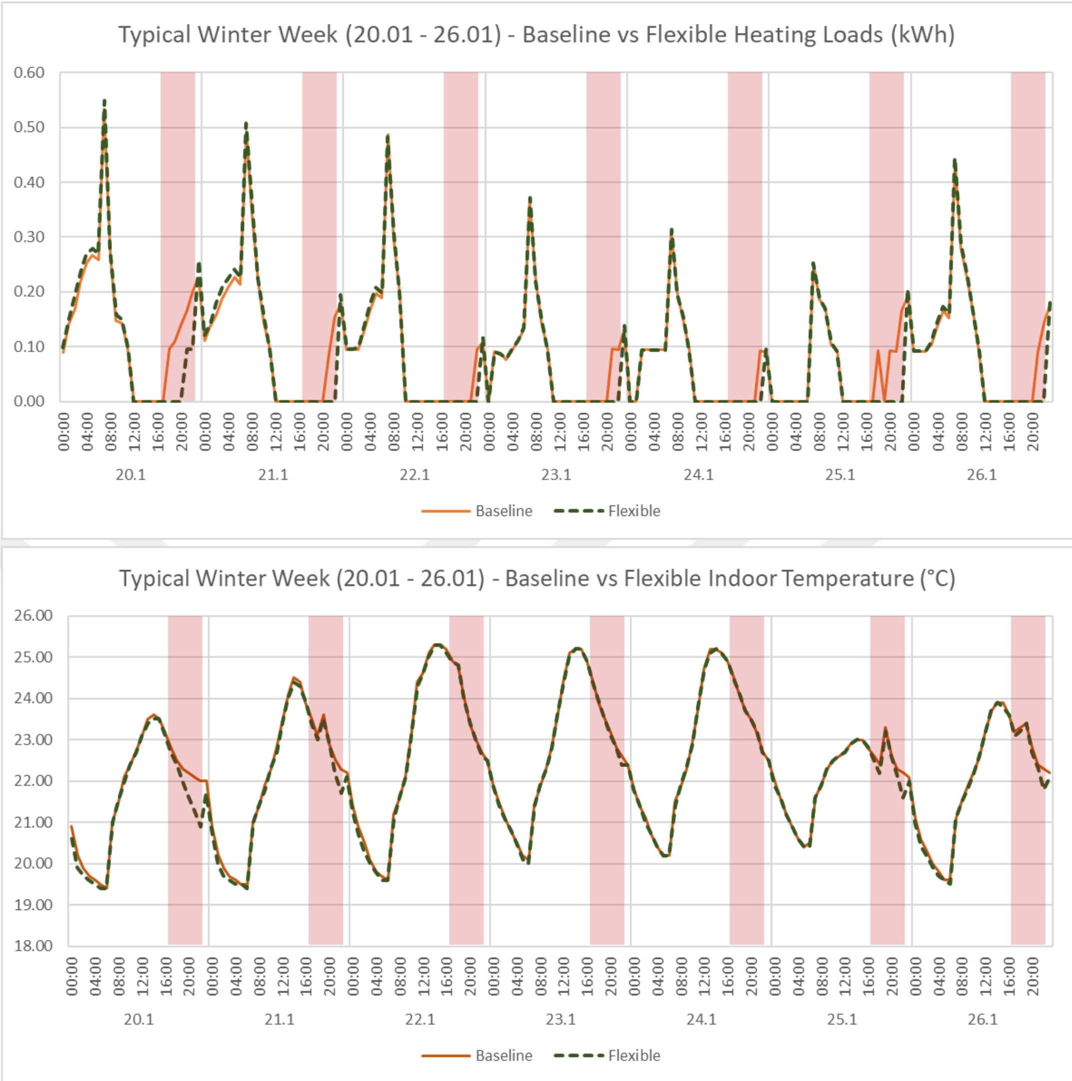

Figure 4.14. Baseline vs flexible heating loads (above, kWh) and operative temperature (below, °C) for the typical winter week
(the pink regions represent peak hours)

Clearly observed from the figure, the indoor (operative) temperature drops in accordance with the integration of the new heating schedule. While this change contributes to the achievement of energy flexibility, it inevitably results in certain decreases in the operative temperature. Nevertheless, all the decreased temperatures are above 20°C (except between 00:00 - 07:00), which complies with the occupant comfort. Furthermore, the total heating load decreases from 15.66 kWh to 14.34 kWh for the typical winter week. A critical remark from the graphic is that the majority of heating loads occur during the earlier hours of the day (04:00 – 08:00). The peak electricity usage occurs at that time for this building. However, it should be noted that the scheduling system in this study operates on a price-based strategy. As the electricity price is the highest between 17:00 – 22:00 (provided by the Republic of Turkiye Energy Market Regulatory Authority), this period of time is considered.

Table 4.8 presents the quantification of the achieved energy flexibility through the KPIs of "Peak Power Reduction" and "Flexibility Savings Index", using Equation (3) and (4).

Table 4.8 Quantification of energy flexibility through scheduling operations

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (F*I*)
20.01	0.71	0.19	0.52	0.30
21.01	0.24	0.00	0.24	0.18
22.01	0.09	0.00	0.09	0.11
23.01	0.19	0.00	0.19	0.25
24.01	0.09	0.00	0.09	0.15
25.01	0.44	0.00	0.44	0.49
26.01	0.23	0.00	0.23	0.22

In order to evaluate the cooling schedules and the impact of their flexible alteration, each zone is treated separately as they have varying cooling schedules. The schedules are generated for Zone 1, as it is day occupied.

Table 4.9 depicts the existing baseline schedule for Zone 1, and the alternative schedules.

Table 4.9 Alternative cooling schedules for HVAC equipment (heat pump) (°C)

Time	Base	i0	i1.1	i1.2	i2.1	i2.2	i2.3	i3.1	i3.2	i3.3	i3.4
00:00	off	off	off	off	off	off	off	off	off	off	off

01:00	off	off	off	off	off	off	off	off	off	off	off
02:00	off	off	off	off	off	off	off	off	off	off	off
03:00	off	off	off	off	off	off	off	off	off	off	off
04:00	off	off	off	off	off	off	off	off	off	off	off
05:00	off	off	off	off	off	off	off	off	off	off	off
06:00	off	off	off	off	off	off	off	off	off	off	off
07:00	24	24	24	24	24	24	24	24	24	24	24
08:00	24	24	24	24	24	24	24	24	24	24	24
09:00	24	24	24	24	24	24	24	24	24	24	24
10:00	24	24	24	24	24	24	24	24	24	24	24
11:00	24	24	24	24	24	24	24	24	24	24	24
12:00	24	24	24	24	24	24	24	24	24	24	24
13:00	24	24	24	24	24	24	24	24	24	24	24
14:00	24	24	24	24	24	24	24	24	24	24	24
15:00	24	24	24	24	24	24	24	24	24	24	24
16:00	24	24	24	24	24	24	24	24	24	24	24
17:00	24	off	off	24	off	off	24	off	off	off	24
18:00	24	off	24	off	off	24	off	off	off	24	off
19:00	24	off	off	24	24	off	off	off	24	off	off
20:00	24	off	24	off	off	off	24	24	off	off	off
21:00	24	off	off	24	off	24	off	off	off	off	24
22:00	24	off	24	off	24	off	off	off	off	24	off
23:00	24	24	24	24	24	24	24	24	24	24	24

According to the results of the iterative simulations, if the upper temperature limit for occupant comfort is taken as 26°C, none of the schedules work since all of them result in operative temperatures higher than 26°C for Zone 1. Hence, even though it is less acceptable regarding occupant comfort, 27°C is selected for the purpose of energy flexibility achievement (Zhang et al., 2011).

Table 4.10 The accepted and disregarded schedules (1: accepted, 0: disregarded)

Day	i0	i1.1	i1.2	i2.1	i2.2	i2.3	i3.1	i3.2	i3.3	i3.4
10.08	0	1	1	0	0	0	0	0	0	0
11.08	0	0	0	0	0	0	0	0	0	0
12.08	0	1	1	0	0	0	0	0	0	0
13.08	0	1	1	0	0	0	0	0	0	0
14.08	0	1	1	0	0	0	0	0	0	0
15.08	0	1	1	0	0	0	0	0	0	0
16.08	0	0	0	0	0	0	0	0	0	0

As inferred from the table, each day has at least two applicable alternative schedules. Since the i3 group provides more flexibility, for the first 5 days, i3.3 is used. For the last 2 days, i1.2 has been used.

Figure 4.15 depicts a comparison of baseline vs flexible heating loads and indoor (operative) temperatures (of Zone 1) for the typical summer week.

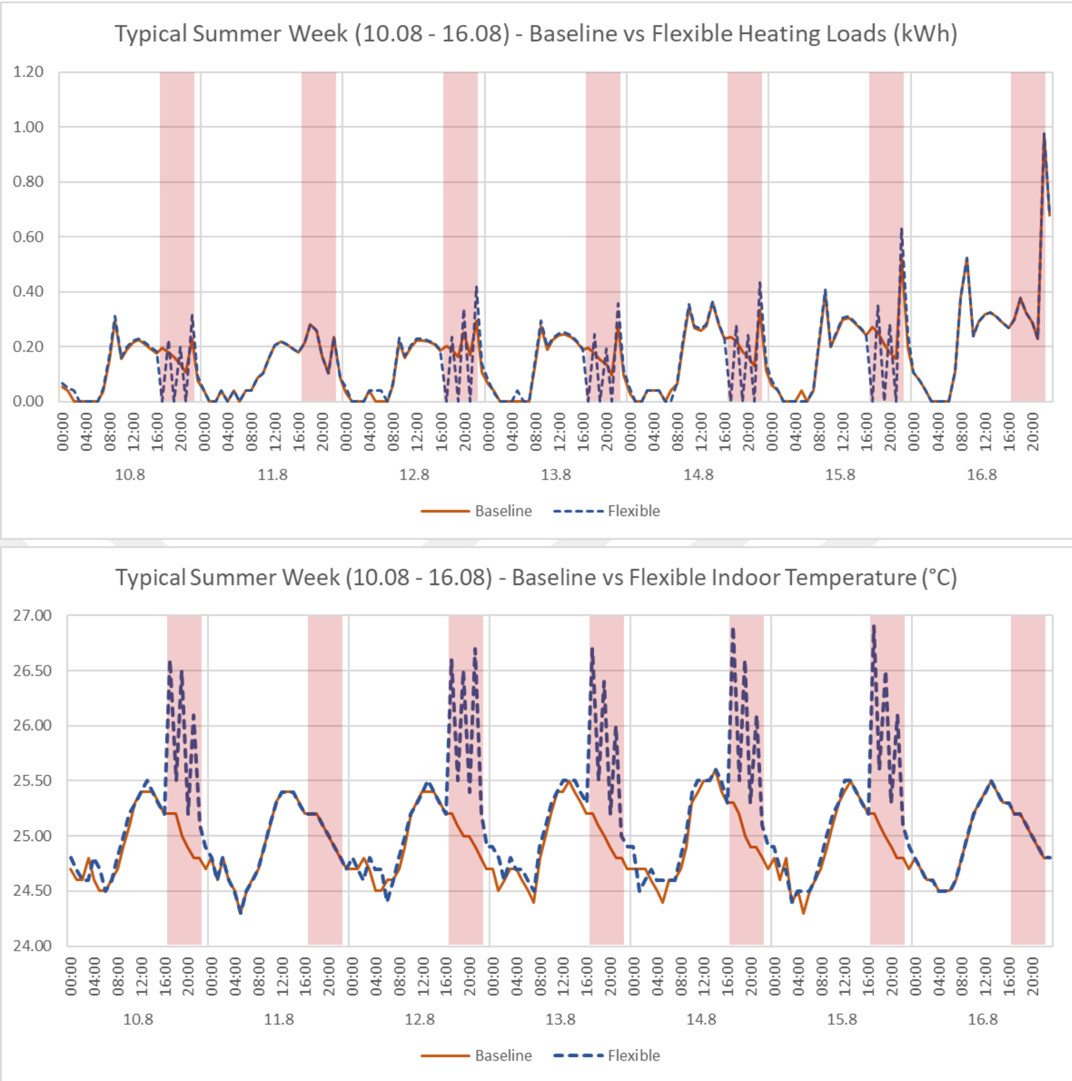

Figure 4.15. Baseline vs flexible heating loads (above, kWh) and operative temperature (below, °C) for the typical summer week
(the pink regions represent peak hours)

As illustrated in the figure, the indoor (operative) temperature goes above 24°C during the hours when the HVAC equipment (heat pump) is off. However, the temperatures never increase above 27°C, therefore being suitable for energy flexibility achievement. Additionally, the total cooling load drops from 26.97 kWh to 26.19 kWh.

Table 4.11 expresses the quantification of the achieved energy flexibility through the KPIs of “Peak Power Reduction” and “Flexibility Savings Index”, using Equation (3) and (4).

Table 4.11 Quantification of energy flexibility through scheduling operations

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (F*I*)
10.08	1.01	0.74	0.27	0.11
11.08	1.25	1.25	0.00	0.00
12.08	1.27	0.99	0.28	0.10
13.08	1.04	0.80	0.24	0.09
14.08	1.27	0.96	0.31	0.12
15.08	1.59	1.26	0.33	0.10
16.08	2.49	2.49	0.00	0.00

4.2.3 Flexibility of Household Appliances

Upon the achievement of flexibility with smart scheduling of HVAC equipment (heat pump), the next step is to evaluate the flexibility of household appliances. For this purpose, the load distributions from the Load Profile Generator are utilized. Among the appliances, the calculations for the flexibility of household appliances necessitates the shiftable loads and to operate on them. In this case, the shiftable loads are regarded as the loads coming from the clothes dryer, clothes washer, and dishwasher.

Table 4.12 Shiftable household appliance loads

Equipment name	Location	Type	Function	Total loads (kWh) (20.01 - 26.01)	Total loads (kWh) (10.08 - 16.08)
Clothes Dryer	Kitchen	Appliance	Cleaning	6.43	2.87
Clothes Washer	Kitchen	Appliance	Cleaning	2.39	1.50
Dishwasher	Kitchen	Appliance	Cleaning	3.00	4.19

Following the determination of shiftable loads, whether their schedule is juxtaposing with the peak electricity hours is checked. The loads are re-scheduled in case they overlap with peak electricity hours, to a time period where renewable energy generation is ongoing, which is the sunlight hours when PV panels are producing electricity energy.

Figure 4.16 illustrates the baseline and flexible load profiles of the shiftable appliance loads for the typical winter week.

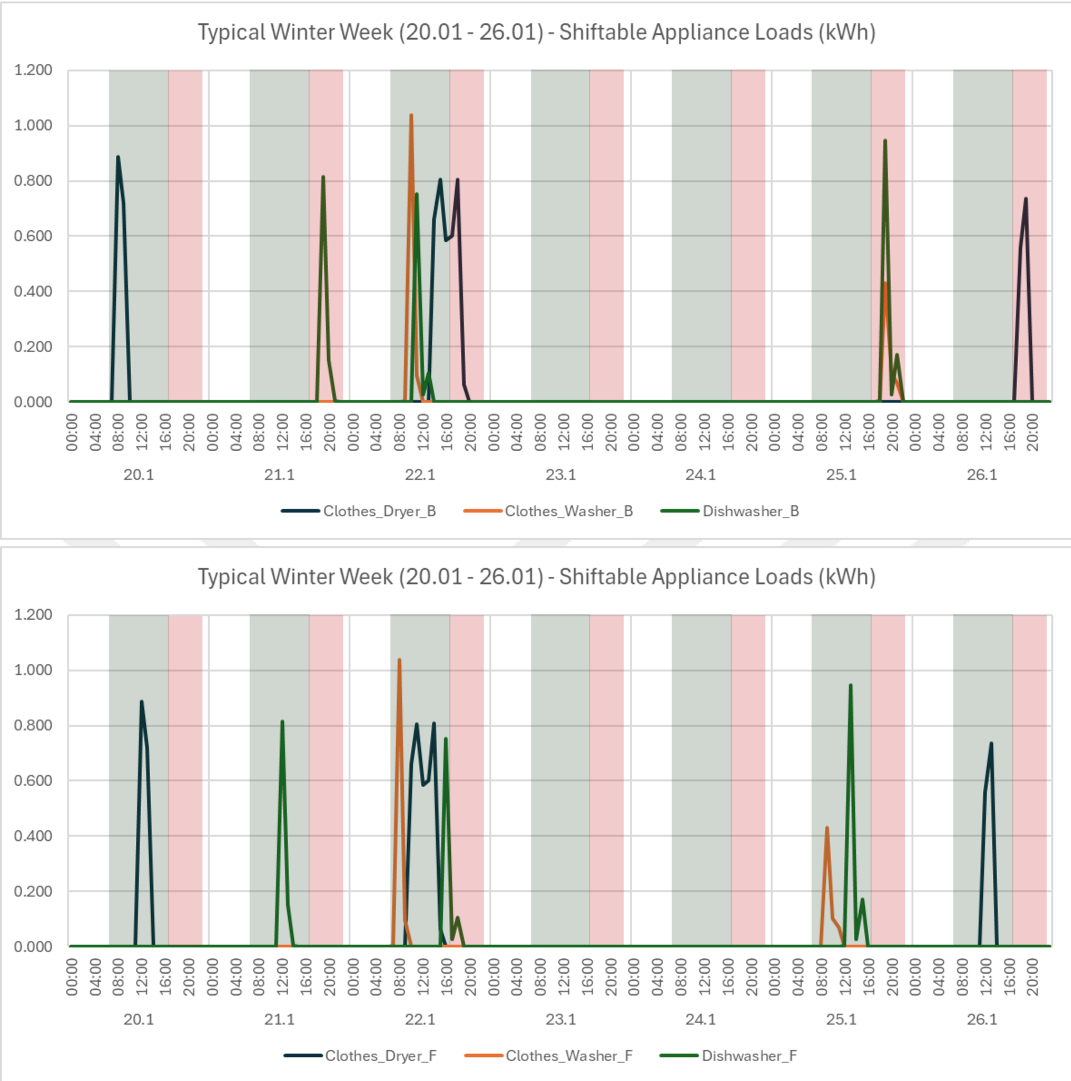

Figure 4.16. Baseline load profile (above, kWh) vs flexible load profile (below, kWh) of shiftable appliance loads for the typical winter week
(the pink regions represent peak hours, green regions represent sunlight hours)

As inferred from the consecutive figures, the loads are shifted from time periods that juxtapose with peak electricity hours, to time periods when renewable energy is actively being produced, abstaining from peak electricity hours.

Table 4.13 illustrates the quantification of the achieved energy flexibility through the KPIs of "Peak Power Reduction" and "Flexibility Savings Index", using Equation (3) and (4).

Table 4.13 Quantification of energy flexibility through shiftable appliance loads

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (F*I*)
20.01	0.00	0.00	0.00	0.00
21.01	0.97	0.00	0.97	0.47
22.01	1.47	0.13	1.34	0.18
23.01	0.00	0.00	0.00	0.00
24.01	0.00	0.00	0.00	0.00
25.01	1.75	0.00	1.75	0.47
26.01	1.30	0.00	1.30	0.47

Similarly, Figure 4.17 expresses the baseline and flexible load profiles of the shiftable appliance loads for the typical summer week.

Figure 4.17. Baseline load profile (above, kWh) vs flexible load profile (below, kWh) of shiftable appliance loads for the typical summer week (the pink regions represent peak hours, green regions represent sunlight hours)

Table 4.14 illustrates the quantification of the achieved energy flexibility through the KPIs of "Peak Power Reduction" and "Flexibility Savings Index", using Equation (3) and (4).

Table 4.14 Quantification of energy flexibility through shiftable appliance loads

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (F*I*)
10.08	0.00	0.00	0.00	0.00
11.08	1.73	0.00	1.73	0.47
12.08	1.49	0.00	1.49	0.47
13.08	0.00	0.00	0.00	0.00
14.08	0.00	0.00	0.00	0.00
15.08	0.00	0.00	0.00	0.00
16.08	1.00	0.00	1.00	0.47

The Load Profile Generator is a partially stochastic software that generates randomized loads based on certain patterns. Therefore, the appliance loads generated for each week are different from each other. In order to generalize this and obtain a general overview on achieving energy flexibility through shiftable appliance loads, more data needs to be processed. For this purpose, 15 more weeks are analyzed, and the achieved energy flexibility is presented. Figure 4.18 illustrates the baseline load profiles and flexible load profiles of shiftable appliance loads (clothes dryer, clothes washer, and dishwasher) for 15 weeks.

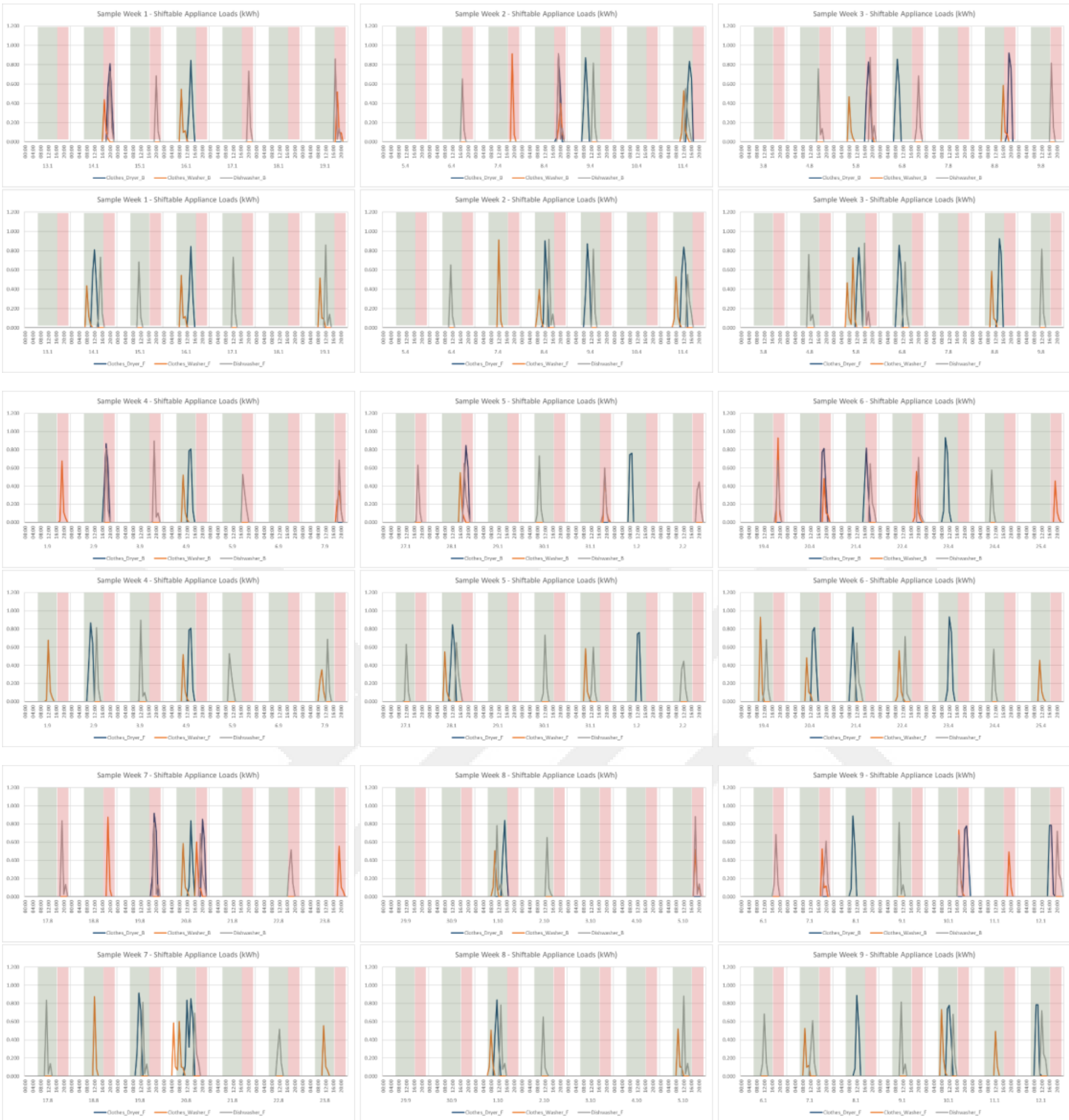
Sample Week 1 - Shiftable Appliance Loads (kWh)
Sample Week 2 - Shiftable Appliance Loads (kWh)
Sample Week 3 - Shiftable Appliance Loads (kWh)
Sample Week 1 - Shiftable Appliance Loads (kWh)
Sample Week 2 - Shiftable Appliance Loads (kWh)
Sample Week 3 - Shiftable Appliance Loads (kWh)
Sample Week 4 - Shiftable Appliance Loads (kWh)
Sample Week 5 - Shiftable Appliance Loads (kWh)
Sample Week 6 - Shiftable Appliance Loads (kWh)
Sample Week 4 - Shiftable Appliance Loads (kWh)
Sample Week 5 - Shiftable Appliance Loads (kWh)
Sample Week 6 - Shiftable Appliance Loads (kWh)
Sample Week 7 - Shiftable Appliance Loads (kWh)
Sample Week 8 - Shiftable Appliance Loads (kWh)
Sample Week 9 - Shiftable Appliance Loads (kWh)
Sample Week 7 - Shiftable Appliance Loads (kWh)
Sample Week 8 - Shiftable Appliance Loads (kWh)
Sample Week 9 - Shiftable Appliance Loads (kWh)

Figure 4.18. Baseline vs flexible load profiles for 15 sample weeks (kWh)
(the pink regions represent peak hours, green regions represent sunlight hours)

Table 4.15 presents the quantification of energy flexibility achieved for the sample weeks. The results cover a total of 105 days, covering the span of 15 weeks.

Table 4.15 Quantification of energy flexibility for sample weeks

Energy flexibility KPI	Minimum	Maximum	Average
Peak power reduction (Δp) (kWh)	0	3.72	0.86
Flexibility savings index (*FI*)	0	0.47	0.23

By conducting this stage of the methodology for more weeks, the flexible operation can be justified by means of being applicable for different contextual shiftable loads rather than a specific stream of loads.

4.2.4 Coupling the Flexible Loads

In this stage, the flexible load profiles obtained from HVAC equipment scheduling and appliance scheduling operations are coupled together to evaluate the total amount of energy flexibility. In this respect, Figure 4.19 expresses a comparison between the initial electricity load profile including heating, lighting and appliance loads, and the load distribution after the smart scheduling operations, for the typical winter week.

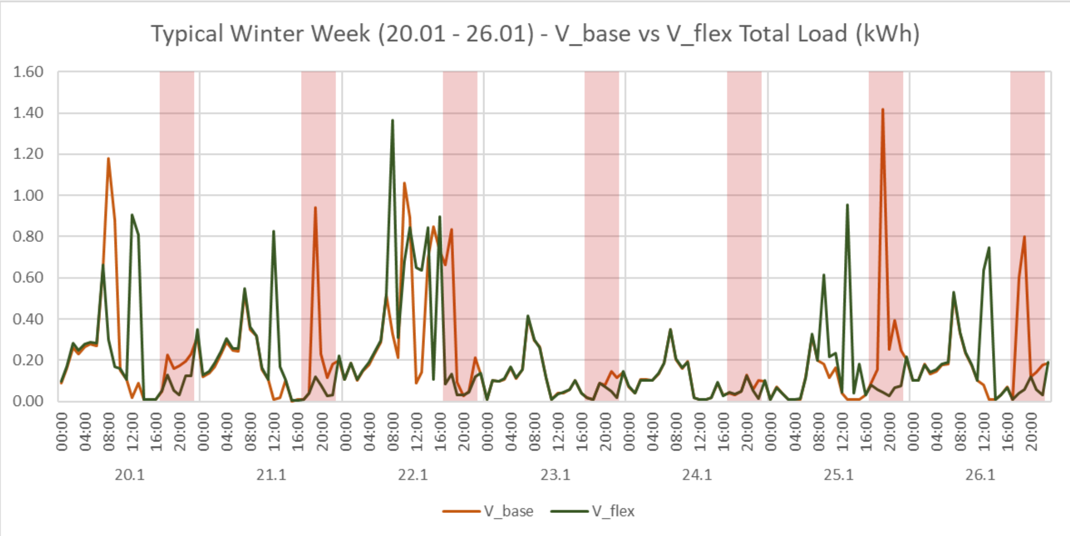

Figure 4.19. V_base vs V_flex total load profile for typical winter week (kWh) (the pink regions represent peak hours)

Clearly seen from the figure, the V_base load profile has many juxtapositions and accumulations in the peak electricity hours. The V_flex load profile, on the other hand, tackles this through energy flexibility operations of HVAC equipment for heating, and shiftable appliance loads. For the typical winter week, a total of 7.20 kWh (%74.1) was reduced from the peak electricity hours.

Table 4.16 expresses the quantification of the achieved energy flexibility through the KPIs of “Peak Power Reduction” and “Flexibility Savings Index”.

Table 4.16 Quantification of overall energy flexibility

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (*FI*)
20.01	1.03	0.52	0.52	0.16
21.01	1.52	0.31	1.21	0.25
22.01	1.88	0.45	1.44	0.14
23.01	0.46	0.26	0.20	0.15
24.01	0.41	0.32	0.10	0.09
25.01	2.55	0.36	2.20	0.40
26.01	1.84	0.31	1.53	0.29

Figure 4.20 illustrates a comparison between the initial electricity load profile including cooling, lighting and appliance loads, and the load distribution after the smart scheduling operations, for the typical summer week.

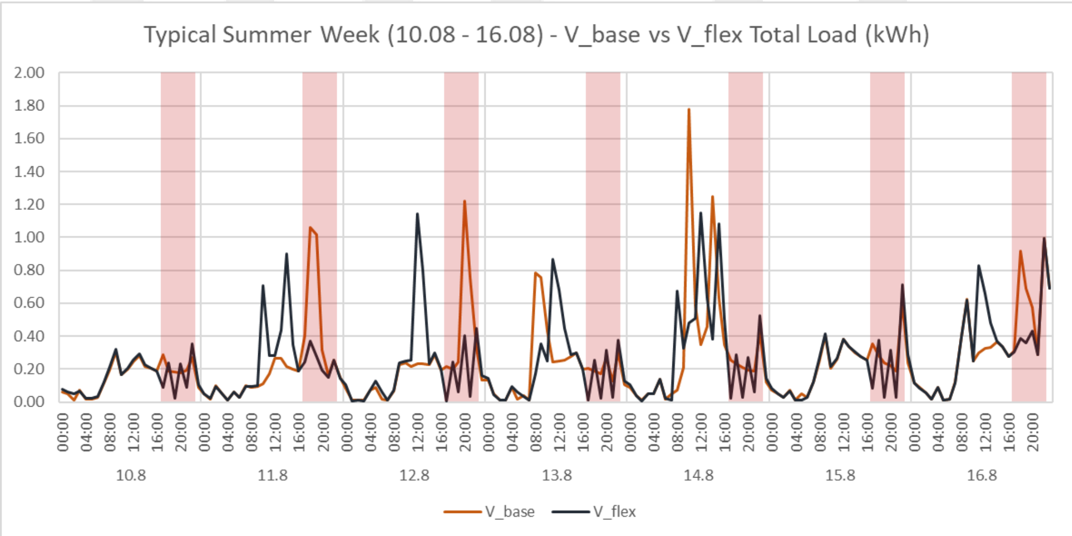

Figure 4.20. V_base vs V_flex total load profile for typical summer week (kWh) (the pink regions represent peak hours)

The flexible load distribution illustrates that a significant amount of peak hour electricity usage is removed through load shifting and load reduction. For the typical summer week, a total of 5.68 kWh (%35.7) was removed from the peak electricity hours.

Table 4.17 expresses the quantification of the achieved energy flexibility through the KPIs of “Peak Power Reduction” and “Flexibility Savings Index”.

Table 4.17 Quantification of overall energy flexibility

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (F*I*)
10.08	1.30	1.02	0.28	0.09
11.08	3.21	1.49	1.72	0.19
12.08	2.96	1.20	1.76	0.23
13.08	1.26	1.01	0.25	0.06
14.08	1.51	1.19	0.32	0.07
15.08	1.88	1.55	0.33	0.09
16.08	3.78	2.76	1.02	0.09

In conclusion, this phase of the exploratory analysis revolved around a three-step process towards the achievement of energy flexibility within the household. The initial step was to evaluate the successful implementation of building thermal mass. For this purpose, a set of materials were considered through a calculation, which in return gave the material combination providing both a good amount of building thermal mass and complying with the U-values legislated by the Turkish Standards of TS-825. Subsequent to that, the heating and cooling loads were re-scheduled for energy flexibility achievement, through smart scheduling of the HVAC equipment. This helped reduce the amount of energy spent within the peak electricity hours, providing energy flexibility within that sense. Lastly, the shiftable appliance loads of clothes dryer, clothes washer, and dishwasher were re-scheduled so as to remove electricity loads from the peak electricity hours. As a result, a total load distribution of V_flex was created and comparatively presented with V_base.

4.3 Fitting Flexible Energy Demand to Renewable Energy

This stage aims to conclude the exploratory analysis through the generation of the last scenario, V_flex_gen. In this stage, the renewable energy potential is evaluated for the building, and compared with the energy demand to explore whether energy positivity is possible or not. Initially, the investigation of renewable energy potential was calculated with a PV calculation that includes building integrated PV panels on the roof. Upon obtaining the results, the energy demand and renewable energy production is comparatively analyzed with respect to the demand production balance of each day. Finally, the results are presented through a set of charts and tables, explaining whether it is possible to reach energy positivity for the household, also concluding the V_flex_gen scenario. With successful implementation of this step, the exploratory analysis is concluded.

4.3.1 Evaluation of Potential Renewable Energy Generation

In order to estimate the local renewable energy generation, a model evaluating the solar energy potential through PV panels was generated. The model was collaboratively constructed within the scope of PED-ACT by Ataberk Yilmaz, a junior researcher in the project. The modeling tool was PVWatts (Dobos, 2014), integrated as add-on components to the plugin of Ladybug Tools (Roudsari & Pak, 2013). PVWatts is a successful tool developed by National Renewable Energy Laboratory (NREL) of the US Department of Energy (Dobos, 2014). The input type that can be loaded into this tool is categorized into two: field inputs and advanced inputs. The options for field inputs include system size (DC output, expressed in kW), module type, system losses, array type (e.g., fixed roof mount, fixed open track, etc.), tilt angle, and azimuth angle. The advanced inputs, on the other hand, include the parameters of DC/AC ratio, inverter efficiency, and ground coverage ratio (Dobos, 2014).

The estimation is done through modeling the PV panels on the roof of the building, oriented as close to optimal as possible to obtain higher amounts of energy. The values of PV type, module efficiency, temperature coefficient, and active module area was inferred from the database of PED-ACT. For this purpose, the technical catalogs of commonly used PV panels were examined (LG NeON 2 LG400N2W-A5 400W 72-Cell PV, Vertex 510W+ TSM-DE18M(II), LONGi 440W 144 cell LR4-72H), and the widely occurring typical values are considered. For the losses, a total amount of %14 was given including inverter, wiring, soiling, mismatches, and light-induced degradation losses (Meuris et al., 2018).

This process results in a dataset containing 8760 values, for each hour of the year, and the corresponding value for each hour is the hourly PV production. Through this method, potential renewable energy generation is measured.

Table 4.18. summarizes the semantic information provided for the PV model.

Table 4.18 Semantic data for the PV modeling

	Value	Unit
PV Type	monocrystalline	-
Module Efficiency	20.00	%
Temperature Coefficient	-0.37	%/ºC
Active Module Area Percent	100	%
Losses (inverter, wiring, etc.)	14	%

Figure 4.21 illustrates the dry bulb temperature values for typical winter and typical summer weeks, and Figure 4.22 depicts the global horizontal radiation values.

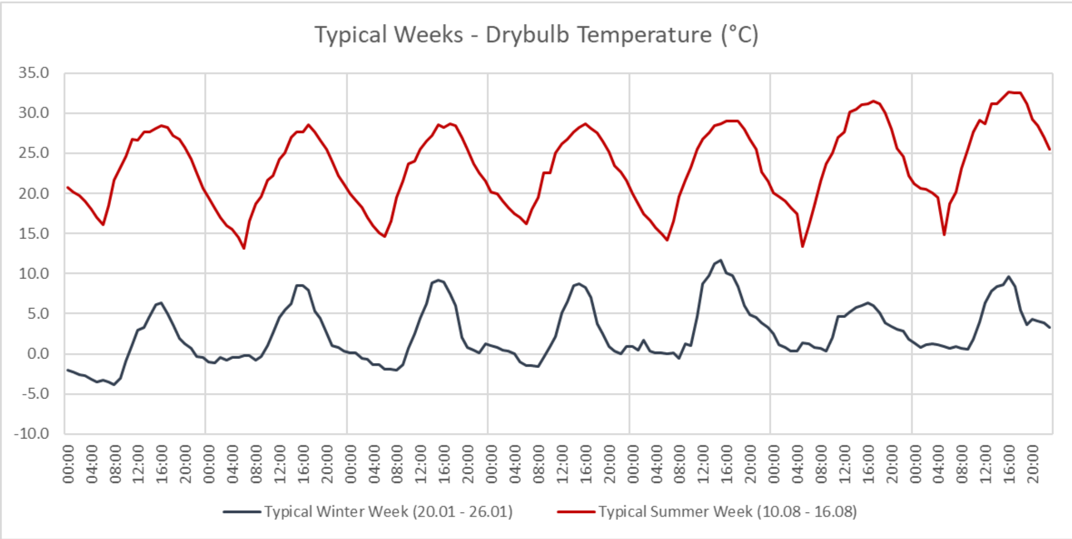

Figure 4.21. Dry bulb temperature for the typical weeks (°C)

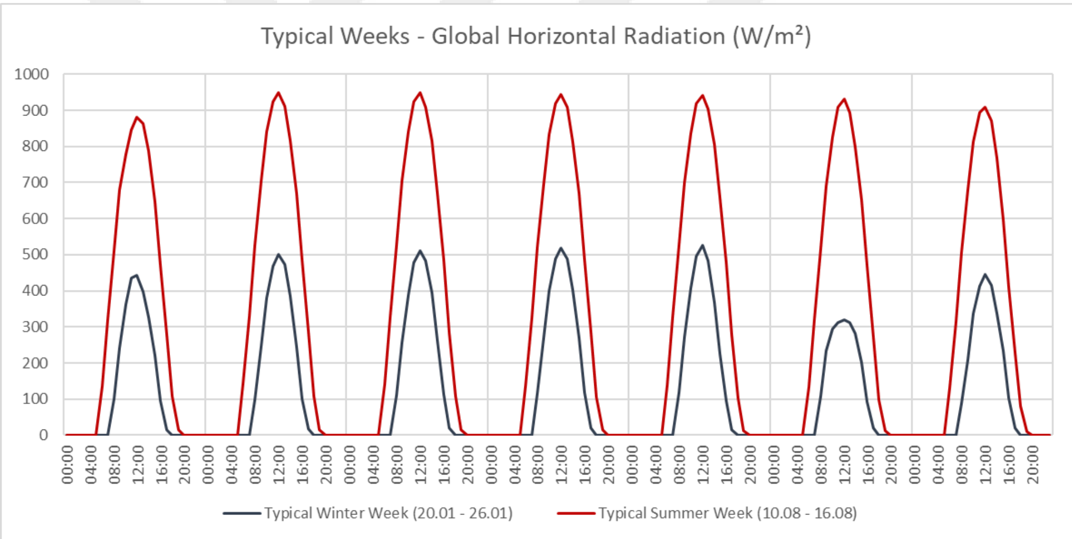

Figure 4.22. Global horizontal radiation for the typical weeks (W/m²)

For the placement and production of PV panels, two main alternatives are considered. The initial option includes positioning of PV panels only on the southern surface of the roof. On the other hand, the alternative option proposed installment of PV panels on both northern and southern surfaces of the roof. Figure 4.23 illustrates the placements of PV panels.

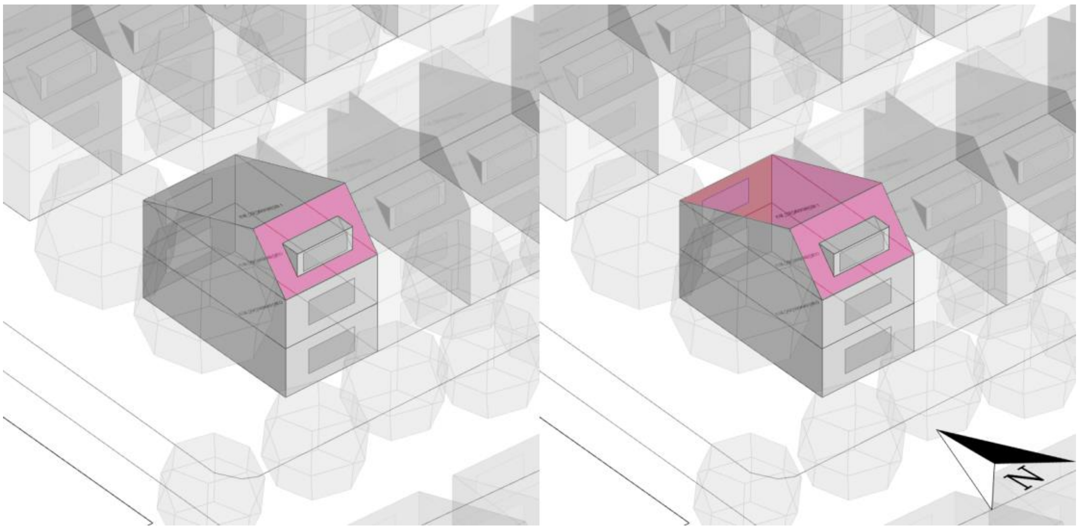

Figure 4.23. The placement of PV panels on the roof
(left: initial option, right: alternative option)

Figure 4.24 illustrates the PV panel production for the typical winter week, and Figure 4.25 presents that of typical summer week.

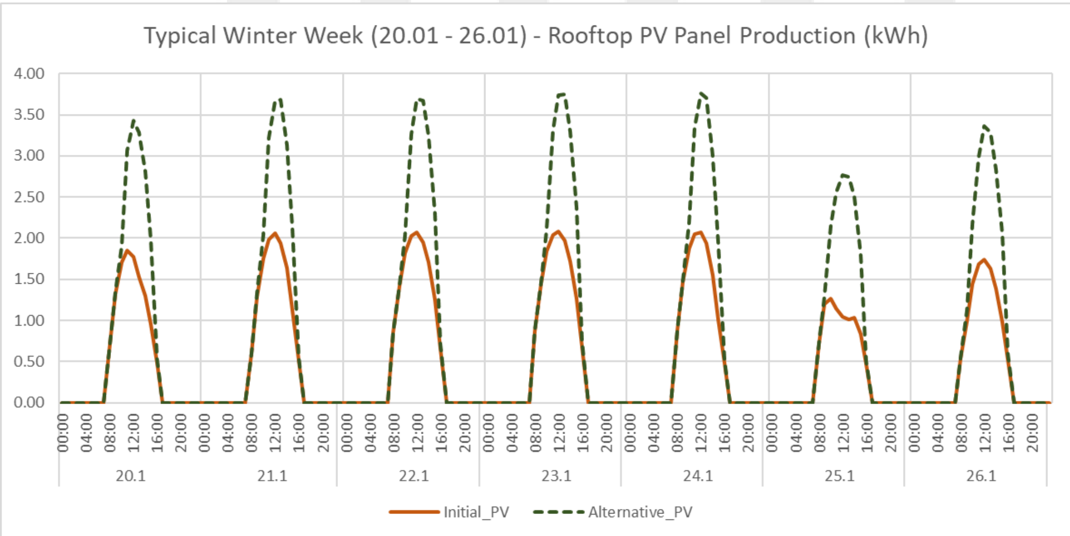

Figure 4.24. Rooftop PV panel energy production for typical winter week (kWh)

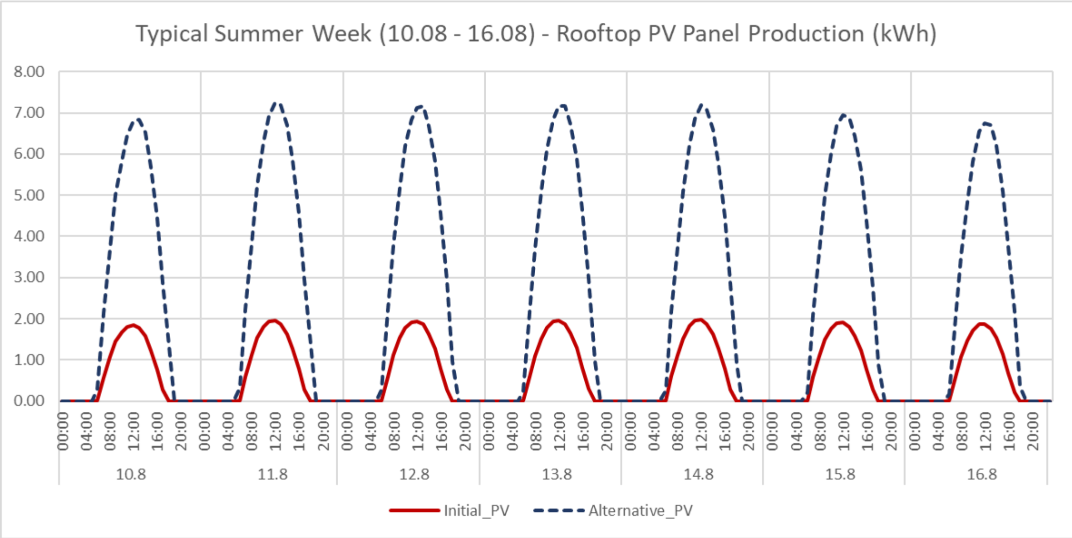

Figure 4.25. Rooftop PV panel energy production for typical summer week (kWh)

The figures illustrate that even though there are small differences, there is constant production during insolation hours, with consistent amounts of energy, as the periods of analysis are the typical weeks. As inferred from the figures, the Alternative PV panels result in a drastic increase in renewable energy production.

Table 4.19 presents the numeric values for the renewable energy generation.

Table 4.19 Results of the renewable energy generation

	Typical winter week		Typical summer week		
PV Panels	Daily average (kWh)	Weekly total (kWh)	Daily average (kWh)	Weekly total (kWh)	Yearly total
Initial PV panels	12.17	85.16	14.52	101.62	4247.23
Alternative PV panels	19.86	139.04	58.39	408.75	13508.77

4.3.2 Comparative Analysis of Demand and Production

Upon the obtaining of the results of potential renewable energy production, the results are compared with the flexible demand profile. This phase of the analysis constitutes the V_flex_gen scenario, where demand and production of energy are included together. Regarding renewable energy generation, firstly, the initial PV panels are considered. Figure 4.26 illustrates the energy demand and both alternatives for production for the typical winter week, and Table 4.20 depicts the achievement of energy positivity for each day of the week.

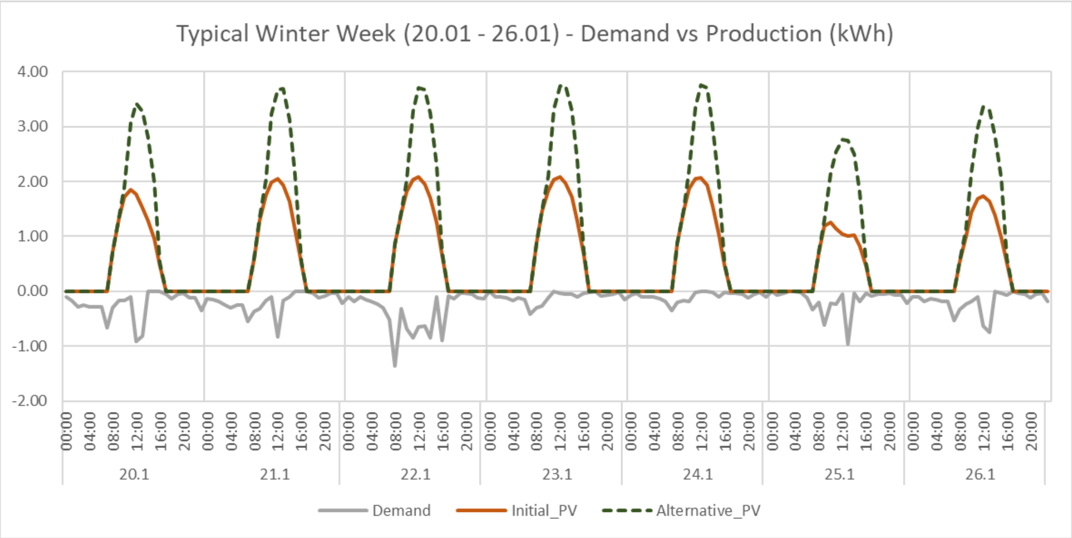

Figure 4.26. Comparison of demand & production for typical winter week (kWh)

As inferred from the figure, the energy production and demand are mainly aligned in similar hours through the flexibility operations carried out in the earlier phases of the study. Certain fluctuations are still present in the demand load profile, however, the reason behind the fluctuations are the non-shiftable loads that are mainly realized based on random patterns of occupant initiative. Additionally, even though there is net-metering, the shiftable loads are aimed to be aligned with the hours of renewable energy production to be able to make use of the immediate renewable energy generation. This chapter presents the daily results, and hourly results are presented in the next chapter.

Table 4.20 Energy balance in typical winter week

		Initial PV panels		Alternative PV panels	
Date	Demand (kWh)	Production (kWh)	Balance (kWh)	Production (kWh)	Balance (kWh)
20.01	5.66	11.64	5.98	19.04	13.38
21.01	4.67	12.89	8.22	20.35	15.68
22.01	8.72	13.77	5.05	21.21	12.50
23.01	2.55	13.93	11.38	21.65	19.10
24.01	2.25	13.32	11.07	20.81	18.56
25.01	3.68	8.70	5.02	17.03	13.35
26.01	4.43	10.92	6.49	18.95	14.52

Regarding both of the PV installment options, the daily energy balance is positive. This means that energy positivity is achieved for the entire week.

For the typical summer week, Figure 4.27 illustrates a comparison of demand and production, and Table 4.21 expresses energy balance for the week.

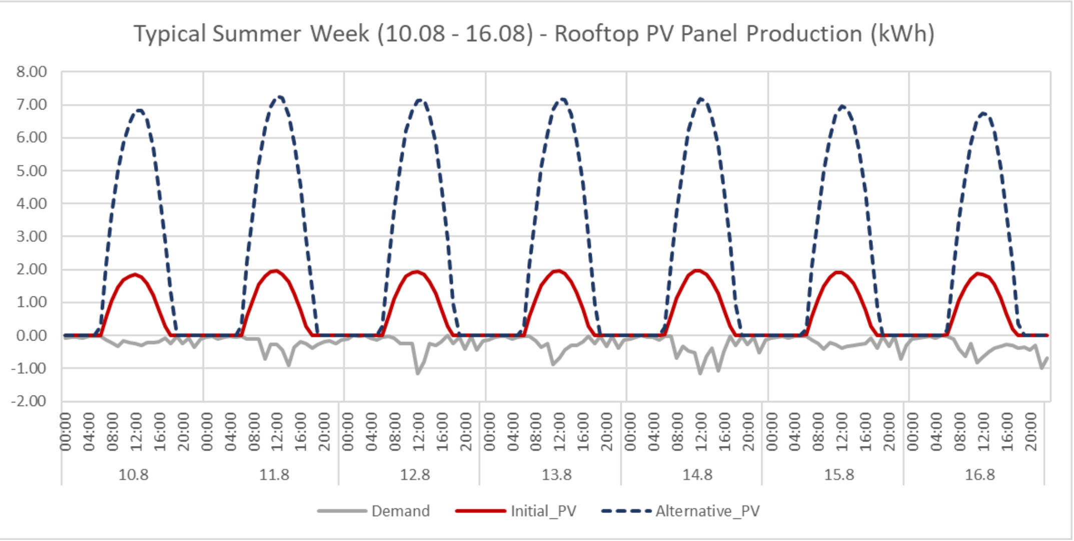

Figure 4.27. Comparison of demand & production for typical summer week (kWh)

Table 4.21 Energy balance in typical summer week

		Initial PV panels		Alternative PV panels	
Date	Demand (kWh)	Production (kWh)	Balance (kWh)	Production (kWh)	Balance (kWh)
10.08	3.66	14.04	10.38	57.93	54.27
11.08	5.39	14.81	9.42	60.73	55.35
12.08	5.26	14.73	9.47	59.71	54.45
13.08	5.10	14.80	9.70	59.69	54.58
14.08	7.50	14.84	7.34	59.24	51.74
15.08	4.95	14.48	9.53	57.50	52.56
16.08	8.18	13.92	5.73	53.96	45.78

Inferred from the figure and the table, energy balance is positive for each day, making the building energy positive for the entire week.

Both of the cases regarding renewable energy production have their advantages and disadvantages. The initial alternative costs less time and money, as there are fewer PV panels to install. However, it results in lower amounts of energy production. On the other hand, the latter alternative for renewable energy production carries the potential for remarkable amounts of energy surplus for each day. Nevertheless, the time and money cost drastically increase as the amount of PV panels heavily increases as well.

4.3.3 Presentation of the Results

The last phase of the exploratory analysis is devoted to the presentation of the end results. Through the developed scenarios of V_base, V_flex and V_flex_gen, a comparative presentation through charts and tables is aimed. The initial step of the analysis is the formation of V_base. For this purpose, a single building within Çamlık District was selected, and the model developed by the research team of PED-ACT in METU was used. The building was a three-storey single house, the third floor being an attic. The model employed a heat pump for heating and cooling operations, the source of energy was therefore electricity, instead of natural gas. Along with the lighting and electrical appliance loads generated by the Load Profile Generator (Pflugradt et al., 2022), the initial electricity load profiles for V_base scenario were complete.

Table 4.22 Schematization of the scenarios (0: no, 1: yes)

	V_base	V_flex	V_flex_gen
Baseline load distribution	1	0	0
Flexible load distribution	0	1	0
Renewable energy generation	0	1	1

Figure 4.28 illustrates the V_base loads of heating, electricity (including lighting loads), and the total load profile.

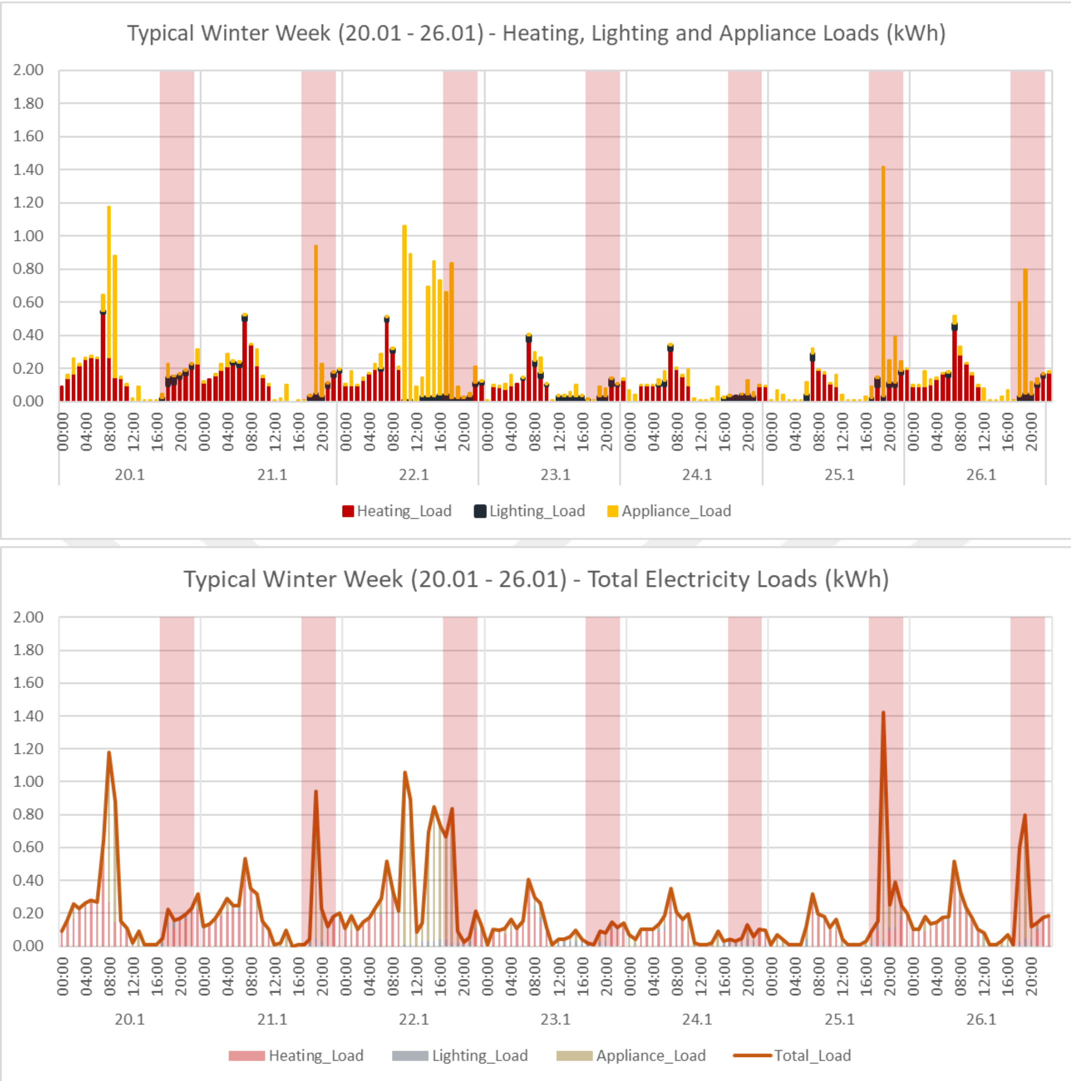

Figure 4.28. V_base loads for the typical winter week (kWh)
(the pink regions represent peak hours)

The next step is the configuration of the scenario V_flex. For this scenario, the building thermal mass potential is evaluated, and potential retrofits are considered. Furthermore, the HVAC equipment (heat pump) and shiftable appliance loads are re-scheduled to abstain from the peak hours of electricity usage. A comparison of V_base and V_flex total electricity loads is expressed by Figure 29. The total electricity loads include heating, lighting and appliance loads.

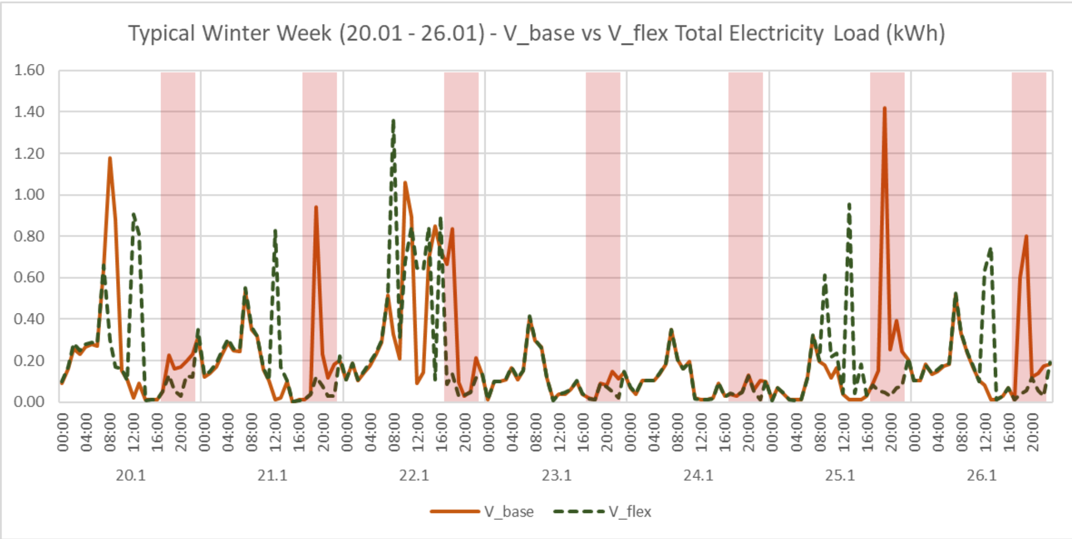

Figure 4.29. V_base vs V_flex load profiles for typical winter week (kWh) (the pink regions represent peak hours)

Table 4.23 expresses the quantification of the achieved energy flexibility through the KPIs of "Peak Power Reduction" and "Flexibility Savings Index".

Table 4.23 Quantification of overall energy flexibility

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (*FI*)
20.01	1.03	0.52	0.52	0.16
21.01	1.52	0.31	1.21	0.25
22.01	1.88	0.45	1.44	0.14
23.01	0.46	0.26	0.20	0.15
24.01	0.41	0.32	0.10	0.09
25.01	2.55	0.36	2.20	0.40
26.01	1.84	0.31	1.53	0.29

Following this step, the last scenario of V_flex_gen is generated, in which the renewable energy production is investigated. Along with that, the energy positivity potential of each day is evaluated through comparative analyses of each day. Figure

4.30 expresses a comparison of energy demand and energy production for the initial and alternative PV panel scenarios.

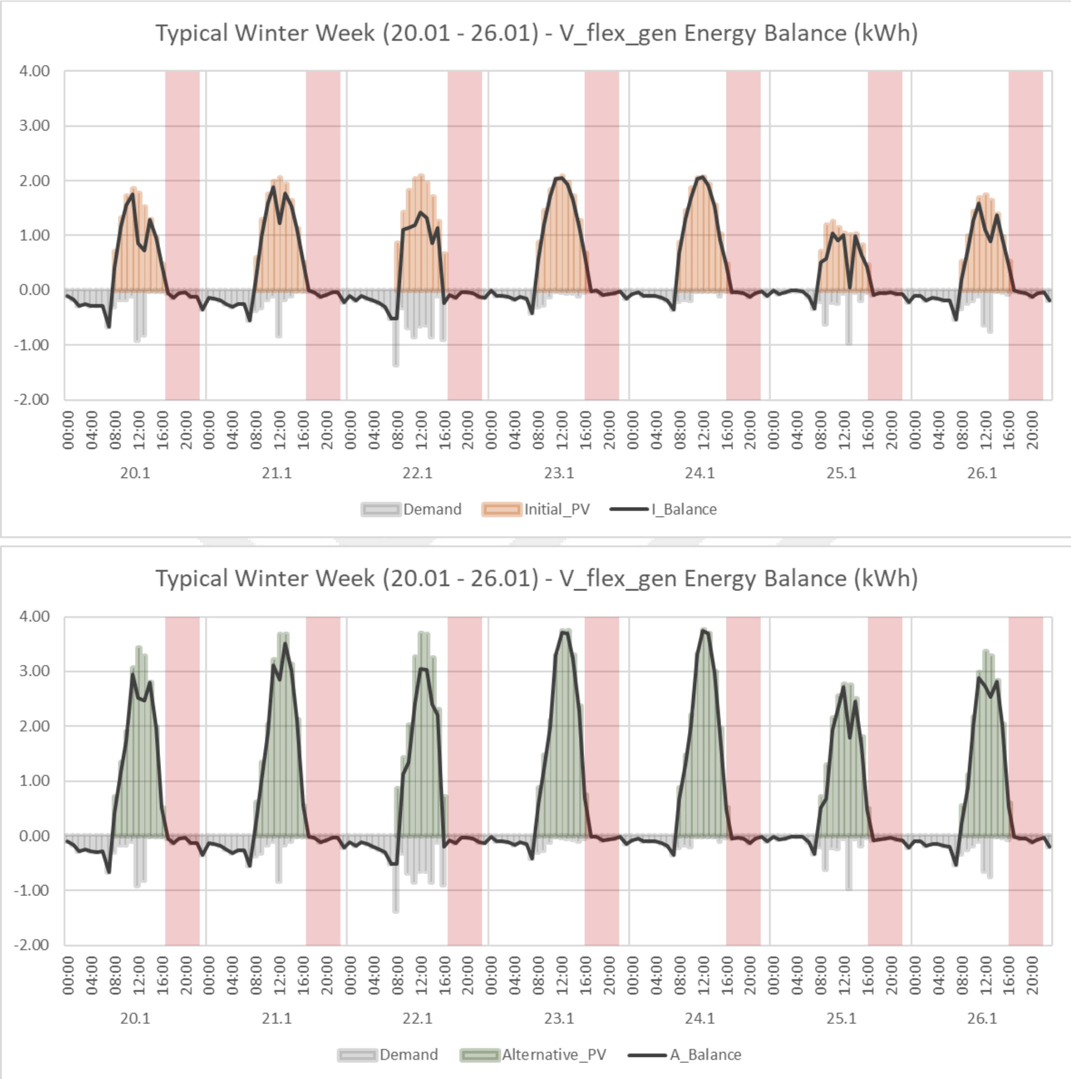

Figure 4.30. V_flex_gen energy balance for typical winter week (kWh), initial PV panels (above) vs alternative PV panels (below)
(the pink regions represent peak hours)

It is clearly visible that the demand does not always follow the production, however, through the operations realized on V_flex scenario, the shiftable loads are aimed to be arranged according to the energy production hours as much as possible. For the rest of the hours of the day when energy production is non-existent and energy demand is still valid, through net-metering operations, energy positivity would be reached for the entire week. This concludes the presentation of the results for the typical winter week.

Typical summer week unfolds in a similar manner, with similar tendencies in energy profiles. Figure 4.31 depicts the V_base loads of cooling, electricity (including lighting loads), and the total load profile.

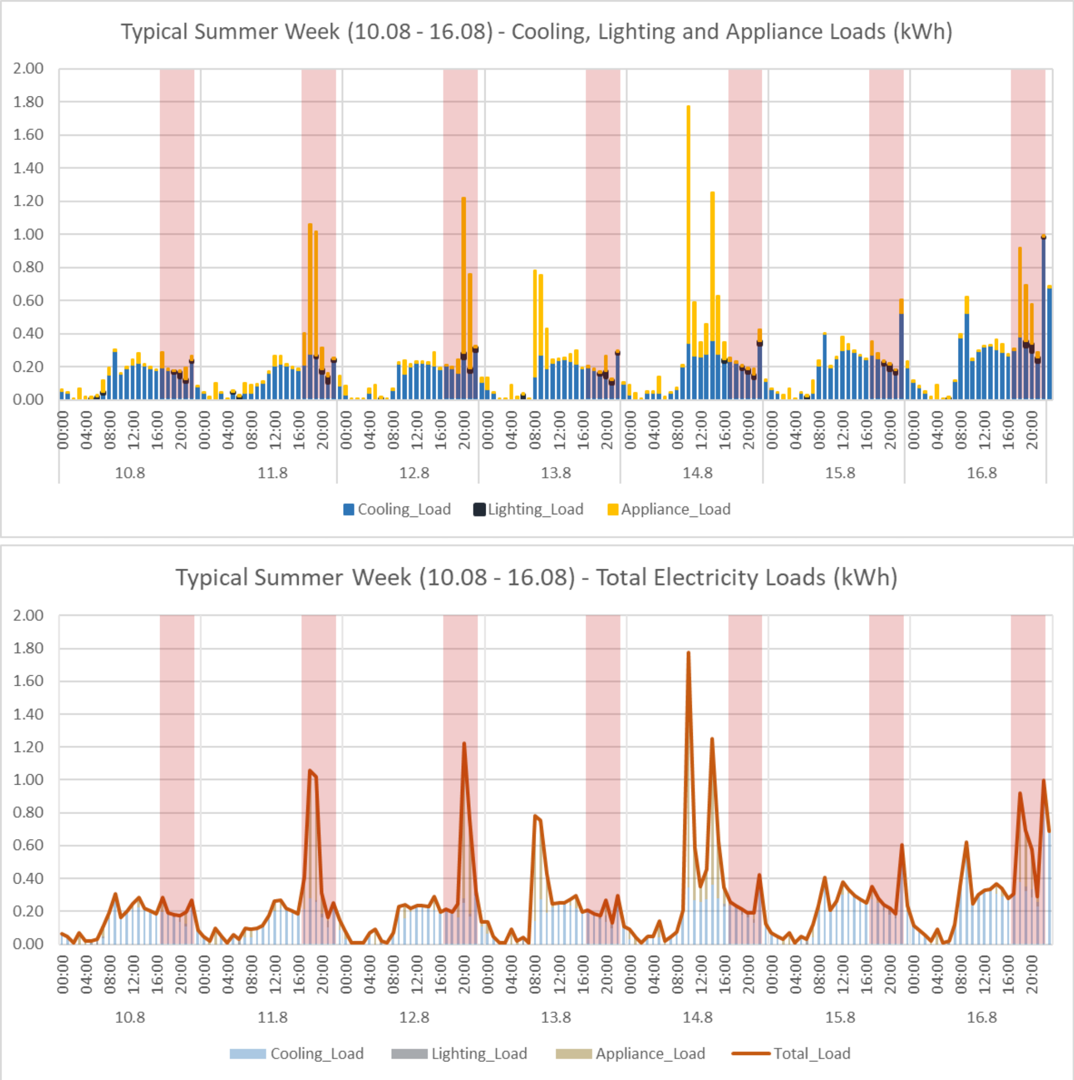

Figure 4.31. V_base loads for the typical summer week (kWh)
(the pink regions represent peak hours)

Upon the obtaining of V_base loads, the scenario of V_flex is configured. A comparison of V_base and V_flex total electricity loads is expressed by Figure 32. The total electricity loads include cooling, lighting and appliance loads.

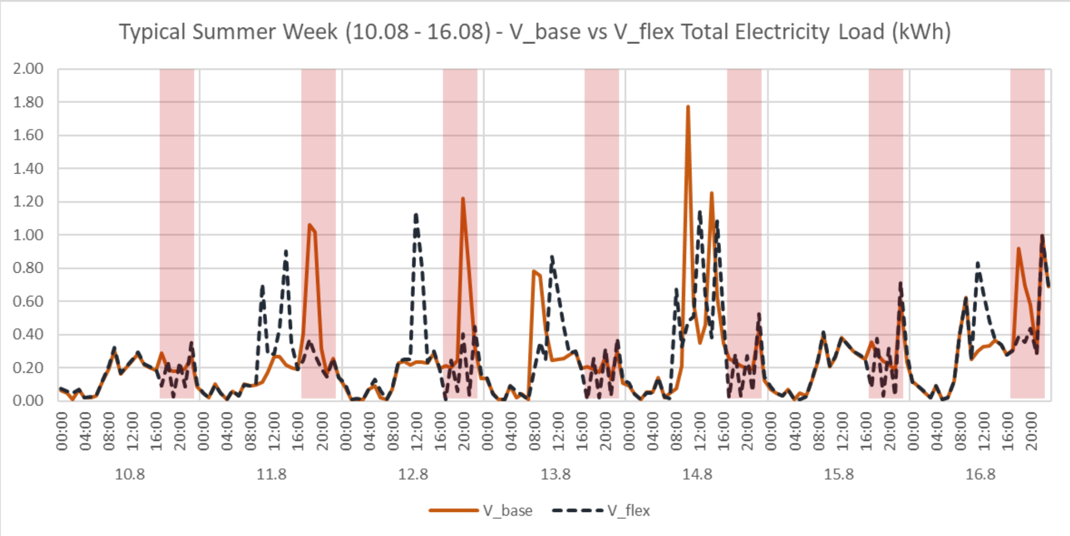

Figure 4.32. V_base vs V_flex load profiles for typical winter week (kWh) (the pink regions represent peak hours)

Table 4.24 depicts the quantification of the achieved energy flexibility through the KPIs of “Peak Power Reduction” and “Flexibility Savings Index”.

Table 4.24 Quantification of overall energy flexibility

Date	V_base energy demand in peak hours (kWh)	V_flex energy demand in peak hours (kWh)	Peak power reduction (Δp) (kWh)	Flexibility savings index (*FI*)
10.08	1.30	1.02	0.28	0.09
11.08	3.21	1.49	1.72	0.19
12.08	2.96	1.20	1.76	0.23
13.08	1.26	1.01	0.25	0.06
14.08	1.51	1.19	0.32	0.07
15.08	1.88	1.55	0.33	0.09
16.08	3.78	2.76	1.02	0.09

The last step constitutes the formation of the V_flex_gen scenario. Figure 4.33 illustrates a comparison of energy demand and energy production for the initial and alternative PV panel scenarios.

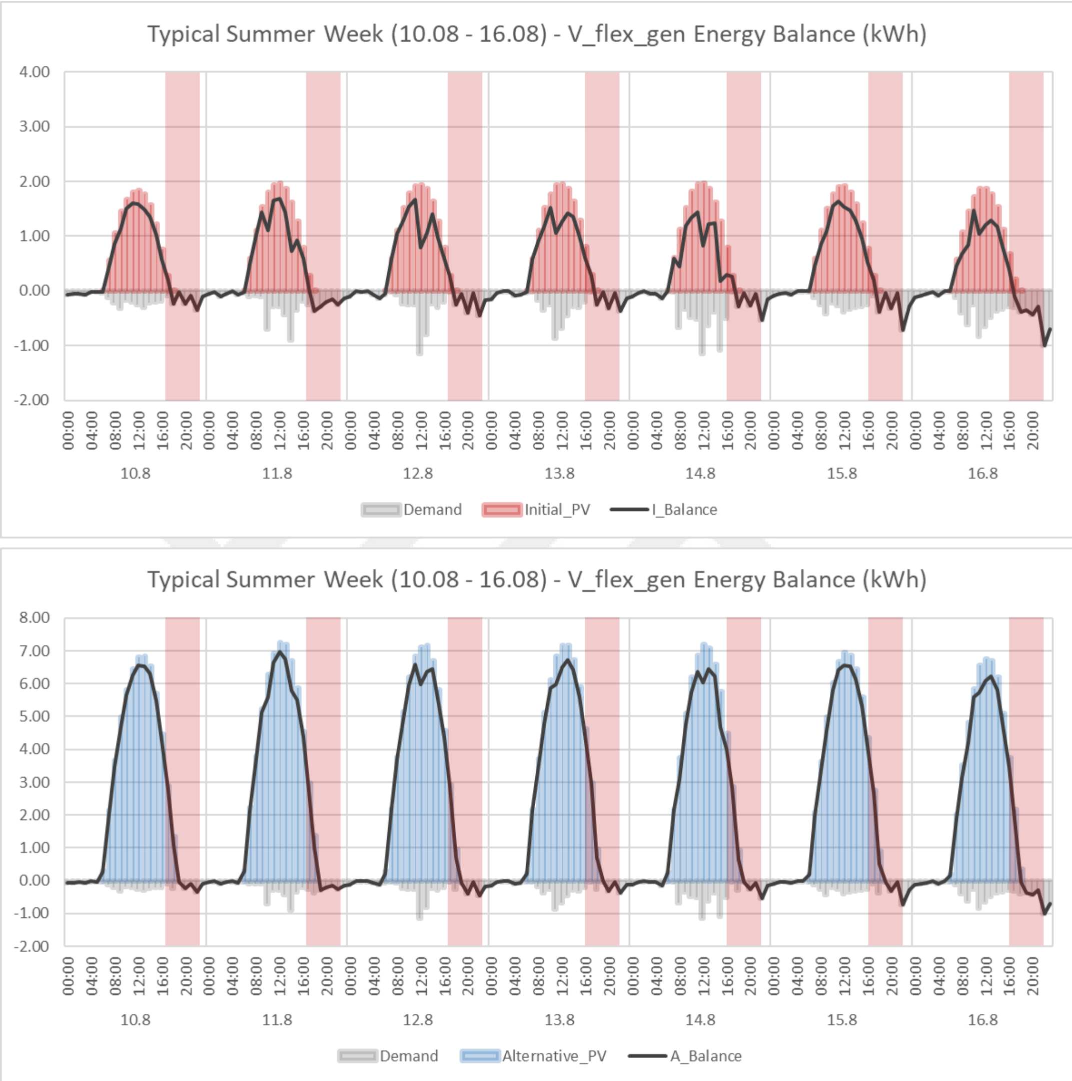

Figure 4.33. V_flex_gen demand vs production for typical summer week (the pink regions represent peak hours)

The complete presentation of these figures concludes the analyses for typical summer week.

Along with the typical weeks, the energy flexibility operations were conducted for each day of the year. Table 4.25 expresses the yearly results.

Table 4.25 Yearly results

Energy flexibility KPI	Minimum	Maximum	Average	Total
Peak power reduction (Δp) (kWh)	0	3.84	0.68	213

According to the table, a total of 251 kWh loads were removed from the peak electricity hours to reach energy flexibility. The major portion of the removed loads belong to the appliance loads with 185 kWh. Through the flexibility operations on heat pump, the heating load decreased from 460 to 445 kWh, and the cooling load decreased from 345 to 332 kWh.

CHAPTER 5

CONCLUSION

The ever-increasing defects of climate change and the energy crisis foster the buildings to reconsider their energy usage. Through this approach, architects are in need of re-thinking the relationship between buildings and the electricity grid. The unidirectional connection between the grid and the buildings is outdated, and bidirectional connection through energy flexibility is needed for the building to mitigate energy balance between the electricity grid and the fluctuating energy loads, along with local renewable energy generation. In this respect, the main aim of this thesis was to conduct an exploratory analysis on energy flexibility, coupled with energy generation to reach energy positivity, and present this as a framework for the architects to utilize. The following chapters summarize the outcomes and contributions of this thesis, along with a recap of the research questions.

5.1 Research Questions

The transition process towards sustainable buildings necessitate radical changes in architectural design. So far, architects have been trying to tackle this by the use of renewable energy generation, or the usage of green elements. However, by themselves, they are not enough. A holistic consideration of electricity and the building is necessary. Energy flexibility is a means of balancing the electricity loads between the building's energy demand, the electricity grid, and renewable energy generation. Hence, energy flexibility is a significant aspect that should be integrated as a tool for the design stage of the buildings. In this study, a three-step framework to establish energy positivity through energy flexibility and energy generation was developed. The framework was tested as an exploratory analysis on a case study. To address the issue, a recap of research questions is necessary.

How could a smart scheduling system of HVAC equipment with respect to heating and cooling loads contribute to achieving energy flexibility without jeopardizing

occupant comfort? A significant portion of energy flexibility reached within the scope of the analysis was due to the smart scheduling of HVAC equipment (heat pump). As the aim has been to generate on/off schedules during peak electricity hours, the schedules applied in the analysis portray critical decreases in the electricity load during peak electricity hours. A critical approach in this case can be towards jeopardizing the occupant comfort. During daytime, the heating setpoint of the day occupied zone has been 21°C. Without energy flexibility, it would have been continuing as 21°C, fully satisfying occupant comfort. However, due to the new schedules, the indoor (operative) temperature inevitably dropped below 21°C. Nevertheless, the calculations always ensured that the indoor (operative) temperature does not go below 19°C. Only the schedules that satisfy this condition were used. Considering that the heating setpoint was also 19°C during night time, any degree between 21°C and 19°C can be approached as a minor discomfort for the occupants, which can be compensated through occupant behavior (adaptive comfort). In brief, the smart scheduling system majorly contributed to the achievement of energy flexibility through HVAC equipment.

How could a smart scheduling system of household appliances help establish energy flexibility, through which appliances? Following detailed literature research outcomes and simulation results, the household appliances that supplied shiftable loads were deemed appropriate for appliance scheduling. The appliances of clothes dryer, clothes washer, and dishwasher were proven to be impactful in achieving energy flexibility, as their loads were shiftable loads and were not as much dependent on occupant behavior as leisure appliances (TV, laptop, etc). Moreover, re-scheduling the loads of the appliances contributed not only to decreasing electricity loads from peak electricity hours, but also the immediate consumption of renewable energy generation. This was possible since the appliance loads were rescheduled to a time period in which renewable energy was being produced, the sunlight hours in other words.

To what extent can a flexible load distribution be compatible with energy generation and self-consumption? The applications of energy flexibility are often coupled with energy generation, as the former can facilitate the usage of the latter. In this study, it was proven that self-consumption can be facilitated through energy flexibility, and a flexible load distribution is indeed compatible with energy production. Energy flexibility brings about further understanding regarding the electricity loads, and how to manage their time periods better. Moving the loads to the times of renewable energy generation directly facilitates the immediate consumption of the generated energy, fostering self-consumption within the building. The smart scheduling of HVAC equipment, on the other hand, does not move the loads to different periods of time, but rather decreases the amount of energy demand in peak electricity hours. Nevertheless, this also contributes to self-consumption as it decreases the energy demand from the electricity grid. Adding a battery on top of this system can therefore potentially facilitate full autonomy (independence from electricity grid) for the building.

Is reaching energy positivity a realistic goal with respect to coupling energy flexibility and energy production? To answer this question, the issue of scale must be clarified. In this thesis, the scope has been a single household. Therefore, the research question was answered on building scale. The results of this thesis show that it is definitely possible to reach energy positivity through coupling energy flexibility and energy generation. Energy generation is the key to reaching energy positivity, however, the renewable energy generation is intermittent and fluctuating. By the help of energy flexibility, the energy generation can cover the energy demand more evenly, facilitating energy positivity for the building. The electrification of the household is crucial for this purpose. Once heating and cooling loads are electrified (through using heat pumps for example), along with lighting and plug loads, the house operates the energy demand solely through electricity. This enables the integration of renewable energy usage for the building, and only then, energy positivity can be reached.

5.2 Contributions, Limitations, and Future Work

The contributions provided by this thesis can be summarized as:

- A three-step framework in order to reach energy flexibility was provided for the architects to utilize.
- Coupling energy flexibility and energy production to test whether energy positivity is possible, was proposed and tested on a case study.

Along with certain minor contributions such as:

- Testing whether building thermal mass can be simulated by building energy simulation tools
- A smart means of scheduling HVAC equipment through using a building energy simulation model
- A smart means of scheduling household appliances through using a building energy simulation model

Along with the contributions, there were certain limitations to the thesis that should be underlined.

First of all, there are many means of achieving energy flexibility. Generating building thermal mass, smart scheduling of HVAC equipment and smart scheduling of household appliances were the three chosen means for the scope of this thesis. For a future study, several other means of energy flexibility can be included and compared with the aforementioned ways.

Secondly, the consideration of batteries can contribute to this study in means of reaching complete autonomy and not using the electricity grid at all. This study assumed the usage of net-metering considering the surplus of renewable energy, however, through the usage of a battery, any electricity exchange with the grid can be replaced with full self-consumption of local renewable energy generation.

Additionally, a tracking parameter can be integrated to the PV panels, which would form the basis for a future work. Tracking feature for the PV panels can have critical impact on the renewable energy generation due to their positions in reference to the sun. If PV panels were to face east and west directions, the energy generation curve would follow a different trend, creating possibilities for energy flexibility in different time periods within the day. Moreover, the incorporation of optimum tilt and azimuth angles would increase the PV energy production, laying the ground for future research.

Last but not least importantly, electric vehicles (EV) carry the potential of adding another layer to this study, and many similar studies. EVs not only constitute shiftable electricity loads, but also can be used as batteries when needed. The relationship between an EV battery and the electricity grid is highly discussed in the literature, and it carries the potential of majorly contributing flexibility discussions. However, there is a major lack of data with respect to Turkiye. In order to use EVs for similar studies, the least amount of needed data would be the electricity usage of EVs throughout a whole year, with hourly time resolution.

All in all, this research has presented a framework on utilizing energy flexibility in the buildings, for the architects to make use of. The energy flexibility was collaboratively evaluated with energy generation, and whether energy positivity was possible, has been explored. The architects need to consider these aspects from the design stage, in order to carry the buildings through the incoming energy transformation process successfully, fostering resilient environments for the future.

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