Master Thesis

Towards Zero-Emission Energy Autarky: Techno-economic optimisation of multi-carrier energy system for a residential neighbourhood in Hilversum.

- Vivek Vats

Towards Zero-Emission Energy Autarky: Techno-economic optimisation of multi-carrier energy system for residential neighbourhood in Hilversum.

Thesis report

By

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To obtain the degree of Master of Science at the Delft University of Technology.

To be defended publicly on 11th August 2025

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Project Duration:	November 2024- August 2025
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Sustainable Energy Technology (SET)
TU Delft

August 11th, 2025

Abstract

The global energy transition poses significant challenges for urban infrastructure as it necessitates robust sustainable energy systems. In the Staatsliedenbuurt Oost neighbourhood of Hilversum, Netherlands, the grid is experiencing congestion due to a convergence of factors: rising electricity consumption from electric vehicles (EVs) and heat pumps (HPs), and the intermittent nature of local solar generation. This situation complicates the neighbourhood's ability to reduce its dependency on fossil fuels. This thesis aims to determine optimal, economically feasible configurations for a multi-carrier energy distribution system for a block in the neighbourhood to meet projected energy demand by 2030, reduce grid dependence, and quantify its CO2 emissions reduction potential.

A linear programming (LP) model was developed to minimize the net annual cost (NAC) of the system, optimizing the capacity of solar photovoltaics (PV), battery energy storage systems (BESS), air source heat pumps (ASHPs), and seasonal thermal energy storage (STES). The model utilised 15-minute resolution, simulation data and incorporated scenario-based analysis for varying EV and HP adoption rates, including an ambitious "Net Zero" scenario that eliminates grid import. Block 7 was selected for detailed analysis after an initial optimization across 14 neighbourhood blocks.

For Block 7, under a 50% EV and 50% HP adoption scenario, the optimal configuration included 121.467 kW_p Solar PV, 36.801 kW BESS power, 151.602 kWh BESS energy, 55.782 kW_{th} ASHP, and 526.053 kWh_{th} STES. This configuration achieved a NAC of €50,792.02, with grid-related costs forming the largest portion. The system demonstrated a degree of autarky (DoA) of 48.06%, with a levelized cost of electricity (LCOE) of 0.362 €/kWh and a levelized cost of heat (LCOH) of 0.120 €/kWhth. Increasing EV and HP adoption generally led to higher unit costs and increased grid reliance, along with a decrease in DoA. The "Net Zero" scenario achieved 100% DoA but at significantly higher costs (€1.857/kWh LCOE, €0.634/kWhth LCOH) and an extremely high PV curtailment rate (PVCR) of 88.97%. Environmentally, the system showed substantial greenhouse gas (GHG) emissions reduction potential, saving 32,834 Kg CO_2 equivalent in the base scenario, which rose to 93,516 kg CO_2 equivalent in the Net Zero scenario.

This research provides a practical framework for mitigating energy challenges in urban environments, contributing to a more resilient, sustainable, and cost-effective local energy ecosystem. It addresses critical research gaps by offering a holistic techno-economic assessment of total residential energy demand within a specific national context, and by exploring the synergistic integration of diverse energy storage technologies and comprehensive sector coupling.

Preface

This research, conducted in the context of my master's thesis, is the culmination of my studies at TU Delft, within the MSc Sustainable Energy Technology program. The thesis, titled 'Towards Zero-Emission Energy Autarky: A Techno-Economic Optimization of Multi-Carrier Energy Systems for Residential Neighbourhood in Hilversum,' focuses on developing innovative energy solutions for urban environments.

I extend my sincere gratitude to my main thesis supervisor, Dr. Laura Ramirez Elizondo, for providing the opportunity to conduct this thesis at DCE&S and for her invaluable guidance. Her insightful feedback during our monthly meetings was instrumental in shaping my research.

My deep appreciation also goes to Dr. Joel Alpizar Castillo, my PhD supervisor, for his extensive guidance throughout this project during our weekly meetings which improved my skills as a researcher. I am particularly thankful for his kind and timely responses, even amidst his demanding schedule.

I would like to thank my other thesis committee members, Jeroen Pool from HET Cooperative and Jasper Stoter from Emmett Green. Their support in providing comprehensive household-level, simulation data for the Staatsliedenbuurt Oost neighbourhood, which was a fundamental input for this research and their quick responses to my questions were greatly appreciated.

I am also deeply grateful to Dr. Mohamad Ghaffarian Niasar for accepting to be part of my thesis committee.

I would also like to acknowledge the use of Gemini in creating the cover image for this thesis and enhancing the clarity and impact of the sentences.

To my family and friends, thank you for standing by my side throughout this academic journey. Your unwavering belief in me has been a constant source of motivation and strength.

I sincerely hope this thesis inspires further research, particularly in the integration of Vehicle-to-Grid (V2G) technology within future energy systems. May its findings contribute meaningfully to the collective pursuit of a more resilient, sustainable, and cost-effective local energy ecosystem, aligning with the broader goal of achieving a sustainable energy future.

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1. Introduction

The transition to sustainable energy is a global necessity [1],but it's especially complex in crowded urban areas [2]. The Netherlands, for example, heavily relies on fossil fuels, which make up about 84% of its total energy use [3]. This is particularly true in homes, where natural gas heats 93% of dwellings and accounts for roughly 75% of residential energy supply [4], [5]. While renewable sources like solar and wind are growing, supplying about 15% of the domestic energy supply [3], their intermittent nature creates challenges [6]. The fluctuating availability of these sources leads to a mismatch between when energy is generated and when it's needed [7]. Additionally, the existing electrical grid, which was built for one-way power flow from large, central power plants, is struggling to adapt [8]. The rise of distributed energy resources (DERs), such as rooftop solar panels, electric vehicles, and heat pumps, is causing power to flow in both directions and increasing the unpredictability of the energy load [9].

The Staatsliedenbuurt Oost neighbourhood in Hilversum Zuid exemplifies these broader challenges, serving as a compelling case study for transitioning to a sustainable energy model. This residential area, comprising 546 households and nearly 1500 residents, faces significant grid congestion problems due to increased electricity consumption and local generation from solar panels. The adoption of EVs, induction cooking, and HPs is contributing to higher electricity consumption. Simultaneously, 200 homes are equipped with solar panels, generating 650,000 kWh annually, which adds complexity to grid management due to the fluctuating nature of solar energy. These factors collectively pose a significant threat to the reliability and efficiency of electricity distribution, limit the community's ability to accommodate new energy demands, and highlight the inefficient use of grid and energy resources.

Addressing these critical energy challenges demands immediate attention to ensure a sustainable and resilient future for communities like Hilversum. The growth of electric mobility and the electrification of heating and cooking place additional strain on the already congested grid, necessitating substantial upgrades and innovative solutions. The current slow pace of grid adaptation impedes the efficient integration and utilization of renewable energy resources (RES), hindering progress towards sustainability goals. This research is crucial as it explores a forward-thinking approach to addressing the energy challenges of the 21st century by focusing on local energy generation, sharing, and storage to create a more resilient, sustainable, and cost-effective energy ecosystem. The study's findings will provide a foundational understanding of the energy landscape in Hilversum and its broader implications for urban energy systems, informing the development of innovative technological configurations.

The main research question guiding this thesis is:

What should be the configurations of the energy distribution system for a residential neighbourhood block in Hilversum to meet the projected energy demand in 2030 while reducing the dependence on the electricity grid and ensuring economic feasibility?

To thoroughly address the main research question, the following sub-research questions will be explored:

> **Technological Options:** What renewable energy technologies are most suitable for the neighbourhood to improve the DoA?

System Integration and Modelling: How can the suitable renewable energy technologies be effectively integrated into a cohesive energy system to reduce grid dependence?

Economic Assessment and Optimisation: What should be the capacity configuration of renewable energy technologies if the energy system is optimised for annual energy cost? And how does the unit economics (LCOE and LCOH) compare to the existing solution?

Environmental Impact: What is the GHG emissions reduction potential of the proposed technological configuration?

The primary objectives of this study are to:

Analyse the current energy landscape and identify specific challenges within the neighbourhood.

Identify and evaluate suitable renewable energy technologies for local generation and consumption within the neighbourhood.

Develop a scientific methodology for optimizing the configuration of a multi-carrier energy system for a residential neighbourhood block.

Determine the optimal capacity configurations of renewable energy for the selected neighbourhood block by minimizing the NAC.

Assess the economic feasibility of the proposed energy system configurations by calculating and comparing unit economics, specifically LCOE and LCOH, to existing solutions.

Quantify the potential for CO2 emissions reduction of the proposed technological configuration, contributing to the goal of achieving zero-emission energy autarky.

By developing a scientific methodology for optimizing the configuration of a multi-carrier energy system and addressing identified research gaps such as comprehensive sector coupling and the integration of diverse, seasonal energy storage, this study aims to yield a foundational understanding of Hilversum's energy landscape and its broader implications for urban energy systems. Ultimately, the research seeks to identify targeted solutions necessary for overcoming complex energy hurdles, quantify their CO2 emissions reduction potential, thereby contributing valuable knowledge to the field of sustainable urban energy systems.

2. Literature Review

The purpose of this literature review is to provide a comprehensive overview of the existing research and knowledge related to the energy challenges faced by urban areas, with a specific focus on residential neighbourhoods within the context of urban settings in western Europe. This review aims to contextualize the study by examining the current state of energy systems, the integration of renewable energy technologies, and the technological configurations that can facilitate a transition towards zero-emission energy autarky for a residential neighbourhood In Hilversum, North Holland. By synthesizing relevant literature, this review will identify gaps in the current understanding and highlight the significance of exploring innovative solutions to meet future energy demands.

The literature review overarches the following themes and topics

Energy Challenges in Urban Areas: Overview of common energy challenges, including grid congestion, reliance on fossil fuels, and increasing energy demands, with a focus on the specific context of Hilversum.

Current Energy Systems and Technologies: Examination of existing energy systems, including traditional and renewable energy sources, and the limitations of current grid infrastructure.

Renewable Energy Integration: Analysis of the potential for various RES to be integrated into urban energy systems, supported by case studies of successful implementations.

Technological Configurations for Energy Systems: Exploration of different technological configurations, such as Microgrids, Smart Grids, and Energy Hubs, along with their advantages and challenges.

Economic Feasibility of Energy Solutions: Review of the economic aspects of implementing renewable energy technologies, including cost-benefit analyses and financial models relevant to urban energy systems.

Gaps in Literature: Identification of gaps in the existing literature that the current research aims to address, emphasizing the need for further exploration of specific technological configurations.

Ultimately, this literature review will serve as a critical component of the thesis, guiding the research methodology and framing the analysis of findings in subsequent chapters.

2.1. Energy Challenges in Urban Areas

Urban areas face several critical energy challenges that significantly impact their ability to transition to sustainable energy systems. These challenges encompass grid congestion, reliance on fossil fuels, increasing energy demands, and difficulties in integrating renewable energy technologies [2]. The growth of electric mobility and the electrification of heating and cooking further exacerbate these issues, highlighting the need for innovative solutions to create a resilient energy infrastructure [10].

Grid Congestion

Grid congestion is a prominent issue in urban environments, where high population density leads to increased electricity demand. The existing grid infrastructure often struggles to accommodate this demand, resulting in potential disruptions and inefficiencies in electricity distribution [10]. For example, in New England, the circuits operate near their limits [11]. In Germany and China, renewable generation plants have been curtailed to address the congestion on the grid [12]. Strategies to electrify transportation and heat further strains the grid, adding highly stochastic power demands to the weather-dependent network [6]. The integration of RES, such as solar panels, can create reverse power flows that lead to voltage violations and further strain the grid. For instance, the inclusion of EV chargers in the low voltage (LV) grid, without aggregated energy management, can cause severe voltage drops, failing to comply with the technical standards [8]. The necessity for substantial upgrades to the grid infrastructure is critical to ensure reliable energy distribution and to support the integration of new technologies.

Reliance on Fossil Fuels

The significant reliance on fossil fuels constitutes a critical energy challenge, historically rooted in the development of centralized energy production and distribution systems over the past century [13]. This dependence has been further exacerbated by increasing global energy demands across heating, electricity, and transportation sectors. The primary consequence of this reliance is a high carbon footprint, contributing substantially to GHG emissions and environmental pollution. Electricity generation from fossil fuels has long been a major concern due to its contribution to GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), leading to rising global warming [9]. Quantitatively, in 2018, modern renewable energy production accounted for only 11% of total world energy consumption, while in Europe, it was 18% [14]. Globally, fossil fuels constituted 80% of the total energy supply, and in the Netherlands, this figure reached 84% for total energy consumption [3]. This pervasive reliance on fossil fuels not only accelerates climate change but also contributes to the depletion of finite resources.

Increasing Energy Demands

The escalating energy demands in urban areas present a significant vector of complexity for contemporary energy systems, primarily driven by the pervasive electrification of sectors such as transportation and domestic heating [9]. This transition, while crucial for decarbonization efforts, places increasing strain on existing electrical infrastructure, potentially leading to operational challenges [10]. For instance, scenario analysis suggests a substantial amplification of peak charging demand with increasing EV penetration, as evidenced by a surge from 117.6 kWh to 466.32 kWh in December with a rise in EV adoption from 25% to 100% within a community [8]. Similarly, a study focused on a Swedish neighbourhood indicated that the planned deployment of distributed HPs would overload the local electricity distribution grid [15], highlighting the capacity constraints imposed by increased heating electrification. Furthermore, research in Germany projects that load peaks could intensify by up to 3.6 times contingent on the deployed EV charging infrastructure, with EVs potentially constituting approximately one-third of the expected load during peak hours and one-fifth of the total daily electricity usage [16]. These quantitative insights underscore the imperative need for holistic energy management strategies and infrastructure adaptation to accommodate the burgeoning energy demands in urban environments.

Integration of Renewable Energy Resources

The integration of distributed renewable energy resources (DRES) within urban energy systems presents a multifaceted challenge, primarily stemming from the inherent intermittency of sources such as solar PV and wind power. This temporal variability necessitates sophisticated grid management to ensure a continuous balance between energy supply and demand [9]. Furthermore, the existing electricity grid infrastructure, traditionally designed for unidirectional power flow from centralized generation, can face technical constraints with the influx of decentralized renewable generation, potentially leading to voltage limit violations due to reverse power flow from PV systems

[17]. For example, in a simulated residential grid in the Netherlands relying solely on decentralized solar PV and wind, significant levels of RES excess (up to 70%) were observed without energy storage, resulting in low self-consumption rates (as low as 30%) within the energy district [7]. Consequently, grid operators may be compelled to curtail renewable generation to maintain grid stability [12]. The challenge is further compounded by the increasing electrification of heating and transport, where the peak demand from EVs and HPs might not coincide with peak renewable energy generation, requiring energy storage or demand-side management strategies to optimize the utilization of locally produced renewable electricity [2]. The sheer scale of distributed PV adoption, exemplified by over one million small-scale (<4 kW) systems in the UK, underscores the magnitude of effectively integrating these resources into urban grids [9].

Addressing these energy challenges in Hilversum requires a comprehensive strategy that includes targeted infrastructure upgrades, the adoption of advanced technologies, and the implementation of robust control strategies. By focusing on these areas, Hilversum can work towards creating a sustainable and resilient energy system that meets future energy demands while achieving zero-emission energy autarky.

2.2. State of Current Energy System and Technologies

The ongoing energy transition in the Netherlands, necessitates a fundamental shift from a historically dominant fossil fuel-based energy paradigm towards a system increasingly reliant on RES. However, the existing energy infrastructure, deeply rooted in centralized generation and the widespread use of natural gas, coupled with the increasing deployment of distributed and intermittent renewable generation, EVs, and HPs, presents significant challenges to the current grid infrastructure, which was not originally designed for such a dynamic and bidirectional flow of energy. Understanding the current state of these elements is crucial for navigating a successful energy transition.

While fossil fuels remain dominant, RES, particularly solar and wind, are currently contributing an increasing, albeit still minority, share to the Dutch energy mix. Solar and wind contribute 15% of domestic energy supply [3], while rooftop PV panels in specific neighbourhoods generate 9% of annual electricity consumption [4]. The electricity sector, which accounted for 19% of total primary energy supply in 2018, is expected to shift further toward renewables [18]. However, the inherent intermittency of these variable renewable energy sources (vRES) leads to temporal mismatches between electricity generation and consumption. This variability can result in periods of excess renewable generation, which can potentially overload distribution lines and necessitate curtailment to maintain grid stability [7]. Conversely, periods of low wind or solar generation require the grid to compensate for the shortfall, currently often through dispatchable fossil fuel power plants or reliance on interconnections [6]. The increasing penetration of vRES also poses challenges to grid stability, potentially leading to voltage fluctuations and requiring enhanced real-time situational awareness for power system operation [19].

Recognizing the challenges posed by the variability of renewable energy, energy storage systems (ESS) are gaining prominence as crucial components for the ongoing energy transition in the Netherlands [20]. Currently, BESS are being deployed at both household and potentially community levels in various smart grid pilot projects to enhance self-consumption of locally generated PV electricity and provide some grid support [7]. Thermal Energy Storage (TES), such as hot water tanks and Aquifer Thermal Energy Storage (ATES), are also being explored and implemented, particularly in conjunction with HPs, to manage thermal energy demand and provide flexibility [12]. Furthermore, EVs, with the potential for vehicle-to-grid (V2G) functionalities, are increasingly recognized as a distributed energy storage resource that can contribute to peak shaving and grid balancing [19]. While the widespread deployment and full integration of these energy storage solutions are still in relatively early stages, their current implementation in pilot projects and increasing consideration in research and development underscore their growing importance in facilitating a more reliable and sustainable energy system in the Netherlands [5].

The examination of current energy systems reveals a complex landscape where traditional and renewable sources coexist. Transitioning towards more sustainable energy solutions is essential for addressing the challenges posed by conventional systems and meeting the future energy demands of urban areas. By understanding the dynamics of these energy systems, stakeholders can develop innovative configurations that promote zero-emission energy autarky in residential neighbourhoods like Hilversum.

2.3 Renewable Energy Technologies

The integration of RES into urban energy systems is essential for achieving sustainability and reducing carbon emissions. Various technologies can be employed to harness renewable energy effectively in urban settings, including solar energy, wind energy, energy storage systems, innovative heating solutions, and V2G technology. This section explores the potential of these renewable energy technologies.

Solar Energy

Solar energy presents a compelling avenue for decarbonizing urban energy systems due to its distributed generation potential via rooftop PV installations and decreasing costs [10]. The integration of PV with decentralized heat production, such as ultra-low temperature heat grids utilizing PV-Thermal (PVT) collectors and seasonal storage illustrates the technical feasibility of localized renewable energy supply in urban neighbourhoods [1]. However, the widespread deployment of urban solar energy confronts significant challenges. The inherent intermittency of solar irradiance necessitates robust energy storage solutions to ensure temporal alignment of supply and demand [10]. Furthermore, grid congestion in densely populated urban areas can constrain the effective integration of distributed generation, potentially leading to renewable energy curtailment [12]. Spatial limitations within urban landscapes may also restrict the overall capacity for rooftop PV deployment [21]. Despite these complexities, substantial opportunities exist to leverage solar energy in urban contexts. The synergistic combination of PV systems with other DERs, coupled with the implementation of smart grid technologies, can enhance system resilience and stability [19]. Sector coupling strategies, such as the integration of PV generation with EV charging infrastructure, including V2G capabilities, and with HP technologies for building heating and cooling, offer pathways to optimize solar energy utilization and improve energy efficiency across multiple sectors [2]. Moreover, the development of energy sharing mechanisms at the neighbourhood level, potentially facilitated by DC microgrids, can enhance the self-consumption of locally generated solar electricity [16]. Continued advancements in PV technology and further reductions in associated costs will continue to bolster the economic and technical viability of solar energy as a cornerstone of sustainable urban energy futures [13].

Wind Energy

Wind energy also plays a crucial role in urban energy systems, particularly in areas with favorable wind conditions [22]. A study highlighted the successful integration of wind and solar PV systems in community energy setups, showing that a combination of these sources can significantly enhance energy reliability and sustainability. For instance, in a community in the UK, a renewable energy system with a 50% integration of wind and solar resources was able to meet a substantial portion of the local energy demand, demonstrating the effectiveness of hybrid renewable systems [8]. However, the urban environment introduces unique challenges to wind energy harvesting. Aero-acoustic noise pollution and spatial constraints significantly impede the deployment of large-scale, efficient wind turbines. While small-scale wind turbines are technically feasible for residential applications, their economic viability and efficiency in typically lower urban wind speeds and higher turbulence remain concerns. Nevertheless, opportunities arise from innovative architectural integration, such as building-integrated wind turbines (BIVTs), particularly vertical-axis wind turbines (VAWTs) mounted on rooftops, which can exploit localized wind resources [22]. Coupling wind generation with energy storage solutions and power-to-x technologies, such as power-to-heat (P2H) and power-to-gas (P2G), can mitigate intermittency and enhance overall system flexibility [23].

Energy Storage Systems

The widespread integration of vRES into urban energy systems necessitates the robust deployment of ESS to mitigate mismatches between generation and demand and to enhance overall system flexibility and resilience [24]. Diverse storage modalities are critical, each possessing distinct characteristics and optimal use cases [14]. Electrical energy storage (EES), primarily through BESS, is vital for managing the stochastic nature of renewable generation, notably PV systems, enhancing local self-consumption, and providing grid support [20]. While effective for short-duration balancing, electrochemical batteries can be costly compared to other storage forms for thermal applications [7]. TES, ranging from hot water tanks to large-scale ATES, offers a cost-effective solution for storing heat, playing a crucial role in integrating HPs and providing flexibility to manage their electrical demand [2]. TES, particularly ATES, can also facilitate seasonal storage, addressing longer-term temporal disparities. Molecular energy storage (MES), such as hydrogen produced via P2G pathways, presents potential for large-scale and long-duration or seasonal energy storage, complementing electrical storage for different time horizons [2], [7]. Furthermore, EVs act as dynamic storage units with V2G capabilities, offering flexible capacity for grid support and peak shaving when connected [20]. Effectively addressing the complexities of urban energy transitions requires the synergistic integration of these diverse ESS technologies within multi-carrier energy systems to leverage their combined strengths and optimize system performance [25].

Innovative Heating Solutions

Addressing the substantial energy consumption attributed to heating in buildings is paramount for the decarbonization of urban energy systems [2]. HPs have emerged as a leading technology for this transition, leveraging their high efficiency to convert electricity and ambient heat into thermal energy[12]. Coupled with renewable electricity sources, HPs can significantly reduce carbon emissions from heat supply [9]. However, the widespread adoption of electrically driven HPs can induce significant increases in annual electricity consumption and, critically, peak loads, potentially straining low-voltage distribution networks [21]. This challenge necessitates innovative strategies beyond simple electrification. A key pathway involves the integration of HPs with energy storage solutions [26]. TES, such as hot water tanks or large-scale systems like ATES, offers a cost-effective method compared to electrical storage for storing heat, providing flexibility to shift HP operation to periods of high renewable generation or low electricity prices. Combining HPs with PV systems and TES can notably enhance local PV self-consumption and self-sufficiency. Furthermore, sector coupling strategies are vital for enhancing system flexibility. P2H, primarily via HPs integrated with TES, allows surplus renewable electricity to be stored as heat [2]. Exploring synergies with other sectors, such as using P2G pathways for hydrogen production or leveraging V2G capabilities of EVs to provide electrical flexibility, can further optimize the use of intermittent renewable energy and support the grid, including managing the electrical demand imposed by HPs [8]. Advanced smart grid technology and energy management systems are essential for coordinating these integrated technologies and managing loads within complex urban networks. These integrated, multi-carrier energy system configurations demonstrate greater potential for deep decarbonization, and improved cost-effectiveness compared to solutions focusing solely on single technologies or sectors [27]

V2G Technology

V2G technology represents a significant paradigm shift in urban energy management, transitioning EVs from mere loads to dynamic, bidirectional energy assets [9]. This concept allows EVs to both draw power from the grid (Grid-to-Vehicle, G2V) and supply stored energy back to it (V2G) [2]. As such, EVs can function as mobile energy storage units, charging during periods of high renewable generation or low demand and discharging to support the grid during peak load events or renewable energy shortfalls [9]. This capability is particularly valuable for enhancing grid stability and facilitating the integration of vRES like wind and solar PV, effectively mitigating their intermittency [28]. By strategically managing EV charging and discharging, peak demand can be reduced (peak shaving), alleviating strain on distribution networks [29]. However, widespread V2G deployment in urban contexts faces notable challenges. Battery degradation due to frequent cycling remains a concern for EV owners and requires careful management [8]. The necessary bidirectional charging infrastructure and communication capabilities between vehicles and the grid operators or aggregators are also crucial requirements [28]. Furthermore, securing sufficient participation from vehicle owners in smart charging and V2G schemes is essential, as consumer behavior significantly impacts effectiveness [2]. There can also be a temporal mismatch between EV availability (when vehicles are parked and connected) and the grid's need for support Despite these complexities, V2G offers substantial opportunities [15]. Beyond grid support, it can provide ancillary services and potentially offer economic benefits to EV owners [30]. Its synergy with other urban energy technologies, such as complementing solar generation during nighttime or providing flexibility for HP integration, is being actively explored [31]. Advanced smart grid technologies and energy management systems are vital for coordinating V2G operations to maximize these benefits and address the challenges within complex urban distribution networks [9].

2.4. Case Studies

Several studies focus on urban or residential districts, highlighting the crucial role of integrating DERs and flexible technologies to enhance local energy balance, improve grid stability, and progress towards decarbonisation goals. The scale of a neighbourhood is frequently identified as particularly relevant for studying these interactions and implementing coordinated energy management strategies.

Ramplaankwartier, Haarlem, the Netherlands (Smart Urban Isle approach)

One notable area of research involves case studies situated in the Netherlands, which appears frequently in the provided literature. For instance, the Ramplaankwartier, a residential neighbourhood in Haarlem, the Netherlands, served as a case study for applying the 'Smart Urban Isle' (SUI) approach. The SUI project aimed at developing neighbourhood energy systems that locally balance energy production, exchange, and storage to minimise external energy import. The approach in this case study led to the development of an energy concept involving a local, ultra-low temperature heat grid heated by decentralised PVT collectors on individual roofs and connected to a collective seasonal underground storage, specifically ATES. This demonstrates a systematic approach to generating potentially innovative energy system configurations for existing neighbourhoods based on local conditions and potential. The study highlights the usefulness of this approach in generating alternative, locally balanced energy concepts [1].

Nieuwegein neighbourhood, the Netherlands (Power-to-H3 concept)

Another study examines the potential of the "Power-to-H3" concept in an existing neighbourhood in Nieuwegein, the Netherlands, comprising 900 houses situated near an 8.7 MWp solar park. This concept integrates locally produced renewable energy, converting and storing it as heat and hydrogen, and also includes rainwater collection and use. The simulation model results indicate that the solar park, combined with solar panels on roofs and rainwater collection, could supply the neighbourhood's heat demand (20 TJ/year) via an underground heat storage system (ATES) and almost half of its water demand. Furthermore, it could supply 540 hydrogen EVs with hydrogen (90 tonnes/year). The study found that production costs for both hydrogen (€8.7/kg) and heat (€26/GJ) were below current end-user prices in the Netherlands, suggesting affordability. Including avoided social costs could further decrease these prices. This case study serves to introduce and evaluate the feasibility of an integrated energy and water system for a neighbourhood aiming for complete reliance on solar power and rainwater in a reliable, affordable, and clean manner. The high-temperature ATES (HT-ATES) employed here, storing heat at 40–60°C, is noted as a unique aspect compared to typical seasonal storage literature. This approach, combining multiple consumption sectors (electricity, heat, mobility, water) and energy carriers (electricity, heat, hydrogen) with local conversion and seasonal storage, is considered novel and shows potential for enhancing the performance and robustness of neighbourhood energy systems [13].

Cabauw, Netherlands

Another Dutch context is a residential case study in Cabauw, Netherlands, used to validate a multi-objective optimisation procedure for sizing PV, battery, and grid converter for microgrids. The study compares this case with a US case study (Austin) and finds that installing PV and battery systems for the Dutch case study is economically more viable, partly because the lower solar potential leads to less dumping of excess solar power into the grid. This highlights how local conditions and grid interaction dynamics influence the optimal sizing and economic feasibility of residential PV-battery systems [32].

Switzerland sector coupling case study

A research conducted for Switzerland, specifically addressing the decarbonisation of residential heat demand, uses a detailed sector coupling modelling framework with flexible HP operation and considers PV and battery storage investments. While not strictly a single neighbourhood case study, the analysis is applied to Switzerland as a whole, examining the impact of HP deployment and energy retrofitting rates on optimal PV and storage capacities. It concludes that HPs induce significant increases in optimal PV and storage capacity requirements. Notably, the local use of PV for electric heating can reduce the peak demand induced by HPs to the level of conventional electricity peak demand, and HPs add flexibility to the system [21].

Hammarby Sjöstad neighbourhood, Stockholm, Sweden

Moving to Sweden, a case study set in the Hammarby Sjöstad neighbourhood in Stockholm, investigates the potential of using V2G technology for peak shaving to facilitate the integration of distributed domestic HPs. A previous study in this neighbourhood assessed that installing distributed HPs would overload the local electricity distribution grid. Using the thermal mass of buildings as TES could improve the situation but not fully solve the overloading issue. The V2G study explored using electricity stored in EV batteries to cover the peak power demand from HPs, acknowledging challenges related to EV availability and battery charge levels. This case study provides a specific example of how coupling the transport and heating sectors through V2G can address local grid challenges posed by HP electrification. The approach highlights the benefits for city planners, energy utilities, and citizens of adopting a district-level perspective on integrated energy systems [15].

Collectively, these case studies, predominantly located in the Netherlands and Sweden, but also touching upon Switzerland, demonstrate a concerted research effort to understand and optimise the integration of various DERs and flexible technologies at the neighbourhood or district scale. They highlight the potential of technologies such as PV, battery storage, thermal storage (including ATES), HPs, and EVs (especially with V2G capabilities) in increasing local energy self-consumption, providing grid flexibility, reducing peak loads, and contributing to decarbonisation goals. The studies also underscore the complexity involved, the need for sophisticated modelling and optimisation techniques, the importance of considering local conditions and sector coupling, and the ongoing challenges related to optimal sizing, control strategies, and achieving high levels of energy autarky or self-sufficiency in a cost-effective manner. The potential for significant improvements through integrated multi-carrier energy systems and coordinated strategies is clearly demonstrated across these diverse examples.

2.5. Technological Configurations for Energy Systems

The transition to sustainable urban energy systems can be significantly enhanced through various technological configurations, including Microgrids, Smart Grids, and Energy Hubs. Each of these configurations offers unique benefits and faces specific challenges that must be addressed to facilitate their successful implementation.

Microgrids

Microgrids are localized energy systems capable of operating independently or in conjunction with the main grid. They integrate various energy sources, including renewable energy, which enhances reliability and resilience [25]. One of the primary advantages of microgrids is their ability to provide energy independence, allowing them to function autonomously during grid outages and ensuring energy security for local communities [33]. Additionally, microgrids facilitate the integration of distributed RES, reducing transmission losses and enhancing local energy generation. Their design can be tailored to meet specific local energy needs, providing flexibility in energy management [19]. However, the implementation of microgrids comes with challenges, including high initial costs associated with installation and maintenance of the infrastructure. Regulatory barriers may also complicate their operation, as existing regulations might not support autonomous microgrid functionality. Furthermore, managing the balance between supply and demand within a microgrid requires sophisticated control systems, adding to the technical complexity of these systems[32].

Smart Grids

Smart Grids utilize advanced communication and information technologies to enhance the efficiency, reliability, and sustainability of electricity services. They enable real-time monitoring and management of energy flows, which significantly improves operational efficiency [24]. One of the key advantages of smart grids is their ability to facilitate demand response programs, allowing consumers to adjust their energy usage based on real-time pricing signals. This capability not only optimizes energy consumption but also enhances the integration of diverse energy sources, including renewables and storage systems. Despite these benefits, smart grids face several challenges [34]. The increased connectivity associated with smart grids raises concerns about cybersecurity and data privacy, making them vulnerable to potential attacks. Additionally, significant investments are required to upgrade existing grid infrastructure to smart grid capabilities, which can be a barrier to implementation. Consumer acceptance is another challenge, as there may be resistance to adopting smart technologies and changes in energy pricing structures [35].

Energy Hubs

Energy Hubs represent integrated systems that manage multiple energy carriers, such as electricity, heat, and gas, to optimize energy use and enhance overall efficiency. The primary advantage of energy hubs lies in their ability to facilitate the integration of various energy sources and technologies, maximizing resource utilization and promoting sustainability [6]. They provide flexibility in energy management, allowing for dynamic adjustments of energy flows based on real-time demand. Furthermore, by optimizing energy flows, energy hubs can significantly reduce conversion losses associated with traditional energy systems [36]. However, the management of multiple energy carriers introduces complexity, requiring sophisticated control systems and algorithms to ensure efficient operation. The development of energy hubs also involves substantial upfront costs for infrastructure and technology, which can be a barrier to their implementation. Additionally, existing regulations may not adequately support the operation of integrated energy systems, posing further challenges to the widespread adoption of energy hubs [37].

The key differences and similarities between Microgrids, Smart Grids, and Energy Hubs by examining several critical dimensions are presented in Table 1.

Table 1 : Comparison of Energy System Configuration [2], [9], [12], [24], [13], [15], [38], [39].

Aspect	Microgrid	Smart Grid	Energy Hub
Scope/Scale	Typically refers to a localized energy system serving a defined geographical area such as a neighbourhood, building cluster, or campus.	A large-scale or systemic concept encompassing the entire electrical grid infrastructure, from generation to consumption, potentially extending to broader energy systems. Can include analysis at the residential scale.	A conceptual or modelling framework focusing on the integration and interaction of energy carriers and conversion/storage technologies within a system boundary, which could represent a single building, a district, or a larger region.
Energy Carriers	Primarily focused on **electricity**. Increasingly integrates technologies like HPs (coupling heat demand electrically) and EVs (mobility), but the core network is electrical.	Primarily the **electrical grid** but actively integrates data and control across sectors like heat (via electrification), gas, and transport (e.g., EVs, hydrogen) to optimize the overall energy system performance.	Explicitly designed to model and manage the flow, conversion, and storage of **multiple distinct energy carriers** such as electricity, heat, gas, hydrogen, biomass, and potentially water.
Primary Focus	Managing local energy generation (e.g., PV, wind) and consumption within the microgrid boundary, often aiming to enhance self-consumption/sufficiency, reduce peak grid interaction, and address local grid issues like voltage deviations and congestion caused by distributed assets.	Enhancing the overall efficiency, reliability, security, and sustainability of the energy system. This involves advanced monitoring, communication, control, and optimization to integrate distributed resources, manage demand, and improve grid stability.	Analysing the **synergies and interdependencies** between different energy sectors and technologies. Optimizing the conversion, storage, and distribution of multiple energy forms to meet diverse demands and improve system performance, often with a focus on sector coupling and flexibility.
Key Technologies	Distributed generation (PV, wind), energy storage (BESS, TESS), flexible loads (HPs, EVs), local control systems, potentially DC networks and Energy Hub *devices* within the microgrid infrastructure.	Wide array of technologies across the entire grid, including smart meters, advanced sensors, communication networks, sophisticated control algorithms, demand response systems, grid-scale and distributed storage, utility-scale renewables, and enabling infrastructure for integrating distributed assets (PV, EVs, HPs).	Conversion technologies (e.g., HPs, combined heat and power (CHPs), electrolysers, fuel cells, boilers) and storage technologies (e.g., TESS, BESS, hydrogen tanks) that interface between different energy carriers. Modelling and optimization tools are integral.

Grid Connection	Can operate connected to the main grid, providing services or receiving/exporting energy. May also have the capability to disconnect and operate autonomously ("island mode"). Addresses connection challenges like voltage limits and congestion.	Fundamentally interconnected with the large-scale grid infrastructure. The objective is often to enhance the performance and stability of *this interconnected grid* by integrating distributed resources and enabling smarter operation.	Can interact with external energy networks (e.g., electricity grid, gas grid, district heating network) for importing/exporting energy carriers. The focus is on managing energy flows *between* carriers and meeting demands *within* the defined system boundary using various sources.
Integration Level	Integrates generation, load, and storage assets primarily within the electrical domain, focusing on localized energy balancing. Thermal loads are integrated typically through HPs consuming electricity.	Focuses on integrating distributed resources and active demand management *across the electrical grid*, utilizing advanced information and communication technology (ICT). Aims for sector coupling by influencing electrical loads/generation linked to heat or transport.	Represents a high level of **sector coupling**, explicitly modelling and optimizing the conversion and interaction pathways between different energy carriers (electricity, heat, hydrogen, etc.). Emphasizes the flow and transformation of energy between different forms.
Control/Management	Local control algorithms and energy management systems. Can employ optimization techniques for sizing or operation.	Advanced, often hierarchical or distributed control and management systems. Utilizes real-time data and predictive analytics. May involve market mechanisms and demand response programs.	Utilises modelling frameworks and optimization algorithms to determine the optimal dispatch and sizing of conversion and storage technologies based on energy prices, demands, and availability of sources. Focuses on the optimal transformation and allocation of energy carriers.

Microgrids, Smart Grids, and Energy Hubs each present unique opportunities for enhancing energy efficiency and sustainability in urban settings, they also face significant challenges that must be addressed to realize their full potential. By leveraging these technologies, urban areas can move towards more resilient and sustainable energy systems that effectively meet future energy demands.

2.6. Modelling Optimal Energy Systems

An optimally modeled energy system is crucial for navigating the energy transition, especially at residential and district scales. These models are indispensable for minimizing total system costs and ensuring economic feasibility by optimizing investments and operations across diverse energy carriers [38]. Critically, they address grid stability challenges, such as voltage issues and congestion, which arise from integrating intermittent renewables, EVs, and HPs [12]. Optimal modeling facilitates the efficient utilization of local renewable energy, maximizing self-consumption and reducing reliance on the main grid, thereby preventing costly infrastructure upgrades [3].

For robust energy system design, diverse modeling techniques are employed. Simulation models, often developed in Python or utilizing tools like EnergyPLAN and MATLAB Simulink, allow for comprehensive analysis of energy and water balances across various scenarios over time [2], [3], [7]. Optimization models, particularly Mixed-Integer Linear Programming (MILP), are indispensable for determining cost-optimal system configurations, asset sizing, and operational dispatch strategies. These frameworks are crucial for integrating multiple energy carriers to leverage synergies inherent in multi-energy systems and sector coupling [27].

A primary benefit of linear modeling (e.g., LP/MILP) is its capacity to achieve global optima in complex, multi-constrained systems [20]. This directly enables the minimization of total system costs (CAPEX and OPEX) and the precise determination of optimal component sizing and dispatch schedules under various techno-economic and regulatory conditions [6]. Furthermore, these models are lauded for their computational efficiency, facilitating rapid and extensive scenario analysis, which is crucial for robust decision-making in the face of evolving energy landscapes and inherent uncertainties from elements like renewable generation and demand [18].

> **Solar PV Systems:** The electrical generation profile of PV systems is typically linearized by assuming proportionality to solar irradiation, factoring in parameters such as cell temperature and a temperature coefficient for efficiency estimation. Hourly calculations are common, which allow for the incorporation of system losses, including shading and wiring [17].
>
> **Battery Energy Storage Systems:** BESS are typically modeled using an energy-balance approach within linear frameworks. This involves accounting for the previous state of charge (SoC), internal self-discharge rates, and charging/discharging efficiencies. Constraints are rigorously applied to limit charging and discharging power, as well as SoC, to reflect physical and operational boundaries [17], [20].
>
> **Heat Pumps:** HPs are linearly modeled by translating thermal demand into electrical consumption using a Coefficient of Performance (CoP), which can be either a fixed value or a variable dependent on ambient temperature. Their operational flexibility, including start/stop variables, can be explicitly represented [17], [40].
>
> **Seasonal Thermal Energy Storage:** TES systems, such as water tanks or ATES, are modelled to capture the seasonal dynamics of heat storage and release, including heat losses to the surrounding environment. Such systems are modelled using an energy-balance approach to track their SoC. This includes accounting for thermal losses, such as self-discharge to the surrounding soil, which are often proportional to the reservoir temperature [17].

These linear models, by abstracting complex physical phenomena into solvable mathematical problems, allow for critical insights into optimal system design and operation, especially for residential and district-scale new energy systems.

Optimisation plays a central and crucial role in determining the cost-optimum configuration of energy systems. This involves finding the ideal capacities and configurations for various technologies to achieve specific goals [6]. The core application is to formulate an objective function that the model aims to minimize or maximize. A common objective for cost-optimum configurations is minimizing total system costs, encompassing both capital expenditures (CAPEX) for installation and operational expenditures (OPEX) over the system's lifetime [6].

Optimisation considers numerous constraints including the physical limits of each component (e.g., battery capacity, charge/discharge rates, PV panel area, HP capacity, thermal storage volume), grid operational limits (e.g., voltage and thermal limits of cables/transformers, feed-in limits), demand fulfillment, and operational dynamics/strategies [21]. LP and MILP are frequently used for their ability to find globally optimal solutions for problems with linear objective functions and constraints [18].

By applying these methods, optimization determines the cost-optimal configuration for various energy system components. Optimization enables strategic planning by evaluating various scenarios and performing sensitivity analyses to understand how changes in parameters influence the optimal sizing and overall system performance [19]. Key Performance Indicators (KPIs) are crucial for evaluating how well an energy system is performing against its objectives, especially in the context of increasing renewable energy penetration and decarbonization efforts.

Degree of Autarky: The DoA quantifies the percentage of energy consumption met by local sources within the system. It is also referred to as the "energy autonomy factor" or "self-sufficiency" [36]. DoA indicates how well a household or community can rely on its own renewable energy production and independently operate from the local grid. Achieving a high DoA with optimal control and storage, shows significant energy independence compared to a traditional system. This metric helps assess the effectiveness of energy systems in increasing local consumption of renewable energy and reducing reliance on external energy supply [33].

Solar PV Curtailment Rate: PV curtailment refers to the reduction or stopping of electricity generation from PV systems. It's calculated as the difference between potential generation, and the actual generation limit imposed [41]. This KPI is vital for understanding grid stability and congestion issues caused by high penetration of vRES. When PV generation surpasses local demand and grid capacity, curtailment becomes necessary to prevent overloading or voltage problems. While some curtailment may be unavoidable, this KPI helps assess the efficiency of renewable energy utilization and the effectiveness of congestion management strategies [24].

GHG emissions reduction: It is a crucial KPI for evaluating an energy system's environmental impact and its progress toward decarbonization. It quantifies the decrease in harmful gases, such as CO_2, released into the atmosphere. This KPI provides direct insight into how well a system is meeting climate change targets and commitments, enabling the comparison of different energy configurations [10].

In conclusion, optimal energy system modeling and optimization are indispensable for achieving cost-effective, sustainable, and resilient energy solutions. By leveraging advanced techniques and KPIs, these models provide critical insights that drive the transition to a decarbonized energy future.

2.7. Economic Feasibility of Energy Solutions

The implementation of various technological configurations in energy systems has significant cost implications that must be carefully evaluated to ensure economic feasibility. Several widely recognized financial indicators have been employed in the literature to assess the economic feasibility of renewable energy projects, as outlined below.

CAPEX

CAPEX is defined as the initial investment costs associated with the installation of energy systems, which cover expenditure for a specific system component such as solar panels, wind turbines, batteries, and other components. The CAPEX values themselves are typically pre-determined inputs based on component specifications and external economic data understanding. CAPEX is vital for budgeting and financial planning in renewable energy projects. CAPEX is a fundamental input used to determine the annual levelized costs for the energy system [42].

OPEX

OPEX often referred to as Operation and Maintenance (O&M) costs, is fundamentally defined as the recurring annual financial outlays necessary for the day-to-day operation, upkeep, and maintenance of a specific system component or the system as a whole over its economic or operational lifetime. Several sources indicate that these annual O&M costs are frequently determined as a percentage of the component's initial CAPEX to be directly incorporated into the calculation of the annual levelized cost for the system. Ongoing costs for operating and maintaining the energy systems can significantly impact overall economic feasibility. The effective management of OPEX can enhance the long-term profitability of energy systems[42].

LCOE

Represents the average cost of energy generated over the lifetime of a system, factoring in total costs and energy produced. The LCOE is a critical metric for comparing different energy generation technologies as it standardises and assessing their competitiveness. LCOE is calculated as the Net Present Value (NPV) of the total costs over the economic lifetime of the system, divided by the NPV of the total energy produced or demanded over that same economic lifetime. This calculation incorporates the total investment costs (C_I) and total operating costs (C_O), discounted over the project's economic lifetime (N) using a specific discount rate (D). The denominator accounts for the total energy demand (E_T, both electrical and thermal) over the simulation interval, also considered in terms of NPV [43].

$$LCOE = \frac{C_I + \sum_{n=1}^{n \in N} \frac{C_O}{(1+D)^n}}{\sum_{n=1}^{n \in N} \frac{E_T}{(1+D)^n}}$$

Total Net Present Cost (TNPC)

TNPC represents the cumulative cost associated with all components of the energy system over its entire economic or operational lifetime. This encompasses the entirety of financial flows throughout the system's duration, specifically including CAPEX, replacement costs, and ongoing O&M expenses for each system constituent. Essentially, it quantifies the system's total expenditure in terms of its equivalent value at the present moment. TNPC is derived directly from the system's total annual cost, discounted back to a present value using the Capital Recovery Factor (CRF). The explicit formula provided is:

$$TNPC = \frac{CACS}{CRF(i, N)}$$

Here, CACS signifies the Total Annual System Cost, which aggregates the yearly costs of the system components and any energy interaction costs with the grid (specifically, energy purchased minus energy sold to the grid, plus the costs of components like the inverter, wind turbine, battery, and PV system). The CRF(i,N) is utilized to determine the present value of a series of equal annual costs over a defined period. This factor is calculated based on the real interest rate (ir), and the economic lifetime of the system in years (N). The formula for the CRF is given as:

$$CRF = \frac{ir \times (1 + ir)^N}{(1 + ir)^N - 1}$$

Thus, the TNPC calculation standardises the total lifecycle costs to a single present value, enabling direct economic comparison of different system configurations. The research indicates that minimizing TNPC is essential for improving the economic feasibility of energy systems [44].

The economic feasibility of energy solutions is a critical aspect of transitioning urban areas towards sustainable energy systems. By leveraging insights from these studies, researchers and practitioners can better assess the viability of proposed solutions.

2.8. Gaps in Literature

The existing literature on urban energy systems has critical research gaps pertinent to achieving zero-emission energy autarky in a residential neighbourhood for the Hilversum case. Based on the literature, it is apparent that while significant progress has been made in understanding individual components and partial system integrations, a comprehensive, integrated, and context-specific approach remains an active area of research. The challenges faced by areas like Hilversum underscore the necessity for tailored, comprehensive solutions. Identifying and addressing the gaps in current research is crucial for developing such solutions.

The Design Process: Beyond Optimization to Concept Generation

A primary gap identified in the literature concerning neighbourhood energy systems is the emphasis on optimising predefined energy configurations rather than focusing on the initial, creative phase of generating diverse alternative system concepts. While optimization methods are crucial for refining specific solutions, they are inherently limited if the initial set of concepts is not sufficiently innovative or representative of the full solution space. Studies often present comparative analyses of a limited number of pre-determined concepts. The "SUI" approach is explicitly introduced to address this gap by providing a systematic step-by-step method for generating various integrated energy system configurations for neighbourhoods, incorporating aspects like setting KPIs and energy potential mapping [4]. This is critical because the specific characteristics of a neighbourhood, such as building types, existing infrastructure, and local resources, significantly influence the feasibility and performance of different energy system designs [2]. Applying optimization to a sub-optimal set of initial designs will not yield the best possible outcome for a specific case like Hilversum. Therefore, research is needed that provides robust methodologies for concept generation, allowing for the exploration of a wider range of potentially innovative integrated system designs tailored to the unique context of a neighbourhood [4].

Energy Storage Diversity, Synergy, and Seasonal Capacity

Effective energy storage is vital to manage the intermittency of RES like solar and wind and to balance local demand and supply [14]. The literature widely acknowledges the need for energy storage [2]. However, two key gaps emerge regarding storage: the underexplored synergy between different storage technologies within the same decentralized system and the insufficient focus on seasonal storage options like ATES. While electric batteries (BESS) are commonly integrated with PV systems, their potential is often considered lower than other sector coupling strategies for optimizing energy and economic parameters at the district level, and they may not provide sufficient capacity for long-duration or seasonal storage [2]. The large seasonal mismatch between solar generation (peak in summer) and heat demand (peak in winter) highlights the necessity of seasonal storage solutions. Studies that do mention heat storage often focus only on short-term options like hot water tanks, concluding they are insufficient for seasonal needs [14]. Research explicitly exploring the integration and optimization of subsurface seasonal heat storage, such as HT-ATES, with HPs and renewable generation (like PVT systems) in neighbourhood energy systems is needed [45]. A case study considering Thermal Storage and HPs as suitable technologies, and performing research into optimal sizing, integration, and control of seasonal thermal storage systems is highly relevant.

Comprehensive Sector Coupling: The Interplay of Multiple Vectors

The transition to a zero-emission energy system necessitates a deep integration across traditionally separate sectors, such as electricity, heat, and transport[2]. This cross-sector integration, or "sector coupling," is recognized as crucial for improving system flexibility, increasing self-consumption of locally generated renewable energy, and potentially reducing costs [2]. While the literature contains studies focusing on specific couplings, such as P2H or Power-to-Vehicle (P2V)[14], and some combine two sectors, a significant gap lies in the comprehensive analysis of the combined implementation and synergies of multiple sector coupling strategies within urban energy districts. For instance, one study explicitly states that the combined implementation of P2H and P2V strategies in urban energy districts has been little analysed [2]. For a neighbourhood striving for zero-emission energy autarky, leveraging the flexibility and storage potential across all relevant sectors – including using EVs as flexible storage (V2G), HPs coupled with thermal storage, is essential. Research that rigorously models and evaluates the technical and economic performance of such integrated multi-carrier systems with combined sector coupling strategies is needed [20].

Comprehensive Techno-Economic Assessment

Evaluating proposed energy system configurations requires a holistic assessment that goes beyond technical feasibility to include economic viability and environmental impact [2]. A research gap exists in providing integrated models and studies that comprehensively assess the economic and technical impacts of the total residential energy demand (both heat and electricity) in a unified framework, especially in specific national contexts like the Netherlands [5]. While many studies perform techno-economic analyses or evaluate operational improvements, a model that fully integrates the interdependencies between system sizing, operation, different flexibility options, and their impact on grid integration is needed [46]. Economic evaluations should include detailed cost estimations (CAPEX and OPEX) for all system components, considering different technological configurations, and should assess overall feasibility using LCOE [14].

The lack of systematic concept generation methods means that existing standard solutions (like simple PV + battery) might not be optimal or sufficient for Hilversum's specific characteristics [4]. Hilversum's challenges with increasing electric mobility and heating demand require a solution that effectively integrates EVs and HPs, leveraging sector coupling for flexibility. The gap in analysing comprehensive sector coupling means that simply adding these technologies without integrated management could exacerbate grid issues [8]. To achieve near autarky and manage the seasonal variability of renewables, robust and potentially seasonal energy storage solutions are needed [30]. Effectively managing the total energy balance in Hilversum requires integrating all local generation sources, storage, and flexible loads (electricity, heat, transport). The identified research gaps directly underscore the need for a custom-tailored energy solution for the Hilversum neighbourhood.

2.9. Implications

The existing literature provides foundational knowledge and methodologies but reveals several critical gaps concerning integrated system design, comprehensive sector coupling, diverse and seasonal storage, holistic technology integration, and practical implementation. Addressing these gaps through context-specific research is essential for developing a robust, feasible, and tailored energy distribution system configuration capable of meeting Hilversum's energy demands while achieving zero-emission energy autarky. The findings from the literature review will serve as a foundation for the subsequent chapters of the thesis. This structured approach will ensure that the research contributes valuable knowledge to the field of sustainable urban energy systems.

3. Current Energy Landscape

The Netherlands is targeting a 95% reduction in GHG emissions by 2050 and is actively phasing out natural gas for domestic heating [18]. A significant roadblock to this transition is that the widespread adoption of electric HPs and vehicles dramatically increases electricity consumption and peak loads, straining the existing electrical grid, which is not designed for such demands [24]. Looking at decarbonization pathways at the local level helps mitigate these issues. Multi-carrier energy systems that integrate HPs, solar PV, and thermal or battery energy storage are crucial. These systems, supported by smart controls and local energy management, enhance self-consumption and self-sufficiency, thereby reducing dependence on the main grid and alleviating congestion. This approach ensures grid stability and efficient renewable energy integration, contributing to climate targets [2].

3.1. The Dutch Energy Transition: A Case for Local Autonomy

A cornerstone of the national strategy is the widespread electrification of two major energy-consuming sectors: residential heating and personal transport. New buildings are no longer allowed natural gas connections, promoting electric HPs for residential heating [24]. Simultaneously, the Dutch government aims for all new passenger vehicles to be zero-emission by 2030, accelerating EV adoption [18]. This push for electrification is happening in parallel with a massive expansion of renewable generation, particularly solar PV encouraged by policies and declining costs. While beneficial for decarbonization, the confluence of these two powerful trends imposes unprecedented stress on the national electricity grid [12].

This dual strategy leads to severe grid congestion, a critical bottleneck for the Dutch energy transition. The widespread electrification of heating via HPs and EVs significantly increases electricity consumption and peak loads, straining the existing electrical grid not designed for such demands [24]. The temporal mismatch between solar PV generation and residential demand creates a classic "duck curve" issue, straining local distribution networks to their limits [6].

3.2. Case Study: A neighbourhood in Staatsliedenbuurt Oost, Hilversum Zuid.

The Staatsliedenbuurt Oost, a neighbourhood in Hilversum Zuid, Netherlands, presents a compelling case study for examining the challenges and opportunities of transitioning to a sustainable energy model. This residential area, located between Gijsbrecht van Amstelstraat and Diependaalselaan, and bordered by Bosdrift and Oude Loosdrechtsweg/Johan de Withlaan, is home to 546 households, further divided in 14 blocks, comprising nearly 1500 residents. The neighbourhood is characterized by a mix of residential properties and is now the focus of an initiative aimed at developing a local energy system.

Figure 1: Satellite view and block demarcation of the Staatsliedenbuurt Oost neighbourhood.

Challenges with current infrastructure

Like many communities, Staatsliedenbuurt Oost is grappling with the complexities of the ongoing energy transition. A key concern is the growing strain on the existing electricity grid due to the increase in electricity consumption and the increase in local generation of electricity with solar panels leading to congestion problems.

The adoption of EVs, induction cooking, and HPs is contributing to higher electricity consumption within the neighbourhood. Specifically, 40% of the households use induction cooking, and there are 68 EVs in the neighbourhood. The neighbourhood has 86 chargers with 11kW charger load capacity. At the same time, many residents are contributing to the energy supply through solar panels, with 200 homes equipped with this technology. This local generation adds complexity to grid management, particularly with the fluctuating nature of solar energy availability. The total solar generation in the neighbourhood is 650,000 kWh, while the total electricity consumption is 1,910,968 kWh. The electrical infrastructure of the neighbourhood consists of medium voltage cables, low voltage cables and high voltage cables.

The energy landscape faces challenges due to fluctuating and unpredictable prices, influenced by the variability of RES like wind and solar. This variability in supply causes price fluctuations, with periods of very low to negative prices alternating with very high prices, necessitating strategies to balance these extremes. Furthermore, the upcoming abolition of net metering for solar panel owners will remove their ability to offset generated electricity against consumption. This change will significantly increase the cost of purchased electricity relative to supplied electricity, diminishing the financial benefit of residential solar power generation and requiring new solutions.

A Local Energy Ecosystem

In response to these challenges, a local energy initiative is being explored in Staatsliedenbuurt Oost, spearheaded by HET, a local civic energy cooperative. The goal is to develop a more localized and sustainable energy system. The vision involves maximizing the use of locally generated energy within the neighbourhood, reducing reliance on the broader grid. This approach envisions neighbours collaborating in electricity generation, storage, and consumption. The concept includes the possibility of energy sharing among neighbours and storing surplus energy generated during peak times (e.g., summer, midday) for use during periods of higher demand (e.g., winter, evenings).

The initiative in Staatsliedenbuurt Oost represents a forward-thinking approach to addressing the energy challenges of the 21st century. By focusing on local energy generation, sharing, and storage, the neighbourhood aims to create a more resilient, sustainable, and cost-effective energy ecosystem.

HET supplied comprehensive household-level data for the neighbourhood, encompassing individual metrics such as annual electricity demand, annual thermal demand, energy label, construction year, annual gas consumption, usable area, and house type. Neighbourhood characteristics derived from these data are visually represented in Figures 2 and 3. Table 2 provides the description of the neighbourhood block scraped from the provided dataset by HET.

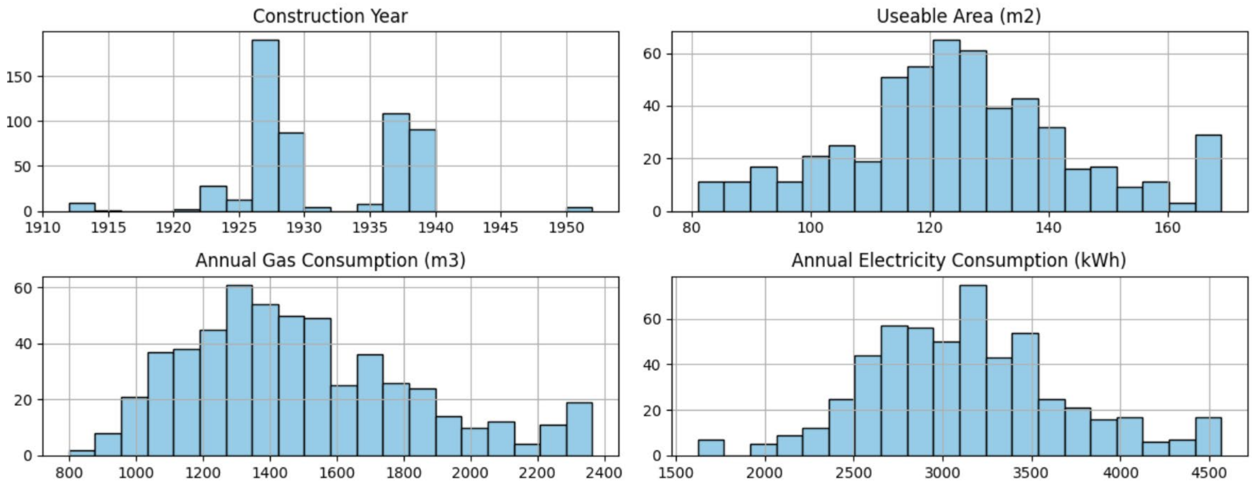

Figure 2 : Construction Year, Useable Area, Annual Gas Consumption and Annual Electricity Consumption for number of houses in the neighbourhood is shown by Y axis.

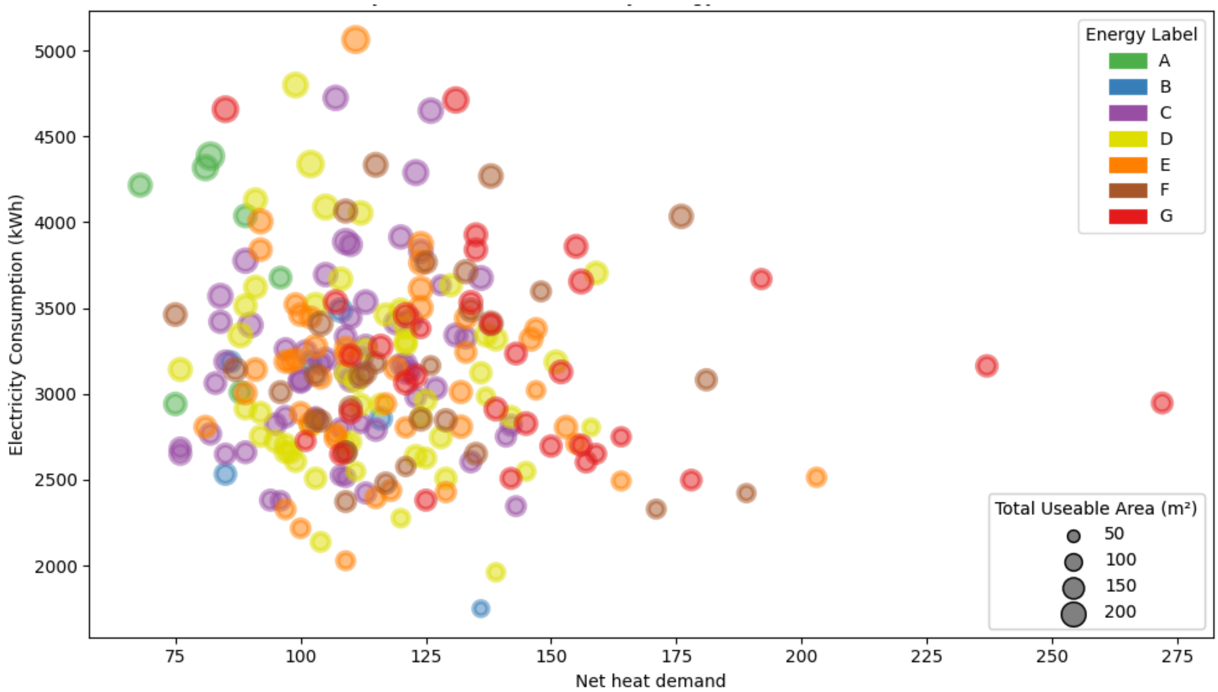

Figure 3 : Electricity consumption (kWh) vs Net heat demand (kWh/m2) by Energy Label and Total Useable Area (m2)

Table 2 : Neighbourhood blocks description.

Block	Houses	PV Capacity Installed (kW_p)	Number of EVs
1	43	51.35	3
2	45	58.8	8
3	31	25.3	2
4	32	6.65	4
5	28	15.5	3
6	45	50.65	0
7	29	63.75	4
8	40	81.15	7
9	40	46.65	5
10	54	59.45	11

11	60	33.875	7
12	48	72	8
13	29	32.05	3
14	21	25.575	3

4. Methodology

This methodology section details the systematic approach employed to address the research question concerning the optimal configurations for a multi-carrier energy distribution system within a residential neighbourhood block in Hilversum. The methodological framework involved a comprehensive techno-economic optimization of multi-carrier energy systems (in Python programming language), which included initial data acquisition and analysis of the current energy landscape (as discussed in the previous section), followed by time series data generation. The energy system was then meticulously modelled, leading to the formulation of a LP optimization model. This model was specifically designed to minimize the NAC of the energy system, which accounts for both the Annualized CAPEX and the Annual OPEX.

The primary objective of this step was to simulate and perform energy system optimisation for each of the fourteen neighbourhood blocks individually to identify the one that demonstrated the most promising characteristics or suitability to serve as a "pilot" for further, more detailed analysis. This analysis is conducted as a scenario-based sensitivity analysis to comprehensively evaluate and compare the performance of optimized energy systems under varying rates of EV and HP adoption, as described in Table 3. This approach allows for the exploration of diverse future states, particularly those characterized by high electrification, which are critical for addressing the escalating energy demands in urban areas like Hilversum. This sensitivity analysis specifically examines how the energy system in a residential neighbourhood block in Hilversum responds to these changes, aiming to reduce dependence on the electricity grid while ensuring economic feasibility.

Furthermore, an optimistic "Net-zero" scenario is simulated, characterized by 100% EV and HP adoption and the complete elimination of grid electricity import. This extreme scenario serves to assess the technical and economic implications of achieving zero-emission energy autarky, pushing the boundaries of local energy self-sufficiency.

Table 3 : Simulated scenarios for the chosen block.

Adoption Scenarios (%)	
EV	**HP**
50	50
70	50
90	50
50	70
50	90
70	70

90	90
100	100
100% EV and HP with zero grid import	

4.1. Time Series Data Generation

To facilitate detailed modelling, the annual electricity and thermal demand data for individual houses were transformed into 15-minute resolution time series data. Probabilistic demand generation scripts, based on the Python models described in [17], were employed to create base electricity and thermal demand profiles, which were subsequently scaled to align with the recorded annual electricity and gas consumption for each household. For thermal demand profile generation, the Energy Label of each house served as an additional input parameter, allowing for the integration of insulation characteristics and thus improving the accuracy of the generated profiles. Similarly, for the EV load, aggregated power profiles were adopted from the literature. These profiles are the result of a bottom-up methodology that generates synthetic weekly data by modelling charging demand and mobility consumption for an EV fleet [47].

4.2. Energy System Modelling

The modelling process for the energy system aims to determine the optimal configuration of a hybrid, grid-connected energy system for a residential neighbourhood block. This process is grounded in a LP model, which seeks the most cost-effective combination of selected technologies and grid interaction to reliably meet energy demands.

The methodology for this energy system optimization involves several key steps:

Data Foundation and Scenario Modelling:

The optimization relies on 15-minute resolution, simulation data for a full year (35,040 time-steps). Key data sources include synchronized CSV files for base electrical demand, base thermal demand, EV charging demand, and normalized solar energy production potential along with ambient air temperature. User-defined HP and EV adoption scenarios are incorporated to account for future changes in technology adoption, allowing for the analysis of various future states like high electrification.

Techno-Economic Parameterization:

A system-wide discount rate is established to calculate CRF for each technology, effectively annualizing upfront CAPEX over the component's lifetime. Detailed parameters are defined for each system component to ground the optimization in economic reality, depicted in Figure 4:

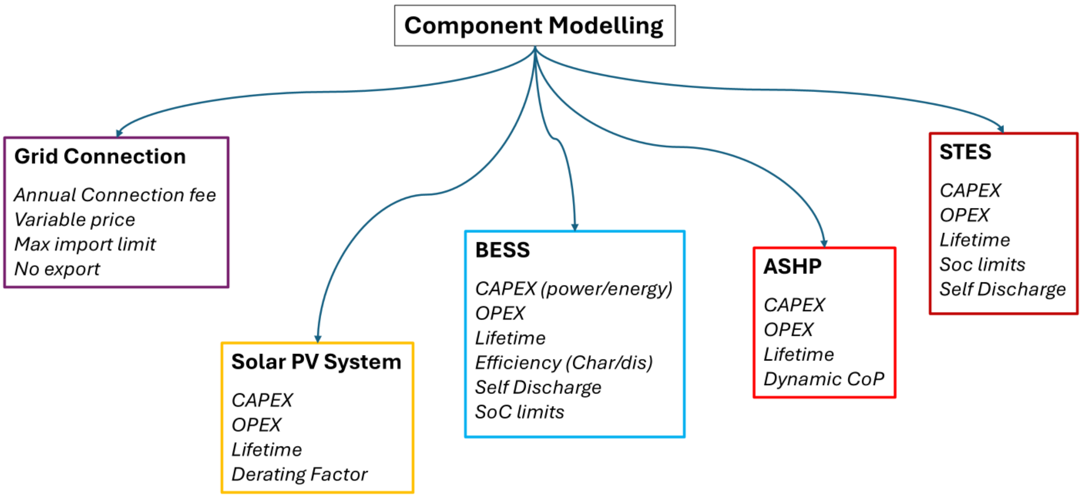

Figure 4 : Techno-Economic Parameterisation of each component of the neighbourhood energy system.

Grid Connection: Modelled with a fixed annual connection fee, a variable price for imported electricity, and a maximum power import limit, with no electricity export allowed.

Solar PV: Defined by CAPEX, annual OPEX, lifetime, and a derating factor to account for real-world performance losses. The total solar PV production at any given time step is defined as the sum of the PV energy generated and used, and any curtailed PV power. This total potential is calculated by multiplying the normalized solar energy production potential by the optimal installed PV capacity and a derating factor.

The equation is:

$$P\_pv\_gen + P\_curtail = G\_pv \times Cap\_pv \times \eta\_pv\_derate$$

Where:

P_pv_gen: The amount of PV energy generated and used (kW) at a time step.

P_curtail: The amount of potential PV energy that is curtailed (discarded because it could not be used or stored) (kW) at a time step.

G_pv: The normalized solar energy production potential at a time step.

Cap_pv: The optimal installed PV capacity (kW_p).

η_pv_derate: The PV derating factor, accounting for real-world performance losses.

Battery Energy Storage System: The BESS is modelled with constraints covering its power limits, SoC balance, and SoC operational limits, including initial and final conditions to ensure system stability over the modelling period.

BESS Power Limits

The charging and discharging power of the BESS at any time step cannot exceed its installed power capacity.

$$P\_bess\_ch \le Cap\_bess\_p$$

$$\text{P\_bess\_dis} \leq \text{Cap\_bess\_p}$$

BESS SoC Balance

The SoC of the BESS at any given time step is determined by its SoC in the previous time step, accounting for self-discharge, charging, and discharging efficiencies.

$$\text{SoC\_bess}[t] = (\text{SoC\_bess}[t\text{-}1] \times \text{qh\_remaining\_fraction}) + (\text{P\_bess\_ch}[t] \times \eta\text{\_bess\_ch}) - (\text{P\_bess\_dis}[t] / \eta\text{\_bess\_dis})$$

BESS SoC Limits

The BESS SoC must remain within predefined minimum and maximum fractions of its total energy capacity.

$$\text{SoC\_bes} \geq \text{soc\_min\_bess} \times \text{Cap\_bess\_e}$$

$$\text{SoC\_bess} \leq \text{soc\_max\_bess} \times \text{Cap\_bess\_e}$$

Initial and Final SoC Constraints

To ensure year-over-year operational stability, the initial SoC (at t=0) is set to 50% of the optimal energy capacity, and the final SoC (T_final) must be greater than or equal to the initial SoC.

$$\text{SoC\_bess} = 0.50 \times \text{Cap\_bess\_e}$$

$$\text{SoC\_bess}[\text{T\_final}] \geq \text{SoC\_bess}$$

Where:

P_bess_ch: BESS charging power (kW)

P_bess_dis: BESS discharging power (kW)

SoC_bess: BESS SoC (kWh)

Cap_bess_p: Optimal installed BESS power capacity (kW

Cap_bess_e: Optimal installed BESS energy capacity (kWh)

η_bess_ch: BESS charging efficiency

η_bess_dis: BESS discharging efficiency

daily_self_discharge_bess: Daily BESS self-discharge rate

soc_min_bess: Minimum BESS SoC (Fraction)

soc_max_bess: Maximum BESS SoC (Fraction)

T_final: The last time step in the simulation period

Air Source Heat Pump: Defined by CAPEX, fractional OPEX, and lifetime, the ASHP is characterized by its thermal output, which is a function of its electrical input and a dynamic COP. Its operation is also constrained by its installed capacity.

ASHP Performance and Capacity

The thermal output of the ASHP is directly related to its electrical input by its COP. Additionally, the ASHP's thermal output cannot exceed its optimal installed capacity.

$$Q\_ashp\_out = P\_ashp\_in \times COP\_ashp$$

$$Q\_ashp\_out \le Cap\_ashp$$

Dynamic COP

The ASHP's COP is not static, it is dynamically calculated for each time step based on the ambient air temperature, making the model more realistic.

$$COP\_ashp[t] = cop\_slope \times ambient\_temperature\_deg\_c[t] + cop\_intercept$$

Where:

Q_ashp_out: ASHP thermal output (kW_th)

P_ashp_in: ASHP electrical input (kW)

Cap_ashp: Optimal installed ASHP capacity (kW_th)

COP_ashp[t]: The COP of the ASHP

cop_slope: A parameter for the COP calculation

cop_intercept: A parameter for the COP calculation

ambient_temperature_deg_c: The ambient air temperature (°C)

Seasonal Thermal Energy Storage: Modelled with CAPEX, fractional OPEX, lifetime, operational SoC limits, and an annual self-discharge loss.

The STES is modelled with constraints governing its charging and discharging, its SoC balance over time, and operational SoC limits.

STES Power Limits

The rate at which the STES can be charged is limited by the output capacity of the ASHP, as the ASHP is the sole source for charging the thermal storage.

$$Q\_stes\_ch[t] \le Cap\_ashp$$

STES SoC Balance

The SoC of the STES at any given time step is calculated based on its SoC in the previous time step, accounting for self-discharge and the thermal energy charged into or discharged from the storage.

$$SoC\_stes[t] = (SoC\_stes[t-1] \times timestep\_remaining\_fraction) + Q\_stes\_ch[t] - Q\_stes\_dis[t]$$

STES SoC Limits

The STES SoC must always remain within predefined minimum and maximum fractions of its total energy capacity.

$$SoC\_stes \geq soc\_min\_stes \times Cap\_stes$$

$$SoC\_stes \leq soc\_max\_stes \times Cap\_stes$$

Initial and Final SoC Constraints

To ensure year-over-year operational stability and prevent unrealistic depletion, the initial SoC (at t=0) is set to 50% of the optimal energy capacity, and the final SoC (T_final) must be greater than or equal to the initial SoC.

$$SoC\_stes = 0.50 \times Cap\_stes$$

$$SoC\_stes[T\_final] \geq SoC\_stes$$

Where:

Q_stes_ch: STES charging power (kW_{th}).

Q_stes_dis: STES discharging power (kW_{th}).

SoC_stes[t]: STES SoC (kWh_{th}).

Cap_stes: Optimal installed STES energy capacity (kWh_{th}).

Cap_ashp: Optimal installed ASHP capacity (kW_{th}), which limits STES charging.

timestep_remaining_fraction: The fraction of energy remaining after self-discharge for one time step.

soc_min_stes: Minimum STES SoC (Fraction).

soc_max_stes: Maximum STES SoC (Fraction).

T_final: The last time step in the simulation period.

Optimization Model Formulation (LP):

The problem is formulated as an LP model using the Gurobi optimization library.

Objective Function: The primary goal is to minimize the NAC of the entire system, calculated as the sum of total annualized capital costs and total annual operating costs. This includes annualized costs of PV, BESS, ASHP, STES, fixed annual grid connection fee, operational costs of technologies, and variable cost of imported electricity.

Minimise NAC = Total Annualized CAPEX + Total Annual OPEX

Decision Variables: The solver adjusts two categories of variables to find the optimal solution. Figure 5 lists all the decision variables modelled in the energy system:

Capacity Variables: Single, continuous variables representing the total size of each component to be installed.

Operational Variables: Represent energy flows for every time step of the year.

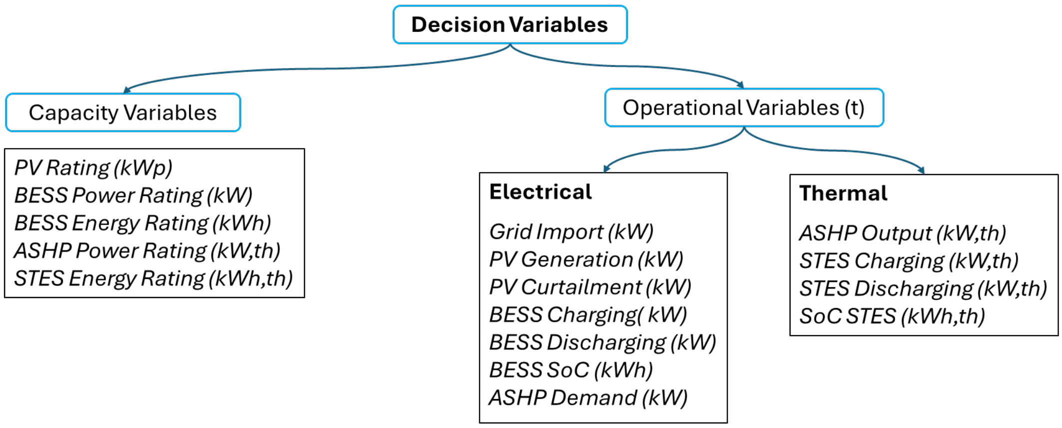

Figure 5: Decision Variables classification for the optimisation model.

System Constraints: These are the rules and physical laws that the solution must obey for every time step, visualised in Figure 6:

Energy Balance: Ensures that energy generation precisely meets energy demand for every 15-minute interval, covering both electrical balance (PV Generation + BESS Discharge + Grid Import = Base Demand + EV Demand + ASHP Input + BESS Charge) and thermal balance (ASHP Output + STES Discharge = Thermal Demand + STES Charge).

Component and Grid Limits: Each technology can only operate within its physical limits, such as grid import limits, PV generation limits, ASHP performance and capacity limits, BESS power limits, and STES charging limits.

Storage Dynamics and Stability: Govern the behaviour of BESS and STES, including SoC balance (energy stored in one step equals previous step plus charged, minus discharged, accounting for efficiencies and self-discharge), SoC limits (stored energy within defined min/max percentage of capacity), and year-end stability (stored energy at end of year greater than or equal to beginning) to ensure sustainability.

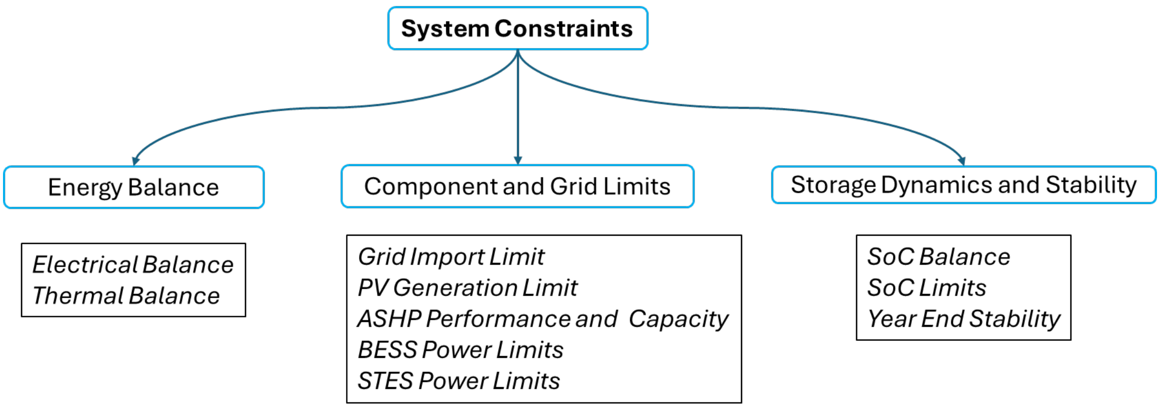

Figure 6 : Modelling the system constraints.

4.3. Post-Processing Calculations, Simulation Results and Visualisations

After Gurobi finds the optimal solution, the script extracts decision variable values and performs post-processing for actionable insights. A comprehensive set of metrics and KPIs are calculated to describe system performance.

Result Presentation: Optimal capacities for each system component, along with a detailed NAC breakdown illustrating CAPEX and OPEX contributions, are presented. An Annual Demand Summary, encompassing individual base electrical, thermal, and mobility demands, is also provided. KPIs such as the LCOE, LCOH, DoA, and PVCR are also displayed. Furthermore, annual system totals pertinent to performance assessment, including annual electricity demand, annual grid import, annual demand met by ASHPs, annual BESS and STES charge throughput, and annual PV generation and curtailment, are shown.

Plots/Visualizations: The script generates plots to visualize system performance, including SoC profiles for BESS and STES, total electricity consumption, and grid electricity import profiles.

4.4. Finding the most promising Block

Optimization is performed on all the blocks to identify the most suitable block for pilot based on KPI and system parameter comparisons.

Once a block is selected, the research focuses on analysing its energy system under various future technology adoption scenarios, specifically varying HP and EV adoption rates. For each scenario, a comprehensive set of KPIs and unit economics were calculated and compared. These KPIs includes DoA, LCOE, LCOH, PVCR, Annual Grid Electricity Import (AGI) and Total Annual Electricity Demand (TED).

This step also involved calculating the GHG emissions reduction potential for these proposed configurations under the different adoption scenarios.

This structured approach allows the stakeholders to move from a broad screening of the entire neighbourhood to an in-depth, scenario-based analysis of the most promising block, providing critical insights into the potential configurations and impacts of a future energy distribution system.

5. Results

This section presents the outcomes of the techno-economic optimization model applied to a residential neighbourhood block in Hilversum. It details the identified optimal energy system configurations, assesses their economic viability, and quantifies their environmental impact under various future technology adoption scenarios. The findings aim to address the research question regarding the optimal configurations for a residential neighbourhood block in Hilversum to meet projected energy demand in 2030, while reducing grid dependence and ensuring economic feasibility.

5.1. Initial Optimization and Selection of the Pilot Block

The initial phase of this research involved a comprehensive energy system optimization across all 14 neighbourhood blocks. Economic realism was ensured by incorporating a comprehensive set of techno-economic parameters for each component, including Solar PV, BESS, ASHP, STES, and the grid connection listed in Figure 7.

Scenario
EV Adoption Scenario = 50% HP
Adoption Scenario = 50% ;
Discount Rate = 5%

PV Parameters
CAPEX = 950 €/kWp
OPEX = 17 €/kWp/year
Lifetime = 25 years
Derating factor = 89%

Grid Parameters
Grid Import Limit = 6 kW/house
Grid Electricity Tariff = 0.3 €/kWh
Fixed Grid Cost = 100 €/year/house

ASHP Parameters
CAPEX = 800 €/kW_th
OPEX = 2% of ASHP CAPEX per year
Lifetime = 20 years
*CoP = 0.11 * (Ambient Temperature) + 3*

STES Parameters
CAPEX = 15 €/kWh_th
OPEX = 0.5% of CAPEX per year
Lifetime = 30 # years
Annual self-discharge = 30%
SoC Range = 5% to 95 %

BESS Parameters
CAPEX Power = 250 €/kW (Power component)
CAPEX Energy = 150 €/kWh (Energy component)
OPEX = 4% of total BESS CAPEX per year
Lifetime = 20 years
Charging & Discharging efficiency = 0.94 (individually)
Self Discharge Loss = 1% per day
SoC Range = 10% to 90 %

Figure 7 : A snippet of the model input parameters.

Based on the results of these individual block optimizations, Table 4 shows that "Block 7" exhibits among the lowest LCOE and LCOH values. Furthermore, its existing PV capacity already fulfills over 50% of the requirement for the current scenario. Therefore, Block 7 was identified for further detailed analysis.

Table 4 : Block-wise result comparison.

Block	PV Capacity Installed (kW_p)	Optimal PV Capacity (kW_p)	LCOE (€/kWh)	LCOH (€/kWh_{th})
1	51.35	153.33	0.379	0.125
2	58.8	159.60	0.375	0.124
3	25.3	105.63	0.362	0.121
4	6.65	115.37	0.366	0.121
5	15.5	92.25	0.385	0.126
6	50.65	156.15	0.381	0.126
7	63.75	121.47	0.362	0.120
8	81.15	153.23	0.365	0.121
9	46.65	144.02	0.362	0.121
10	59.45	198.16	0.375	0.124
11	33.875	414.79	0.361	0.120
12	72	193.12	0.367	0.122
13	32.05	102.73	0.371	0.123
14	25.575	77.32	0.385	0.127

Figure 8 has the profiles of input data for block 7. Figure 9 has all results from the energy system optimisation for block 7. Figure 10 has the plots of electricity consumption, grid electricity import, BESS SoC and STES SoC profile illustrating the system's performance dynamics throughout the year for the block.

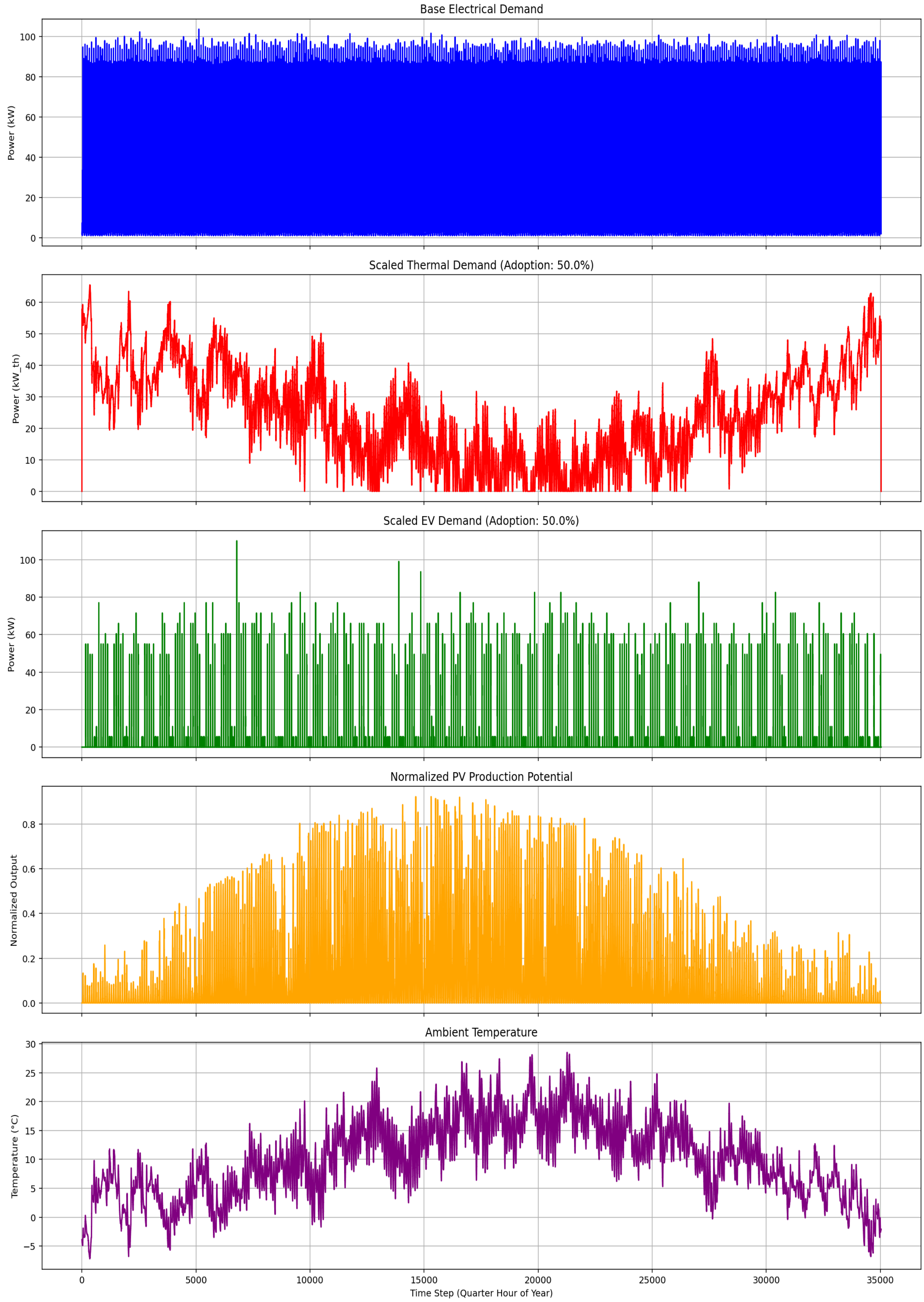

Figure 8 : 15-minute resolution input data profile for Block 7.

No. of Houses: 29
PV Installed: 63.75 kWp

Optimal Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	121.4666979	kWp
BESS Power	36.80078792	kW
BESS Energy	151.6017129	kWh
ASHP	55.78194282	kW_th
STES	526.0533291	kWh_th

NAC Breakdown			
Component	Annualized CAPEX (€)	Annual OPEX (€)	Total Annual Cost (€)
PV	8187.442658	2064.933864	10252.37652
BESS	2562.984658	1277.618157	3840.602815
ASHP	3580.869929	892.5110852	4473.381014
STES	513.3078598	39.45399968	552.7618595
Grid	2900	28772.90017	31672.90017
Total	17744.60511	33047.41727	50792.02238

Annual Demand Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	107,389	kWh
Annual Scaled Thermal Demand	216,860	kWh,th
Annual Scaled Mobility Demand	19,042	kWh

Key Performance Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	48.06	%
BESS Equivalent Full Cycles	175.4	Cycles
Curtailment Rate	26.40	%
Levelized Cost of Electricity (LCOE)	0.362	€/kWh
Levelized Cost of Heat (LCOH)	0.120	€/kWh_th

Annual System Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	184,651	kWh
Annual grid electricity import	95,910	kWh
Annual electricity demand by ASHP	58,219	kWh
Annual BESS Charge Throughput	33,395	kWh
Annual STES Charge Throughput	87,836	kWh_th
Annual PV generation	95,539	kWh
Annual PV curtailment	34,262	kWh

Figure 9 : Block 7 Simulation and optimisation Results.

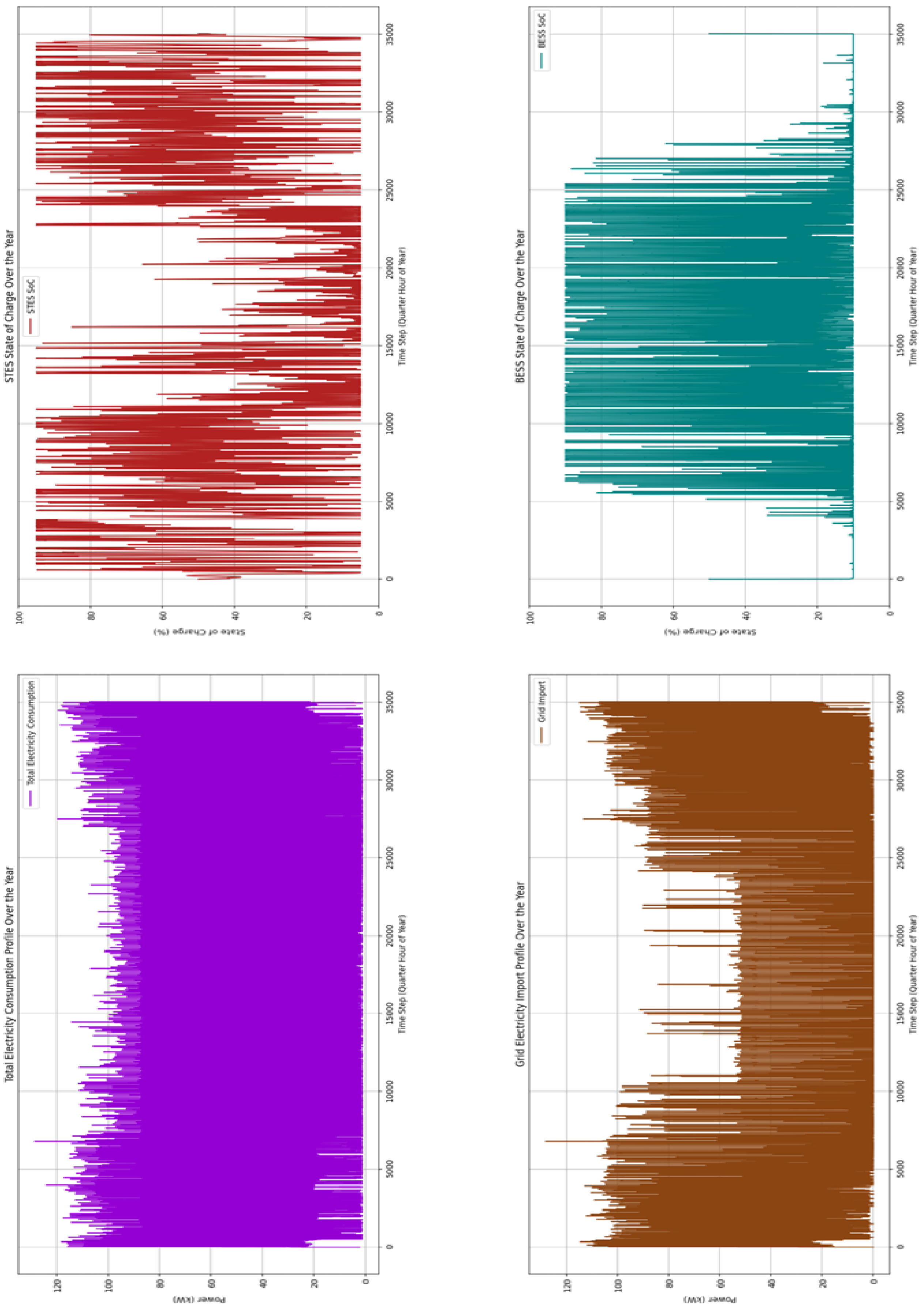

Figure 10 : System Performance Dynamics Visualisations.

5.2. Scenario-Based Performance Comparison for Block 7

This section compares the optimized energy system performance of Block 7 under various future technology adoption scenarios for EVs and HPs. The analysis spans adoption rates from 50% EV/HP up to 100% EV/HP, and critically, a "Net Zero Scenario (No grid Import)". Table 5 presents a comparative overview of KPIs across these scenarios

Table 5 : Multiple adoption scenarios comparative overview of the KPIs for block 7.

Adoption Scenarios (%) EV/HP	PVCR (%)	DoA (%)	LCOH (€/kWh)	LCOE (€/kWh)	AGI (kWh)	TED (kWh)
50/50	26.40	48.06	0.120	0.362	95,910	184,651
70/50	26.50	47.93	0.119	0.358	96,817	185,940
90/50	26.31	47.45	0.118	0.354	101,568	193,292
50/70	27.78	46.31	0.132	0.407	107,950	201,078
50/90	28.16	44.81	0.144	0.452	123,411	223,609
70/70	27.18	46.18	0.130	0.400	112,201	208,466
90/90	28.65	45.10	0.139	0.433	130,869	238,394
100/100	28.70	45.56	0.143	0.448	137,917	253,360
Net Zero Scenario	**88.97**	**100**	**0.634**	**1.857**	**0**	**252,748**

Impact on Costs: As EV and HP adoption increases, there is a general trend of increasing LCOE and LCOH, primarily due to the rise in TED and the increased reliance on technologies like ASHP and STES to meet higher thermal loads. The Net Zero Scenario exhibits significantly higher LCOE and LCOH, indicating the substantial cost implications of eliminating grid imports.

Grid Reliance and Autarky: The DoA generally decreases with higher EV/HP adoption, reflecting increased demand that outstrips local generation capacity, leading to higher AGI. Conversely, the Net Zero Scenario achieves 100% DoA, at the cost of significantly higher PV curtailment and unit energy costs.

Renewable Energy Utilization: PVCR generally increases with higher adoption scenarios, peaking dramatically in the Net Zero Scenario. This suggests that without the grid as a sink for excess generation, or further storage optimization, a significant portion of potential solar energy is wasted as on-site demand and storage capacity are saturated.

5.3. GHG Emissions Reduction Potential

Beyond the techno-economic performance, the proposed energy system configurations offer a significant potential for **GHG emissions reduction**. Table 6 quantifies the estimated emissions saved for Block 7 under different EV and HP adoption scenarios, including the ambitious Net Zero Scenario (No grid Import). The GHG reduction calculations are derived from operational lifecycle emissions, explicitly excluding upstream emissions from material production. GHG emissions from the Dutch electricity grid is 370 g CO_2eq/kWh [48].

Table 6 : GHG Emission Reduction potential of the Energy System in each scenario.

Adoption Scenarios (%) EV/HP	Emissions Saved (Kg CO2 eq)
50/50	32,834
70/50	32,975
90/50	33,937
50/70	34,457
50/90	37,073
70/70	35,618
90/90	39,784
100/100	42,713
Net Zero Scenario	**93,516**

The results clearly demonstrate that increasing EV and HP adoption and particularly moving towards a "Net Zero Scenario (No grid Import)", yields a substantial increase in GHG emissions saved. The Net Zero Scenario, despite its higher unit costs, offers the largest potential for decarbonization, achieving over 93,500 kg CO2 equivalent emissions saved. This highlights the significant environmental benefits of transitioning to a localized, highly self-sufficient energy system.

6. Discussion

This section interprets the findings from the techno-economic optimization of a residential neighbourhood block in Hilversum, specifically Block 7, in the context of the broader energy transition challenges and the research objectives. It critically evaluates the identified optimal energy system configurations, their economic implications, and environmental benefits, while also reflecting on the methodology and highlighting areas for future research.

6.1. Interpretation of Optimal System Configurations and Economic Feasibility

The primary research question sought to determine the optimal energy distribution system configurations for a residential neighbourhood block in Hilversum to meet projected energy demand in 2030, while reducing grid dependence and ensuring economic feasibility. The optimization model, grounded in 15-minute resolution, simulation data from modelled real-world conditions and techno-economic parameters, has provided a definitive optimal configuration for Block 7 under the base scenario.

The optimal capacities for Block 7 in the base scenario (50% EV/HP adoption) indicate a significant deployment of Solar PV (121.467 kW_p), complemented by a BESS of 36.801 kW power and 151.602 kWh energy, and a substantial ASHP capacity of 55.782 kW_{th} supported by a large STES of 526.053 kWh_{th}. This configuration directly addresses the need for local energy generation and storage to manage the increasing electricity consumption due to EV adoption and HPs, which are known to strain the existing electricity grid and cause congestion problems in communities like Staatsliedenbuurt Oost.

Economically, the NAC for Block 7 under the base scenario was €50,792.02. A crucial insight from the NAC breakdown is that grid-related costs constitute the largest portion of the total annual cost (€31,672.90), comprising both fixed annual connection fees and variable electricity import costs. This highlights the ongoing reliance on the main electrical grid, even within an optimized local system aiming for reduced dependence. The LCOE of 0.362 €/kWh and LCOH of 0.120 €/kWh_{th} for the base scenario provide key unit economics for comparison with existing solutions, directly addressing a sub-research question. These figures represent the average cost per unit of energy delivered, considering the total annualized capital and operating costs of the respective systems.

The strategic inclusion of both BESS and STES as energy storage solutions directly responds to the identified research gap regarding the insufficient exploration of synergistic integration of diverse energy storage technologies and seasonal storage requirements in decentralized urban energy systems. The significant capacity of STES suggests its vital role in managing seasonal demand-supply mismatches, particularly for thermal loads, which are substantial given the high annual scaled thermal demand of 216,860 kWh_{th} for Block 7.

6.2. Grid Dependence, Autarky, and Renewable Energy Utilization

The DoA of 48.06% for Block 7 in the base scenario indicates that nearly half of the total electricity consumption can be met by on-site generation. While this demonstrates a significant step towards local energy use as envisioned by the HET initiative, it also underscores the continuing reliance on AGI, which was 95,910 kWh. This balance reflects the optimization model's objective to minimize NAC, implying that complete grid independence may not always be the most cost-effective solution under current economic parameters, particularly with the availability of grid electricity.

A notable finding is the PVCR of 26.40% in the base scenario. This signifies that over a quarter of the potential solar energy generated by the system was discarded because it could not be used or stored. This high curtailment, even with substantial BESS capacity, points to the challenges of managing the fluctuating nature of solar energy and maximizing self-consumption, especially given that no electricity export to the grid was allowed in the model. The upcoming abolition of net metering for solar panel owners further emphasizes this challenge, as it will diminish the financial benefit of supplying excess generation back to the grid, thus increasing the cost of purchased electricity and necessitating new solutions for local energy management.

6.3. Scenario-Based Performance and the Net Zero Ambition

The comparative analysis across various EV and HP adoption scenarios provides critical insights into future energy system evolution. As EV and HP adoption rates increase, there is a general trend of increasing LCOE and LCOH, along with a decrease in the DoA and a rise in AGI. For instance, moving from the 50/50 scenario to the 100/100 scenario sees LCOE rise from 0.362 €/kWh to 0.448 €/kWh, and AGI increase from 95,910 kWh to 137,917 kWh. This indicates that while higher electrification contributes to decarbonization, it also places greater demands on the local energy system, potentially requiring larger capacities and increasing overall costs or grid reliance if local generation cannot keep pace.

The Net Zero Scenario (No grid Import) presents a stark contrast and highlights the economic and operational challenges of achieving complete energy autarky. While this scenario achieves 100% DoA and zero AGI, it comes at a significantly higher cost, with an LCOE of 1.857 €/kWh and an LCOH of 0.634 €/kWh$_{th}$. This dramatic increase in unit costs is accompanied by an extremely high PVCR of 88.97%. This suggests that achieving 100% autarky, without the grid as a buffer or export mechanism, would lead to massive over-sizing of generation and storage assets, resulting in substantial CAPEX and significant wasted renewable energy. This finding is crucial for policymakers and urban planners in Hilversum, as it quantifies the trade-offs involved in pursuing complete grid independence versus an optimized, grid-connected approach that balances local self-sufficiency with economic pragmatism.

6.4. GHG Emissions Reduction Potential

Beyond techno-economic considerations, the proposed energy system configurations offer substantial environmental benefits, directly addressing the fourth sub-research question on CO2 emissions reduction potential. The results demonstrate a clear positive correlation between increasing EV and HP adoption and the amount of GHG emissions saved. The base 50/50 scenario already saves 32,834 kg CO2 eq, which progressively increases with higher electrification. Critically, the Net Zero Scenario (No grid Import) achieves the highest emissions savings of 93,516 kg CO_2 eq. This considerable reduction, approximately three times that of the base scenario, highlights the profound environmental impact of a fully decarbonized, localized energy system. The findings underscore that while economic costs may increase with higher autarky, the environmental gains in terms of avoided emissions are substantial, providing a compelling argument for such transitions from a sustainability perspective.

6.5. Addressing Research Gaps and Limitations

This study has made strides in addressing several identified research gaps. The comprehensive techno-economic parameterization and the inclusion of diverse technologies like PV, BESS, ASHP, and STES contribute to a more holistic techno-economic assessment of total residential energy demand within a specific national context. The synergy between BESS and STES for both daily and seasonal storage requirements has been explicitly modelled and optimized, tackling the gap in diverse energy storage integration and seasonal capacity. Furthermore, by considering EV charging (P2V) and ASHP (P2H), the study implicitly explores aspects of comprehensive sector coupling within an urban energy district.

However, the study also has limitations that warrant discussion:

No Grid Export: A significant limitation is the assumption that no electricity export to the grid is allowed. Particularly with high PV generation and curtailment rates, the ability to export surplus electricity could drastically alter the optimal capacities, NAC, and PVCR, especially in a post-net metering future where new market mechanisms for export might emerge.

LP Model: While robust for optimization, the LP model assumes linear relationships and might not fully capture all non-linear complexities or uncertainties inherent in real-world energy systems.

Fixed Parameters and Future Uncertainty: The study relies on a fixed discount rate and static techno-economic parameters. Future technological advancements, policy changes (e.g., carbon pricing, subsidies), and fluctuating energy prices could impact the optimal configurations and economic viability.

Data Resolution and Scope: While 15-minute resolution data was used, the analysis is for a single year and a single block. Broader application might require multi-year analysis to capture long-term climate variations and the consideration of inter-block energy sharing beyond simple aggregation.

6.6. Future Work and Recommendations

Based on these findings and limitations, several avenues for future research emerge:

Exploring Grid Export and Market Mechanisms: Future models should incorporate scenarios where electricity export to the grid is possible and investigate the economic impact of different grid remuneration policies or local energy market designs, especially in light of the abolition of net metering.

Detailed Sensitivity Analysis: Conduct extensive sensitivity analyses on key techno-economic parameters (e.g., future technology costs, grid tariffs, discount rates) to assess the robustness of optimal solutions under uncertainty.

Advanced Optimization Models: Explore MILP or non-linear programming (NLP) models to capture more complex, non-linear relationships and discrete technology sizing options.

Demand-Side Management (DSM) Integration: Integrate active demand-side management strategies, such as flexible EV charging or intelligent building controls, to further optimize energy consumption patterns and reduce peak loads.

V2G Integration: For future work, the model should incorporate V2G capabilities. By allowing EVs to act as a distributed energy storage system, discharging power during peak demand, the neighbourhood could significantly enhance grid stability, increase its DoA, and potentially lower overall system costs.

Community-Scale Energy Sharing: Investigate more sophisticated models for energy sharing within the neighbourhood, moving beyond block-level aggregation to truly capture the neighbours collaborating vision of the local energy ecosystem. This could involve peer-to-peer energy trading mechanisms.

Lifecycle Assessment: Extend the analysis to include a full lifecycle assessment (LCA) of the proposed systems to quantify their cradle-to-grave environmental impacts beyond operational GHG emissions.

By addressing these points, the thesis can provide a comprehensive and insightful discussion of its findings, contextualizing them within the broader energy transition landscape and guiding future research and implementation efforts in Hilversum and similar urban environments.

7. Conclusion

This thesis aimed to determine the optimal configurations for an energy distribution system within a residential neighbourhood block in Hilversum to meet projected energy demand by 2030, reduce dependence on the electricity grid, and ensure economic feasibility. Specifically, the research addressed the central question: "What should be the configurations of the energy distribution system for a residential neighbourhood block in Hilversum to meet the projected energy demand in 2030 while reducing the dependence on the electricity grid and ensuring economic feasibility?". This comprehensive inquiry was guided by sub-research questions focusing on suitable technological options, effective system integration, economic assessment and optimization, and environmental impact. The methodology employed a LP model, grounded in 15-minute resolution simulation data, to identify the most cost-effective combination of technologies and grid interaction for the selected case study in Staatsliedenbuurt Oost, Hilversum Zuid.

7.1. Summary of Key Findings

This section summarizes the pivotal outcomes of the techno-economic optimization, directly addressing the main research question and its sub-components for the residential neighbourhood block in Hilversum.

Main Research Question: What should be the configurations of the energy distribution system for a residential neighbourhood block in Hilversum to meet the projected energy demand in 2030 while reducing the dependence on the electricity grid and ensuring economic feasibility?

The optimization process identified cost-effective energy distribution system configurations for Block 7 under a 50% EV and 50% HP adoption scenario:

Solar PV: 121.467 kW_p

BESS Power: 36.801 kW

BESS Energy: 151.602 kWh

ASHP: 55.782 kW_{th}

STES: 526.053 kWh_{th}

Regarding grid dependence, the optimal configuration for Block 7 achieved a DoA of 48.06%, significantly reducing reliance on the broader grid.

Sub-Research Question 1: What renewable energy technologies are most suitable for the neighbourhood to improve the DoA?

The optimization process identified Solar PV, Battery Energy Storage (BESS), ASHP, and STES as the most suitable renewable energy technologies for improving the DoA and for integration into a cohesive energy system.

Sub-Research Question 2: How can the suitable renewable energy technologies be effectively integrated into a cohesive energy system to reduce grid dependence?

The research demonstrated the effective integration of these technologies through an optimized configuration, with specific capacities for Solar PV, BESS, ASHP, and STES. This integrated local energy ecosystem leverages on-site generation, energy sharing among neighbours, and storage of surplus energy to meet demand, leading to a DoA of 48.06% and an AGI of 95,910 kWh for Block 7.

Sub-Research Question 3: What should be the capacity configuration of renewable energy technologies if the energy system is optimised for annual energy cost? And how does the unit economics (LCOE and LCOH) compare to the existing solution?

The system's capacity configuration was optimized by minimizing the NAC. For Block 7, the minimized Total Annual Cost was €50,792.02, with specific annualized CAPEX and annual OPEX for each component. The unit economics for this optimized system showed a LCOE of €0.362/kWh and a LCOH of €0.120/kWh_{th}, serving as a benchmark for comparison with existing energy provisions.

Sub-Research Question 4: What is the GHG emissions reduction potential of the proposed technological configuration?

The study quantified a significant CO2 emissions reduction potential for the proposed configuration. For the 50% EV and 50% HP adoption scenario in Block 7, the system demonstrated the potential to save 32,834 Kg of CO_2 equivalent emissions, highlighting its substantial contribution towards zero-emission energy autarky.

7.2. Implications and Contributions

This research, focusing on a specific neighbourhood in Hilversum, offers a forward-thinking approach to addressing contemporary energy challenges. It provides a practical framework for mitigating issues such as the growing strain and congestion on the existing electricity grid, which is exacerbated by increased electricity consumption from EVs and HPs, and increased local generation from solar panels. The findings are particularly pertinent given the fluctuating and unpredictable energy prices and the upcoming abolition of net metering for solar panel owners, which necessitates new solutions for optimizing the financial benefit of local solar generation. By demonstrating a viable local energy ecosystem that maximizes the use of locally generated energy, shares energy among neighbours, and stores surplus energy, this study supports the vision of a more resilient, sustainable, and cost-effective energy future.

The study also contributes to filling identified research gaps in the literature. It provides a holistic techno-economic assessment of total residential energy demand (heat and electricity) within a specific national context, considering the interdependencies of system sizing and detailed grid integration impacts, which was previously an area lacking integrated models. Moreover, it explores the synergistic integration of diverse energy storage technologies (BESS with STES) and addresses seasonal storage requirements, an area insufficiently explored in previous research for decentralized urban energy systems. The use of simulation data with 15-minute resolution further enhances the practical relevance and accuracy of the insights for decision-making regarding energy transition initiatives.

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9. Appendix

9.1. GitHub Links

https://github.com/jjac13/Probabilistic_Load_Profile_Generator : Probabilistic load profile generator code, used for generating base electricity load profile.

https://github.com/jjac13/MCES_Library : Multi-carrier energy system library code, used for generating thermal load profile.

https://github.com/Vivek-Vats/Hilversum-Neighbourhood-Optimisation : Hilversum neighbourhood block energy system modelling and optimisation code, used for generating results for the project.

9.2. Simulation results for each block in the neighbourhood

(Scenario: EV 50 HP 50)

Block 1	
PV Installed (kWp)	51.35
No. of Evs	3
House IDs	1 to 43
No. of Houses	43

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	153.33	kWp
BESS Power	45.08	kW
BESS Energy	189.20	kWh
ASHP	76.51	kW_th
STES	689.82	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.37	%
BESS Equivalent Full Cycles	173.0	Cycles
Curtailment Rate	26.95	%
Levelized Cost of Electricity (LCOE)	0.379	€/kWh
Levelized Cost of Heat (LCOH)	0.125	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	234,924	kWh
Annual grid electricity import	123,638	kWh
Annual electricity demand by ASHP	79,073	kWh
Annual BESS Charge Throughput	41,140	kWh
Annual STES Charge Throughput	120,614	kWh_th
Annual PV generation	119,697	kWh
Annual PV curtailment	44,151	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	10335.03	2606.57	12941.60
BESS	3181.56	1585.97	4767.53
ASHP	4911.41	1224.14	6135.55
STES	673.10	51.74	724.84
Grid	4300.00	37091.41	41391.41
Total	23401.10	42559.82	65960.93

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	127,718	kWh
Annual Scaled Thermal Demand	294,417	kWh,th
Annual Scaled Mobility Demand	28,134	kWh

Block 2	
PV Installed (kWp)	58.8
No. of Evs	8
House IDs	44 to 88
No. of Houses	45

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	159.6064746	kWp
BESS Power	47.640755	kW
BESS Energy	201.0803244	kWh
ASHP	76.92076969	kW_th
STES	703.0647812	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.96	%
BESS Equivalent Full Cycles	176.3	Cycles
Curtailment Rate	26.79	%
Levelized Cost of Electricity (LCOE)	0.375	€/kWh
Levelized Cost of Heat (LCOH)	0.124	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	241,460	kWh
Annual grid electricity import	125,652	kWh
Annual electricity demand by ASHP	79,688	kWh
Annual BESS Charge Throughput	44,504	kWh
Annual STES Charge Throughput	121,866	kWh_th
Annual PV generation	124,867	kWh
Annual PV curtailment	45,691	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	10758.24799	2713.310068	13471.55806
BESS	3375.985179	1682.889496	5058.874675
ASHP	4937.857255	1230.732315	6168.58957
STES	686.0305946	52.72985859	738.7604531
Grid	4500	37695.74577	42195.74577
Total	24258.12102	43375.40751	67633.52853

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	132,892	kWh
Annual Scaled Thermal Demand	296,935	kWh,th
Annual Scaled Mobility Demand	28,880	kWh

Block 3	
PV Installed (kWp)	25.3
No. of Evs	2
House IDs	89 to 119
No. of Houses	31

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	105.6305745	kWp
BESS Power	33.16934788	kW
BESS Energy	137.8847638	kWh
ASHP	46.330892	kW_th
STES	428.0266299	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	48.23	%
BESS Equivalent Full Cycles	176.9	Cycles
Curtailment Rate	26.43	%
Levelized Cost of Electricity (LCOE)	0.362	€/kWh
Levelized Cost of Heat (LCOH)	0.121	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	159,258	kWh
Annual grid electricity import	82,441	kWh
Annual electricity demand by ASHP	47,990	kWh
Annual BESS Charge Throughput	30,622	kWh
Annual STES Charge Throughput	72,922	kWh_th
Annual PV generation	83,041	kWh
Annual PV curtailment	29,838	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	7120.011386	1795.719767	8915.731153
BESS	2325.033099	1159.002061	3484.035161
ASHP	2974.168513	741.294272	3715.462785
STES	417.6561979	32.10199724	449.7581952
Grid	3100	24732.3473	27832.3473
Total	15936.8692	28460.4654	44397.33459

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	90,936	kWh
Annual Scaled Thermal Demand	178,524	kWh,th
Annual Scaled Mobility Demand	20,332	kWh

Block 4	
PV Installed (kWp)	6.65
No. of Evs	4
House IDs	120 to 151
No. of Houses	32

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	115.3693801	kWp
BESS Power	35.07557135	kW
BESS Energy	150.1119716	kWh
ASHP	52.35457027	kW_th
STES	479.7123204	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	48.11	%
BESS Equivalent Full Cycles	172.4	Cycles
Curtailment Rate	26.45	%
Levelized Cost of Electricity (LCOE)	0.366	€/kWh
Levelized Cost of Heat (LCOH)	0.121	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	174,579	kWh
Annual grid electricity import	90,595	kWh
Annual electricity demand by ASHP	54,788	kWh
Annual BESS Charge Throughput	32,569	kWh
Annual STES Charge Throughput	81,825	kWh_th
Annual PV generation	90,680	kWh
Annual PV curtailment	32,605	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	7776.453967	1961.279462	9737.73343
BESS	2510.444593	1251.427543	3761.872136
ASHP	3360.852936	837.6731243	4198.52606
STES	468.089623	35.97842403	504.068047
Grid	3200	27178.45738	30378.45738
Total	17315.84112	31264.81593	48580.65705

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	98,724	kWh
Annual Scaled Thermal Demand	203,973	kWh,th
Annual Scaled Mobility Demand	21,066	kWh

Block 5	
PV Installed (kWp)	15.5
No. of Evs	3
House IDs	152 to 180
No. of Houses	28

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	92.25415327	kWp
BESS Power	27.93360465	kW
BESS Energy	117.9318279	kWh
ASHP	45.86532744	kW_th
STES	411.9951317	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.37	%
BESS Equivalent Full Cycles	172.4	Cycles
Curtailment Rate	26.91	%
Levelized Cost of Electricity (LCOE)	0.385	€/kWh
Levelized Cost of Heat (LCOH)	0.126	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	141,020	kWh
Annual grid electricity import	74,213	kWh
Annual electricity demand by ASHP	48,020	kWh
Annual BESS Charge Throughput	25,570	kWh
Annual STES Charge Throughput	71,794	kWh_th
Annual PV generation	72,050	kWh
Annual PV curtailment	26,534	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	6218.375927	1568.320606	7786.696533
BESS	1979.839424	986.927014	2966.766438
ASHP	2944.282029	733.8452391	3678.127268
STES	402.0131185	30.89963488	432.9127534
Grid	2800	22263.9496	25063.9496
Total	14344.5105	25583.94209	39928.45259

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	73,946	kWh
Annual Scaled Thermal Demand	178,818	kWh,th
Annual Scaled Mobility Demand	19,055	kWh

Block 6	
PV Installed (kWp)	50.65
No. of Evs	0
House IDs	181 to 225
No. of Houses	45

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	156.152239	kWp
BESS Power	46.48420028	kW
BESS Energy	199.2278654	kWh
ASHP	78.46059029	kW_th
STES	717.8281586	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.38	%
BESS Equivalent Full Cycles	171.6	Cycles
Curtailment Rate	26.32	%
Levelized Cost of Electricity (LCOE)	0.381	€/kWh
Levelized Cost of Heat (LCOH)	0.126	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	240,832	kWh
Annual grid electricity import	126,733	kWh
Annual electricity demand by ASHP	81,734	kWh
Annual BESS Charge Throughput	43,021	kWh
Annual STES Charge Throughput	123,044	kWh_th
Annual PV generation	122,940	kWh
Annual PV curtailment	43,927	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	10525.41582	2654.588063	13180.00388
BESS	3330.487028	1660.209195	4990.696223
ASHP	5036.704606	1255.369445	6292.074051
STES	700.4362779	53.8371119	754.2733898
Grid	4500	38019.82037	42519.82037
Total	24093.04373	43643.82418	67736.86791

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	129,667	kWh
Annual Scaled Thermal Demand	304,296	kWh,th
Annual Scaled Mobility Demand	29,430	kWh

Block 7

PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	121.4666979	kWp
BESS Power	36.80078792	kW
BESS Energy	151.6017129	kWh
ASHP	55.78194282	kW_th
STES	526.0533291	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	48.06	%
BESS Equivalent Full Cycles	175.4	Cycles
Curtailment Rate	26.40	%
Levelized Cost of Electricity (LCOE)	0.362	€/kWh
Levelized Cost of Heat (LCOH)	0.120	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	184,651	kWh
Annual grid electricity import	95,910	kWh
Annual electricity demand by ASHP	58,219	kWh
Annual BESS Charge Throughput	33,395	kWh
Annual STES Charge Throughput	87,836	kWh_th
Annual PV generation	95,539	kWh
Annual PV curtailment	34,262	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	8187.442658	2064.933864	10252.37652
BESS	2562.984658	1277.618157	3840.602815
ASHP	3580.869929	892.5110852	4473.381014
STES	513.3078598	39.45399968	552.7618595
Grid	2900	28772.90017	31672.90017
Total	17744.60511	33047.41727	50792.02238

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	107,389	kWh
Annual Scaled Thermal Demand	216,860	kWh,th
Annual Scaled Mobility Demand	19,042	kWh

Block 8	
PV Installed (kWp)	81.15
No. of Evs	7
House IDs	255 to 294
No. of Houses	40

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	153.29	kWp
BESS Power	45.60	kW
BESS Energy	193.96	kWh
ASHP	71.27	kW_th
STES	671.10	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.90	%
BESS Equivalent Full Cycles	170.9	Cycles
Curtailment Rate	26.41	%
Levelized Cost of Electricity (LCOE)	0.365	€/kWh
Levelized Cost of Heat (LCOH)	0.121	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	233,757	kWh
Annual grid electricity import	121,798	kWh
Annual electricity demand by ASHP	74,075	kWh
Annual BESS Charge Throughput	41,723	kWh
Annual STES Charge Throughput	112,026	kWh_th
Annual PV generation	120,538	kWh
Annual PV curtailment	43,269	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	10332.44	2605.92	12938.36
BESS	3249.29	1619.73	4869.03
ASHP	4575.23	1140.35	5715.57
STES	654.84	50.33	705.17
Grid	4000.00	36539.43	40539.43
Total	22811.79	41955.77	64767.56

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	133,385	kWh
Annual Scaled Thermal Demand	275,770	kWh,th
Annual Scaled Mobility Demand	26,297	kWh

Block 9	
PV Installed (kWp)	46.65
No. of Evs	5
House IDs	295 to 334
No. of Houses	40

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	144.0232491	kWp
BESS Power	43.90124555	kW
BESS Energy	185.0846827	kWh
ASHP	64.31951662	kW_th
STES	634.7936926	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	48.33	%
BESS Equivalent Full Cycles	174.2	Cycles
Curtailment Rate	26.59	%
Levelized Cost of Electricity (LCOE)	0.362	€/kWh
Levelized Cost of Heat (LCOH)	0.121	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	216,621	kWh
Annual grid electricity import	111,932	kWh
Annual electricity demand by ASHP	66,544	kWh
Annual BESS Charge Throughput	40,537	kWh
Annual STES Charge Throughput	102,125	kWh_th
Annual PV generation	112,981	kWh
Annual PV curtailment	40,924	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	9707.863264	2448.395236	12156.2585
BESS	3108.438449	1549.520552	4657.959001
ASHP	4128.931537	1029.112266	5158.043803
STES	619.4136103	47.60952695	667.0231372
Grid	4000	33579.52864	37579.52864
Total	21564.64686	38654.16622	60218.81308

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	123,646	kWh
Annual Scaled Thermal Demand	248,008	kWh,th
Annual Scaled Mobility Demand	26,432	kWh

Block 10	
PV Installed (kWp)	59.45
No. of Evs	11
House IDs	335 to 388
No. of Houses	54

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	198.1636246	kWp
BESS Power	58.78246455	kW
BESS Energy	250.1471273	kWh
ASHP	95.97559299	kW_th
STES	886.705149	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.82	%
BESS Equivalent Full Cycles	170.9	Cycles
Curtailment Rate	26.59	%
Levelized Cost of Electricity (LCOE)	0.375	€/kWh
Levelized Cost of Heat (LCOH)	0.124	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	301,963	kWh
Annual grid electricity import	157,563	kWh
Annual electricity demand by ASHP	100,286	kWh
Annual BESS Charge Throughput	53,806	kWh
Annual STES Charge Throughput	150,952	kWh_th
Annual PV generation	155,464	kWh
Annual PV curtailment	56,297	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	13357.1863	3368.781617	16725.96792
BESS	4190.08216	2088.707409	6278.78957
ASHP	6161.063911	1535.609488	7696.673399
STES	865.2216365	66.50288617	931.7245227
Grid	5400	47268.79102	52668.79102
Total	29973.55401	54328.39242	84301.94643

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	166,276	kWh
Annual Scaled Thermal Demand	373,461	kWh,th
Annual Scaled Mobility Demand	35,401	kWh

Block 11	
PV Installed (kWp)	33.875
No. of Evs	7
House IDs	389 to 448
No. of Houses	60

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	414.7889538	kWp
BESS Power	128.3509203	kW
BESS Energy	462.4408688	kWh
ASHP	212.9997573	kW_th
STES	1925.465969	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	46.75	%
BESS Equivalent Full Cycles	174.4	Cycles
Curtailment Rate	25.88	%
Levelized Cost of Electricity (LCOE)	0.361	€/kWh
Levelized Cost of Heat (LCOH)	0.120	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	659,672	kWh
Annual grid electricity import	351,246	kWh
Annual electricity demand by ASHP	220,371	kWh
Annual BESS Charge Throughput	100,765	kWh
Annual STES Charge Throughput	329,944	kWh_th
Annual PV generation	328,538	kWh
Annual PV curtailment	114,712	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	27958.78075	7051.412214	35010.19297
BESS	8140.920238	4058.154415	12199.07465
ASHP	13673.32127	3407.996116	17081.31739
STES	1878.814867	144.4099477	2023.224815
Grid	6000	105373.7893	111373.7893
Total	57651.83713	120035.7619	177687.5991

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	399,790	kWh
Annual Scaled Thermal Demand	820,274	kWh,th
Annual Scaled Mobility Demand	39,511	kWh

Block 12	
PV Installed (kWp)	72
No. of Evs	8
House IDs	449 to 496
No. of Houses	48

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	193.1179881	kWp
BESS Power	57.35105749	kW
BESS Energy	239.7115046	kWh
ASHP	90.8006743	kW_th
STES	840.4843048	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	48.02	%
BESS Equivalent Full Cycles	187.8	Cycles
Curtailment Rate	26.43	%
Levelized Cost of Electricity (LCOE)	0.367	€/kWh
Levelized Cost of Heat (LCOH)	0.122	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	292,888	kWh
Annual grid electricity import	152,230	kWh
Annual electricity demand by ASHP	94,392	kWh
Annual BESS Charge Throughput	56,180	kWh
Annual STES Charge Throughput	143,281	kWh_th
Annual PV generation	151,823	kWh
Annual PV curtailment	54,546	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	13017.08602	3283.005798	16300.09181
BESS	4035.760004	2011.779602	6047.539606
ASHP	5828.86482	1452.810789	7281.675608
STES	820.1206528	63.03632286	883.1569757
Grid	4800	45668.97744	50468.97744
Total	28501.83149	52479.60995	80981.44145

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	166,868	kWh
Annual Scaled Thermal Demand	351,456	kWh,th
Annual Scaled Mobility Demand	31,628	kWh

Block 13	
PV Installed (kWp)	32.05
No. of Evs	3
House IDs	497 to 525
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	102.650667	kWp
BESS Power	31.28708444	kW
BESS Energy	130.7293481	kWh
ASHP	48.2751069	kW_th
STES	434.867807	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.82	%
BESS Equivalent Full Cycles	174.8	Cycles
Curtailment Rate	26.57	%
Levelized Cost of Electricity (LCOE)	0.371	€/kWh
Levelized Cost of Heat (LCOH)	0.123	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	156,198	kWh
Annual grid electricity import	81,506	kWh
Annual electricity demand by ASHP	50,353	kWh
Annual BESS Charge Throughput	28,714	kWh
Annual STES Charge Throughput	75,890	kWh_th
Annual PV generation	80,550	kWh
Annual PV curtailment	29,144	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	6919.151211	1745.061338	8664.212549
BESS	2201.148317	1097.246933	3298.395251
ASHP	3098.975579	772.4017103	3871.37729
STES	424.3316237	32.61508553	456.9467093
Grid	2900	24451.76657	27351.76657
Total	15543.60673	28099.09163	43642.69836

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	86,655	kWh
Annual Scaled Thermal Demand	187,462	kWh,th
Annual Scaled Mobility Demand	19,190	kWh

Block 14	
PV Installed (kWp)	25.575
No. of Evs	3
House IDs	526 to 546
No. of Houses	21

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	77.31589275	kWp
BESS Power	22.61506797	kW
BESS Energy	93.28750156	kWh
ASHP	40.22135571	kW_th
STES	365.9764969	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.00	%
BESS Equivalent Full Cycles	174.1	Cycles
Curtailment Rate	26.73	%
Levelized Cost of Electricity (LCOE)	0.385	€/kWh
Levelized Cost of Heat (LCOH)	0.127	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	119,919	kWh
Annual grid electricity import	63,555	kWh
Annual electricity demand by ASHP	41,881	kWh
Annual BESS Charge Throughput	20,411	kWh
Annual STES Charge Throughput	63,377	kWh_th
Annual PV generation	60,534	kWh
Annual PV curtailment	22,087	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	5211.46495	1314.370177	6525.835126
BESS	1576.517462	785.875689	2362.393151
ASHP	2581.972514	643.5416913	3225.514205
STES	357.1094449	27.44823726	384.5576822
Grid	2100	19066.64283	21166.64283
Total	11827.06437	21837.87863	33664.943

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	64,927	kWh
Annual Scaled Thermal Demand	156,008	kWh,th
Annual Scaled Mobility Demand	13,111	kWh

9.3. Simulation results for different scenarios in Block 7

Block 7	
Scenario: HP 50 - EV 70	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	122.6693523	kWp
BESS Power	38.64578808	kW
BESS Energy	162.5141026	kWh
ASHP	54.15991195	kW_th
STES	498.2584709	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.93	%
BESS Equivalent Full Cycles	173.3	Cycles
Curtailment Rate	26.50	%
Levelized Cost of Electricity (LCOE)	0.358	€/kWh
Levelized Cost of Heat (LCOH)	0.119	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	185,940	kWh
Annual grid electricity import	96,817	kWh
Annual electricity demand by ASHP	56,512	kWh
Annual BESS Charge Throughput	35,394	kWh
Annual STES Charge Throughput	84,402	kWh_th
Annual PV generation	96,351	kWh
Annual PV curtailment	34,735	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	8268.507385	2085.37899	10353.88637
BESS	2731.342312	1361.542496	4092.884808
ASHP	3476.745165	866.5585912	4343.303757
STES	486.1864286	37.36938532	523.5558139
Grid	2900	29045.04033	31945.04033
Total	17862.78129	33395.88979	51258.67108

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	210,328	kWh,th
Annual Scaled Mobility Demand	25,708	kWh

Block 7	
Scenario: HP 50 - EV 90	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	126.3552808	kWp
BESS Power	41.68442623	kW
BESS Energy	176.280374	kWh
ASHP	54.13416973	kW_th
STES	504.2807446	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	47.45	%
BESS Equivalent Full Cycles	170.9	Cycles
Curtailment Rate	26.31	%
Levelized Cost of Electricity (LCOE)	0.354	€/kWh
Levelized Cost of Heat (LCOH)	0.118	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	193,292	kWh
Annual grid electricity import	101,568	kWh
Annual electricity demand by ASHP	56,518	kWh
Annual BESS Charge Throughput	37,897	kWh
Annual STES Charge Throughput	84,097	kWh_th
Annual PV generation	99,501	kWh
Annual PV curtailment	35,524	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	8516.956785	2148.039774	10664.99656
BESS	2957.995543	1474.526506	4432.52205
ASHP	3475.092667	866.1467156	4341.239383
STES	492.0627918	37.82105584	529.8838476
Grid	2900	30470.29164	33370.29164
Total	18342.10779	34996.82569	53338.93348

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	210,328	kWh,th
Annual Scaled Mobility Demand	33,054	kWh

Block 7	
Scenario: HP 70 - EV 50	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	128.6834086	kWp
BESS Power	34.5518932	kW
BESS Energy	140.1678279	kWh
ASHP	75.86489755	kW_th
STES	687.9652286	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	46.31	%
BESS Equivalent Full Cycles	172.5	Cycles
Curtailment Rate	27.78	%
Levelized Cost of Electricity (LCOE)	0.407	€/kWh
Levelized Cost of Heat (LCOH)	0.132	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	201,078	kWh
Annual grid electricity import	107,950	kWh
Annual electricity demand by ASHP	78,995	kWh
Annual BESS Charge Throughput	30,365	kWh
Annual STES Charge Throughput	119,682	kWh_th
Annual PV generation	99,317	kWh
Annual PV curtailment	38,196	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	8673.883851	2187.617946	10861.5018
BESS	2380.247698	1186.525899	3566.773598
ASHP	4870.076525	1213.838361	6083.914886
STES	671.2968811	51.59739215	722.8942733
Grid	2900	32384.94162	35284.94162
Total	19495.50496	37024.52122	56520.02617

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	294,459	kWh,th
Annual Scaled Mobility Demand	18,363	kWh

Block 7	
Scenario: HP 90 - EV 50	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	139.223512	kWp
BESS Power	33.41722201	kW
BESS Energy	135.4145121	kWh
ASHP	97.6485737	kW_th
STES	859.2626938	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	44.81	%
BESS Equivalent Full Cycles	210.0	Cycles
Curtailment Rate	28.16	%
Levelized Cost of Electricity (LCOE)	0.452	€/kWh
Levelized Cost of Heat (LCOH)	0.144	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	223,609	kWh
Annual grid electricity import	123,411	kWh
Annual electricity demand by ASHP	101,526	kWh
Annual BESS Charge Throughput	35,121	kWh
Annual STES Charge Throughput	155,868	kWh_th
Annual PV generation	106,880	kWh
Annual PV curtailment	41,896	kWh

NAC_Breakdown

Component	Annualized CAPEX (€)	Annual OPEX (€)	Total Annual Cost (€)
PV	9384.337777	2366.799704	11751.13748
BESS	2300.272707	1146.659293	3446.932
ASHP	6268.459351	1562.377179	7830.836531
STES	838.4440702	64.44470204	902.8887722
Grid	2900	37023.22818	39923.22818
Total	21691.51391	42163.50906	63855.02296

Annual_Demand_Summary

Demand Type	Value	Unit
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	378,590	kWh,th
Annual Scaled Mobility Demand	18,363	kWh

Block 7	
Scenario: HP 70 - EV 70	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	132.8375868	kWp
BESS Power	37.91865812	kW
BESS Energy	156.901061	kWh
ASHP	75.87143408	kW_th
STES	686.4360362	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	46.18	%
BESS Equivalent Full Cycles	180.9	Cycles
Curtailment Rate	27.18	%
Levelized Cost of Electricity (LCOE)	0.400	€/kWh
Levelized Cost of Heat (LCOH)	0.130	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	208,466	kWh
Annual grid electricity import	112,201	kWh
Annual electricity demand by ASHP	79,038	kWh
Annual BESS Charge Throughput	35,497	kWh
Annual STES Charge Throughput	119,142	kWh_th
Annual PV generation	103,375	kWh
Annual PV curtailment	38,578	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	8953.895544	2258.238975	11212.13452
BESS	2649.194868	1320.592947	3969.787816
ASHP	4870.496132	1213.942945	6084.439077
STES	669.8047386	51.48270271	721.2874413
Grid	2900	33660.20804	36560.20804
Total	20043.39128	38504.46562	58547.8569

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	294,459	kWh,th
Annual Scaled Mobility Demand	25,708	kWh

Block 7	
Scenario: HP 90 - EV 90	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	150.6886925	kWp
BESS Power	41.25246251	kW
BESS Energy	169.9657051	kWh
ASHP	97.58945563	kW_th
STES	873.0930936	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	45.10	%
BESS Equivalent Full Cycles	166.9	Cycles
Curtailment Rate	28.65	%
Levelized Cost of Electricity (LCOE)	0.433	€/kWh
Levelized Cost of Heat (LCOH)	0.139	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	238,394	kWh
Annual grid electricity import	130,869	kWh
Annual electricity demand by ASHP	101,620	kWh
Annual BESS Charge Throughput	35,737	kWh
Annual STES Charge Throughput	151,817	kWh_th
Annual PV generation	114,887	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	10157.14637	2561.707773	12718.85414
BESS	2873.324267	1432.318856	4305.643123
ASHP	6264.664322	1561.43129	7826.095612
STES	851.9393804	65.48198202	917.4213624
Grid	2900	39260.81242	42160.81242
Total	23047.07434	44881.75232	67928.82666

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	378,590	kWh,th
Annual Scaled Mobility Demand	33,054	kWh

Block 7	
Scenario: HP 100 - EV 100	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	162.4005668	kWp
BESS Power	49.26289067	kW
BESS Energy	191.5182333	kWh
ASHP	108.3536063	kW_th
STES	988.6136966	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	45.56	%
BESS Equivalent Full Cycles	168.7	Cycles
Curtailment Rate	28.70	%
Levelized Cost of Electricity (LCOE)	0.448	€/kWh
Levelized Cost of Heat (LCOH)	0.143	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	253,360	kWh
Annual grid electricity import	137,917	kWh
Annual electricity demand by ASHP	112,914	kWh
Annual BESS Charge Throughput	40,608	kWh
Annual STES Charge Throughput	167,663	kWh_th
Annual PV generation	123,743	kWh
Annual PV curtailment	49,801	kWh

NAC_Breakdown			
Component	**Annualized CAPEX (€)**	**Annual OPEX (€)**	**Total Annual Cost (€)**
PV	10946.58332	2760.809635	13707.39295
BESS	3293.43323	1641.738306	4935.171536
ASHP	6955.658963	1733.657701	8689.316664
STES	964.6610955	74.14602724	1038.807123
Grid	2900	41375.08545	44275.08545
Total	25060.3366	47585.43712	72645.77372

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	420,656	kWh,th
Annual Scaled Mobility Demand	36,726	kWh

Block 7	
Net Zero Scenario: HP 100 - EV 100	
PV Installed (kWp)	63.75
No. of Evs	4
House IDs	226 to 254
No. of Houses	29

Optimal_Capacities		
Component	**Optimal Capacity**	**Unit**
Solar PV	2744.84884	kWp
BESS Power	238.9151416	kW
BESS Energy	1217.289794	kWh
ASHP	113.3524167	kW_th
STES	46750.07734	kWh_th

Key_Performance_Indicators		
KPI	**Value**	**Unit**
Degree of Autarky (DoA)	100.00	%
BESS Equivalent Full Cycles	88.7	Cycles
Curtailment Rate	88.97	%
Levelized Cost of Electricity (LCOE)	1.857	€/kWh
Levelized Cost of Heat (LCOH)	0.634	€/kWh_th

Annual_System_Totals		
Parameter	**Value**	**Unit**
Total annual electricity demand	252,748	kWh
Annual grid electricity import	0	kWh
Annual electricity demand by ASHP	112,302	kWh
Annual BESS Charge Throughput	178,722	kWh
Annual STES Charge Throughput	700,911	kWh_th
Annual PV generation	323,473	kWh
Annual PV curtailment	2,609,715	kWh

NAC_Breakdown			
Component	**Annualized CAPEX**	**Annual OPEX**	**Total Annual Cost**
PV	185016.081	46662.4302	231678.511
BESS	19444.5646	9692.89018	29137.4548
ASHP	7276.55294	1813.63866	9090.19161
STES	45617.3943	3506.255	49123.6501
Grid	0	0	0
Total	257354.593	61675.2149	319029.808

Annual_Demand_Summary		
Demand Type	**Value**	**Unit**
Annual Base Electricity Demand	103,720	kWh
Annual Scaled Thermal Demand	420,656	kWh,th
Annual Scaled Mobility Demand	36,726	kWh