Building(s') Energy Independence

Modelling Energy Self-Sufficiency in Polish Homes by 2050

by

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AUTHOR'S DECLARATION

I, the undersigned, Kamila Konik, candidate for the MSc degree in in Environmental Sciences, Policy and Management declare herewith that the present thesis titled "Building(s') Energy Independence: Modelling Energy Self-Sufficiency in Polish Homes by 2050." is exclusively my own work, based on my research and only such external information as properly credited in notes and bibliography. I declare that no unidentified and illegitimate use was made of the work of others, and no part of the thesis infringes on any person's or institution's copyright. I also declare that no part of the thesis has been submitted in this form to any other institution of higher education for an academic degree.

Vienna, 30 May 2025

Kamila Konik

ABSTRACT

This study investigates the extent to which single-family buildings in Poland could become energy self-sufficient (meeting real-time demand with on-site generation) by 2050 through retrofitting, rooftop photovoltaics (PV), and battery storage. It fills a key research gap by quantifying the potential and implications of large-scale household energy self-sufficiency for decarbonisation, energy security, resilience, and citizen empowerment. The research simulates hourly energy flows for two retrofit scenarios in five representative buildings with different energy performance levels, each equipped with the same PV+battery system. Results show that annual self-sufficiency ranges from 42% in the least efficient homes to 77% in the most efficient buildings, with an aggregated national self-sufficiency level of 64.4%. Deep retrofits amplify the impact of solar and storage, as for the same PV installation and battery, a highly efficient home achieves far greater autonomy than an inefficient one. Findings highlight the importance of coupling renewable generation with efficiency improvements, but also battery storage, as in PV-only systems, every 1000 kWh/year reduction in demand per building increases self-sufficiency by around 2 percentage points, whereas the addition of battery storage disproportionately benefits more efficient buildings, amplifying gains by up to 6.7 percentage points. Adding a battery improves self-consumption by around 21–24 percentage points, and therefore, storage can be applied to mitigate grid constraint problems, especially around midday, when the number of prosumers causes significant issues. At the national scale, such a transition could reduce operational CO_2 emissions from 66.7 Mt to nearly zero, and slash total residential electricity net demand by 176 TWh. Taking into consideration Poland's high dependence on fossil fuel imports and its inefficient building stock, improving energy self-sufficiency is critical both for reducing GHG emissions and enhancing energy security. Simultaneously, greater autonomy would improve climate resilience, enabling households to maintain essential functions during outages and strengthening energy democracy by decentralising control over energy generation and flow. To make this happen, Poland will need to install 118 GWh of distributed storage, increase prosumer PV generation fivefold, and implement ambitious retrofits, steps that are technically feasible, especially with strong policy support and infrastructure improvements.

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LIST OF ABBREVIATIONS

CO_2 - Carbon Dioxide
EU - European Union
SS - Degree of Self-Sufficiency
SC - Self-Consumption Ratio
PV - Photovoltaic
GHG - Greenhouse Gas
NZEB - Net-Zero Energy Building
ZEB - Zero-Emission Building
EPBD - Energy Performance of Buildings Directive
IPCC - Intergovernmental Panel on Climate Change
CO_2e - Carbon Dioxide Equivalent
UNFCCC - United Nations Framework Convention on Climate Change
NDCs - Nationally Determined Contributions
SDGs - Sustainable Development Goals
RES - Renewable Energy Sources
DSM - Demand-Side Management
P2P - Peer-to-Peer
EP - Energy Performance
PEF - Primary Energy Factor
HVAC - Heating, Ventilation, and Air Conditioning
IoT - Internet of Things
nZEB - Nearly Zero-Energy Building
c-Si - Crystalline Silicon
Yf - Final Yield
PR - Performance Ratio
V2H - Vehicle-to-Home
Li-ion - Lithium-ion
DoD - Depth of Discharge
WAM - With Additional Measures
NECP - National Energy and Climate Plan
EED - Energy Efficiency Directive
RED II - Renewable Energy Directive II
RED III - Renewable Energy Directive III
ktoe - Kilotonne of Oil Equivalent
PEP2040 - Energy Policy of Poland until 2040
NAS - National Adaptation Strategy
NAP - National Adaptation Plan
URE - Urząd Regulacji Energetyki (Polish Energy Regulatory Office)

1. INTRODUCTION

"Not mass production but production by the masses."

Gandhi's famous maxim envisions a world where people take control of meeting their own needs. This trend can also be seen in the current European energy landscape, as individuals are no longer just consumers but producers (prosumers) of energy. Rooftop solar panels, home batteries, and energy-efficient measures are turning ordinary homes into small-scale power plants. The extent to which buildings' energy demand can be met by locally produced energy, also known as energy self-sufficiency, is becoming widely studied, which underscores its role in the challenges of climate change, energy security, and citizens' access to the energy transition.

The global climate crisis requires urgent action to reduce greenhouse gas emissions and build resilience against disruptions, such as extreme weather or grid failures (IPCC 2023). Buildings, responsible for approximately 40% of European Union energy consumption, are central to this challenge (European Commission 2024). To address it, the Energy Performance of Buildings Directive recast sets ambitious energy efficiency standards, while the Green Deal and RePowerEU promote renewable energy adoption, such as rooftop solar, to meet climate, energy security, and just transition goals (European Commission 2019; European Commission 2024; European Commission 2025).

In Poland, there are 15.2 million buildings, 46% of which are single-family homes, heavily reliant on fossil fuels, in particular coal (Attia et al. 2022; KAPE 2024). Consequently, Poland has the most carbon-intensive energy grid in Europe, which, in connection with post-Soviet, highly energy-inefficient infrastructure, makes Polish buildings' decarbonisation and energy autonomy both a major challenge and an opportunity (Ember 2024). Moreover, lower energy needs and decentralised, domestic energy production reduce Poland's dependence on fossil fuel imports. This is particularly important considering recent geopolitical tensions, as the use of energy as a political weapon by Russia exposed the vulnerability of countries reliant on external suppliers (Sovacool et al. 2023).

In addition to national-scale strategies, enhancing energy self-sufficiency also brings a variety of benefits to citizens. First, it builds climate resilience by helping households stay powered during storms, heatwaves, or blackouts, reducing their exposure to increasingly frequent extreme weather events (Hasselqvist et al. 2022). Beyond infrastructure, the shift toward citizen-owned energy systems redistributes decision-making power, giving individuals and communities greater control over energy production and consumption, allowing them to benefit from it (Wahlund & Palm, 2022).

Most self-sufficiency studies evaluate systems with different photovoltaics and storage configurations, treating the building as a fixed environment. Yet EU policy implements the 'Energy Efficiency First' principle, underlining the need to prioritise energy-saving measures, particularly in buildings (European Union 2023). Despite growing interest in energy independence, there is a research gap in understanding how the ambitious retrofitting strategy set by the EU will influence energy self-sufficiency levels, and what level of energy self-sufficiency can be achieved on the national scale with a PV + battery system.

This study addresses these gaps as it aims to explore the technical limits of energy self-sufficiency that could be achieved in Poland's single-family stock by 2050, using an 'efficiency-first + PV + battery' approach and assessing what it could mean for national CO_2 reductions, energy security, climate resilience, and the advancement of energy democracy.

The research is guided by four key questions:

RQ1. What level of energy self-sufficiency can single-family buildings in Poland achieve by 2050 through retrofitting, rooftop photovoltaics, and battery storage?

RQ2. How does annual energy demand in single-family buildings influence energy self-sufficiency, and what are the implications for household climate resilience and energy democracy?

RQ3. To what extent can widespread self-sufficiency in single-family buildings contribute to national CO_2 emissions reduction and enhance energy security by 2050?

RQ4. What are the implications required to scale energy self-sufficiency in Poland's single-family housing stock by 2050?

To address these questions, several steps and objectives were taken. First, Chapter 2 reviews the literature and presents the existing state of the art in the field, which is followed by Chapter 3 describing the methodology. The study uses the High-Efficiency Building (HEB) model to simulate energy demand under two retrofit scenarios, Frozen and Ambitious, for the years 2025–2050. Then, it applies a tailor-made Python script to simulate PV production, battery operation, and hourly energy flow for different building vintages (representing different energy efficiency levels) and calculate key metrics, such as Self-Sufficiency (SS). The next step upscales these results to the national level for 2050 to calculate operational CO_2 emissions and total energy demand. Outcomes from all these steps are then used to evaluate system implications for climate mitigation, resilience, energy democracy, and national energy security. Finally, the research also assesses the technological advancements needed to achieve high levels of energy self-sufficiency in Poland by 2050. All simulation and calculation results are shown in Chapter 4. Chapter 5 then discusses and interprets the outcomes and answers the research questions, while Chapter 6 concludes with study takeaways and recommendations for future research.

2. BACKGROUND OF BUILDINGS ENERGY SELF-SUFFICIENCY

Energy-independent and low-energy-demand buildings are no longer an off-grid curiosity but the EU policy goal. Ambitious climate law, rising prices of fossil fuels and rapid drops in solar panels and energy storage make this idea more and more realistic and, in many cases, more cost-efficient (Benalcazar et al. 2024).

This chapter aims to understand the existing state-of-the-art covering low-demand, self-sufficient single-family buildings. The first subchapter covers the foundations of the concept, including definitions, different approaches, the "efficiency first" perspective, global megatrends, and possible disadvantages. Then, subchapter 2 justifies the topic's relevance from the perspectives of climate mitigation, resilience, energy security, and energy democracy. Subchapter 3 explores the characteristics of energy self-sufficiency performance, such as daily and seasonal variations, and discusses possible ways of enhancing it. The next subchapter, 4th, provides an overview of the technological background, evaluating energy efficiency, photovoltaics, and battery storage while exploring their future potential. Moreover, subchapter 5 presents the policy background at both the EU and Polish levels, identifying the political momentum behind energy self-sufficiency. Next, Subchapter 6 evaluates the existing state-of-the-art of energy self-sufficiency in Poland. Finally, subchapter 7 outlines the existing research gaps to guide the direction of further research.

2.1. Foundations of Building Energy Self-Sufficiency

Following Socratic thought, before assessing any phenomenon, there needs to be a common understanding of its definition and scope. To address it, this subchapter will determine the studied system boundaries and clarify its fundamental aspects, as well as megatrends and possible disadvantages brought by energy independence among households.

2.1.1. What Does It Mean To Be Energy Self-Sufficient?

The concept of energy-independent households and communities started to be discussed over a century ago; however, it gained significant momentum in the 1970s when the oil crisis highlighted awareness of energy security, which overlapped with advancements in solar panel technology (Lopez 2021). Since building energy self-sufficiency is gaining popularity and shifting from a niche idea to a mainstream concept, there are many attempts to establish its accurate definition. In the common understanding, energy self-sufficiency is examined as the extent to which energy demand can be met by local energy generation, normally quantified through the Degree of Self-Sufficiency (SS) value (Simic et al. 2021; Aranda et al. 2025). Along with SS scholars assess Self-Consumption ratio (SC) indicating what part of the generated energy was used on-site, what is especially relevant for grid maintenance (Simic et al. 2021).

Building Energy Self-Sufficiency as a phenomenon is widely studied from the perspective of various academic disciplines, methodologies and scopes of the system itself. Still, the most common approach focuses primarily on on-site energy production by rooftop solar panels combined with energy storage (Gstöhl and Pfenninger 2020). Going further, Energy Self-Sufficiency is considered with different degrees of freedom of applied technologies like demand-side adjustments, heat pumps or thermal or hydrogen storage to explore how they impact the overall performance (Huang et al. 2019; Fedorczak-Cisak et al. 2023; Luthander et al. 2019; Gstöhl and Pfenninger 2020). In the bigger picture, there is a growing amount of research approaching energy autonomy as a part of a larger system like smart grids or urban planning, which places the concept as a part of development strategies (Huang et al. 2019; Paszkowski and Golebiewski 2017; Fell 2017). Nevertheless, few scholars have studied the importance of building energy efficiency or retrofit measures in boosting energy self-sufficiency (Klingler and Schuhmacher 2018; Miranda et al. 2024).

Scholars mainly evaluate the concept of partial self-sufficiency since fully self-sufficient households, while technically feasible, are not economically viable (Pena-Bello et al. 2020; Kleinebrahm et al. 2023; McKenna, Merkel, and Fichtner 2017; Benalcazar, Kalka, and Kamiński 2024; Mutani and Todeschi 2021). Kleinebrahm et al. (2023) showed in their study that for a residential building with solar panels and energy storage, achieving up to 80% energy self-sufficiency makes economic sense, while further investments are not financially justified, which will be further discussed in the chapter. Therefore, projects of fully energy-independent households or communities are mostly considered for remote, off-grid communities or plot microgrid projects, but over time, as technology improves and costs decrease, fully energy-self-sufficient households may become more widespread (Pena-Bello et al. 2020; Kleinebrahm et al. 2023; Benalcazar, Kalka, and Kamiński 2024; Mutani and Todeschi 2021). However, for now, the term "energy self-sufficient building" or "energy-independent building" is most used in discussions referring to partially self-sufficient buildings.

2.1.2. Different Perceptions: From Net-Zero to Full Independence

As mentioned before, several approaches exist to establish energy independence levels in the building. Still, the crucial one determining the nature of the research is their time resolution (time increments) (Hall and Geissler 2017). Two main resolutions are *net self-sufficiency* based on annual time steps, which are approached as net-zero energy buildings, and *self-sufficiency (autarky)* based on 15-minute or hourly resolutions. An established consensus is that hourly resolution is the maximum time step that allows for the proper assessment of real-time self-sufficiency performance (Klingler and Schuhmacher 2018; Simic et al. 2021). The main reason for that is the accuracy level that goes from the hourly mismatch between energy demand and production within the site, which is presented in Figure 2-1, where in early resolution building can achieve complete autarky, but evaluating higher resolution (hour or 15 min) shows that in fact, it balances on level of 40% (Hall and Geissler 2017).

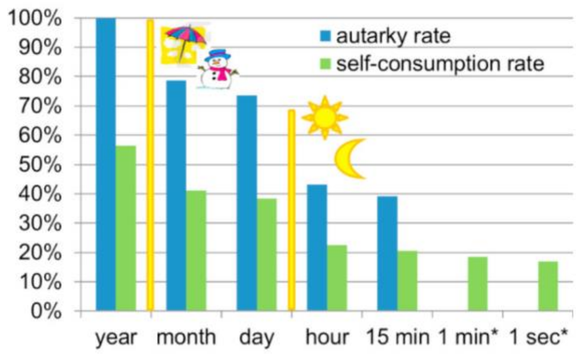

Figure 2-1. Different time steps represent energy self-sufficiency (autarky) and self-consumption rate. Source: Figure reproduced from Hall and Geissler (2017). © 2017 Elsevier. CC BY 4.0.

The first and most well-known yearly resolution is used in net-zero buildings, producing as much energy as they consume over a year (*Net self-sufficiency)*. They primarily address climate mitigation by balancing annual energy usage and production through energy efficiency and renewable energy by reducing GHG emissions (Hu and Pavo-Zuckerman 2021).   On the other hand, energy-self-sufficient buildings emphasise energy independence (*Self-sufficiency*), ensuring improved reliability during grid disruptions (Byrne et al. 2015; Falarz et al. 2021).

The core idea of both concepts is similar, as they integrate on-site use of renewable energy and demand-side measures, but the main difference lies in the strategy's aim. While net-zero buildings seek long-term sustainability, self-sufficient buildings maximise real-time energy independence. Consequently, the first relies on the grid as an energy buffer, while the other aims to minimise this dependency. To do so, approaches that consider self-sufficient buildings often consider some on-site storage to manage energy fluctuations and optimise self-consumption. Therefore, the idea of energy self-sufficiency can be seen from a bottom-up perspective since it aims to sustain operations for a limited time during grid outages, representing the perspective of the average household. It is also worth noting that every fully self-sufficient building can be classified as a net-zero house; however, the reverse is not necessarily true (Andrić et al. 2017). Consequently, net-zero energy buildings also support the development of energy self-sufficiency.

2.1.3. Beyond PV and Battery: 'Efficiency First' Approach

Traditionally, scholars approaching energy self-sufficiency consider PV generation and energy storage as core elements (Lokar and Virtič 2020; Gstöhl and Pfenninger 2020). Since this study will evaluate the concept from an efficiency-first perspective, a brief overview of terms in energy efficiency in buildings is needed. Generally, an energy-efficient building aims to reduce its energy demand without specific targets, standards, certifications or renewable-energy installations, often focusing on improved insulation, efficient heating systems or low-energy appliances (Attia et al. 2022a; Ahmed et al. 2022). The literature includes concepts such as Net-Zero Buildings, Passive Houses or Plus Energy Buildings to standardise terms and implement policies (Kołodziejczyk-Kęsoń and Grebski 2023; Ramirez Camargo, Pagany, and Dorner 2016). Since the last two approaches are overambitious for typical applications in building retrofits, they are treated as voluntary, pioneering models.

A Net-Zero Energy Building (NZEB) is broadly defined as a building or construction that achieves zero-net energy consumption or zero carbon emissions over a set period (usually one year), which means the building's annual energy generation equals its energy demand (Ahmed et al. 2022). A key aspect of NZEBs is a significant reduction in energy demand coupled with on-site renewable generation, which causes their high performance and minimal environmental impact (Firląg and Piasecki 2018; Ahmed et al. 2022; Chatterjee et al. 2025). The precise concept of NZEB is demonstrated in Figure 2-2, where the sum of weighted demand and weighted supply gives a neutral yearly energy balance.

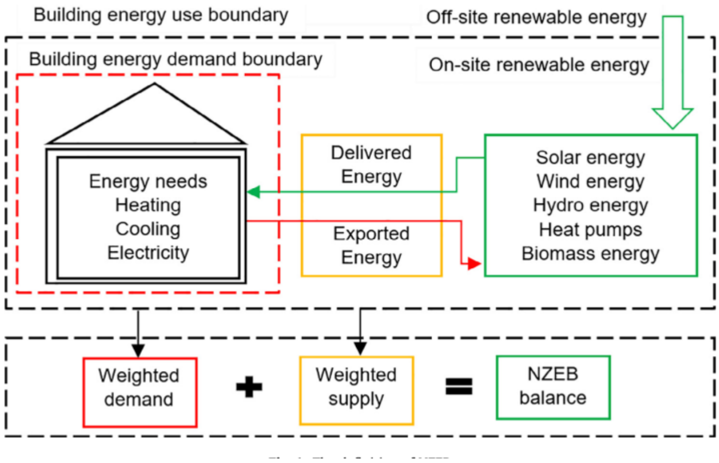

Figure 2-2. Schematic workflow of a Net Zero Energy Building (NZEB) showing the main components, building energy demand and use of on-site or off-site renewable energy. The energy flows within the system, where the red arrow represents energy exported from the building to the grid, and the green arrow represents energy delivered to the building from the grid Source: Figure reproduced from Ahmed et al. (2022). © 2022 Elsevier. Reproduced under Licence No. 6039130334348.

Since Net-zero energy buildings balance energy annually, they are often studied from a top-down perspective as an economy-wide decarbonisation metric, which can drastically reduce CO_2 emissions (Xian et al. 2019). Spotting potential in building-stock decarbonisation, the EU conducted many investments and policies to promote net-zero buildings within member states through modernising existing stock and designing new buildings (Szymańska et al. 2022a). The EU's Energy Performance of Buildings Directive, for the first time, legally defined the Nearly Zero-Energy Building (NZEB) concept within the EU as a building with "very high energy performance" whose "nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources" (European Commission 2019). Furthermore, in 2024 the European Commission replaced the term 'nearly-zero energy buildings' with 'zero-emission buildings' in the recast of the Energy Performance of Buildings Directive (EU 2024/1275), emphasising their climate-mitigation function. The recast requires all new residential buildings to be zero-emission from January 2030, which means they cannot have on-site carbon emissions from fossil fuels (no boilers or heaters burning coal, gas, or oil) and must meet very high primary-energy performance standards. It is essential to acknowledge that in the definition of NZEB or ZEB, there is a focus on primary energy, not useful energy, meaning every imported kilowatt-hour is adjusted to reflect how much non-renewable energy was needed to produce it, and any renewable energy used is removed from the calculation of energy demand.

2.1.4. Megatrends Pushing Energy Independence

The above and other policy measurements are influenced by several long-term shifts that are reshaping societies and industries all around the globe. Understanding existing megatrends and the changes they bring is crucial for predicting the transition humankind is undergoing. Using megatrends as a driving force in establishing strategies and policies is essential as they influence the rate of technological progress and economic systems' mood swings, all of which eventually determine the feasibility of achieving energy self-sufficiency. One of the most fundamental megatrends pushing for energy independence is decarbonisation, driven globally by the Paris Agreement and implemented in the European Union through the Green Deal (European Commission, 2019). As part of emission reduction efforts, EU member states are introducing measures to lower energy demand while maximising renewable energy generation. Closely tied to this is the electrification trend, which builds on decarbonisation by replacing fossil-fuel-based technologies with electric alternatives, such as heat pumps, and enabling seamless integration with renewable electricity from on-site photovoltaic systems (IEA, 2023). Furthermore, there has been a significant advancement in digitalisation and smart grid technologies development (by implementing, for instance, smart meters), reshaping how energy is produced, distributed, and consumed (Mastrucci et al. 2023). These innovations allow for two-way energy flows and enable demand-response mechanisms, boosting both energy efficiency and system resilience (Gellings, 2020; Mishra et al., 2023). Simultaneously, decentralisation is becoming an increasingly important aspect of energy system development, encouraging greater uptake of on-site PV generation, empowering local communities, and fostering regional energy independence (Yadav, 2020; Igliński et al., 2022). Within this evolving landscape, the sharing economy has also emerged as a disruptive force, redefining traditional ownership models and enabling solutions that might elevate energy self-sufficiency through energy collectives (Mastrucci et al., 2023). Finally, the progress of smart city implementations brings all these elements together, placing decarbonisation, electrification, decentralisation, digitalisation, and energy-sharing models into urban and regional planning strategies designed to create resilient and citizen-centred environments (Mishra et al., 2023; Fedorczak-Cisak et al., 2023).

2.1.5. Disadvantages of Widespread Energy Independence

As megatrends are pushing forces for energy self-sufficiency, spreading and enabling it to evolve, it is also essential to understand the possible negative consequences of widely spread energy independence among households. Firstly, the most often mentioned challenge is electricity grid integration and stability (Moshövel et al. 2015; Aoun et al. 2024). The Polish grid infrastructure has been built around centralised power generation and is not ready to accommodate many distributed sources (Benalcazar, Kalka, and Kamiński 2024). Also, scholars underline that the increasing number of prosumers requires significant and costly upgrades to existing infrastructure (Obuseh et al. 2025; Hung et al. 2016). During peak production hours, the infrastructure might not allow further feeding into the grid due to generation curtailment (too much electricity in the grid), which can destabilise the system, as was observed in Germany (Meena et al. 2024).

Additionally, the more people reach higher levels of energy self-sufficiency, the less they rely on the grid, and therefore, network expenses are distributed across fewer end-users. This phenomenon leads to the so-called utility death spiral, where rising network charges make energy self-sufficiency more beneficial and therefore explored, resulting in a continued rise in grid costs (Chen et al. 2023; Kleinebrahm et al. 2023). The most significant issue of the utility death spiral is that it would affect mostly low-income households, which cannot afford solar panels or battery systems (Chen et al. 2023). Following that, high upfront costs for individuals are considered one of the main barriers to energy self-sufficiency (Ciocia et al. 2021). However, the rapid development of both PV and battery technologies and their sharp price decline are making cost-optimal analyses outdated even before they are published (Candelise et al. 2013; Breyer et al. 2022). Nevertheless, policymakers should address this issue to ensure low-income households are not left behind.

Furthermore, some scholars also recognise the possibility of a rebound effect, as individuals might increase overall energy consumption after implementing energy efficiency measures or experiencing surplus energy production (Sorrell et al., 2020). In a study carried out in the US, Beppler et al. (2021) noticed an increase in total electricity production of 28.5%, and Galvin et al. (2022), in a study on German households, found that prosumers not only increased their energy use, but that financial savings from lower electricity bills encouraged additional purchases, such as a new car, and gave a sense of moral justification to consume more energy for activities like holidays or excessive heating.

Finally, it is important to acknowledge that both solar panels and energy storage systems require critical materials, and the environmental and ethical aspects of their mining, processing, and disposal raise concerns (Sovacool et al. 2020; Kramarz et al. 2021). This brings reflection on whether the green energy transition might become another version of colonialism, as developed countries offload environmental burdens onto the Global South, where most of these materials are sourced (Blanc 2022; Dorn 2022). This issue is magnified by the limited lifespan of batteries and solar PV panels and their currently limited recycling or upcycling capabilities (Sim et al. 2025; Sahajwalla et al. 2023).

2.2. Why Buildings' Energy Self-Sufficiency is Relevant?

Despite several challenges, pushing for energy-independent and low-demand buildings is recognised as a great solution to a wide range of challenges- from the global climate goals or improving air quality to the personal trauma of opening a winter energy bill. Due to the environmental focus of the research, climate and energy arguments will primarily be discussed in detail, showcasing how they can contribute to both mitigating and building resilience to climate change while also strengthening energy security or promoting energy democracy.

Addressing the concept from both authority-driven and community-driven interests is underlining the importance of local empowerment and community-centred planning, which is often overlooked by scientists who focus solely on climate mitigation and national-level energy security, as if energy transitions happened exclusively in government offices (Figure 2-3).

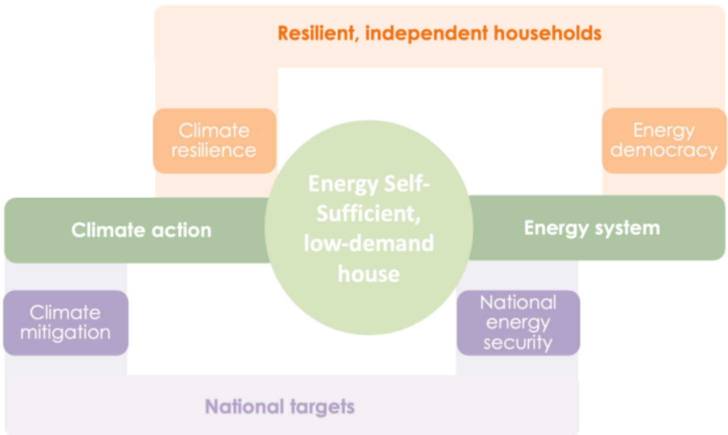

Figure 2-3. The relevance of energy-self-sufficient, low-demand houses lies in their contribution to climate action and energy systems. From the top-down perspective on national targets, it helps mitigate climate change and enhance national energy security. From the bottom-up perspective, it facilitates resilient and independent households by improving their resilience to climate change and energy democracy.

The solutions discussed throughout the thesis also align with several Sustainable Development Goals (SDGs) objectives, such as Affordable and Clean Energy (SDG 7), Climate Action (SDG 13), Sustainable Cities and Communities (SDG 11), Responsible Consumption and Production (SDG 12), and Industry, Innovation and Infrastructure (SDG 9), which further supports the relevance of the topic. Additionally, it is essential to acknowledge that improving energy performance and shifting towards more sustainable energy sources brings benefits beyond climate and energy targets. One of the most significant is the positive impact on human health, as energy self-sufficiency solutions contribute to reduced air pollution and smog, leading to higher living standards and better overall public health (Pablo-Romero et al. 2016).

2.2.1. Relevance from the Perspective of the Climate Change Action

There is a common consensus among scholars on the high importance of climate action, both in terms of climate change mitigation, adaptation or resilience. As reported by the latest Intergovernmental Panel on Climate Change (IPCC) report, the global warming level of 1.5 °C (compared to 1850-1900) will most probably overshoot in the following decades (IPCC 2023). Only immediate, rapid, and ambitious action can slow down and prepare societies for this process and, therefore, impact fewer various natural or human-created systems. The consequences of inaction will be tragic: existing infrastructure is becoming outdated since it was built for different climatic conditions, while climate change is already causing more frequent and severe droughts, heatwaves, and heavy rainfall, leading to an increased frequency of natural disasters (IPCC 2022). These changes will strain essential resources such as food, water, and habitable land, potentially triggering widespread migration and conflicts (IPCC 2022).

2.2.1.1. Climate Change Mitigation

To address climate change progression, many international efforts have been made for immediate greenhouse gas emission reductions, commonly expressed in CO_2 equivalent reductions (CO_2e). The first direction-setting international climate agreement was the Kyoto Protocol, which introduced binding emission-reduction targets for developed nations (UNFCCC 1998). Then, it was suspended by the Paris Agreement, which requires all countries to contribute to emission reductions (UFCCC 2015). The Paris Agreement, until now, remains the most crucial climate international arrangement guiding policy development and GHG target-setting, with the established goal of limiting temperature rise "to well below 2 °C above pre-industrial levels" while pursuing efforts to limit the increase to 1.5 °C (UFCCC 2015). Following that, involved states must communicate their actions towards their greenhouse gas emissions reduction or adaptation and resilience to the impacts of climate change in Nationally Determined Contributions (NDCs).

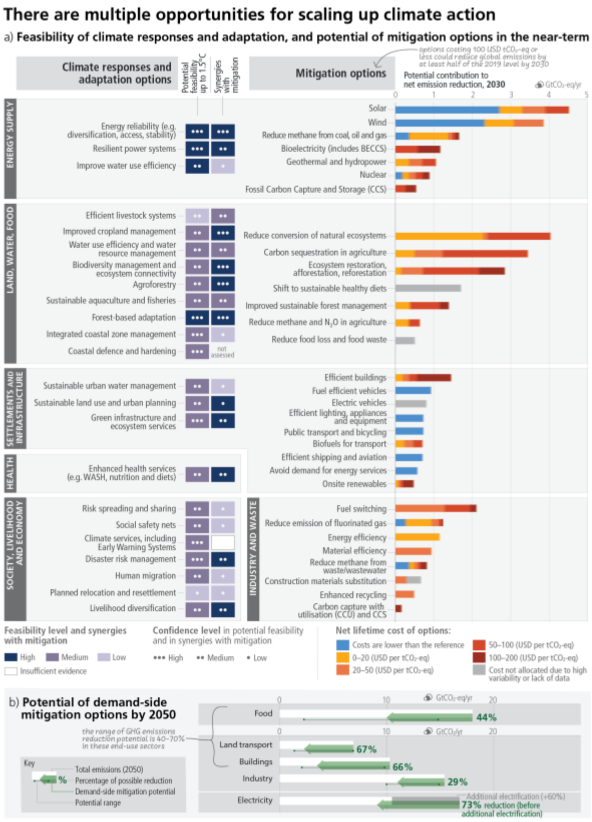

Figure 2-4. Multiple Opportunities for scaling up climate action. Panel (a) presents selected mitigation and adaptation options across different systems. Panel (b) displays the indicative potential of demand-side mitigation options for 2050 Source: Figure reproduced from (IPCC 2023). © 2023 IPCC. CC BY 4.0.

Among the most prominent actions and opportunities that might scale up climate-mitigation efforts, the authors of IPCC AR6 identified efficient buildings, on-site renewables, or switching energy supply to solar, as shown in Figure 2-4. Furthermore, AR6 WG III Chapter 9 on Buildings evaluates the global mitigation potential at 8.2 Gt CO_2 per year in 2050, translating to around two-thirds of baseline emissions from this sector (Cabeza et al. 2022). Energy-self-sufficient, low-demand buildings contribute to climate mitigation by both reducing GHG emissions through decreased energy demand and increasing the use of decentralised, renewable energy. Combined effects of end-user electrification in the residential sector, decarbonisation of electricity and heating/cooling, and improvements in energy efficiency in buildings can significantly reduce GHG emissions.

In the European Union, around 40 % of consumed energy is used in buildings, corresponding to one-third of all energy-related GHG emissions; therefore, the sector has a huge decarbonisation potential (European Commission 2024). Maduta et al. (2025) demonstrated that, based on current projections for the building sector, even a 35% reduction in GHG emissions is expected by 2030 compared to the 2019 baseline.

Poland's Specific GHG Emission Reduction Potential in Buildings

Among all countries within the European Union, Poland has a high decarbonisation potential in the building sector due to its relatively energy-inefficient building stock and heavy coal-based energy mix, which, under current background conditions, could allow single-house GHG emissions to be reduced by 80–96 % (Firag et al. 2018; Fedorczak-Cisak et al. 2023). It is essential to acknowledge that when scholars assess building emission reductions, they usually consider the combined effects of energy-demand reduction, electrification, and on-site renewable energy generation, which aligns with the net-zero-emission-building classification. As shown in Figure 2-5, Poland's electricity-emission intensity is the highest in the EU, almost three times the European average (Ember 2024). This stems from Poland's failure to carry out deep energy decarbonisation over the past decades and its high reliance on coal, leading to only an 18% GHG emissions decline between 2000 and 2023, which is well behind the EU-wide reduction of 41% (Ember 2024).

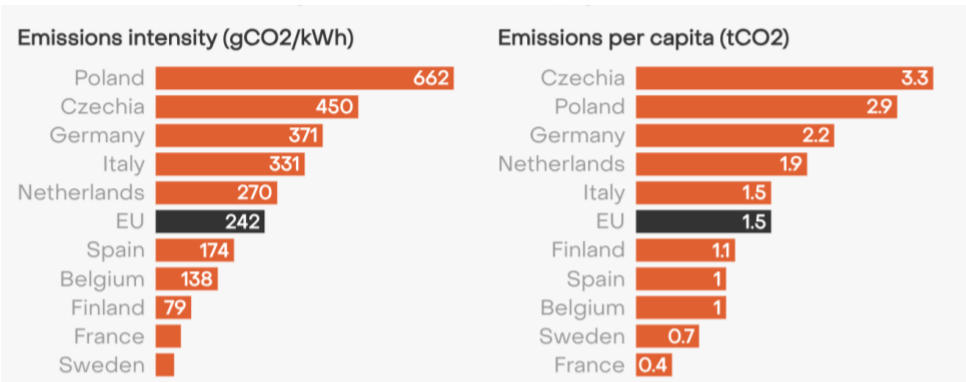

Figure 2-5. The highest emissions of the top EU electricity producers in 2023. Source: Figure reproduced from Ember (2024). © 2024 Ember. CC BY 4.0.

Similarly to electricity, heating in Poland relies heavily on fossil fuels, and Poland has an unpopular reputation as a coal-dominant country in Europe. As shown in Figure 2-6, in 2020, around 65% of heating in Poland was coming from coal (Attia et al. 2022b). Poland's high reliance on fossil fuels is a matter of many disputes since phasing them out is not only a technological challenge, but also a social transition: coal mining is deeply rooted in the culture, and conservative governments have been hesitant to undergo energy transition and gradually close coal mines (Szulecki et al. 2024). All the above has brought Poland to an aggregated emission factor of 652 g CO_2 eq/kWh in 2024, with over 57 % of it caused by coal, shown in Figure 2-7 (Nowtricity 2025). To mitigate this, rapid change and decarbonisation are needed; for residential buildings, responsible for 27 % of total final energy consumption, that means installing and maximising RES, electrifying heat sources, and accelerating thermomodernisation efforts (IEA 2025).

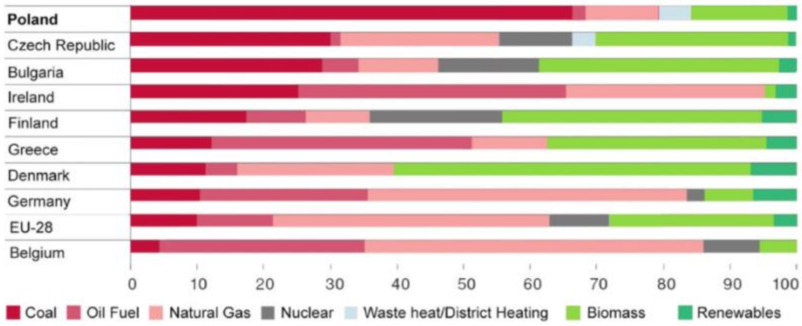

Figure 2-6. Share of heat sources among private households in Poland and Europe in 2020. Source: Figure reproduced from Attia et al. (2022). © 2022 Elsevier. Reproduced under Licence No. 6039130519641.

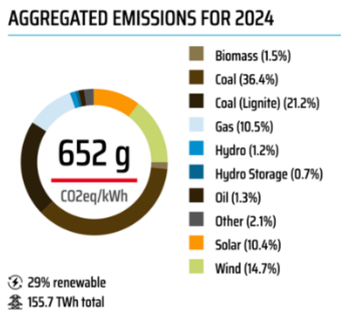

Figure 2-7. Aggregated emissions for 2024 in Poland. Source: Figure reproduced from Nowtricity (2025). © 2025 Nowtricity.

Like the rest of the EU, Poland is moving toward low-emission energy sources. Under the Polish Energy Policy to 2040, the country aims to cut economy-wide greenhouse gas emissions by 30% by 2030, which will be further discussed in the policy section (Ministry of Climate and

Environment 2021). It is essential to acknowledge that incentives for maximising energy self-sufficiency will decrease from a climate mitigation perspective as the grid decarbonises, but at the current state of the energy mix, energy self-sufficiency measures can be seen as climate mitigation efforts. Furthermore, scholars underline the significant potential for energy savings among single-family homes, which collectively have a considerable energy-saving and decarbonisation potential (Jezierski et al. 2020).

2.1.1.2. Climate Change Resilience and Adaptation

The energy system is a fundamental piece of critical infrastructure, functioning much like society's "nervous system" and supporting various societal functions, including security, safety, health, and general well-being. As climate change intensifies the nature, scale, and frequency of extreme events, it raises the risk of energy system failures, such as power outages and infrastructure disruptions (Seneviratne et al. 2021; Eitan 2024; Nowakowska et al. 2024; Yamagata et al. 2016; Charani Shandiz et al. 2020; Gunasingh et al. 2017). Strengthening energy resilience, especially by improving household-level self-sufficiency and energy efficiency, can reduce exposure to these climate-induced risks, as distributed energy systems with lower demand are less vulnerable to disruptions caused by single points of grid failure (Hasselqvist et al. 2022; Sanduleac, Eremia, and Picioroaga 2018; Yamagata et al. 2016). Moreover, home batteries can sustain critical household appliances for days during blackouts (Chatterji et al. 2020).

Climate Change Risks

According to the IPCC AR6, climate change is expected to drive increasingly abnormal weather patterns in magnitude and frequency, causing new risks to energy infrastructure such as power plants and electricity grids (Seneviratne et al. 2021). A growing body of research confirms that climate-related outages have already become more frequent over the last few decades (Lyster et al. 2022; Larsen 2021). As shown in Figure 2-8a from the IPCC AR6 report, the annual chances of extreme events are growing as the temperature is increasing, which might be magnified for future generations living in even hotter and more extreme reality in terms of disruptive events (Figure 2-8b) (Seneviratne et al. 2021; IPCC 2023).

a b

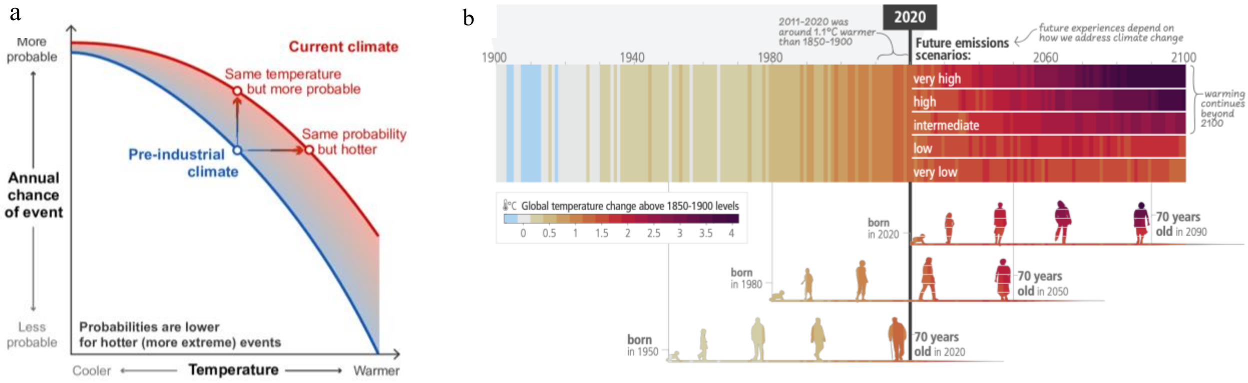

Figure 2-8. Changes in the magnitude and probability of extreme weather behaviours and events as a result of changes in climate (a) and the degree to which future emissions scenarios will cause next and current generations to be exposed to more disruptive climate (b). Source: Figure adapted from: a(Seneviratne et al. 2021) b(IPCC 2023). © 2021/2023 IPCC. CC BY 4.0.

Similarly to most of the world, Poland is projected to experience significant warming trends by the end of the 21st century, as mean annual temperatures are expected to increase by 2–3.5°C (RCP 4.5) up to 4.5°C (RCP8.5), compared to the reference period of 1971–2000 (Falarz et al., 2021). Extreme thermal conditions will not only intensify but will also occur more frequently and for prolonged periods. Consecutive days with maximum temperatures exceeding 30°C are expected to reach 8 days (RCP 4.5) or 14 days (RCP 8.5) by 2100 (Falarz et al., 2021).

Among the most probable climate change-related hazards for Poland that might cause blackouts are storms (Sulik 2022), floods (Kundziewicz et al. 2023; WMO 2023), wildfires (Kurowski et al. 2023; Pińskwar et al. 2024) and heatwaves causing a higher level of electricity consumption (Graczyk et al. 2023). Severe storms have already caused numerous blackouts, and due to Poland's reliance on overhead lines, power restoration has sometimes taken days (IEA 2022).

Also, the Eastern Europe sub-region is expected to have more fire-weather days since heatwave frequency and drought length are rising (Bednar-Friedl et al. 2022). Another accelerating factor is the shift in precipitation patterns, both in intensity and timing, likely leading to more frequent floods, which can damage substations and other vital infrastructure (Dąbrowska et al. 2024). Additionally, grid disruptions combined with insufficient cooling during increasingly frequent and prolonged heatwaves may lead to a rise in heat-related mortality (Nowakowska et al. 2024; Yamagata et al. 2016; Eitan 2024). Reducing energy demand during such periods is particularly critical, as high ambient temperatures impair the efficiency of energy transmission systems, increasing the likelihood of power outages (Taylor et al., 2018; Rempel et al., 2022). The IPCC AR6 WGII warns that, without effective adaptation measures, annual heat-related deaths in Europe could triple by 2050, identifying heat stress as one of the region's most pressing risks (Bednar-Friedl, 2022).

Defining Climate Resilience at The Single-Family Scale

A resilient system should maintain functionality during and after extreme climate events, and to understand this capacity, various taxonomies and frameworks have been developed to define energy system resilience. Among the most recognised ones is the Four Rs of resilience, expressing resilience by robustness, redundancy, resourcefulness and rapidity (Irfanullah 2021). In the context of single-family homes, robustness can be enhanced through energy efficiency, which lowers demand during disruptions, redundancy is achieved through backup supply sources, such as batteries or PV systems and resourcefulness and rapidity through on-site energy self-sufficiency, which makes it possible to operate during outages. There's no universally accepted, agreed-upon method for measuring energy resilience (Charani Shandiz et al. 2020; Zhou 2023). One of the popular metrics used by scholars is energy self-sufficiency, as it reflects a system's ability to supply critical loads during disruptions using local resources (Barroca 2019; Sanduleac, Eremia, and Picioroaga 2018). Scholars emphasise the importance of integrating resilience into energy transformation planning by actively empowering citizens. They also highlight that distributed energy management and production enhance resilience when implemented through shared systems such as microgrids, energy clusters, or energy communities (Yamagata et al. 2016).

Discussion about adapting households to climate change also lies on retrofits and new building codes since most high-efficiency building measures can serve as both climate mitigation and climate adaptation strategies; however, it is important to note that these approaches cannot always be used simultaneously (Liyanage et al. 2024). As many studies have shown, improved insulation can increase overheating risks if not paired with a low-energy space cooling system, potentially causing increased heat stress and raising the frequency of overheating in the future (Rempel et al. 2022; Taylor et al. 2018; Zhang et al. 2021). Therefore, there is a need to rethink building codes to address both climate mitigation and resilience to climate change phenomena (Liyanage et al. 2024).

2.2.2. Energy System Impacts and Benefits

As shown, energy-independent, low-demand houses are highly important in climate action, but their impacts go beyond that, influencing the energy system. Scaling up this solution to a whole country can significantly reshape fuel-import balances electricity grid and redistribute power (in both the literal and political sense) from large utilities to ordinary citizens.

2.2.2.1. Energy Security on a National Level

Improving energy efficiency and installing additional domestic energy capacity plays a crucial role in reducing Poland's energy imports enhancing national energy security and sovereignty. Back in 2020, Russia was Poland's primary energy supplier, contributing 35% of the country's total available energy, and the following year, Russian gas made up over 50% of the gas supplied and consumed in Poland (Maj 2023). However, Russia's 2022 full-scale invasion of Ukraine, which is Poland's neighbour, overhauled the existing energy market and geopolitics in the region and the whole world (Goldthau et al. 2023; Koilo 2025). During the Ukrainian-Russian war, it was observed that Russia weaponised its energy resource supplies to Europe (for example, by cutting off gas supplies to Poland in April 2022), causing a crisis in the European energy market (Sovacool et al., 2023). This compelled many countries to rethink their energy strategy, aiming for independence from Russian gas, coal, and oil (Sovacool et al. 2023). As a consequence, the EU established the RePowerEU action plan, focusing not only on diversifying supplies but also on energy conservation and acceleration of the green energy transition (for example, through the Solar Rooftop Initiative described in the EU policies chapter) (European Commission 2022). Through this action plan, the EU managed to reduce the share of Russian gas imports from 45% in 2022 to 19% in 2024, primarily due to a significant rollout of renewable energy, alongside more energy-efficiency measures and supply diversification (European Commission 2025).

Having prepared years before the war to cut energy imports from Russia, Poland ended them entirely in 2023, shifting to reliance on countries like Qatar, the USA, Saudi Arabia, or Norway (Buras and Kardaś 2024). Even though Poland has its domestic fossil fuel resources, they are insufficient to meet national energy demand. Therefore, increasing the national capacity of RES and reducing energy demand is crucial to decrease Poland's dependence on external energy sources and to become more resilient to external shocks, such as geopolitical tensions or global fuel price fluctuations.

Moreover, diversifying and decentralising energy sources mitigates risks of possible cyberattacks or disruptions, particularly relevant for Poland, which has been exposed to many cybersecurity challenges from neighbouring Russia (Bartłomiej Igliński et al., 2022).

To sum up, improving energy self-sufficiency and simultaneous energy efficiency improvements that lead to decreased energy demand and RES capacity expansion align with national energy security objectives.

2.2.2.2. Energy Democracy

With the *Clean Energy for All Europeans* package, the European Union signalled boldly in 2019 that citizens will be key participants in the energy transition by enabling them to contribute to the energy market (European Commission 2019). Thanks to advancements in renewable energy technologies and growing public awareness, Poland's historically centralised energy system is gradually becoming more decentralised (Bartłomiej Igliński et al. 2022). Furthermore, this aligns with the Poland's 2040 Energy Policy (PEP40) as it explicitly emphasises the increase of citizen-owned generation to ensure they share the benefits of the changing energy landscape (Ministry of Climate and Environment 2021).

There are two similar concepts in the literature on the participatory energy transition: energy democracy and energy citizenship. While both explore more decentralised, inclusive, and locally owned energy as a core pathway, the first focuses more on structural change, and the second on the role and responsibilities of individuals in the energy transition (Wahlund and Palm, 2022). When assessing energy self-sufficiency on a national level, the idea of redistributing energy ownership from corporations to citizens is studied through the movement empowering individuals rather than by examining prosumerism on the individual scale. Therefore, energy democracy is the more accurate term from the taken perspective of energy self-sufficiency.

The main idea behind energy democracy is represented by the slogan "power to the people", advocating for shifting production, management and co-governance from the hands of utilities to individuals and communities (Huang et al., 2019; Szulecki and Overland, 2020; Janikowska, 2023; Wahlund and Palm, 2022). Through this, households, instead of relying solely on centralised utilities, can generate their energy and actively participate in the energy market, which gives citizens more control over their production and consumption. Energy democracy has high relevance, as it facilitates people's engagement in energy decisions and the process of energy system transformation, which aligns with a just energy transition since the benefits of RES are more equally distributed in society (Wahlund and Palm, 2022). Furthermore, it is crucial to underline that energy democracy relies on decentralising energy sources and requires equity, meaning all citizens should have equal chances to participate actively in the energy transition (Szulecki and Overland, 2020). This can often be challenging, as many scholars have pointed out that even just the financial aspect of making an initial investment in PV and battery storage is a significant barrier for low-income households (Brown et al.2020).

Furthermore, Sovacool et al. (2022) observed that prosumerism may also exclude older people, renters, people with disabilities, and students while also recognising patriarchal gender roles in the energy decision-making process. Therefore, to ensure the energy transition towards decarbonisation is leaving no one behind, scholars suggest community or cooperative financing solutions that can fully democratise access to solar energy and ensure a fair transition (Stephens et al. 2019). In fact, energy communities are often the core topic of the energy democracy debate, as they allow peer-to-peer (P2P) energy trading and enhance energy self-sufficiency(Fettweis, Zimmermann 2008; Gupta, Bruce-Konuah 2019). For now, collective prosumers in Poland are highly underutilised; as of 2024, only three were registered (Energy Regulatory Office 2025).

Additionally, it is interesting to mention that energy democracy is the backbone of the energy transition envisioned by both post-growth and degrowth research, as it aligns with the ideas of redistributing resources, phasing out fossil fuels, and participatory governance (Ferrari et al. 2018; Buke et al. 2022).

2.3. Characteristics of Energy Self-Sufficiency

To explore how such principles can be operationalised at the single-family buildings level, the following section will evaluate technical characteristics of energy self-sufficiency with an "efficiency first" approach, combining deep renovation measures (typical of net-zero buildings) with detailed hourly energy balancing based on rooftop PV and battery systems.

2.3.1. Performance Dynamics

Understanding how energy self-sufficiency acts at the building level is crucial by examining the time-dependent characteristics of energy demand and solar generation throughout the year and the mismatches between them.

Daily Variations

Daily energy balances often show an apparent mismatch between hourly energy demand and photovoltaic (PV) generation, as solar energy peaks at midday when household consumption is usually at its lowest due to little occupancy. Researchers have explored several strategies to mitigate this mismatch, including storage systems (Simic et al. 2021; Hoppmann et al. 2014; Benalcazar, Kalka, and Kamiński 2024), demand side management (DSM) techniques, such as shifting energy-intensive tasks like laundry to times with excess PV production (Sugiyama et al. 2024), diversifying energy sources or integrating various consumer types, including small businesses with higher daytime energy loads, into energy communities (Kowalska-Pyzalska 2018; Jurasz, Dąbek, and Campana 2020). Figure 2-9 illustrates daily energy flows within a residential PV+battery system, highlighting how midday surplus energy charges batteries for later use during evening demand peaks, therefore increasing energy self-sufficiency sufficiency (Avenston 2025; Nyholm et al. 2016a; Simic et al. 2021).

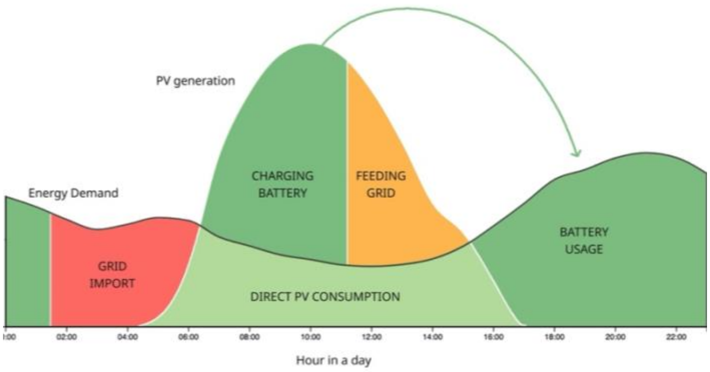

Figure 2-9. Daily energy flows in a residential PV + battery system. The black line represents the household energy demand. The light green area shows the energy directly from photovoltaic (PV) generation. The dark green area represents the energy used for charging the battery and later discharged to supply the load. The orange area indicates excess PV energy fed into the grid, while the red area shows energy imported from the grid to meet demand. This graph is conceptual and doesn't represent real quantities of energy flow.

Seasonal Variations

Energy self-sufficiency also faces significant challenges due to seasonal mismatches between peak solar generation (summer) and peak energy demand (winter) in the northern hemisphere (Benalcazar, Kalka, and Kamiński 2024; Petrichenko, Ürge-Vorsatz, and Cabeza 2019; Gstöhl and Pfenninger 2020). This imbalance, characterised by summer overproduction and winter shortages, represents a critical difficulty. Researchers suggest solutions such as oversizing PV systems, which leads to lower summer self-consumption, or employing long-term seasonal storage technologies like hydrogen (Lokar and Virtič 2020; Knutel et al. 2020; Simic et al. 2021). For example, a study in Portugal by Lopez et al. (2023) reported self-sufficiency rates of 85% in summer but only 45% in winter for a building equipped with an 8 kW PV system and 12 kWh storage. Similarly, Poland experiences most solar radiation from April to September, with daylight lasting up to 16 hours per day, whereas winter months get daylight reduced to just 8 hours per day (Igliński et al. 2021).

Regional Variations

The technical potential for buildings to achieve energy self-sufficiency strongly depends on regional climate conditions, impacting energy demands for heating or cooling and the achievable solar energy yields. In sunnier regions such as southern Europe or Australia, high solar yields allow local satisfaction of building energy demands (Gernaat et al. 2020; Olczak et al. 2021; Rojek et al. 2023). Contrariwise, in higher latitude or temperate climates like northern or central Europe, lower solar insolation often requires more extensive investments in PV installations or energy storage systems to achieve a higher level of energy independence (Ramirez Camargo et al. 2018; Molnár et al. 2024; Luthander et al. 2015).

Te Heesen et al. (2019) analysed rooftop PV systems in Germany, finding specific yields ranging from 816 kWh/kW in the north to 1049 kWh/kW in the south. Following that, Schardt and Te Heesen (2021) extended this analysis to countries like the Netherlands (947 kWh/kW) or Italy (1195 kWh/kW), noting a latitude-dependent gradient in PV yields, which highlights that countries like Poland, at higher latitudes, may have lower yields due to reduced solar irradiance through the year.

2.3.2. Ways to Raise Energy Self-Sufficiency

While time or geographical constraints can limit possible levels of energy independence, measures are helping to elevate its value, such as energy storage or decreased energy demand.

Impact of Battery Storage and Levels Of Energy Self-Sufficiency

Studies examining buildings with PV installations without additional storage typically achieve self-sufficiency rates between 20% and 40% (Benalcazar, Kalka, and Kamiński 2024; Moshövel et al. 2015). Introducing energy storage significantly increases these rates, often by more than 12.5-30 percentage points, as daily mismatches between production and demand are mitigated (Luthander et al. 2019; Aranda et al. 2025; Nyholm et al. 2016b). For instance, Aranda et al. (2025) observed an increase from 37% to 62% monthly self-sufficiency with a 17 kWp PV and an 8.3 kWh lithium-ion battery. After analysing many studies, Luthander et al. (2019) highlighted that typical single-home systems rarely exceed 60% self-sufficiency due to seasonal imbalances. The Karlsruhe Institute of Technology (KIT) explored this further, concluding that approximately 53% of 41 million European single-family homes could technically achieve year-round self-sufficiency by 2050 (Kleinebrahm et al. 2023). However, such full autonomy in Central Europe would likely require short-term lithium storage paired with long-term hydrogen storage to bridge seasonal gaps (Kleinebrahm et al. 2023).

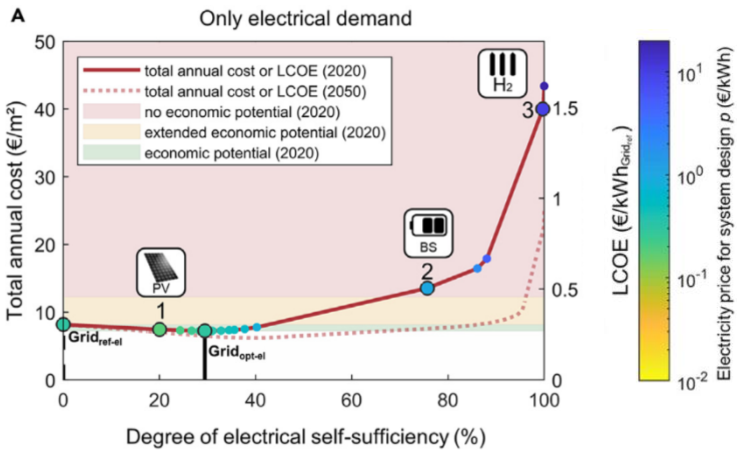

Figure 2-10. Relationship between energy system costs and the degree of self-sufficiency for a representative German building for only electrical demand. Source: Figure reproduced from Kleinebrahm et al. (2023).

Additionally, reaching full off-grid autonomy is economically challenging, notably the last 10-20%, as costs significantly rise, which is shown in Figure 2-10, drawing a current relation between electrical self-sufficiency and the cost of electricity per unit with different technologies involved (Kleinebrahm et al. 2023; Mutani and Todeschi 2021; Hoppmann et al. 2014). Nonetheless, future trends in declining costs for batteries and electrolysers or rising fossil fuel prices might eventually make fully self-sufficient solutions competitive (Gstöhl et al. 2020b).

Impact of Energy Demand

Reducing a building's energy demand through efficiency improvements is as important as increasing generation or storage capacity. Simic et al. (2021) studied Belgian buildings with heating energy demands of 15, 30, and 45 kWh/m²/year, finding self-sufficiency rates of 40%, 38.5%, and 37%, respectively, indicating that lower demand enhances self-sufficiency. Similarly, Gstöhl and Pfenninger (2020) evaluated the feasibility of Swiss self-sufficiency by 2050, finding that lower energy demands allowed rooftop PV alone to suit without additional façade installations. Additionally, Klingler and Schuhmacher (2018) analysed different consumption patterns from 407 German and Austrian households, confirming that higher annual demands are correlated with lower self-sufficiency (Klingler and Schuhmacher 2018). Furthermore, Miranda et al. (2024) showed that in several Spanish single-family houses with varying annual and hourly energy demand, higher annual demand reduced self-sufficiency unless consumption was aligned with PV production. Despite several considerations of energy demand on studies on energy self-sufficiency, their relation hasn't been investigated.

2.4. Technological background

Presented findings show that energy independence is not only a function of how much energy is produced, but also how efficiently it is used and stored. To further examine how energy self-sufficiency can be achieved, this section presents the technological foundation of the proposed approach that will cover the intersection of energy efficiency, rooftop solar panels, and end-of-meter storage systems. A quick overview of technologies will be delivered, emphasising their current state in Poland, modelling approaches, and investigations on their potential.

2.4.1. Energy Efficiency in Buildings

The energy efficiency objective in buildings is to maintain their ability to deliver essential services, such as heating, cooling, hot water, lighting, appliances, and cooking, while minimising energy demand (Fatma et al. 2023). This means that the comfort or functionality a building provides remains uncompromised, even as energy consumption is reduced. A building's energy performance can be evaluated using various metrics, with the most used being

Energy Performance (EP), final energy consumption, and CO_2-equivalent. Among policymakers, EP is the most frequently used metric, as it reflects the amount of non-renewable energy required to deliver a certain level of service, emphasising its environmental significance emissions (Burman et al. 2014). Across the EU, approximately 75% of buildings are considered inefficient, with over half being over 50 years old, and as a result, buildings are recognised by the European Commission as offering a significant opportunity for energy efficiency gains (European Commission 2024).

The Current State of Energy Efficiency in Buildings in Poland

Poland has around 15.2 million buildings, and nearly half of them, about 46%, are single-family homes, what adds up to roughly 6.9 million houses, each with an average floor area of 116.3 m^2 (KAPE 2024). As part of the Soviet Union's influence, under which Poland remained until 1989, buildings were constructed within a centrally planned economy, where technical solutions prioritised high heating use over energy efficiency, as energy prices were relatively low (Ministry of Development and Technology 2022).

Consequently, more than 70% of Poland's building stock is estimated to have an Energy Performance exceeding 150 kWh/(m^2·year) (Ministry of Development and Technology 2022). For older single-family buildings constructed before 1994, the average PEF is even higher, at 263.7 kWh/(m^2·year), and only 4% of the entire stock has a PEF below 90 kWh/(m^2·year), and just 0.5% below 70 kWh/(m^2·year) (Ministry of Development and Technology 2022). This indicates a great need for widespread renovation to improve buildings' energy efficiency and reduce environmental impact.

To evaluate energy efficiency progress, scholars and policymakers use the term thermomodernisation rate, referring to the proportion of buildings undergoing energy efficiency improvements. Poland's annual renovation rate from 2009 to 2019 averaged just 1.13%, ranking it 21st in the EU (Attia et al. 2022). One of the most significant challenges facing Polish residential buildings is, as mentioned before, their heavy dependence on fossil fuels; as of 2020, nearly 70% of residential heating relied on coal or oil, and although this share is slowly declining, it remains the dominant heating source (Szymańska et al. 2022b; Attia et al. 2022).

To simplify the understanding of building energy efficiency, the European Commission mandates using standardised energy class systems similar to those used for household appliances. Surprisingly, Poland remains the only EU member state that has not yet officially implemented such thresholds (GLOBEnergia 2024). However, the Ministry of Development has released a draft version for public consultation, announcing that from 2026, official classifications will be introduced, ranging from A+ (energy-plus buildings) to G (the least efficient), representing the EP value range (Table 2-1) (GLOBEnergia 2024).

Table 1-1. Presented for public consultations buildings energy efficiency classes in Poland. Data source: GLOBEnergia (2024)

Class	EP Value [kWh/(m²·year)]
A+	EP ≤ 0
A	0 < EP ≤ 63
B	63 < EP ≤ 75
C	75 < EP ≤ 94
D	94 < EP ≤ 113
E	113 < EP ≤ 131
F	131 < EP ≤ 150
G	EP > 150

Basics of Technologies for Improving Energy Efficiency in Buildings

Optimising a building's design, construction, and operation to reduce energy consumption involves various technologies. The most impactful technical improvements and retrofits typically fall into the following categories:

- Thermal modernisation can be achieved by upgrading the building envelope (walls, roofs, floors, windows) to reduce heat loss and improving airtightness by sealing gaps to prevent air infiltration. This is especially critical for Poland's older building stock (Firląg and Piasecki 2018).
- Mechanical ventilation with heat recovery ensures indoor air quality while minimising heat loss (Herrera-Limones, León-Rodríguez, and López-Escamilla 2019).
- Modern heating systems replace outdated coal or oil-based boilers with more efficient, low-emission systems, such as gas boilers as a so-called transitional solution or heat pumps that utilise electricity from renewable sources (Liyanage et al. 2024; Zhang et al. 2021).

- Smart building technologies utilise AI and IoT for real-time monitoring and control of lighting, HVAC systems, and energy use to optimise consumption (Liyanage et al. 2024; Rempel et al. 2022; Zhang et al. 2021).
- Passive design principles use natural light and ventilation to reduce the need for artificial lighting and mechanical cooling (Godlewski et al. 2021).

In addition to these measures, technologies like heat pumps, rooftop photovoltaics, solar thermal collectors, and highly efficient appliances are integrated into energy performance calculations, as they significantly reduce a building's energy intensity.

Existing Retrofit Potential

According to currently bonding Poland's Long-Term Building Renovation Strategy, all new single-family homes must be constructed using nearly net-zero energy building (nZEB) technologies, with a maximum EP of 70 kWh/(m²·year). The strategy also sets a goal until 2050 for an annual thermomodernisation rate of 3.8% (Ministry of Climate and Environment 2021). Furthermore, it emphasises that deep renovations and fuel switching in residential buildings are crucial to achieving sectoral CO_2 reductions, which can reach up to 37 million tons of CO_2-equivalent per year by 2050, which corresponds to approximately 10% of Poland's total greenhouse gas emissions (Ministry of Climate and Environment 2021). This can be an effect of a final energy reduction of 147 TWh in the whole residential building sector, which would mean an energy demand reduction of 75%. Some studies forecast even more ambitious decarbonisation potential, with reductions of up to 90% by 2050 (Knobloch et al. 2019) and as much as 97% by 2060 (Chatterjee et al. 2025).

2.4.2. Rooftop Photovoltaic (PV)

The transition towards energy self-sufficiency is interconnected with advancements in solar energy, primarily through the integration of photovoltaic (PV) systems into residential buildings. Moreover, the prosumer is the core element of energy self-sufficiency systems, who simultaneously consumes and produces energy through renewable energy sources (RES) installations, reducing dependence on non-renewable energy sources (Trębska et al. 2024). The EU Electricity Directive 2019/944 defines an "active customer" (prosumer) as any final customer, or group of customers who generates electricity for their own use and may store it or sell any surplus, provided that, for non-household customers, this is not their main commercial activity (European Parliament and Council of the European Union 2019). In practice, this broad definition brings entrepreneurs and public institutions within the prosumer category, enabling residential, community, business, and public prosumers to export excess electricity under the micro-installation discount scheme (Szeląg-Sikora et al. 2021).

The Current State of PV Penetration in Poland

Before 2012, there were almost no photovoltaic (PV) installations in Poland (Energy Regulatory Office 2025). However, due to policy incentives introduced in the following years, by 2020, Poland experienced a PV boom, achieving the leading position in the European Union in terms of annual growth rate (Igliński et al. 2022). According to the 2025 report issued by the Energy Regulatory Office in Poland (*Urząd Regulacji Energetyki*), by the end of 2024, the number of registered renewable energy source (RES) micro-installations with a total installed capacity of up to 50 kW exceeded 1.5 million, representing a 24% PV penetration rate (Energy Regulatory Office 2025). These micro-installations collectively surpassed a total installed capacity of 12.7 GW. Among them, photovoltaics continues to dominate, accounting for 99.7% of the energy fed into the grid, with over 98% of these installations owned by prosumers (Energy Regulatory Office 2025).

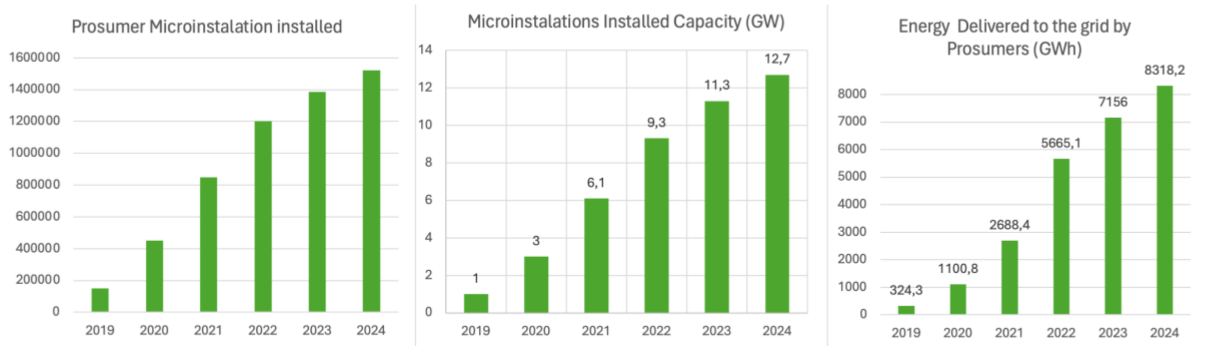

Figure 2-11. Development of PV installations among consumers in Poland over the years 2019. Data Source: (Energy Regulatory Office 2025).

The development of PV installations among consumers in Poland is illustrated in Figure 2-11, highlighting the rapid growth in the number of installations, which consequently led to increasing installed capacity and rising energy fed into the grid. In 2024 alone, the energy delivered to the grid by prosumer PV installations exceeded 8.5 TWh (Energy Regulatory

Office 2025). Dividing the total annual energy production by the number of installations yields an average production per prosumer household of approximately 5,463 kWh annually, which is largely driven by government programmes and financial grants.

Background of Photovoltaic Cells

Photovoltaic cells underwent rapid development and market penetration in the last several decades. As shown in Figure 2-12 from the IPCC AR6 report, from 2020 electricity produced by photovoltaics was cheaper than that produced by fossil fuels, and market adaptation increased exponentially (IPCC 2023).

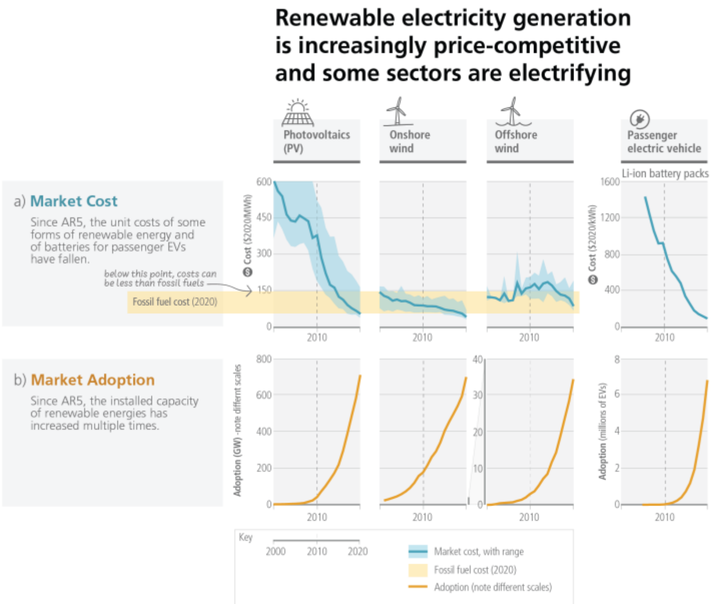

Figure 2-12. Cost reductions and use in photovoltaics, onshore and offshore wind and passenger electric vehicles. Source: Figure reproduced from IPCC (2023). © 2023 IPCC. CC BY 4.0.

The most widely used PV technology is crystalline silicon (c-Si), which dominates the market due to its high efficiency, long service life, and cost-effectiveness (Fazal et al., 2023). To evaluate PV system performance, researchers commonly use metrics such as Final Yield (Yf), the ratio of net AC energy produced to the nominal power of the installation, and the Performance Ratio (PR), which indicates the system's quality regardless of power capacity or location. Additionally, efficiency remains a key metric, reflecting the capability of a PV module to convert sunlight into electricity under ideal conditions (Attari et al., 2016; Ramanan et al., 2019). A PV system's energy yield and performance ratio are influenced by multiple factors, including solar irradiation (insolation), weather conditions, dust accumulation, shading, and ambient temperature (Ramanan et al., 2019). Degradation of panel output over time is slow, about 0.4–0.6% per year for silicon panels, and warranties typically guarantee ~80–90% of original power after 25 years (Huang et al. 2023).

Poland's Specific PV Potential

Poland's temperate climate forces seasonality on solar energy generation. About two-thirds of the annual solar irradiation takes place in the spring and summer (from April to September), whereas the autumn and winter months receive much less sunlight (Gulkowski and Krawczak 2024). Study made by Gulkowski and Krawczak (2024) with a 9.6 kW rooftop PV system in eastern Poland illustrate this variability since the average final yield exceeded 1000 kWh per kW annually, but monthly specific yields peaked at about 164 kWh/kW in the sunniest summer month but dropped below 20–30 kWh/kW during the darkest winter months (Gulkowski and Krawczak 2024). This means that while a properly sized PV system can produce surplus electricity in summer, it will under-produce from November to February (Fedorczak-Cisak et al. 2023). Seasonal variations are further influenced by environmental factors; for instance, very cold but sunny spring weather can boost efficiency and yields (Gulkowski and Krawczak 2024). Furthermore, Krawczak (2023) conducted a detailed study of four prosumer PV installations in Lublin Voivodeship, reporting an average yearly final yield of 1022 kWh/kW, while Igliński et al. (2016) studied that under standard test conditions, each kilowatt of well-oriented PV capacity can produce roughly 950–1100 kWh of electricity per year in Poland's climate.

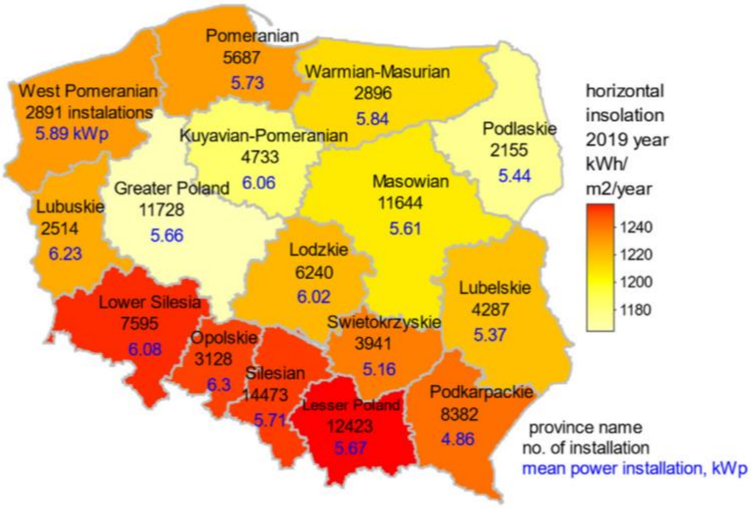

Figure 2-13. Insolation values in Polish provinces in 2019, including names of provinces, number of installations, and average power of PV installations under the "My Electricity" program (until November 2020)
Source: Figure reproduced from Olczak et al. (2021). © 2023 CC BY 4.0.

Most single-family building-mounted PV systems vary between 5–6 kWp, reflecting typical roof area availability and household consumption levels, which is shown in Figure 2-13 (Olczak et al. 2021).

National PV Buildings Potential in Poland

While scientific sources are filled with a variety of photovoltaic case studies covering different geographic locations and technical system configurations, relatively few assess PV potential at the national scale, particularly for Poland. Bódis et al. (2019) conducted a high-resolution geospatial assessment for all EU member states and found that the rooftops of the EU could generate approximately 680 TWh/year of solar electricity. In Poland, they identified 469 km² of suitable rooftop area, with a technical potential of 30.91 TWh/year across all building types, enough to cover about 24 percent of the country's final electricity consumption in 2016. Another study (Igliński et al. 2023) focused on PV potential for commercial, public, and newly constructed buildings over the next decade, excluding the existing residential stock. They estimated a total technical potential of 6.89 TWh/year on roofs, of which newly built buildings would contribute 2.08 TWh. A more comprehensive evaluation of residential rooftop PV was carried out by Molnár et al. (2024) using the Building Integrated Solar Energy (BISE) model. They report a technical potential of approximately 219.5 TWh/year for Poland's rooftops in

2022, projecting an increase in suitable rooftop area from 0.89 billion m² in 2022 to 1.25 billion m² by 2060.

2.4.3. End-of-meter energy storage (Battery)

In parallel with the rapid increase in installed photovoltaic capacity, behind-the-meter battery storage has been gaining popularity and market penetration, becoming an essential complement to renewables (IEA 2024). Batteries charge during midday solar radiation peaks when excess power is produced and then shift consumption to high-demand periods such as mornings or evenings, reducing reliance on the grid. As a result, they are widely recognised as an effective tool for smoothing the intermittency of PV output and are the main part of the strategy for boosting self-consumption and energy self-sufficiency. The International Energy Agency (IEA) estimates that behind-the-meter battery storage will expand to 175 GW worldwide by 2030 under the STEPS scenario and to 200 GW by 2030 under the NZE scenario, with roughly 10 % of rooftop solar PV paired with behind-the-meter battery storage in the largest markets (IEA 2024).

Background of Energy Storage Technologies

There is a wide variety of storage technologies that could be applied to homes; among them, the most common are electrochemical (battery) systems (lead–acid, lithium-ion, sodium-sulfur, redox flow, solid-state), thermal storage (sensible heat, e.g. hot water tanks; latent heat, e.g. phase-change materials) or chemical (hydrogen storage, synthetic methane). Each of these storage technologies gives specific advantages and challenges; however, in residential solar systems, there is a consensus that lithium-ion batteries will remain the dominant choice for energy storage (IEA 2024).

Additionally, hydrogen storage is of special interest, as it could offer seasonal buffering (storing summer solar energy for winter use). Although technically feasible, it currently has low efficiency and higher equipment complexity, so at present, it remains experimental at the building scale (Knutel et al. 2020; Lokar and Virtič 2020). It is also important to acknowledge that a non-stationary energy storage approach vehicle-to-home (V2H) integration using electric-vehicle batteries to supply home loads is under active study and may become a key distributed residential storage in the future (Gstöhl and Pfenninger 2020; Huang et al. 2019).

The Current State of Behind-The-Meter Battery Storage in Poland

Currently, the vast majority of the country's electricity storage capacity is in the form of large-scale pumped hydro storage (Krupa, Nieradko, and Haraziński 2018). Poland's energy storage landscape in the residential building sector is at an early stage of development; nevertheless, home batteries are penetrating the Polish market at a much faster pace than photovoltaics (Wysokie Napięcie 2024). There are various reasons for that growth like the increasing penetration of intermittent renewable energy sources (PV) in households, decreasing prices of battery storage, a shift in Polish power policy from net metering to net billing, and, most importantly, a new subsidy system, which makes it mandatory to install PV together with energy storage beginning in 2024 (Wysokie Napięcie 2024). Additionally, one of the main drivers of energy storage systems in Poland is the continued decline in battery costs, as the average cost per kilowatt-hour of storage dropped by 90 percent over the last decade and or by 20 percent in 2024 alone (Wysokie Napięcie 2024). Data from the Polish Energy Market Agency indicate that in 2024 installed behind-the-meter storage capacity among prosumers increased almost fivefold, reaching 672 MWh, with battery systems installed in over 50,000 residential buildings (Wysokie Napięcie 2024) (Figure 2-14). Energy Regula

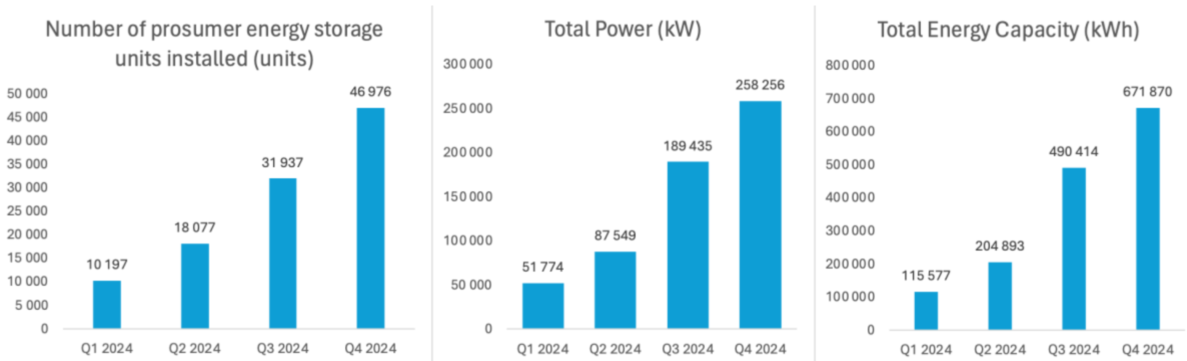

Figure 2-14. Energy Storage systems will be installed among prosumers in the quarters of 2024. Data Source: Wysokie Napięcie 2024

Furthermore, based on information provided by Polish distributors, the average inverter capacity of prosumer energy storage systems is about 5 kW, while the average gross storage capacity is approximately 14 kWh (Polskie Sieci Elektroenergetyczne 2024; Wysokie Napięcie 2024). It is important to acknowledge that these figures may be incomplete, as grid operators do not track storage systems that are not paired with PV installations; therefore, the true numbers may be even higher.

Technological Basics of Lithium-ion Batteries

The principal energy storage in buildings today is electrochemical batteries, with lithium-ion (Li-ion) batteries being the most common one. Li-ion batteries offer compact size (high energy density), high charge/discharge efficiency, and long cycle life, making them ideally suited for daily energy management in homes (Attari et al. 2016; Ramanan et al. 2019).

Battery performance is typically described by the following parameters (Lazaroiu et al. 2023):

- Energy density (Wh/kg or MJ/m^3): Indicates how much energy a battery stores per unit of mass or volume, a key factor when minimising the use of living space
- Rated power (kW): The maximum instantaneous power output a battery can deliver, determining how many appliances it can run simultaneously.
- Energy storage capacity (kWh): The total amount of electrical energy a storage unit can hold.
- Round-trip efficiency (%): The ratio of energy retrieved from a battery to the energy used to charge it. Modern Li-ion systems achieve around 95 percent efficiency, which explains their growing popularity (Attari et al. 2016; Ramanan et al. 2019).
- Depth of discharge (DoD, %): The maximum fraction of a battery's capacity that can be safely used without degrading its performance (Huang et al. 2023).

Battery degradation is another critical consideration since Li-ion batteries typically lose capacity at approximately 0.4–0.6 percent per year, meaning that after roughly 5 000–6 000 full charge-discharge cycles, or 10 to 15 years of normal use, a battery's usable capacity will fall to around 80 percent of its original rating, at which point replacement is recommended (Huang et al. 2023).

Poland's Specific Behind-The-Meter Battery Storage Penetration Potential

Given current trends in photovoltaics and battery expansion and falling Li-ion prices, their adoption in residential buildings is expected to rise in fast peace. Benalcázar et al. (2024) note that coupling batteries with PV could fundamentally change how Polish households use the grid in the coming decades. In their study, Krupa et al. (2018) estimated about 410 MW of battery capacity in Poland by 2030, and Poland's 2040 Energy Policy (PEP40) targets to reach 1 GW of installed capacity by 2040 (excluding pumped storage) (Krupa et al. 2018). Recent trends suggest Poland's actual trajectory could even exceed that figure, as the boom in prosumers and the 2024 shift to self-consumption incentives create conditions for a steeper adoption curve (Wysokie Napięcie 2024). This distributed fleet of batteries could collectively provide load flexibility and grid support; furthermore, continued government support (low-interest loans or new commercial storage incentives) and pressure to meet EU climate targets will support this growth (IEA 2024). In fact, behind-the-meter batteries might become as common as solar panels in Polish homes over the next decade (Wysokie Napięcie 2024a).

In future battery landscape considerations, it is also important to acknowledge that Poland's strong seasonality creates an annual mismatch between summer generation and winter demand, winter months are among the darkest and thus yield very limited PV output (Jurasz, Dąbek, and Campana 2020). Therefore, over the long term, community- or microgrid-scale hydrogen storage may be a vital solution to address this seasonality (Knutel et al. 2020; Lokar and Virtič 2020a).

2.5. Strategies and policies

Technological advancements, even though they are impressive, are not enough to successfully and quickly spread the idea of energy self-sufficiency and low-demand households. Therefore, strategies are crucial to navigate possible directions and to establish adequate legislation that ensures both progress and accuracy in implementation. Hence, a comprehensive analysis of relevant policies is needed to fully understand the legislative background supporting energy self-sufficiency under the "energy efficiency first" principle. Since Poland has been a member of the European Union since 2004, the legislative framework will be examined on both the EU and national levels.

2.5.1. EU-Level Policies

The European Green Deal, the EU’s principal and comprehensive green growth strategy, sets a vision for transforming the entire economy while aiming to make Europe the first climate-neutral continent by 2050 (European Commission 2019). The Green Deal is legally enforced through the European Climate Law (Regulation (EU) 2021/1119). As a mid-term objective of the Green Deal, the Fit for 55 package was introduced to achieve a 55 percent reduction in greenhouse gas emissions by 2030 (European Commission 2021a). One of its key instruments is the Renovation Wave strategy, which aims to increase both the rate and depth of building renovations, targeting 35 million buildings by 2030. This strategy comes from recognising energy efficiency as a major untapped potential for decarbonisation (European Commission 2020). The focus on energy efficiency aligns with the Energy Efficiency Directive (first adopted in 2012); that directive was recast in 2023 as Directive (EU) 2023/1791, introducing a new target to reduce final energy consumption by 11.7 percent by 2030 (Directive (EU) 2023/1791). Before the Green Deal, the EU's energy and climate roadmap was formed by the Energy Union Strategy (2015), which was part of the Clean Energy for All Europeans Package published in 2019. That package included the Electricity Directive (Directive (EU) 2019/944) and the Renewable Energy Directive II (RED II, Directive (EU) 2018/2001), which for the first time granted citizens the right to generate, store, share, and sell electricity in each EU Member State.

As part of the same package, the backbone legislation for building energy efficiency, the Energy Performance of Buildings Directive (EPBD), was introduced to set minimum energy standards for both new and renovated buildings. Its latest recast, Directive (EU) 2024/1275, adopted in 2024 under the Green Deal, targets zero-emission buildings by 2050, with an intermediate goal of a 49 percent reduction in building-related GHG emissions by 2030 through energy efficiency and renewables. The directive mandates harmonisation of national regulations to ensure that new residential buildings comply with zero-emission standards by 2030 and sets a phased timeline to eliminate fossil fuel–based heating systems, starting with a subsidy ban and leading to their full phase-out by 2040.

Beyond climate-oriented policies, the energy crisis caused by Russia's invasion of Ukraine in 2022 pressed the EU to take urgent measures through the RePowerEU package (European Commission 2022a). Its core aim is to reduce dependency on Russian fossil fuels while enhancing national energy sovereignty through actions like improving energy efficiency, accelerating the deployment of renewables, and advancing electrification, especially in heating systems. As part of this effort, the Renewable Energy Directive II (RED II) was updated to RED III in 2023 (Directive (EU) 2023/2413), setting new targets of at least 42.5 percent renewable energy by 2030, with an aspirational goal of 45 percent. Also under RePowerEU, the EU Solar Energy Strategy / Rooftop Initiative was launched, requiring mandatory solar PV installations on new buildings (European Commission 2022b), as reflected in revisions to the EPBD in 2024.

To strengthen climate resilience, the EU also adopted the EU Strategy on Adaptation to Climate Change, setting out principles and objectives to make the EU climate-resilient by 2050 (European Commission 2021b). Under this strategy, the EU recognised the need to develop passive housing and decentralised residential solar energy for climate resilience and energy democracy. The EU Strategy on Adaptation (European Commission 2021b) also emphasised that decentralised energy sources are recognised as important measures for addressing climate disruptions and highlighted the importance of investment in resilient, climate-proof building infrastructure.

2.5.2. Poland-Specific Policies

As part of the European Union, Poland is obliged to implement EU-level regulations and directives at the national level. As mentioned in the previous section, every EU member state must formulate a National Energy and Climate Plan (NECP) for 2021–2030 and update it every five years. Poland is currently updating its 2019 NECP. After submitting a draft to the European Commission in 2024 and incorporating feedback, Poland released a revised version for public consultation in October 2024. As of May 2025, the final updated NECP has not been submitted to the European Commission, missing the original deadline of 30 June 2024 by nearly a year. Nevertheless, even though the most recent version is not officially labelled as final, its WAM (With Additional Measures) scenario will be treated as the most relevant roadmap for Poland's climate and energy policy, as the 2019 version is significantly outdated (Ministry of Climate and Environment 2024). However, since this document is not yet legally binding, caution is needed when taking its outcomes, as further revisions may follow public consultations.

The latest version of the NECP outlines three main targets for 2030: reducing greenhouse gas (GHG) emissions by 50.4 percent compared to 1990 levels across the whole economy, increasing the share of renewable energy sources (RES) to 32.6 percent in gross final energy consumption, and improving energy efficiency to reduce demand by 14.4 percent. Furthermore, the document acknowledges that Poland's current policies are insufficient to meet the updated EU energy efficiency targets for buildings. Under the national application of the existing Energy Performance of Buildings Directive (EPBD), Poland's Long-Term Renovation Strategy set a target of 7.5 million thermal modernisations, with an average annual renovation rate of 3.8 percent, and aimed for 65 percent of buildings to achieve a primary energy demand of no more than 50 kWh/m²/year by 2050 (Ministry of Development 2022). By May 2026, Poland must resubmit its strategy, including the updated requirement that all new buildings be zero-emission from 2030, with a primary energy demand of 15–20 kWh/m²/year. The revised strategy must also include more ambitious thermal modernisation rates, a fossil fuel phase-out plan for heating, and a rooftop solar mandate, among others. In addition, the NECP estimates that GHG emissions in the residential sector will fall by 48 percent between 2020 and 2030, driven by efficiency improvements, reduced fossil fuel use, and electrification. The most challenging component of this transition is phasing out fossil fuels in heating. The plan projects a 65 percent reduction in household fossil fuel use by 2030. To support heating electrification, the NECP foresees an increase in installed capacity from 298 ktoe in 2020 to 1 840 ktoe in 2030 and 4 026 ktoe in 2040, with subsidies playing a key role. Following the above, it is important to underline that there is no existing thermomodernisation strategy in Poland which would follow the most recent EU directives.

Reflecting the EU Electricity Directive (Directive (EU) 2019/944), Poland's primary legislation for renewable energy, the Renewable Energy Sources Act (adopted initially in 2015), has been amended multiple times (Ministry of Economy 2015). These changes have shaped the evolving energy landscape, established the legal status of prosumers, and required electricity suppliers to purchase energy from prosumers or peer-to-peer trading schemes. The Act also sets financial balancing principles between prosumers and utilities by enabling energy trading schemes. The current net billing scheme, introduced in 2022, replaced the earlier net metering system. The key difference between them lies in how energy flows are balanced: net metering allows for annual net energy balances, while net billing assumes that surplus energy is sold at market prices and energy consumed is purchased at standard rates. Prosumers' financial flows are calculated over a 12-month deposit cycle, with a cap on balances exceeding 20 percent, to prevent oversizing of PV systems. Net billing dynamics encourage using energy storage systems to maximise self-consumption, thereby reducing grid strain and increasing financial benefits, especially given that electricity prices are lowest during PV generation peaks around midday.

Table 2-2. Relevant indicators progress from 2020 to 2040. Data source: Ministry of Climate and Environment (2024).

Indicator	2020	2025	2030	2035	2040
Rooftop PV generation (gross) [GWh]	1 527	9 897	14 036	18 780	23 964
Self-consumed energy [GWh]	458	2 969	4 912	7 512	10 784
PV self-consumption share (PV used on-site)	30%	30%	35%	40%	45%
Household OZE share in final demand	24.6 %	30.3 %	41.2 %	52,90%	63.4 %
Behind-the-meter battery capacity [MW]	–	50	1 975	3 690	8 706

The pre-final NECP version also includes a roadmap for solar energy development, targeting 24.6 TWh of annual generation by 2030 and 43.1 TWh by 2040. It also recognises the growing importance of decentralised energy, projecting that the number of prosumers will reach 2 million by 2030; however, it notes that the pace of development is constrained by grid infrastructure. Additionally, NECP emphasises the need for batteries, increased self-consumption, smart grids, and demand-response systems, highlighting continued support for net billing and financial incentives for prosumers. Table 2-1 presents key indicators from the NECP related to household energy self-sufficiency, showing growth in PV generation, rising self-consumption rates, and a skyrocketing number of behind-the-meter battery installations.

To achieve those targets, there are several subsidy programs such as Clean Air, My Heat, My Electricity or Thermomodernisation Tax Relief. Launched in 2018, the Clean Air ("Czyste Powietrze") program offers subsidies for thermal modernisation and heating system replacements in single-family homes built before 2014 (National Fund for Environmental Protection and Water Management 2023). Its primary goals are to reduce smog and lower GHG emissions, and according to the NECP, this subsidy is expected to save 0.65 Mtoe of final energy in single-family homes by 2030 through envelope upgrades. Another incentive, the Thermomodernisation Tax Relief, allows homeowners to deduct modernisation expenses from their taxable income (Ministry of Finance 2019). Additionally, the My Heat ("Moje Ciepło") program, launched in 2022, supports the installation of heat pumps in new single-family homes by covering up to 45 percent of installation costs, promoting the shift away from fossil fuels (National Fund for Environmental Protection and Water Management 2022). Since 2019, the primary subsidy program for solar micro-installations and batteries in Poland has been My Electricity ("Mój Prąd") (National Fund for Environmental Protection and Water Management

2024). Its sixth edition, launched in 2024, offers up to 50 percent coverage of total PV system costs (ranging from 2 kW to 20 kW) and mandates energy storage, either battery systems with a minimum of 2 kWh capacity or thermal storage, starting 1 August 2024.

It is also important to acknowledge that Poland's most recently binding energy policy remains the Energy Policy of Poland until 2040 (PEP2040), adopted in 2021 (Ministry of Climate and Environment 2021). Despite adopting several new EU-level strategies and policies since then, an updated version of PEP2040 has not yet been published. As a result, its numerical targets are outdated, and the NECP now serves as the primary reference for the country's energy transition, and PEP2040 hasn't been assessed in detail, since most of its indicators are expected to improve.

Moreover, the NECP and PEP2040 are not the only strategic documents lacking updated versions. Poland also does not have an updated, detailed national plan for building climate adaptation and resilience, despite the EU Climate Adaptation Strategy's requirement for all Member States to develop National Adaptation Strategies (NAS) and National Adaptation Plans (NAPs). These plans should include clear strategic goals, priorities, timelines, and assigned responsibilities. Poland's last published strategy, the National Strategy for Adaptation to Climate Change by 2020 with a Perspective to 2030, dates to 2013, and even back then, it emphasised local energy production and called for actions to adapt the energy system to climate impacts (Ministry of Environment 2013). While Poland has adopted local initiatives, such as the National Urban Policy and city-level adaptation plans, these remain focused on urban areas and do not constitute a comprehensive national strategy. According to the International Energy Agency 2022, Polish policies have concentrated primarily on climate mitigation and energy security, while measures for climate adaptation have been largely overlooked.

2.6. Energy Self-Sufficiency in Poland

While the previous section outlined the legislative frameworks shaping the energy transition landscape, it is also important to assess how it influences energy self-sufficiency in Poland.

A growing body of research, both modelling-based and empirical, has investigated how Polish households can achieve energy independence under current and evolving conditions. The most comprehensive study on energy self-sufficiency in Polish households, carried out by Benalcazar et al. (2024), found that PV+battery systems achieved median self-sufficiency of 68.1% across 200 Polish single-family households (annual demands ranging from 2500 kWh to 5500 kWh), significantly higher than the 39.5% achieved by PV-only systems, emphasising storage's critical role, what is presented on the Figure 2-15. The study assumed PV system of capacity of 9.6 kW and battery's rated capacity 13.5 kWh (Benalcazar et al. 2024).

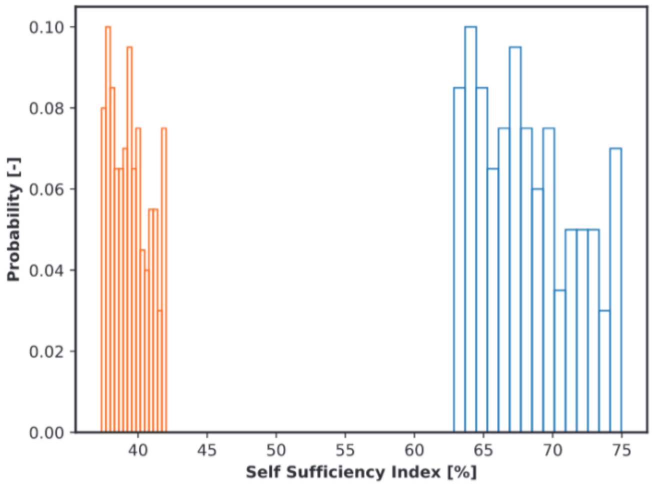

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Figure 2-15. Self-sufficiency for 200 buildings in Poland in 2023. Orange results represent houses only with PV systems, whereas blue PV+battery systems. Source: Figure reproduced from Benalcazar et al. (2024). © 2024 Elsevier. Reproduced under Licence No. 6039130716707.

Furthermore, to investigate the benefits of implementing an electrical energy storage system to a 5 kW photovoltaic (PV) installation in the Polish climatic conditions, Michalski et al. (2024) analysed a system with different storage capacities on an hourly basis for the year 2023. They concluded that for Polish conditions, the most optimal battery capacity ranges from 5 kWh to 15 kWh, covering 20-55.6% of annual daily storage needs, noting that 88% of annual energy production occurred from March to October (Michalski et al. 2024).

There is very limited research on the large-scale feasibility of energy self-sufficiency in Poland, with existing studies typically narrowed down to the level of a province, community or an individual city, not accounting for the full potential of the Polish building stock and the ongoing trend of thermomodernisation and hourly resolution.

For example, Iglinski et al. (2021) confirmed the possibility for the Warmińsko-Mazurskie Voivodeship to achieve annual energy independence through local production of electricity and heat using biomass, wind, and solar energy sources, alongside additional energy storage. In another study, Lipiński et al. (2022) investigated the communal level of energy independence, both for heat and electricity, in five specific communities in northern Poland.

However, their analysis was based solely on existing capacities of biomass, biogas, and other renewables, with relatively low levels of installed solar capacity. As a result, they observed significant differences linked to local conditions and concluded that achieving energy self-sufficiency tends to be easier in terms of electricity than heat. Similar to previous studies, their results were evaluated on a net annual basis, without hourly resolution, allowing for an assessment of a community's theoretical ability to be self-sustaining over a year but not capturing real-time self-sufficiency dynamics.

On the other hand, Trojenowski and Kozak (2023) examined how widespread implementation of PV installations on all single-family houses would affect the share of renewables in Poland's current energy mix. They estimated that equipping all 5.3 million single-family homes with PV could generate 29,150 GWh annually, accounting for 19.7% of Poland's total electricity demand. Their study also confirmed that single-family homes equipped with PV systems could not only meet their own energy needs but also export surplus energy (approximately 1000 kWh per home per year); however, the research did not assess self-sufficiency levels at an hourly resolution, with lowest monthly resolution of energy balances.

A more collective approach was brought in a study carried out by Fedorczak-Cisak et al. (2023) on a community of 40 energy-efficient nZEB buildings (8118 kWh/year per building) in Libertów, achieving near-grid independence on an annual basis. They concluded that it is feasible to design a self-sufficient, solar-powered community in Polish climatic conditions, with highly energy-efficient buildings featuring low final energy demand, additional PV sources, and community-level storage and management infrastructure, underlining that active involvement of residents, from the design stage to daily operation, is critical for success (Fedorczak-Cisak et al. 2023). Additionally, the study calculated that this would result in a 96% reduction in GHG emissions compared to complete reliance on the electricity grid.

There is only one study in Poland that assesses energy self-sufficiency on an hourly scale and at a larger level, though still limited to a single city and covering all building types, including single-family, multi-family, commercial, service, and heritage buildings. There, Jurasz et al. (2020) evaluated the rooftop PV potential of Wrocław to assess whether full utilisation could provide citywide annual energy self-sufficiency. Their findings indicated that even under optimal deployment, PV systems would cover only up to 36.8% of the city's total electricity demand.

2.7. Research Gaps

This study identifies five core research gaps in the literature on energy self-sufficiency in Polish single-family buildings, based on a review of the existing state of the art. The relevance of this research is viewed from both a top-down perspective: climate mitigation and national energy securityand a bottom-up one, focusing on citizen-level resilience and energy democracy.

Gap 1: Lack of high-resolution (hourly), national-scale modelling of energy self-sufficiency in Polish single-family homes. Most existing studies assess energy self-sufficiency either at the scale of a single household or a local demonstration project, often using annual time steps (Simic et al., 2021; Benalcazar et al., 2024; Peña-Bello et al., 2020). This fails to capture real-time dynamics and load-matching challenges crucial for system operation and grid integration (Hall & Geissler, 2017). No study has combined hourly modelling with a national-scale analysis for Poland's single-family stock, which will be undergoing ambitious thermomodernisation along with the EPBD directive. This thesis addresses this gap by applying hourly-resolution simulations of representative building types with consistent PV and battery specifications, allowing the energy self-sufficiency levels of each vintage to be established. Aggregating the results across Poland's entire single-family building stock for 2050 allows, for the first time, a weighted national-scale estimate of hourly self-sufficiency to be produced.

Gap 2: Lack of integrated evaluation of self-sufficiency alongside energy demand reduction in single-family buildings. Most existing work focuses on the supply side, optimising PV and battery systems, without evaluating how energy demand reduction via retrofitting interacts with self-sufficiency potential, what is contrary to the "Efficiency First" principle adopted by the EU (Gstöhl & Pfenninger, 2020; Klingler & Schuhmacher, 2018; Miranda et al., 2024). This thesis fills this gap by evaluating energy demand as a potential driver of self-sufficiency and critically examining their relationship.

Gap 3: Lack of quantified analysis on how self-sufficiency contributes to national climate targets and energy security. While the literature acknowledges that decentralised energy supports decarbonisation and energy security (Cabeza et al., 2022; Huang et al., 2019), quantitative national-scale evaluations in Poland are still missing. Some studies assess overall CO_2 reduction potential alongside the thermomodernisation process, but they do not take into account hourly resolutions or evaluate how PV and PV+battery systems alter total energy imports from the grid, and thus CO_2 emissions. Furthermore, in a similar context, there is no calculation of the total decrease in national grid imports, which directly translates into reduced reliance on fossil fuel imports and hence improved national energy security. Since the potential for achieving energy self-sufficiency among single-family buildings has not been explored in detail, it is unclear what changes to the energy system, such as additional PV capacity or energy storage, would be needed for all single-family buildings to achieve this by 2050. This study contributes to filling this gap by modelling total operational CO_2 savings and reductions in grid energy demand under 2050 scenarios, using both a decarbonising and a fossil-fuel-dependent 2025 grid.

Gap 4: Lack of investigation of household-level impacts such as resilience and energy democracy in self-sufficiency research. Current scholarship rarely explores what energy self-sufficiency means for households beyond financial metrics. The transformative potential of household autonomy for resilience to outages and democratic energy participation remains underdeveloped. This thesis addresses this gap by not only analysing top-down indicators, but also exploring how energy efficiency levels relate to outage resilience and equitable participation in the energy transition.

Gap 5: Lack of understanding of the conditions needed to scale energy self-sufficiency to a national level. Even studies that quantify technical potential rarely address what infrastructure, technological, or policy conditions would be necessary to realise this potential in practice. This thesis fills this gap by quantifying the required scaling of rooftop PV, storage, and deep retrofits, and outlining the conditions needed to make such a transition feasible.

To conclude, the idea of energy-self-sufficient, low-demand single-family buildings offers solutions to a range of existing challenges related to climate, energy, and how society perceives energy ownership. The previous chapters demonstrated that the technological and policy background is mature enough to support the broader adoption of energy efficiency in buildings, PV, and battery storage. Building on this, the following chapter presents the methodology used to address the research gaps and assess the potential for energy self-sufficiency in Polish single-family buildings.

3. METHODS

This chapter describes the methodology applied to investigate the future potential of energy self-sufficiency in Polish single-family buildings. Building on the research gap identified in the previous chapter, it shapes the conceptual and analytical framework that can be used for assessing how retrofitting, rooftop photovoltaics, and battery storage can together enhance households' autonomous, low-demand energy systems. The focus of the approach is not solely technical, as it understands energy self-sufficiency as a proxy to examine climate mitigation and resilience, as well as energy security and households' energy independence.

Through the chapter, conceptual work is explained, followed by the research design and methodological framework. Furthermore, guiding assumptions and hypotheses are formulated. Following that, methods of data collection and step-by-step data analysis procedures are presented. Finally, the chapter ends with outlining research limitations, ethical issues, and AI acknowledgements.

3.1. Conceptual Framework

The research follows a performance-based framework that interprets energy self-sufficiency not only as a technical metric but also as a contributing factor to broader policy changes covering climate mitigation, resilience, energy security, and energy democracy. The methodology combines long-term scenario modelling with hourly performance simulations to explore how energy efficiency, PV deployment, and storage together shape the operational energy profile of single-family buildings in Poland.

As the outcome, these simulations allow energy independence to be quantified on the household level as an indicator of increased autonomy and climate resilience, and moreover, as a contribution to national decarbonisation and energy security goals. The meanings and value-based assumptions behind these concepts are explained in detail in Chapter 1 and are operationalised here through the metrics presented in Table 3-1.

All steps in the modelling were transparently reported and can be reproduced with publicly available data and open-source code.

3.2. Research Design and Methodological Framework

The main purpose of the study is to evaluate the possible degree of energy self-sufficiency that could be achieved in Poland's thermomodernised single-family stock in the year 2050, and how it would impact climate mitigation, resilience or energy security and democracy. Since the research approaches the topic from an efficiency-first perspective, the annual energy demand of buildings will vary, while the PV+battery setup will remain the same for each building. This will allow for an exploration of how building demand influences system performance. The amount of annually generated energy with the PV panel is set at 5910 kWh, and yearly irradiation distributions are equal for each vintage. Battery storage is set at 14 kWh/5 kW.

Energy flows in the studied system will happen between four entities: the building (energy demand), photovoltaic system (energy generation), battery storage (storing energy from PV and delivering it to the building), and electricity grid (energy exports and imports), as presented in Figure 3-1.

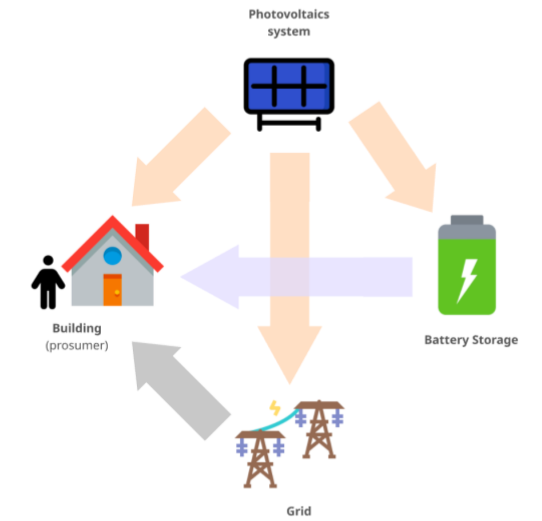

Figure 3-1. Energy Flows Within the System.

As for the scope, the research is limited to single-family buildings in Poland within the timeframe 2025–2050, although hourly calculations will be carried out only for the year 2050. Furthermore, to evaluate potential energy and CO_2eq savings in 2050, two scenarios will be studied: *Ambitious*, featuring high levels of retrofitting, and *Frozen*, with less ambitious retrofit measures. To reflect the different backgrounds of the scenarios, they will be assessed with three supply/generation options: without PV, with PV, and with PV + battery. Also, since the grid will undergo decarbonisation, the results of CO_2eq conservation will be assessed for the energy mix from 2025 and 2050.

Methodological Framework

To evaluate energy self-sufficiency potential and its implications for climate and energy policy in 2050, the methodology was divided into three phases, also graphically represented in Figure 3-2:

Simulations:

1. **Evaluation of building stock dynamics over the years 2025–2050**
   The High-Efficiency Building (HEB) model was used to simulate how Poland's single-family building stock evolves from 2025 to 2050 under two retrofit scenarios: Frozen (slow retrofitting) and Ambitious (deep retrofits). Additionally, the progression of building vintage shares (levels of energy efficiency) was drawn over the years 2025 to 2050.
2. **Annual energy balances over the years 2025–2050**
   Using the adjusted HEB model, annual energy demand was simulated over the years 2025–2050 for both *Frozen* and *Ambitious* scenarios. Cumulative PV generation, matching energy demand in 2050, was identified and interpolated from existing data.
3. **Hourly energy balances in the year 2050**
   For the year 2050, detailed hourly profiles of energy demand and PV generation were simulated for the *Ambitious* scenario for two variants: only PV and PV + battery. To evaluate the building's energy efficiency, a simulation was carried out for five representative buildings from each vintage, each with a 116.2 m² floor area. Here, PV generation, battery operation, and overall energy flow through the system were calculated with a tailor-made Python script using the battery dispatch algorithm (charge-when-surplus, discharge-when-needed).

Calculations:

1. **Energy flows and energy independence metrics in the year 2050**
   Based on hourly energy flows within the system, metrics like import, export, net

import/export, self-sufficiency, and self-consumption were calculated and analysed over time.

2. **CO_2 avoided and energy demand assessment in the year 2050**
   Annual energy balances and hourly flow data were used to estimate energy conservation and operational CO_2eq emissions using primary energy and emission factors, with two energy mixes for 2025 and 2050. Calculations were carried out with three supply/generation options: without PV, with PV, and with PV + battery.

Evaluation:

A combination of listed steps allows for the evaluation of the possible degree of energy self-sufficiency at different efficiency levels, the relationship between self-sufficiency and energy efficiency, and their impacts on climate change mitigation and resilience, as well as energy democracy and energy security in 2050, using metrics from Table 3-1.

Table 3-1. Metrics of Evaluation.

	Climate Mitigation	**Climate Resilience**	**Energy Security**	**Energy Democracy**
Metric of Evaluation	Energy Conservation	Energy Self-Sufficiency	Energy Conservation	Energy Self-Sufficiency
	CO2eq Conservation		Total Energy Generation	

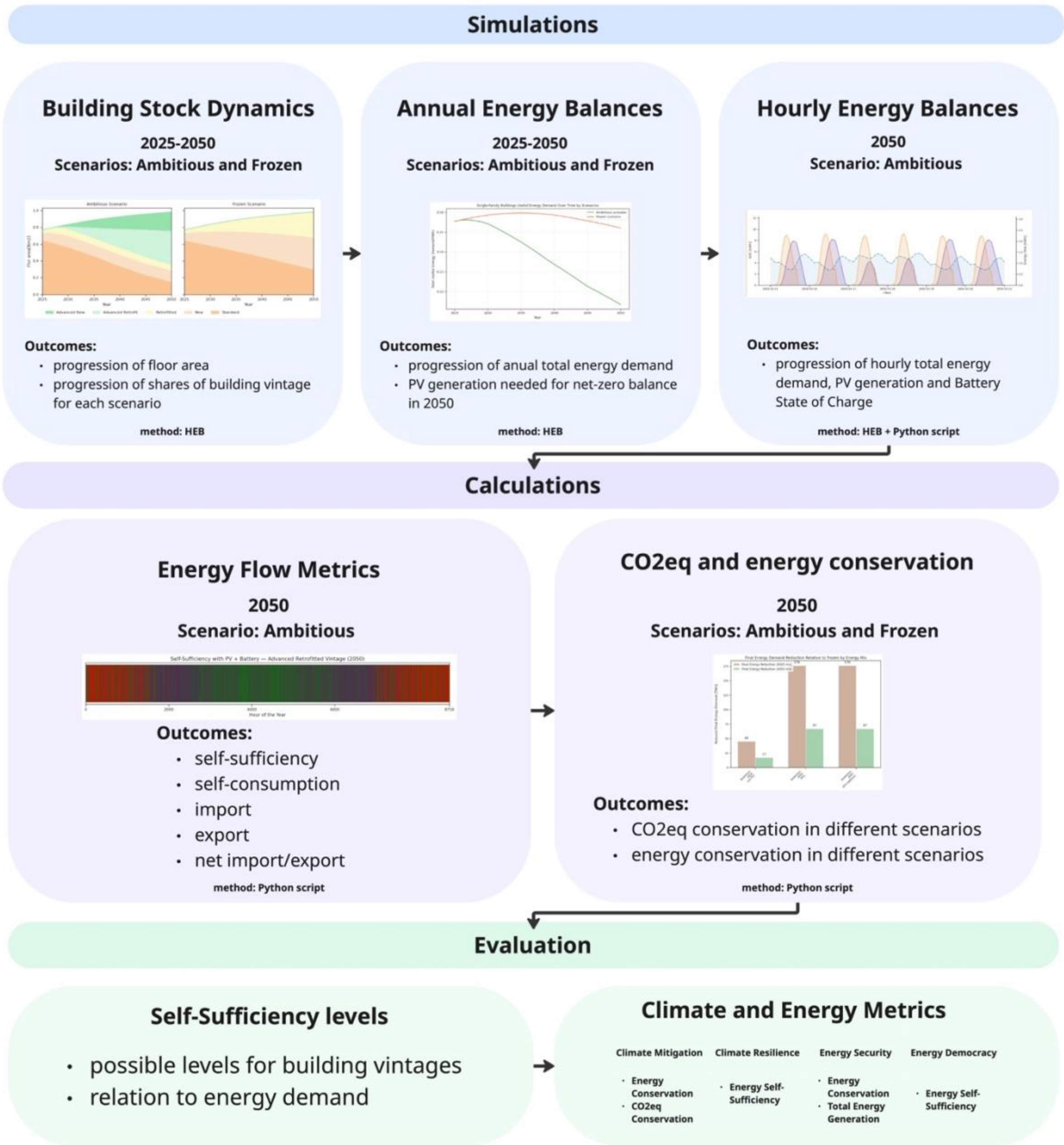

Figure 3-2. Research design.

This study is guided by the following research questions, which explore the technical feasibility and systemic implications of building-level energy self-sufficiency in Poland by 2050:

RQ1. What level of energy self-sufficiency can single-family buildings in Poland achieve by 2050 through retrofitting, rooftop photovoltaics, and battery storage?

RQ2. How does annual energy demand in single-family buildings influence energy self-sufficiency, and what are the implications for household climate resilience and energy democracy?

RQ3. To what extent can widespread self-sufficiency in single-family buildings contribute to national CO_2 emissions reduction and enhance energy security by 2050?

RQ4. What are the implications required to scale energy self-sufficiency in Poland's single-family building stock by 2050?

Guiding Assumptions & Hypotheses

Since the study has a technical nature, there is a need to establish several assumptions to ensure both calculations feasibility and method consistency. Those assumptions are based on the literature review from the field, engineering practices or national policy documents.

Core Assumptions

- Efficiency-first retrofits reduce hourly load without compromising thermal comfort.
- Each house will have an integrated PV + battery system in 2050.
- Each house will have an annual PV installation yield of 5910 kWh, with the same hourly irradiation distribution in 2050, which aligns with literature ranges (Olczak et al. 2021; Gulkowski et al. 2024)
- Each house will have battery storage set at 14 kWh/5 kW, performing equally throughout the year, reflecting the average installed battery in Poland (Wysokie Napięcie 2024).
- The grid accepts unlimited exports and imports (no curtailment).
- The Ambitious scenario assumes full electrification of heating.
- Occupant behaviour in appliance use, lighting, and cooking follows unified weekday and weekend trends, but does not vary between seasons for any buildings (Olczak et al. 2021).
- No ageing or efficiency loss is considered for PV panels or batteries.
- Each building is 116.3 m², reflecting the average from 2024 report (KAPE 2024).

Building on all the above, to answer the research questions, three hypotheses were formulated:

- H1: A retrofitted Polish single-family home with PV and battery storage can achieve an energy self-sufficiency level of 70–80% by 2050 (RQ1).
- H2: Reducing a home's annual energy demand through retrofitting significantly increases its yearly energy self-sufficiency (RQ2).
- H3: Higher energy self-sufficiency levels in single-family buildings contribute directly to CO_2 emissions reduction and national energy security (RQ3).

RQ4 won't answer any hypothesis but rather will summarise and examine technology changes observed within the system.

3.3. Methods of Data Collection

Through the data-collection process, only publicly available information was used, either published under national policies or by government-affiliated agencies, or obtained from peer-reviewed literature and reports from reputable research centres or online energy magazines. All data fall into six components: HEB model for building energy efficiency; appliances, lights and cooking energy demand calculations; model for photovoltaic generation; energy storage calculations; energy self-sufficiency calculations; and CO_2-equivalent emissions calculations, whose data-collection procedures are aggregated and described in the corresponding sections. Due to the enormous amount of input data, all values and their sources are listed in the Appendix. At the same time, it is important to acknowledge that Ambitious Scenario conditions were determined by a document prepared by several energy agencies cooperating with the Polish Ministry of Development, to create a backbone for the new version of the Long-Term Building Strategy, which must be updated following Art. 3 of Directive (EU) 2024/1275 (KAPE 2024). Even though this document is not verified by the Polish government as a national strategy, it was chosen as the most recent source of information about the Polish building stock and possible strategies.

3.4. Methods of Data Analysis

To achieve the aim of the research, several quantitative methods were used. First, energy demand for buildings in terms of their heating, cooling, and water was calculated with the HEB model, and on top of that, the energy demand for appliances, cooking, and lighting was added.

In the next step, PV generation potential was analysed, which was followed by energy storage calculations, establishing a framework for analysing energy flows within the studied system with the help of a tailor-made Python script. Furthermore, outcomes of the previous steps of analysis were assessed to establish system performance by calculating metrics given in Table 3-1.

3.4.1. Energy Demand of Buildings (Heating, Cooling, Hot water)

Modelling buildings' energy efficiency is crucial for evaluating energy consumption, optimising designs, and supporting policy decisions in the energy and environmental sectors. These models simulate how buildings utilise energy under defined conditions and help to plan more sustainable strategies. Over time, they have evolved from basic engineering calculations into a variety of complex approaches, reflecting advancements in IT tools. Among these approaches, the most common are (Sanchez-Escobar et al. 2021b; Chegari et al. 2022; Rubeis et al. 2019):

- **Engineering modelling**, calculating energy consumption based on fundamental principles of thermodynamics and heat transfer, used to replicate energy system operation.
- **Data-driven statistical modelling**, linking building or end-use features with energy use by applying statistical techniques.
- **Data-driven AI-based modelling**, using artificial intelligence techniques to correlate studied features with energy use through tools such as Artificial Neural Networks (ANNs) or Support Vector Regression (SVR).
- **Hybrid methodologies**, combining different approaches, such as engineering and data-driven methods, by integrating simulation and statistical methodologies to model the performance of buildings or generate retrofit scenarios.

From all available energy modelling tools, the High-Efficiency Building (HEB) model was chosen as an adequate tool for accessing annual and hourly results for energy demand profiles of buildings in different energy efficiency categories over a long-term period of 25 years. The HEB model allows tracking changes in energy demand with respect to building stock changes due to thermomodernisation efforts and provides the precise hourly resolution required for conducting an energy self-sufficiency study. Furthermore, since it considers long-term changes driven by macroeconomic and demographic factors, such as changes in total floor area due to population or floor area per capita changes over time, it works as an accurate tool for long-run projections representing building stock dynamics in 2050.

The bottom-up HEB model uses hybrid methodologies and has a performance-oriented approach, meaning it evaluates whole-building energy performance rather than individual components such as equipment or specific modernisation methods.

The overall methodological framework of HEB is presented in Figure 3-3, showcasing steps like disaggregation of input data along with classification, floor area calculation, and dynamics of retrofit and new floor area based on given scenarios, and finally energy calculations leading to energy consumption (demand) results.

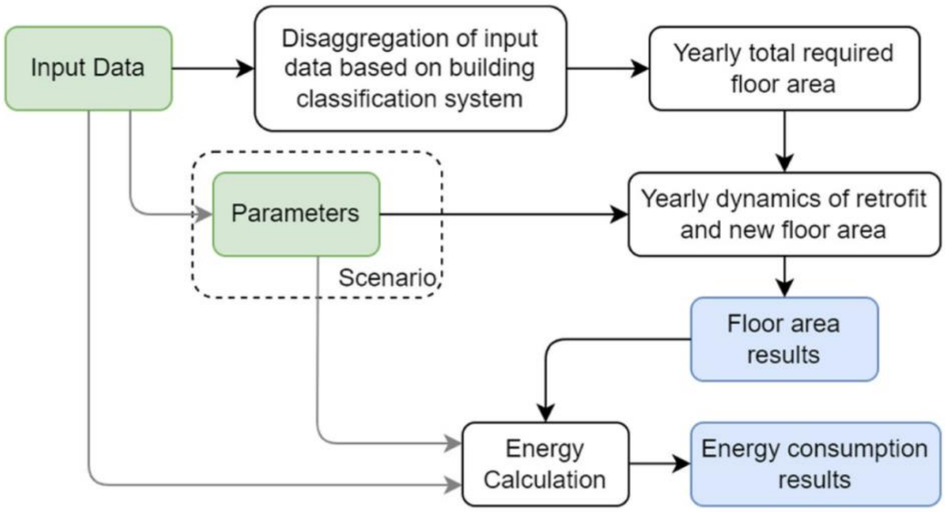

Figure 3-3. HEB model methodological framework. Green entities represent inputs, blue outputs of the model, and white carried-out operation. Source Figure reproduced from Chatterjee et al. 2025 © 2025 CC BY 4.0.

Furthermore, it allows for the disaggregation (classification) of building stock by:

- Regions (11 key geographical regions + 30 focus countries, including Poland)
- Climate zones (19 different climate zones)
- Urbanisation (urban, rural, urban slum)
- Building category (residential, commercial and public, slums)
- Building type (single-family, multi-family, educational, hotel & restaurant, hospital, retail, office, other)
- Building vintage (new, advanced new, retrofitted, advanced retrofitted, standard)

This enables narrowed-down studies, such as the case of single-family buildings in Poland explored in this study. Although the High-Efficiency Building model has universal applications, in this work, it was adjusted to match existing policies, development scenarios, and climate zones, resulting in modifications to components such as scenario settings, building vintages, and climate zones.

Adjustment of Scenarios

To fine-tune the HEB model to Polish conditions, two scenarios were established:

- **Ambitious Scenario**, adjusted from HEB's *Deep Efficiency* scenario, assumes extensive retrofitting and rigorous new building codes with a progressive retrofit rate, following trends set by Polish policymakers (KAPE 2024).
- **Frozen Scenario**, used as the baseline scenario, adapted from HEB's *Moderate* scenario, indicates a slow retrofit pace of 1.2% over the whole period, representing poor thermomodernisation efforts.

Adjustment of Building Vintages

Here, instead of evaluating technological differences, fixed energy use per vintage was given to the model based on calculations made by KAPE (2024). Existing HEB building vintages such as "new, advanced new, retrofitted, advanced retrofitted, and standard" were represented by set, calculated values demonstrating their annual energy needs [kWh/m²/year], in line with building vintage categories in Poland's Long-Term Renovation Strategy (see Figure 3-4). Since exact energy consumption values are attributed to the vintages, no separate evaluation of the technologies used was implemented.

Figure 3-4. Buildings' vintages with yearly final energy demand [kWh/year].

Adjustment to Climate Zones

HEB uses 19 climate zones distinguished based on heating and cooling degree days (HDD/CDD) and humidity according to the Köppen–Geiger climate zones. Nevertheless, after assessing actual Polish climate conditions, there was a need to adjust climatic areas. Consequently, most of Poland was classified under Climatic Zone 2 (CID2) - "Only heating" (high heating demand), with only a small share remaining in CID3 - "Only heating" (moderate heating demand), which reflects warming climate trends.

After adjusting input data and the previously mentioned aspects, simulations were run for single-family buildings in Poland from 2025 to 2050 at an annual timescale, and at hourly resolution for the year 2050. More detailed descriptions of methods and inputs for energy demand calculations can be found in the Appendix.

3.4.2. Methods Used for Appliances, Lights And Cooking Energy Demand Calculations

To access the full energy balance, there is a need to consider also energy used for appliances, cooking and heating. Since those values are not constant over time, but follow an occupancy schedule, daily total energy usage of appliances, cooking and heating per building was distributed over the day with hourly resolution (with distinguish of weekdays and weekdays due to differences in occupancy pattern) following the trend presented by Olczak et al. (2021). More precise assessment of methods used for appliances, lights and cooking energy demand calculations can be found in the Appendix.

3.4.3. Methods Used for PV Technical Potential Evaluation

Scholars use various approaches for PV potential evaluation, but all follow the same core steps, like assessing suitable roof area, estimating solar irradiation, and finally calculating electricity generation. Most often utilised methods are:

- **Geographic Information Systems (GIS)**, using high-resolution satellite or aerial images to define rooftop polygonal shape and orientation, then apply segmentation models to extract building footprints and finally calculate roof area (Fath et al. 2015; Mutani and Todeschi 2021; Gernaat et al. 2020; Molnár et al. 2024b).
- **Machine Learning and Deep Learning**, used to identify rooftop obstructions, such as chimneys and vents, from high-resolution satellite imagery, which improves the accuracy of studies (Ni et al. 2023). Additionally, machine learning algorithms can predict solar radiation on rooftops, considering factors like shading, roof orientation, and inclination (Chen et al. 2022).

- **Light Detection and Ranging (LiDAR)**, creating detailed 3D models of environments, is used to generate digital surface models (DSMs) that provide information on roof geometry, and therefore, researchers can assess the appropriateness of rooftops for PV installations (Palmer et al. 2018; Jurasz et al. 2020).
- **Statistical Methods**, utilised mostly in areas with poor geospatial data or historical measurements, often rely on population density data correlated with floor space to approximate roof area (Gernaat et al. 2020).

In most cases, to assess national-scale potentials, scholars combine data with GIS calculations, performing high-resolution analyses on representative areas and then extrapolating to the national level using either extrapolation methods or generalised statistical data. To simplify technical PV generation potential, research teams or scholars develop models like PVGIS, established by the European Commission's Joint Research Centre (European Commission 2016), IMAGE (Stehfest et al. 2014), or BISE (Petrichenko et al. 2019).

The main goal of the study is to evaluate single-family buildings' self-sufficiency; therefore, hourly profiles of PV generation throughout the year should be investigated. To achieve that, a tailored statistical method was constructed in a Python environment, following these steps (Figure 3-5):

- Setting the cumulative target of PV generation in single-family buildings which offsets their energy demand in 2050 (in line with Polish net-zero targets), based on the HEB energy-demand calculation for 2050
- Ensuring that total PV generation remains within Poland's technical PV potential as evaluated by Molnár et al. (2024) using a feasible subset rather than the full theoretical potential
- Assuming that every single-family building in 2050 has a PV installation, each producing an equal annual yield of 5,911 kWh/year, calculated from total PV generation divided by the projected building count in the HEB model
- Dividing the annual PV yield according to Poland's hourly irradiation profile to derive the hourly PV generation time series
- Performing a linear regression from current PV penetration in single-family buildings to the 2050 target, yielding the required yearly PV-generation growth rate

- To investigate degree of freedom of energy efficiency, all building vintages and locations in Poland are assumed to have the same hourly PV energy generation throughout the year.

To investigate the degree of freedom of energy efficiency, all building vintages and locations in Poland are assumed to have the same hourly PVs energy generation through the year.

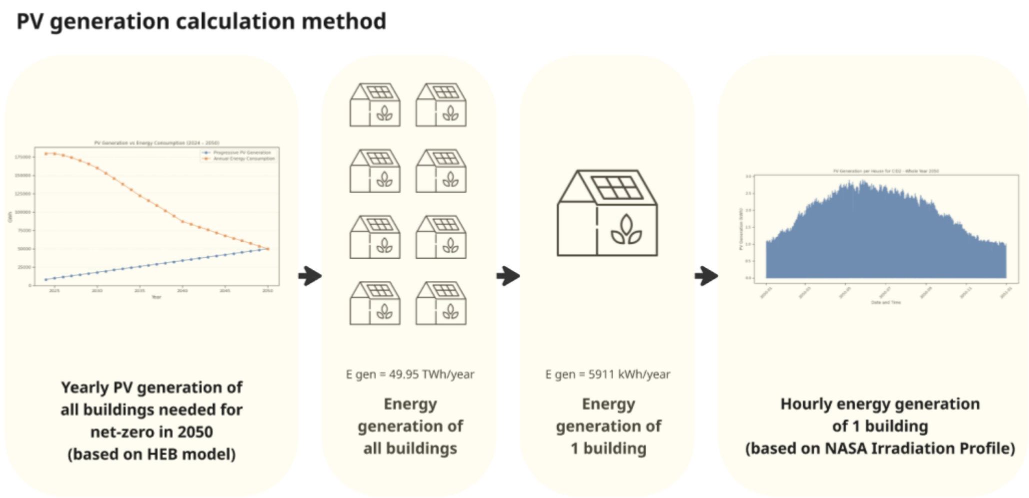

Figure 3-5. PV generation calculation method.

A more detailed description of PV generation calculations can be found in the Appendix.

3.4.4. Methods Used for Energy Storage Calculations

Since PV prosumers are increasingly installing behind-the-meter battery storage systems, there is a growing number of studies calculating energy flows through those systems using simulations, optimisation methods, statistical approaches, and empirical case studies with monitoring:

- **Dynamic simulations** evaluate hour-by-hour (or finer) energy flows in the building over a given period. Even though they have many benefits, such as flexibility to test different scenarios, they require assumptions about occupants' behaviour or load profiles (Benalcazar et al. 2024; Hall et al. 2017; Šimić et al. 2021; Michalski et al. 2024).

- **Optimisation models** investigate optimal energy storage sizing (and other parameters) and are widely used to maximise financial profit or self-consumption rate (Ciocia et al. 2021; Ramírez Camargo et al. 2016).

Among the most popular tools for energy-storage load calculations are TRNSYS, EnergyPlus, HOMER, and PV*Sol, but many scholars tailor-make their own models due to their relatively low complexity, and this approach will also be used in this study.

To simplify the calculation, the study will model five different Polish representative residential vintages, each equipped with a 14 kWh / 5 kW lithium-ion battery. The algorithm follows the self-consumption, maximising strategy described by Moshövel et al. (2015), carrying out hourly, year-long simulations. The calculation of battery behaviour was built on previous results of hourly energy demand for each vintage and PV generation. Each calculation was carried out consecutively for all vintages, following steps for the charge-as-soon-as-possible strategy:

- Assume battery technical properties: 14 kWh capacity / 5 kW power and establish battery parameters.
- Align hourly profiles for vintage demand and PV generation on the same yearly timescale.
- Compute the mismatch between generation and demand each hour.
- Apply energy-flow rules for hourly evaluation:
    - If PV > load, the battery charges until:
        - it reaches its 5 kW power limit, or
        - the battery is full

        Any remaining PV surplus is exported to the grid.
    - If PV < load, the battery discharges until:
        - it reaches its 5 kW power limit, or
        - the battery is empty.

        Any remaining deficit is imported from the grid.

  Update the battery's state of charge (SOC) each hour, following the charge/discharge flows.

There is an additional assumption that the battery starts half charged in 2050. A more detailed description of the battery calculation and inputs can be found in the Appendix.

3.4.5. Methods Used for Energy Self-Sufficiency Calculations

Methods used for assessing Energy Self-Sufficiency build upon previously presented energy storage methodologies, as they evaluate hourly energy flows using simple equations to calculate electricity generation, demand, imports, and exports throughout the year. In other words, for each hour, they examine whether the system could meet its energy demand with locally produced energy (either directly from PV or from battery storage) and express this balance as an annual proportion of self-sufficient hours relative to the total number of 8,760 hours in the year 2050. Similarly, the self-consumption calculation evaluates hourly energy flows, focusing solely on how much electricity produced on-site was consumed there, without exporting it to the grid.

The following formulas were used for hourly calculations in the year 2050 (Aranda et al. 2025):

For self-sufficiency (SS), representing the ratio of self-consumed energy to total energy demand:

$$Self\ sufficiency\ (SS)\% = \frac{\sum_t E_{PV,used\ (t)}}{\sum_t E_{dem\ (t)}} = \frac{\left(\sum_t E_{genPV(t)} - \sum_t E_{export(t)}\right)}{\left(\sum_t E_{import(t)} - \sum_t E_{export(t)} + \sum_t E_{genPV(t)}\right)}$$

For self-consumption (SC), representing the ratio of self-consumed energy to total generated energy:

$$Self\ consumption\ (SC)\ \% = \frac{\sum_t E_{PV,used\ (t)}}{\sum_t E_{genPV(t)}} = \frac{\left(\sum_t E_{genPV(t)} - \sum_t E_{export(t)}\right)}{\sum_t E_{genPV(t)}}$$

Where;

$t - hourly\ timestep$

$E_{PV,used\ (t)}$ – PV-generated energy consumed on-site at hour t, either directly or via battery

$E_{genPV(t)}$– total PV-generated energy at hour t

$E_{dem(t)} - total\ building\ energy\ demand\ at\ hour\ t$

$E_{import\ (t)} - electricity\ imported\ from\ the\ grid\ at\ hour\ t$

$E_{export\ (t)} - electricity\ exported\ to\ the\ grid\ at\ hour\ t$

These two metrics are most frequently used by scholars studying grid balances to assess self-sufficiency (Luthander et al. 2019b; Aranda et al. 2025; Simic et al. 2021). All calculations were carried out under the assumption that the grid will accept any surplus energy and meet any energy deficits. All values of self-sufficiency (SS) and self-consumption (SC) were calculated at hourly resolution for the year 2050, with the results aggregated to an annual scale, representing total annual values.

3.4.6. Methods Used for CO2 Equivalent Calculations

GHG emission reduction is an important indicator in environmental studies; therefore, it is widely addressed from various perspectives, considering different factors. As a result, there are several methods, such as:

- Building Energy Simulation, with built-in CO_2 emission calculations directly derived from energy consumption and grid-specific carbon intensity data.
- Life Cycle Carbon Assessment (LCCA), which calculates CO_2 emissions across a building's life cycle.
- Input-Output (IO) Analysis, estimating CO_2 emissions by analysing economic flows within the building sector and linking energy consumption and construction activities to emissions.
- Primary Energy and CO_2 Emission Factor Assessment, calculating CO_2 emissions using primary energy (PE) factors and CO_2 emission factors (Cabeza et al. 2021; Fell et al. 2023).

Although the HEB model has a built-in module to calculate CO_2 emissions, in order to reflect changes in the electricity grid, this study applied the Primary Energy and CO_2 Emission Factor Assessment method. CO_2 emissions were calculated based on annual energy balances of final energy demand for the years 2025 and 2050. The presented approach considers total operational CO_2 emission balances, covering all direct emissions (caused by fossil fuels used on-site), as well as grid- and heat-related emissions. Upstream and downstream processes were not included. The method mentioned by Aranda et al. (2025) was applied using the following steps:

- Final energy was converted to primary energy using Primary Energy (PE) factors.
- CO_2 emissions were calculated using CO_2 emission factors.

- Calculations were carried out for the grid from 2025 and grid 2050 assumptions to give an idea of grid decarbonisation and the range of possible savings, also for 2050, for three settings: without PV, with PV, and PV + battery.

While slightly modified statistical data could be used for the year 2025, numerous assumptions regarding fuel share among households were made for the year 2050, based on EU and Polish policies, targets, and current electrification and decarbonisation trends. Additionally, for a highly electrified scenario using heat pumps, PV, and batteries, on-site combustion is assumed to be zero. Exact assumptions, factors, and input data can be found in the Appendix.

3.5. Limitations of the Research

Even though methodology was established with care of its robustness, several limitations must be acknowledged, concerning modelling assumptions, system boundaries, and aspects that remain outside the scope of this study.

Identified limitations

- Simulations haven't been validated against the existing scenario from KAPE (2024)
- Rebound effects are not taken into consideration.
- Climate zones are fixed at CID2/3; extreme weather volatility is not simulated, and no climate change-related shifts are included.
- Behavioural changes in energy use caused by climate change are not taken into consideration.
- Uncertainties and limitations of the HEB model can be found in Chatterjee et al. (2025).
- No widespread cooling in single-family buildings is assumed by the model.
- No decrease in PV and battery efficiency over time.
- Seasonal hydrogen or V2H storage, while promising, remains outside the scope. No modelling of heat pump (HP) degree of freedom or solar thermal panels (STP).
- No monetary considerations.
- Only operational CO2eq was taken into consideration.

3.6. Ethical Issues

No third parties improperly influence the outcomes of this research for their benefit and it is not funded by an external organisation. I put much emphasis on proper referencing to ensure that I don't take credit for other researchers' work.

3.7. AI Acknowledgements

Since technological progress is advancing with AI, it provides many tools that accelerate and improve the research process. Nevertheless, this support should be acknowledged. In this study, AI tools such as Research Rabbit, Scispace, and Notebook.LM were used to search for relevant literature.

To conclude, all methodology steps outlined in this chapter allow for a comprehensive and replicable evaluation of energy self-sufficiency in Polish single-family buildings in 2050. Furthermore, it presents a framework allowing to answer given research questions and assess the phenomena of energy self-sufficiency from the perspective of climate change, climate resilience, energy security, and energy democracy.

4. RESULTS

The section illustrates numerical outcomes for the Polish single-family building stock across three levels of simulation: annual dynamics from 2025 to 2050, hourly modelling for the year 2050, and scenario-based assessments. It also presents results related to grid flows, energy self-sufficiency, self-consumption, and estimates for CO_2 emissions and energy demand reductions in 2050. Additional charts and comparisons between indicators are included to explore relationships between key variables.

4.1. Building Stock Dynamics Results

Figure 4-1 shows the evolution of total floor area in single-family buildings between 2025 and 2050 under both the Ambitious and Frozen scenarios. In each case, floor area grows from 0.77 billion m² in 2025 to 0.98 billion m² by 2050, although the composition by building vintages visibly changes between scenarios.

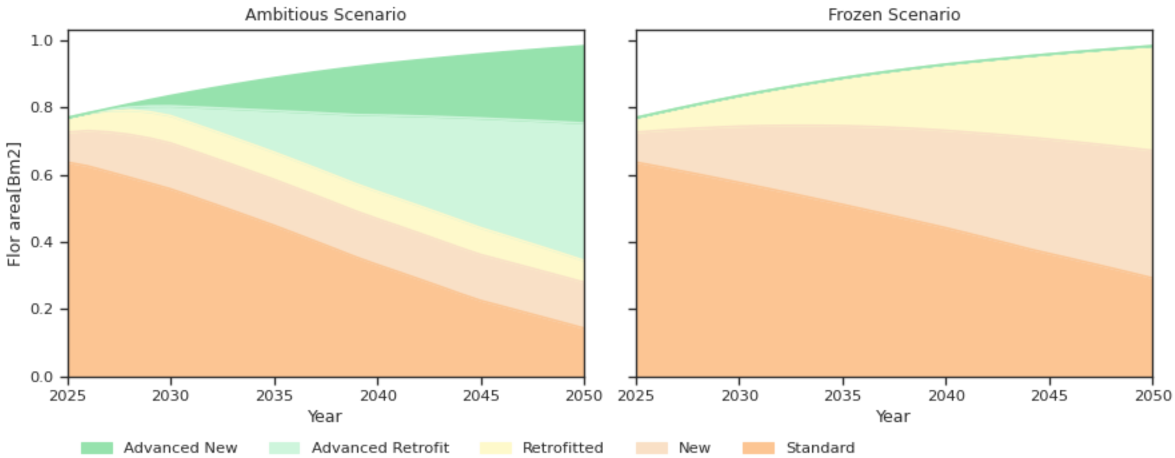

Figure 4-1. Total floor area of single-family buildings in Poland in the years 2025–2050.

To examine how shares of different building vintages change over time, Figures 3-2 and 3-3 present their progression from 2025 to 2050. In the initial year, both scenarios begin with the same distribution: standard buildings account for 82.5%, new buildings 11.6%, and retrofitted buildings 5.6%, however, as the years progress vintages development is varying. In the Ambitious scenario (Figure 4-2) energy-efficient vintages such as Advanced Retrofit and Advanced New show the most significant growth, while the least efficient vintages, Standard and New, gradually decline. The Standard vintage, for instance, drops from 82.8% in 2025 to just 14.5% in 2050, while, Advanced Retrofit grows from 0% to 41.6%, and Advanced New from 0% to 23.6% over the same period.

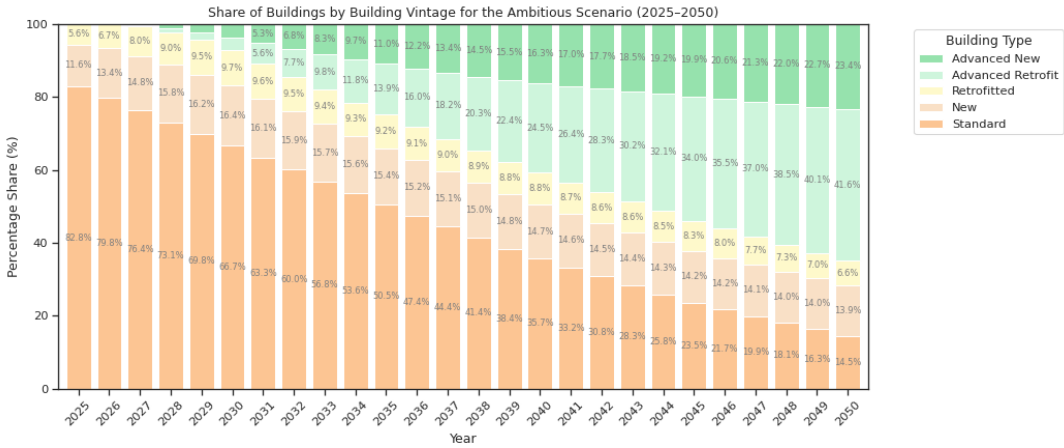

Figure 4-2. Evolution of vintage shares in the Ambitious Scenario in the years 2025–2050.

In contrast, the Frozen Scenario (Figure 4-3) shows no development of the three most efficient vintages. Only the Standard, New, and Retrofitted vintages progress, with noticeable growth in the Retrofitted category from 5.6% to 31.7% and New buildings from 11.6% to 38.6%. In this scenario, the share of Standard buildings declines, from 82.8% in 2025 to 29.7% by 2050.

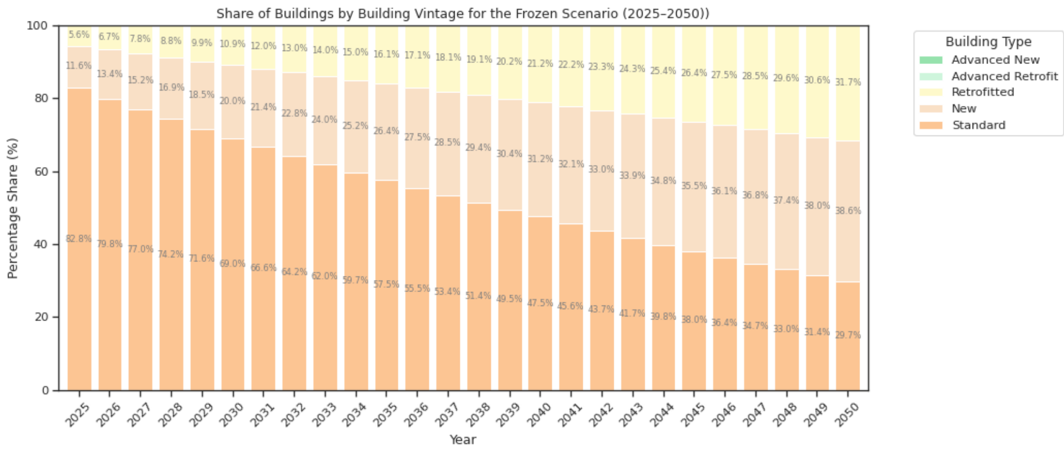

Figure 4-3. Evolution of vintage shares for Frozen Scenario in the years 2025–2050.

4.2. Annual Calculations

Showcasing how building vintages evolve over time allows to understand how total energy demand changes in each scenario, as shown in Figure 4-4. In 2025, both scenarios start with the same total useful energy demand 0.155 PWh across the single-family stock. In the Frozen scenario, demand initially increases and only begins to decline around 2038, eventually reaching 0.152 PWh by 2050. On the other hand, the Ambitious scenario shows a sharp drop in demand starting in 2027, followed by a continuous and almost linear decline from 2030 onwards, reaching 0.114 PWh in 2050.

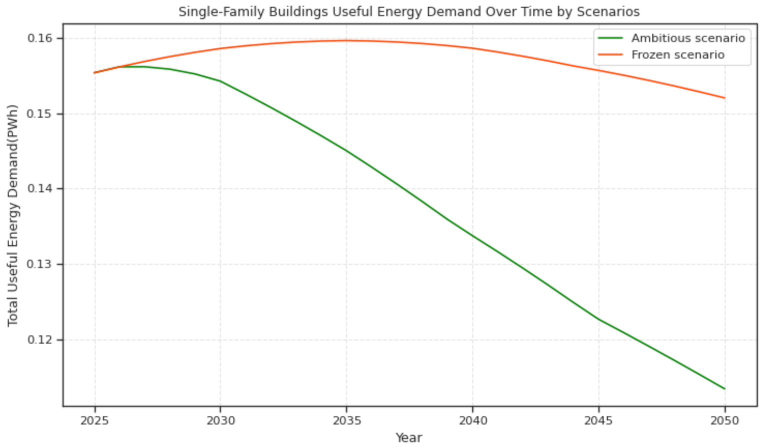

Figure 4-4. Total useful energy demand by in the years 2025–2050.

In the next step, useful energy was converted to final energy, with a conversion factor of 0.44 for 2050, to allow direct comparison with PV generation potential (Figure 4-5). For the Ambitious scenario, final energy demand decreases from 179.6 TWh in 2025 to 49.95 TWh in 2050. This steady decline in the Ambitious scenario is mainly caused by the increasing share of highly efficient vintages. PV generation, linearly interpolated from existing generation potential to matching energy net-zero point in 2050, grows from 9.9 TWh in 2025 to 49.95 TWh by 2050.

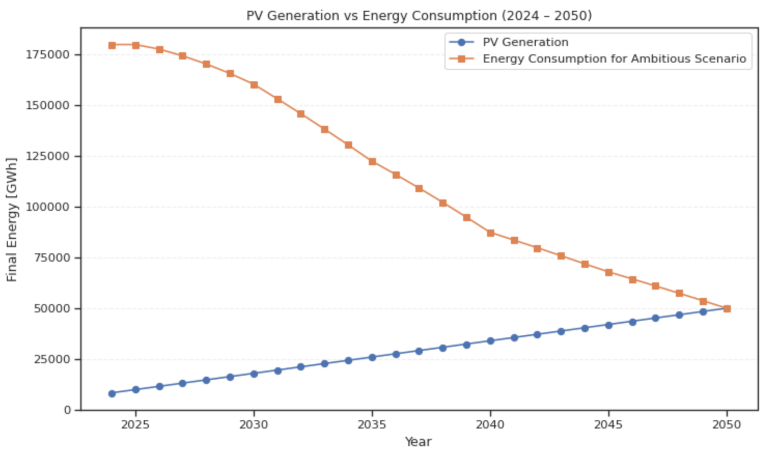

Figure 4-5. PV generation and final energy consumption in the years 2024-2050.

4.3. Hourly Calculations for the Year 2050

In the next step, more detailed daily and hourly resolutions of energy demand were assessed. To evaluate differences between vintages, one representative building was analysed per category, with the assumption that each building has a floor area of 116.3 m². Figure 4-6 shows how each type of energy use, heating, cooling, hot water, and appliances (including cooking and lighting), varied over the year for each vintage type.

Daily appliance use is the same across all vintages, with an average of 5.72 kWh per day per house. Clear seasonality is visible in both heating and cooling demand, as in winter months, heating demand is 14 to 55 times higher than in summer, depending on the building vintage. Conversely, cooling energy peaks appear only during the summer with highest valuest for the most inefficient vintage. It's easy to observe that overall energy demand increases with decreasing building efficiency, however, the seasonal trends and relative distribution of end uses remain broadly similar across vintages, only their proportions differ.

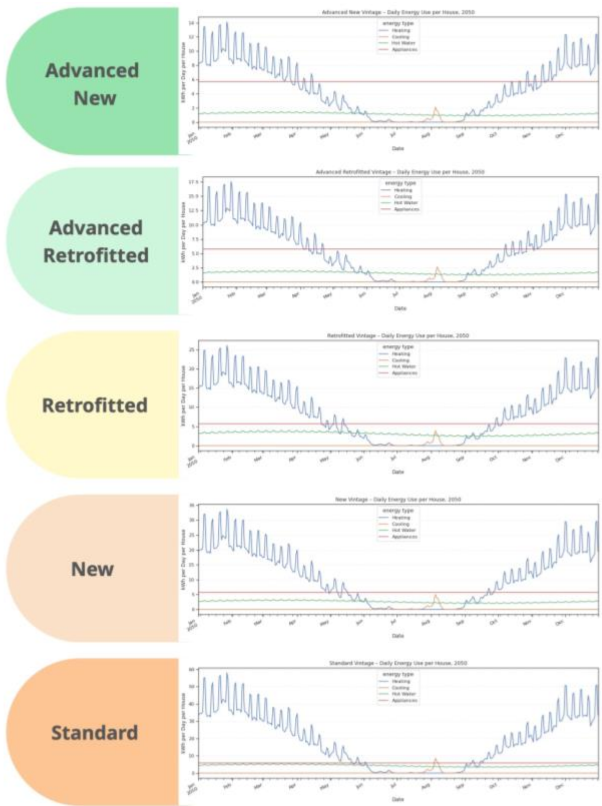

Figure 4-6. Daily results for each vintage disaggregated into heating, cooling, hot water, and appliances (including cooking and lighting) for the year 2050.

As a next step, hourly final energy demand values were calculated for each vintage during representative winter and summer weeks to highlight seasonal behaviour (Figure 4-7). As expected, the most efficient vintages show the lowest energy consumption, in the following order: Advanced New, Advanced Retrofitted, Retrofitted, New, and Standard. The demand curves across all vintages follow the same pattern, aligned with typical occupancy schedules, showing morning and evening peaks, and midday and night-time reductions. During the winter week in hours 120–168, demand rises slightly higher than on other days, reflecting the assumption that occupants spend more time indoors during wintertime weekends.

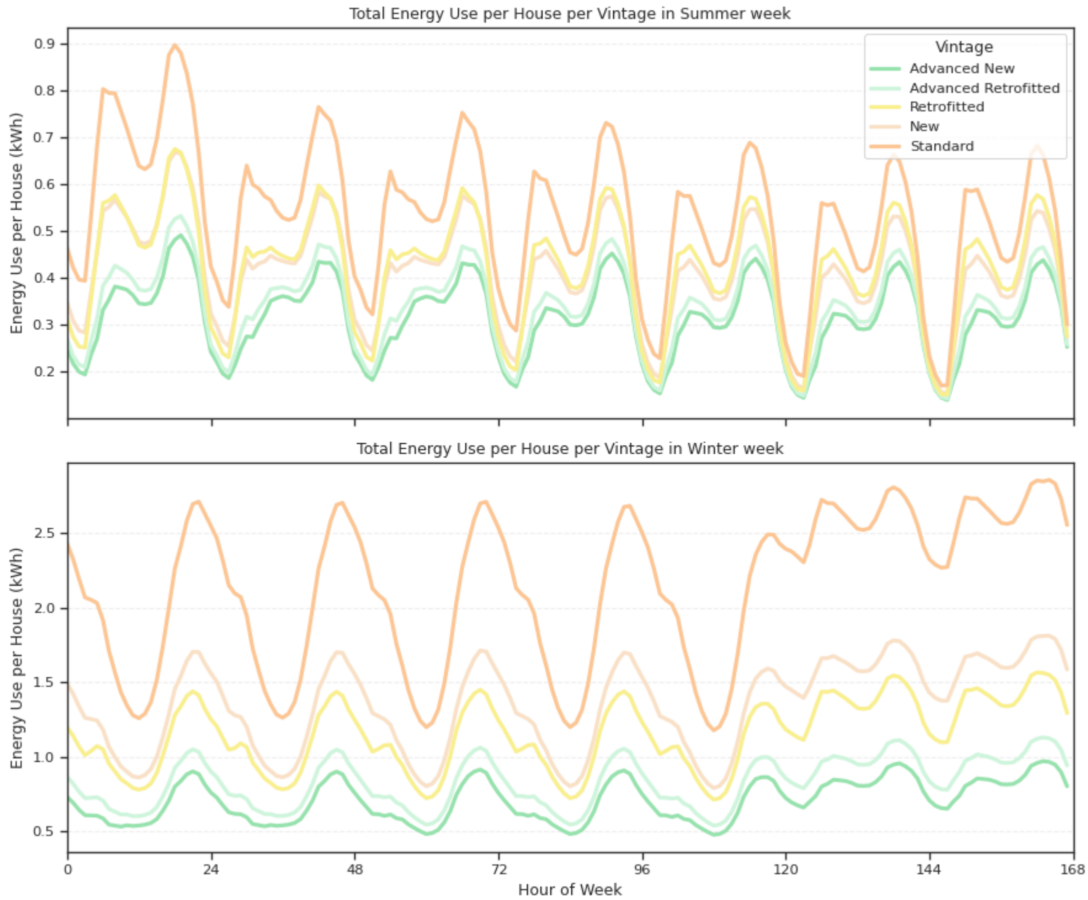

Figure 4-7. Hourly results for total energy demand across all vintages during winter and summer weeks in 2050.

Furthermore, Figure 4-8 presents hourly PV generation across the entire year. Generation peaks during the spring–summer period, reaching up to 2.7 kWh per day, while winter production falls to around 1 kWh.

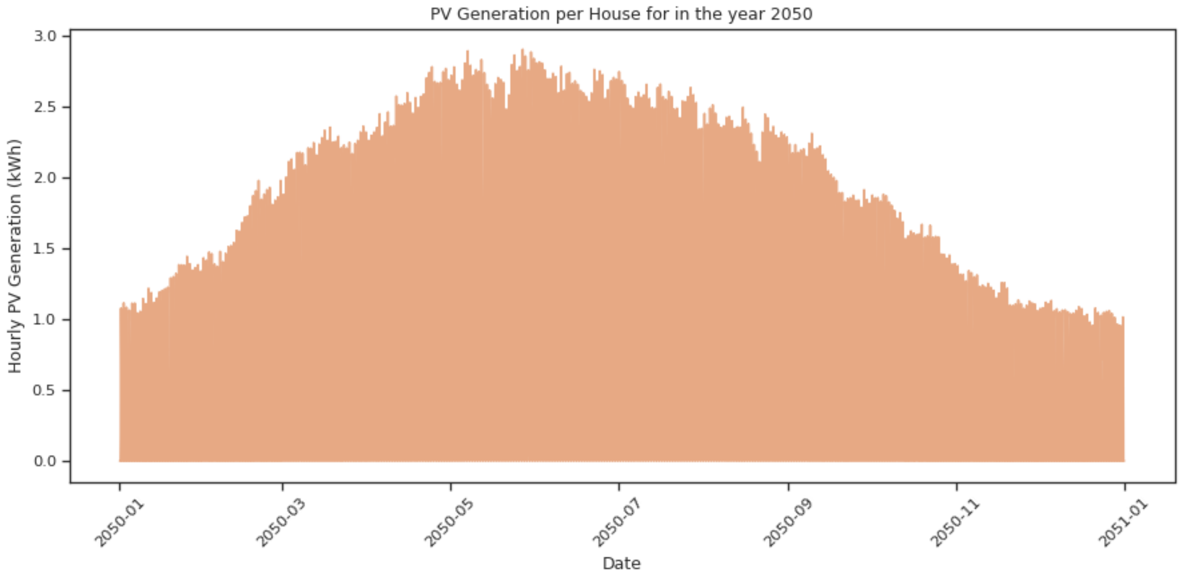

Figure 4-8. Hourly PV generation for an average house throughout the year 2050.

To explore this more precisely, Figure 4-9 presents detailed hourly PV generation for selected winter and summer weeks. Daily production shows sharp midday peaks dropping to zero at night, clearly reflecting the solar insolation pattern. A significant seasonal gap is observed, with winter yields approximately 2.5 times lower than summer, highlighting significant yields seasonality.

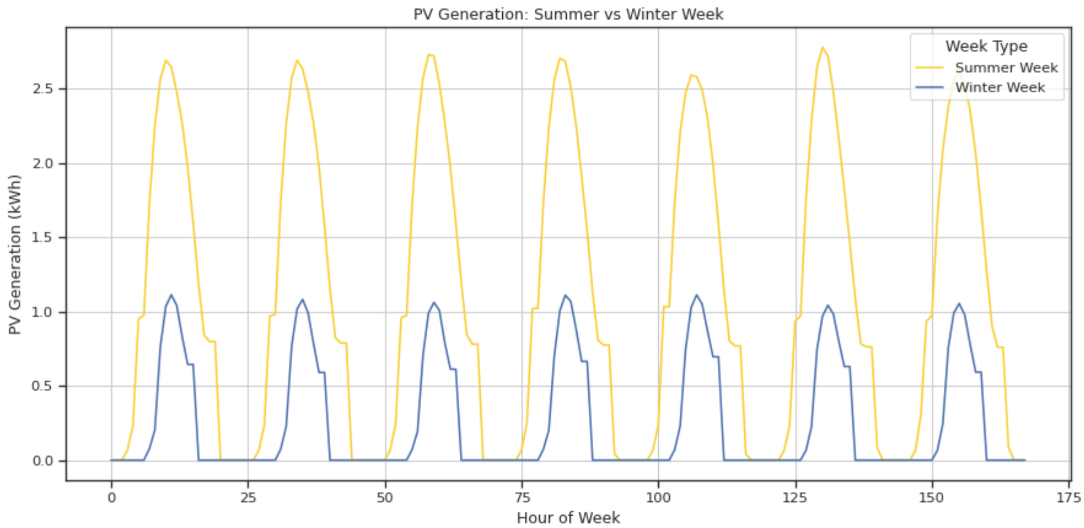

Figure 4-9. Hourly PV generation for an average house during representative winter and summer weeks.

Following steps of the research design, battery state of charge (SOC) calculations for the year 2050 were carried out for each vintage (Figure 4-10). While the overall SOC distribution follows a similar pattern across vintages, differences appear in the timing of full charges and discharges, as more efficient buildings keep their batteries operational throughout most of the year. For instance, the Standard building has roughly 1500 hours when the battery remains unused, whereas in the Advanced New building, the battery keeps operating even during winter, reaching levels up to 2.2 kWh. Moreover, the battery in Advanced New reaches full capacity from early March through mid-October, while for the Standard vintage this window is significantly shorter and ranging only from late April to mid-September, giving a difference of nearly three months.

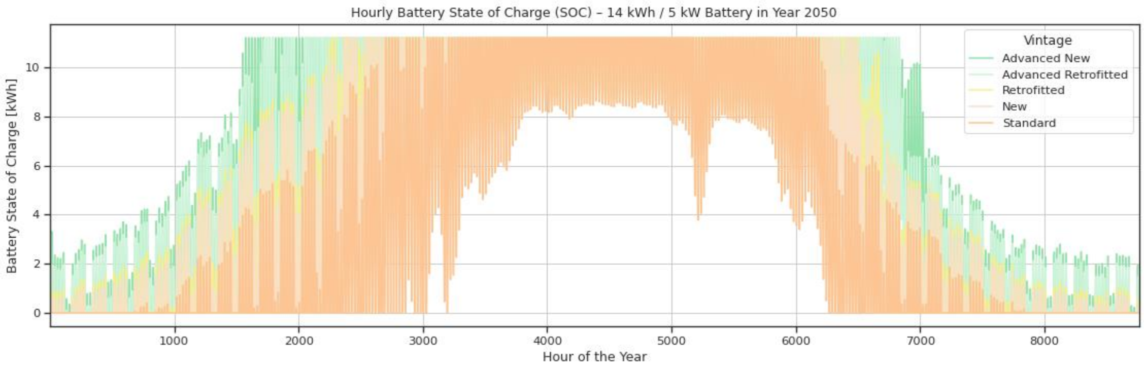

Figure 4-10. Hourly battery state of charge across all vintages for the year 2050.

To better capture mismatches between energy demand and PV generation across vintages, energy evolution graphs for 2050 are presented in Figure 4-10, showing hourly energy demand, PV generation, and battery SOC for each vintage. In more efficient buildings like Advanced New and Advanced Retrofitted, PV generation aligns well with consumption and the battery is active year-round. In contrast, the Standard vintage shows a noticeable mismatch, with PV generation covering only a fraction of demand, particularly during winter, and the battery inactive throughout the visible part of the year.

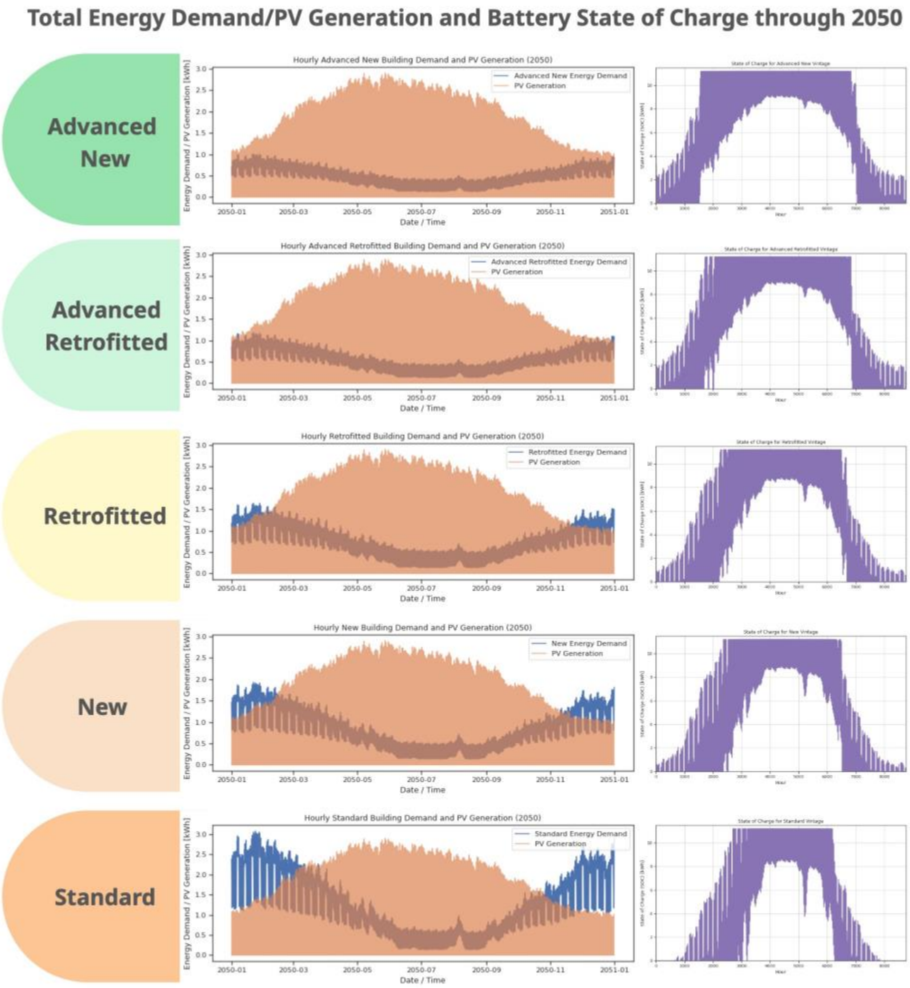

Figure 4-11. Hourly energy demand, PV generation, and battery SOC across all vintages in 2050.

To further explore energy flow dynamics, Figure 4-11 presents representative weeks for winter, summer, and spring in 2050. Each plot shows hourly total energy demand, PV generation, and battery SOC for all vintages. Spring is used to represent transitional months, as autumn results show similar trends. In the Advanced New vintage, even during unfavourable conditions, PV generation typically meets and slightly exceeds demand, allowing battery use. As efficiency decreases, so does the share of demand met by PV in transitional and winter weeks. In the Standard vintage, midday PV peaks rarely exceed demand, therefore battery is not used at all, or used minimally. During summer, heating loads are low, and hourly profiles across vintages look similar and PV output significantly surpasses demand, and batteries remain fully charged for most of the time, with minimum levels rarely dipping below 9 kWh. The spring period highlights the strongest differences between vintages as in efficient buildings, batteries effectively balance mismatches, whereas in inefficient ones, battery use is minimal.

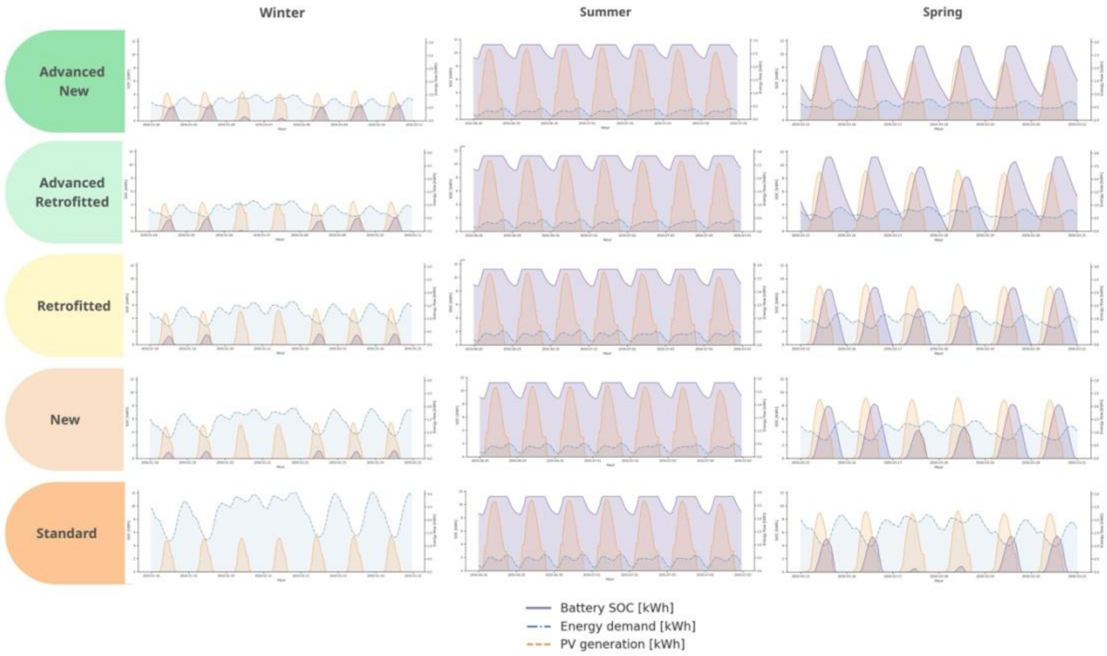

Figure 4-12. Representative winter, summer, and spring weeks of 2050 for each vintage, showing hourly energy demand, PV generation, and battery SOC.

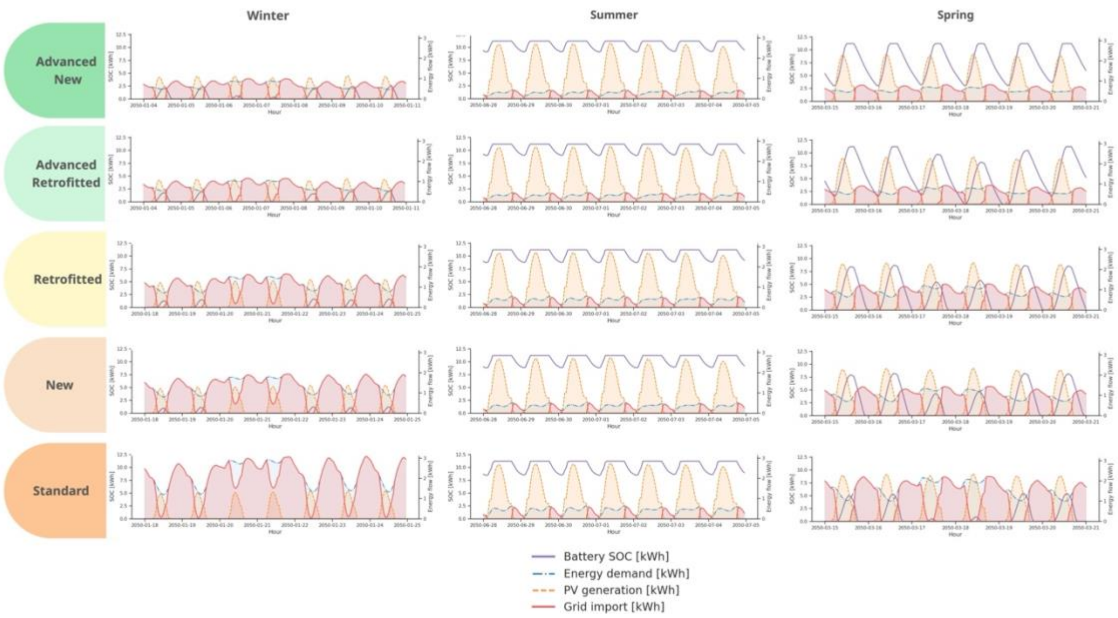

Figure 4-13. Representative winter, summer, and spring weeks of 2050 for each vintage, showing hourly energy demand, PV generation, battery SOC and energy imports.

Building on the previous analysis, Figure 4-13 introduces hourly grid energy import across these same periods, highlighting when local generation and storage cannot meet demand. The most interesting observations coming from the graphs lie in the contrast in total imports between vintages, particularly during winter and the transitional seasons. While highly efficient buildings import energy only in several hours a day and in low amounts, less efficient ones depend heavily on the grid, both in timing and magnitude of import.

4.5. Energy Self-Sufficiency Calculations

Table 4-1 presents the core results of energy balance calculations for each building vintage for the year 2050 like final energy demand, photovoltaic (PV) generation, energy imported and exported to the grid, and self-sufficiency and self-consumption rates, both for systems with and without battery storage. The total final energy demand varies from 4204 kWh for Advanced New to 10615 kWh for Standard, showcasing how the energy efficiency translates to overall energy demand.

PV generation is fixed at 5911 kWh annually for all vintages, simulating equal yields, without consideration of needed rooftop area or irradiation potential, allowing for a direct comparison of energy balances. Annual imports drop significantly with battery application, from 2383 kWh to 973 MWh for Advanced New, and from 7404 MWh to 6149 MWh for Standard, showing the energy time shifting impact of batteries especially in building with better energy efficiency. Similarly, exports also decrease when the battery is introduced, as more PV electricity is self-consumed.

The net import/export values represent the system annual energy balance, where negative values are reflected as plus energy houses, exporting annually more than they import. Gains on net balance after adding battery remain the similar in range 27-31 kWh for all vintages.

Self-sufficiency rates, representing the share of demand covered by PV (and PV + battery) rise from 30.3% (PV only) to 42.1% (PV + battery) in Standard vintage building, and from 43.3% to 76.9% in Advanced New vintage building, showing a battery gain up to 33.6 percentage points. Similar trend is observed for self-consumption rates, which grow from 30.8% to 54.7% for Advanced New and from 54.3% to 75% for Standard, emphasising the role of batteries in improving the share of energy used on site. Additionally, self-consumption gains after adding battery seem to grow as energy demand is decreasing, except for Advanced New, having lower gain than the Advanced Retrofitted building.

Table 4-1. Annual total values for self-sufficiency, self-consumption, energy import and export for a single-family house with PV and with PV+battery with different energy demands in 2050.

	Total demand [kWh]	PV generation [kWh]	Import [kWh]		Export [kWh]		Net import/export [kWh]			Self-sufficiency [%]			Self-consumption [%]		
			PV	PV+battery	PV	PV+battery	PV	PV+battery	Gain [kWh]	PV	PV+battery	Gain [p.p.]	PV	PV+battery	Gain [p.p.]
Great. Gave me Advanced New	4204	5911	2383	973	4090	2649	-1707	-1676	31	43,3	76,9	33,6	30,8	54,7	23,9
Advanced Retrofitted	4766	5911	2758	1331	3903	2444	-1145	-1113	32	42,1	72,1	30	34	58,1	24,1
Retrofitted	6351	5911	3841	2435	3400	1963	441	471	30	39,5	61,7	22,2	42,5	66,3	23,8
New	7073	5911	4501	3121	3339	1928	1163	1193	30	36,4	55,9	19,5	43,5	66,9	23,4
Standard	10615	5911	7404	6149	2700	1418	4704	4731	27	30,3	42,1	11,8	54,3	75	20,7

To further investigate the relation between building energy demand and its level of energy independence, Figure 4-14 illustrates how self-sufficiency varies as a function of total annual energy demand per building, shown separately for systems with and without battery storage. As presented in Figure 4-14, self-sufficiency reveals a negative correlation with total energy demand. For buildings equipped with PV systems only, self-sufficiency levels start at 43.3% for the most efficient vintage and drop gradually to 30.3% for the least efficient one. When battery storage is added, self-sufficiency improves significantly across all vintages, ranging from 76.9% for Advanced New to 42.1% for Standard, underlining the magnifying role of batteries in reducing grid dependency. The gap between the two curves also increases with lower energy demand, showing that batteries become increasingly effective at lowering grid reliance in more efficient buildings.

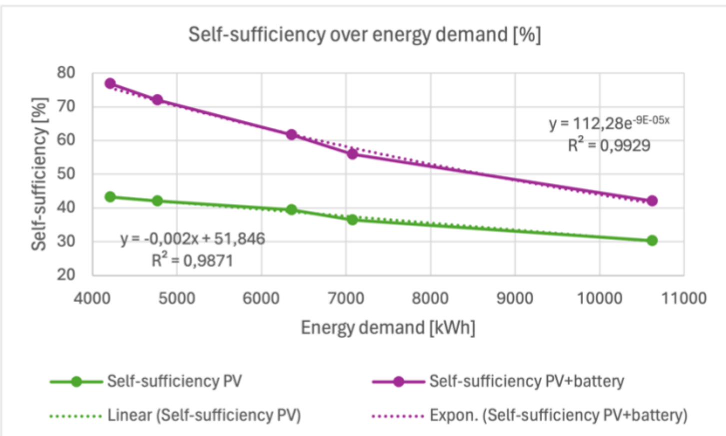

Figure 4-14. Energy self-sufficiency levels over energy demand in 2050 for PV and PV+battery systems..

To better understand how energy self-sufficiency varies over time, Figure 4-15 visualises the hour-by-hour energy balance for a typical house in each building vintage through all 8,760 hours of the year 2050. The heat diagrams are split into two columns: the left side shows buildings powered only by photovoltaic panels (PV), while the right side also takes into consideration battery storage. Different colours represent how energy needs are met at each hour, with green representing energy from solar panels, purple from battery storage, and red from the grid. Starting with the PV-only diagram, it is noticeable that only the most efficient buildings (like Advanced New and Advanced Retrofitted) manage to run on solar power through all seasons of the year, whereas the least efficient building vintages, like New and Standard, rely fully on grid imports in winter (red). After adding battery storage, the picture changes noticeably. Battery usage (purple) appears across the timeline, especially in transitional seasons, showing how batteries step in to cover demand when there is no solar irradiation. There is a significant increase in energy self-sufficiency hours compared to the system based solely on PV panels, with visibly greater shares in more efficient buildings. This comparison again clearly shows that adding storage helps to achieve higher levels of energy self-sufficiency and the benefits are much greater in energy-efficient buildings.

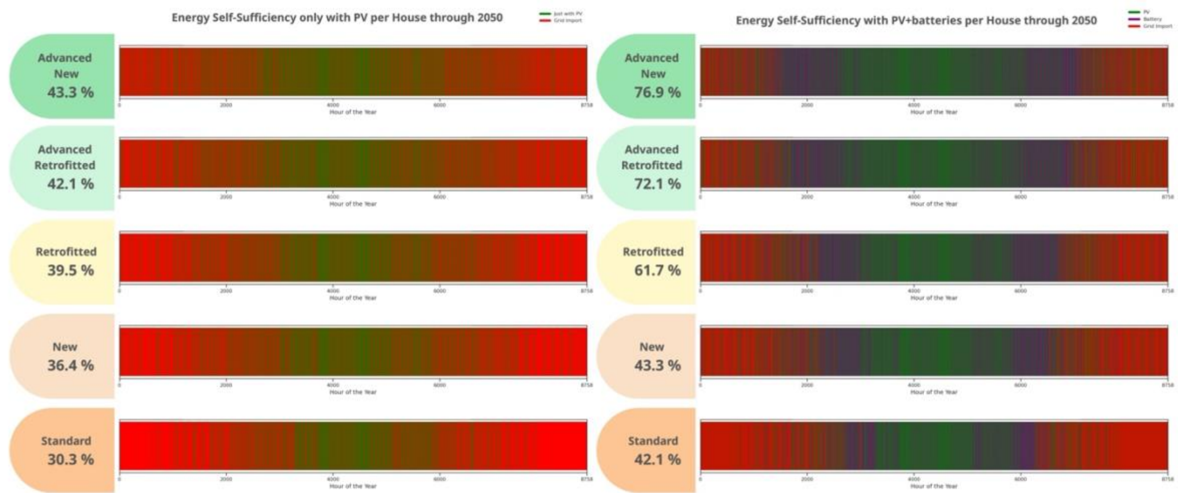

Figure 4-15. Hourly energy self-sufficiency with PV installation (left) and PV+battery installation (right) through year 2050.

Furthermore, Figure 4-16 presents the relationship between self-sufficiency and self-consumption in 2050 for PV-only systems and for PV+storage system. For both systems there is a clear negative relationship between self-sufficiency and self-consumption. The diagram clearly shows that the addition of battery storage leads to simultaneous improvements in both self-sufficiency and self-consumption. Interestingly, PV+battery system has steeper rise in self-sufficiency with decreasing self-consumption, which is caused by the battery's ability to shift excess solar energy to match demand across time, especially in low-demand buildings where a greater share of needs can be met from stored PV. The overall trends of self-consumption is highest for the least effective vintage buildings, since they tend to consume a greater portion of their own PV generation on-site due to higher and more continuous demand.

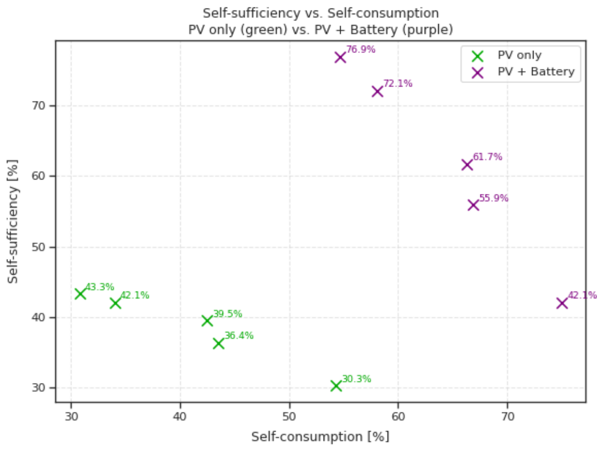

Figure 4-16. Relationship between energy self-sufficiency and enrgy self-consumption in 2050 for PV and PV+battery systems

Building on this, Figure 4-17 illustrates the gain in self-sufficiency measured in percentage points (p.p.) after introducing battery storage, plotted against total annual energy demand. The graph clearly shows a declining trend as the higher is energy demand, the smaller the benefit from battery storage in terms of self-sufficiency gain. For the most energy-efficient buildings, battery storage provides a self-sufficiency boost of over 35 percentage points, while for the least efficient, only around 12 p.p.

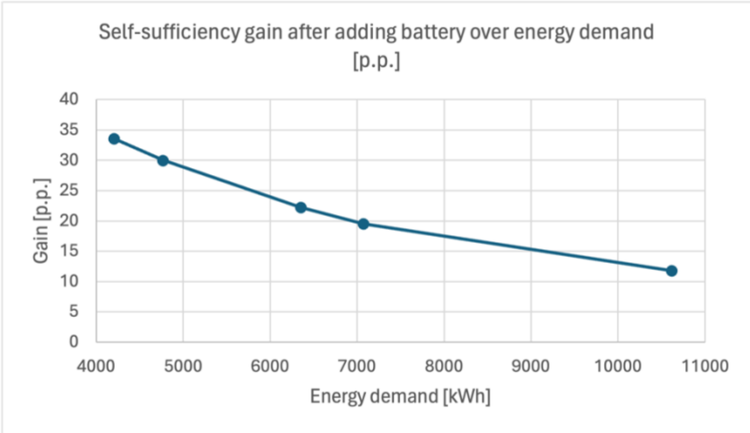

Figure 4-17. Self-sufficiency gain after adding battery to PV system over energy demand for 2050.

Furthermore, to explore how the integration of PV affects building energy performance, Table 4-2 presents a detailed comparison between energy demand, solar generation, and energy classification for each building vintage with two scenarios: without solar and with solar integration. Without PV, all buildings fall into lower energy classes ranging from class D (Advanced New) to class G (Retrofitted, New, and Standard). Once PV is added energy energy-efficient vintages such as Advanced New and Advanced Retrofitted achieve negative net final and primary energy balances per m², which upgrades them to the A+ energy class. Retrofitted and New vintages reach class A. Only the least efficient vintage, Standard, remains in class E, even with PV, indicating that the high energy demand can't be fully offset with PV. These results underline that while solar generation can drastically improve the energy classification of a building, achieving top performance relies strongly on fundamental demand reduction.

Table 4-2. Energy Performance of different vintage buildings in 2050.

	Total demand [kWh]	PV generation [kWh]	no solar			with solar			
			Total final demand per km2 [kWh]	Primary energy per m2 [kWh]	Energy class	Final Energy per building [kWh]	Primary energy per m2 [kWh]	Final energy per m2 [kWh]	Energy class
Advanced New	4204	5911	37,54	102,4	D	-1707	-15,24	-41,6	A+
Advanced Retrofitted	4766	5911	42,55	116,1	E	-1145	-10,22	-27,9	A+
Retrofitted	6351	5911	56,71	154,7	G	440	3,93	10,7	A
New	7073	5911	63,15	172,2	G	1162	10,38	28,3	A
Standard	10615	5911	94,78	258,5	G	4704	42,00	114,5	E

4.6. CO2 and Energy Demand Reduction Calculations

To assess the environmental and energy security impact of highly self-sufficient single-family buildings in Poland, Tables 4-3 and 4-4 present total energy demand and CO_2 emissions results for various scenarios in 2050, using both the 2025 and 2050 national energy mix assumptions. Their visual representation is shown in Figure 4-18.

Two values of the grid were used to look at the results from the perspective of the current fossil-fuel-dominated energy mix and its more decarbonised value, and therefore present the range of possible savings. Among the values presented in those tables are total useful and final energy demand, total CO_2 emissions, per-building CO_2 emissions, and relative savings compared to both the initial 2025 state and the Frozen 2050 scenario.

Under the 2025 energy mix (Table 4-3), emissions in the Frozen 2050 scenario remain high (66.7 $MtCO_2$), with only marginal reductions from the 2025 baseline (68.2 $MtCO_2$). In contrast, the Ambitious 2050 scenario with no PV already achieves a notable reduction to 49.8 $MtCO_2$. Once PV is introduced to the Ambitious scenario, emissions drop drastically to just 0.03 $MtCO_2$ with PV and 0.02 $MtCO_2$ with PV + battery. This represents a 99.95% reduction in CO_2 per building compared to the Frozen scenario without PV.

When the 2050 energy mix is evaluated (Table 4-4), total CO_2 emissions drop across all scenarios due to decarbonisation of the grid. Still, the difference between approaches remains significant, as the Frozen 2050 scenario emits 4.1 $MtCO_2$, while Ambitious (no PV) reduces this to 3.1 $MtCO_2$. The addition of PV brings emissions close to zero (0.002 $MtCO_2$), with PV + battery lowering it even further to just 0.001 $MtCO_2$, which can be interpreted as nearly complete decarbonisation at the household level.

Additionally, evaluation of total useful energy demand shows that Ambitious 2050 (no PV) sets needs at 113 TWh, while Frozen (no PV) reaches 152 TWh, showing a significant difference in total needed energy for the single-family building stock in 2050. Further, after adding PV and PV + battery, total useful energy demand for Ambitious can drop to 0.07 TWh and 0.04 TWh, respectively.

Table 4-3. Energy demand and CO2 emissions savings in 2050 with energy mix from 2025

Scenarios	Total useful net energy demand [TWh]	Total final net energy demand [TWh]	Total CO2 [MtCO2]	CO2/building [kgCO2]	CO2/building saving relative to Initial state 2025 [kgCO2]	CO2/building saving relative to Frozen 2050 [kgCO2]
Initial state 2025	155	180	68,2	10310	-	-
Frozen 2050 (little retrofits, no PV)	152	176	66,7	10089	0,51	-
Ambitious 2050 (no PV)	114	131	49,8	7535	0,58	0,57
Ambitious 2050 (PV)	0,07	0,08	0,03	4,7	0,9994	0,9995
Ambitious 2050 (PV+battery)	0,04	0,05	0,02	2,9	0,9997	0,9997

Table 4-4. Energy demand and CO2 emissions savings in 2050 with energy mix from 2050.

Scenarios	Total useful net energy demand [TWh]	Total final net energy demand [TWh]	Total CO2 [MtCO2]	CO2/building [kgCO2]	CO2/building saving relative to Frozen 2050 [kgCO2]
Frozen 2050 (little retrofits, no PV)	152	67	4,1	484	-
Ambitious 2050 (no PV)	114	50	3,1	362	0,57245
Ambitious 2050 (PV)	0,07	0,03	0,002	0,22	0,99954
Ambitious 2050 (PV+battery)	0,04	0,02	0,001	0,14	0,99971

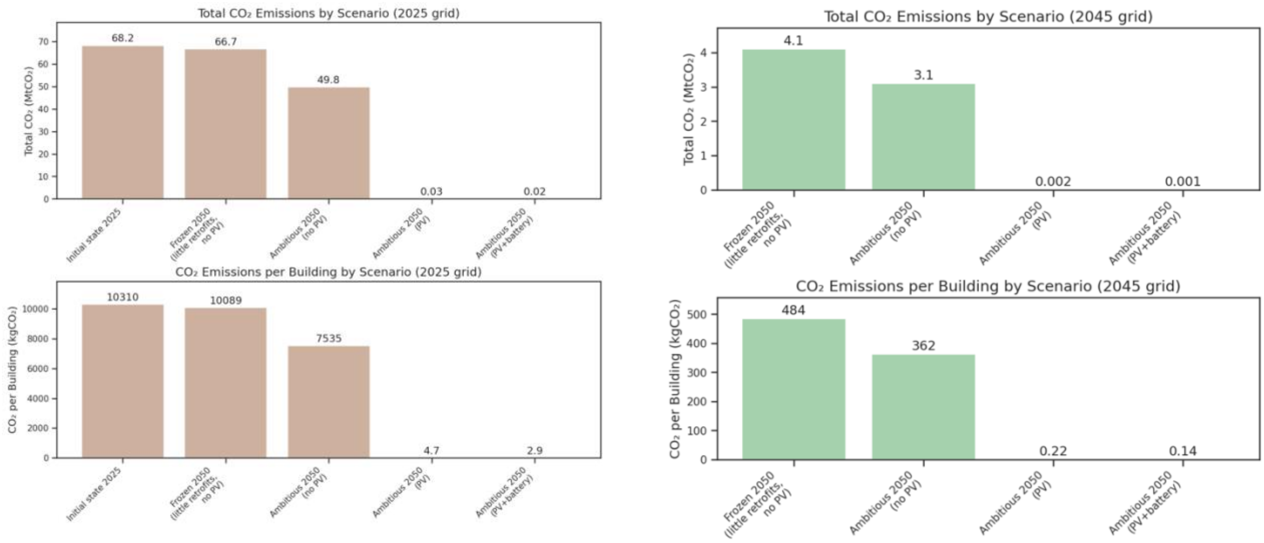

Figure 4-18. Total CO2 emissions for the year 2050 for different scenarios with 2025 and 2025 energy mix.

While assessments of total CO_2 emissions or energy demand might be useful for the evaluation of system needs and environmental impact of each scenario, when comparing them it is also insightful to examine the gains they can deliver. Therefore, Table 4-5 presents a summary of energy and CO_2 emission reductions in Ambitious 2050, based on both the 2025 and 2050 energy mix assumptions, compared to the Frozen scenario (in variants: no PV, with PV, and with PV + battery). This assessment highlights how the combination of demand-side efficiency and on-site generation contributes to the national-level impact in terms of overall CO_2 and energy demand reduction.

In terms of final energy reduction, the Ambitious (no PV) scenario gives a saving of 45 TWh under the 2025 energy mix, and 17 TWh under the more efficient 2050 mix. When PV and storage are included, the energy reduction jumps dramatically to 176 TWh, reflecting the elimination of grid-supplied electricity through on-site generation. On the emissions side, the Ambitious (no PV) scenario leads to a reduction of 2.55 $MtCO_2$ in 2050 under the 2025 energy mix, and grows to over 10 $MtCO_2$ after adding PV or PV + battery. When the grid is decarbonised (2050 mix), Ambitious (no PV) gives a much smaller CO_2 reduction of 1 $MtCO_2$, reaching up to 4.1 $MtCO_2$ after adding PV or PV + battery. A visualisation of the data presented in Table 3-5 is shown in Figures 4-19 and 4-20.

Table 4-5. Energy demand and CO2 emissions reduction in 2050 compared to the Frozen Scenario in 2050.

	Useful energy 2050 [TWh]	Final energy reduction in 2050 with energy mix from 2025 [TWh]	Final energy reduction in 2050 with energy mix from 2050 [TWh]	Total CO2 reduction in 2050 with energy mix from 2025 [MtCO2]	Total CO2 reduction in 2050 with energy mix from 2050 [MtCO2]
Ambitious 2050 (no PV)	38	45	17	2554	1
Ambitious 2050 (PV)	152	176	67	10089	4,1
Ambitious 2050 (PV+battery)	152	176	67	10085	4,1

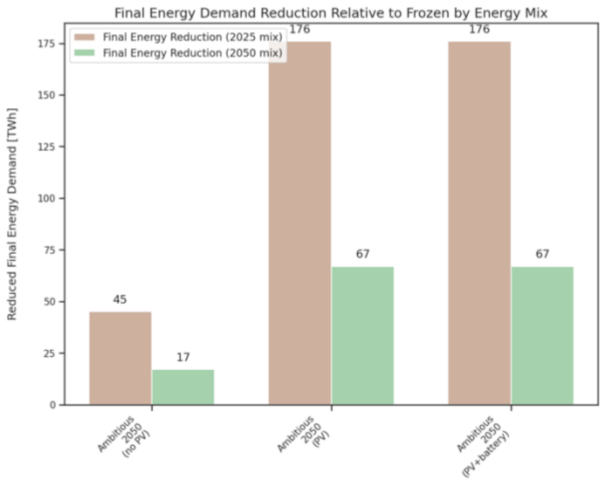

Figure 4-19. Final energy demand reduction relative to frozen scenario for year 2050 for different scenarios with 2025 and 2025 energy mix.

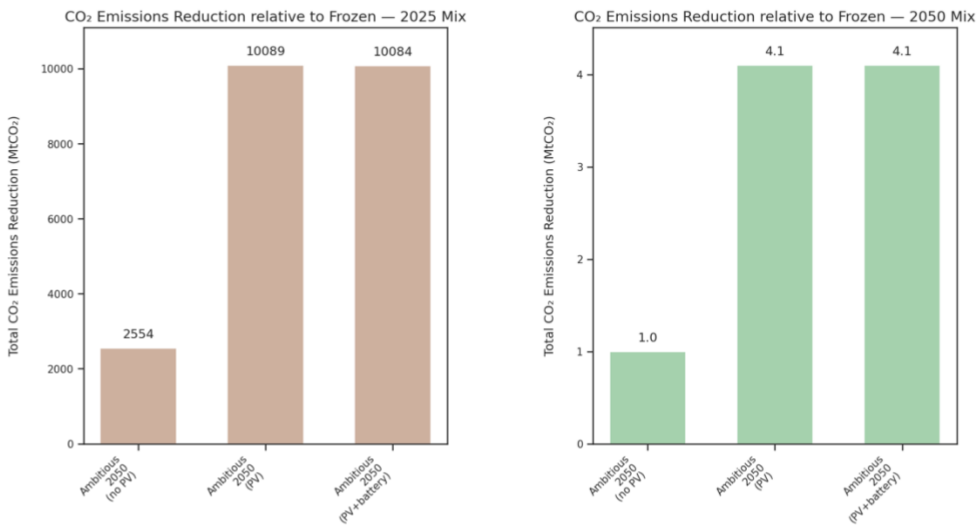

Figure 4-20. CO2 reduction relative to frozen for the year 2050 for different scenarios with 2025 and 2025 energy mix.

This chapter brings together all results, allowing assessment of energy performance, energy self-sufficiency, and energy demand and CO_2 emissions reduction in Polish single-family buildings. Analysing the outcomes demonstrates that thermomodernisation, along with distributed PV and battery systems, can significantly change households' relationship with the grid in Poland, making them more energy self-sufficient. Additionally, while efficiency measures alone decrease environmental impact, adding on-site generation has, in some cases, up to four times stronger impact on GHG reduction, which underlines the importance of on-site RES. Adding batteries to PV also shows that they not only help achieve higher levels of energy self-sufficiency, but also increase the use of on-site produced energy. Furthermore, scenario comparisons confirm that the Ambitious 2050 pathway with PV and storage outperforms all alternatives, ensuring near-zero emissions at the household level, even under current grid conditions.

To summarise, the outcomes of this chapter prove that an integrated approach of demand-side and supply-side measures, which prioritises efficiency, can enhance the decarbonisation potential of the single-family building sector by 2050.

5. DISCUSSION

Following European Union strategies, buildings will significantly lower their energy demand, and each new house will need to install solar panels, which pushes households to be more energy self-reliant. Yet, it has not been investigated how this could be developed on a national scale in Poland. Following plans of thermomodernisation and assuming that each household is equipped with the most common solar installation and battery, this study fills this gap by investigating possible levels of energy self-sufficiency in 2050.The findings show that under an ambitious retrofit scenario, significant levels of self-sufficiency can be achieved, particularly in more energy-efficient buildings, with considerable benefits for climate mitigation, resilience, energy security, and energy democracy.

Energy Self-Sufficiency Potential (RQ1)

RQ1. What level of energy self-sufficiency can single-family buildings in Poland achieve by 2050 through retrofitting, rooftop photovoltaics, and battery storage?

The first research question aims to evaluate what level of energy self-sufficiency (SS) Polish single-family buildings, undergoing thermomodernisation, will be able to achieve in 2050 when equipped with rooftop solar and battery storage. Hypothesis H1 assumed that self-sufficiency could be achieved even at the level of 70–80%. To test this, the whole building stock was divided into five different efficiency levels (from the least efficient "Standard" to the most efficient "Advanced New") and then simulated under identical photovoltaic (PV) and battery specifications in hourly resolution through the year 2050.

Evaluation of achieved levels of energy self-sufficiency under the Ambitious scenario ranges from 77% to 42%, depending on the building vintage, as presented in Figure 5-1.

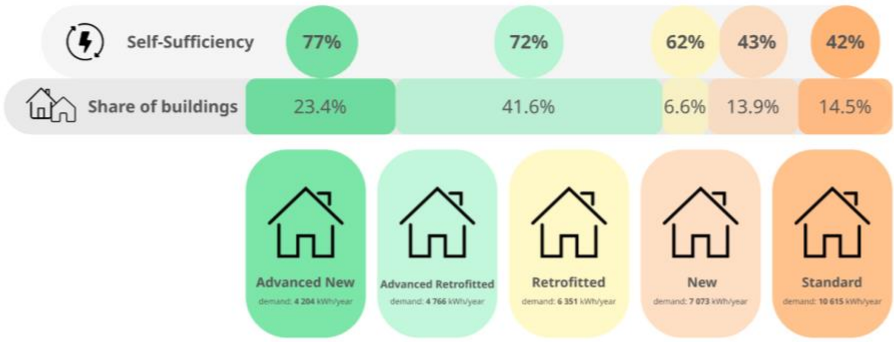

Figure 5-1. Levels of energy self-sufficiency and share of buildings in the total building stock in 2050 among building vintages.

The results show that the most efficient homes, Advanced New, which consist of 23.4% of the total building stock in 2050, can achieve about 77% annual self-sufficiency with the PV-battery system. Similarly, the second most efficient vintage building, Advanced Retrofitted (41.6% share in 2050), could also achieve a relatively high self-sufficiency level, reaching 72%. In contrast, high energy demand houses (Standard, which consist of 14.5% of the total building stock) only reach around 42% under the same conditions. The moderate efficiency buildings, Retrofitted and New, reach SS levels of 62% and 43% respectively. As a result, the 70–80% hypothesised range target was achieved only in the best-performing buildings, which together represent 65% of the building stock. The 77 % peak self-sufficiency achieved in Ambitious scenario closely mirrors the 75–80 % technical ceiling reported for Swedish detached houses by Luthander et al. (2019).

For systems with PV only, energy self-sufficiency levels vary from 30.3% for the Standard building to 43.3% for Advanced New, showing that without the battery, energy self-sufficiency between the least and most efficient buildings varies by only 13 percentage points. In fact, adding energy storage makes a real difference between vintages, as it boosts energy self-sufficiency of the Advanced New building by 33.6 percentage points, but only 11.8 for a Standard building.

When comparing these findings to expectations and prior studies, the overall picture is consistent but more optimistic in some regards. Existing literature suggests that individual buildings can achieve limited self-sufficiency around 20–40% for PV alone, which these results confirm for less efficient houses (Benalcazar, Kalka, and Kamiński 2024; Moshövel et al. 2015). Furthermore, studies indicate that introducing energy storage elevates SS levels by even 20 percentage points, which was confirmed for vintages like Retrofitted or New, but was much higher for Advanced New and Advanced Retrofitted, where those gains were equal to or higher than 30 percentage points (Luthander et al. 2019; Aranda et al. 2025).

On a bigger scale, the nationally aggregated self-sufficiency potential level (weighted SS value) across the entire single-family building stock in 2050 under the Ambitious scenario with PV is approximately 64.4%. This can be interpreted as two-thirds of buildings' real-time (hourly) demand being met by locally produced energy from rooftop PV, without relying on grid imports. This represents a paradigm shift in energy distribution and ownership, where utilities are no longer the default source of electricity.

At the same time, it is important to note that this study assumes all single-family buildings collectively produce as much energy as they consume. Despite this ambitious scenario, approximately 35% of the total energy demand still requires grid balancing, highlighting the continued need for flexible infrastructure and systemic coordination.

Additionally, it is important to point out that the research was carried out using the current state of technology for solar panels and PV systems, whose efficiency and performance may improve over time, potentially leading to higher self-sufficiency levels.

Relationship Between Energy Demand and Self-Sufficiency and Its Impact on Climate Resilience and Energy Democracy (RQ2)

RQ2. How does annual energy demand in single-family buildings influence energy self-sufficiency, and what are the implications for household climate resilience and energy democracy?

The second research question examines how a building's annual energy demand affects its energy self-sufficiency and the implications for climate resilience and energy democracy. Hypothesis H2 stated that reducing demand with retrofitting would significantly increase self-sufficiency. To test that, the same PV–storage systems were compared for five representative buildings with different demand (vintages). The model outcomes support H2, as there is a strong inverse correlation between building energy demand and self-sufficiency. For cases with just PV, self-sufficiency rises from about 30% in the least efficient home (Standard) to about 43% in the most efficient (Advanced New) (see Table 3-1). After adding batteries, these figures jump to roughly 42% and 77%, respectively. In effect, each demand reduction directly translates into higher autonomy.

Analysing Figure 4-14 shows that there is a trend between self-sufficiency level and energy demand, and they vary for PV and PV+battery systems. For systems with only PV, each annual energy demand decrease of 1000 kWh/year corresponds to ~2 percentage points gain in self-sufficiency, with the linear trend ($R^2 = 0.987$). After adding a battery to the system, the benefits are most amplified at lower demands: a drop in energy demand from 5,000 to 4,000 kWh/year gives a gain of ~6.7 percentage points, and from 10,000 to 9,000 kWh/year, a gain of ~4.3 percentage points. This underlines the importance of retrofitting in maximising the benefits of on-site generation and storage, as the trend between self-sufficiency and energy demand becomes exponential ($R^2 = 0.993$). The disproportionate self-sufficiency gains at lower energy demand levels stem mostly from spring and autumn conditions, when low consumption aligns with produced solar energy, allowing batteries to operate at high effectiveness by capturing and redistributing surplus energy through the day (see Spring Diagram in Figure 4-12 and Figure 4-13). It is also important to acknowledge that trends were established for a limited number of five data points and should be treated as a preliminary observation.

This demand–related self-sufficiency link has practical implications for resilience and democracy. From a resilience perspective, a low-demand home can run on its own solar and storage for far longer during a grid outage, whereas a high-demand home would quickly consume its resources and face blackouts. More efficient buildings, with a higher share of their annual demand met on-site (e.g. 77% vs. 42%), can sustain a greater portion of their needs independently, reducing vulnerability to supply interruptions.

Moreover, greater energy independence fosters energy democracy, empowering citizens to control their energy production and consumption, aligning with the principles outlined in the Just Energy Transition (European Commission 2019). While both the most and the least efficient homes may generate the same amount of renewable electricity annually, the former align more closely with the principles of energy democracy. A household which is energy self-reliant in 77%, capable of meeting most of its energy demand in real time through on-site generation and storage, reduces dependence on central utilities and market intermediaries, which strengthens user autonomy and increases energy sovereignty, particularly during grid disruptions or price volatility. In contrast, households with lower energy self-sufficiency levels (44%) rely on the grid for imports, remain rooted in centralised systems, and are vulnerable to changing policy frameworks. Therefore, higher levels of temporal energy self-sufficiency can be seen as a practical expression of energy democracy, especially when paired with equitable access to technologies like photovoltaics and batteries. However, ensuring that this transition does not deepen social inequalities is a critical challenge for democratic energy governance, safeguarding low-income households are taking part in energy transition.

To summarise, retrofits not only lower the "energy bar" to be met by buildings but also increase the impact of batteries on energy self-sufficiency levels, which translates to enhanced climate resilience and a more democratised contribution to the energy transition.

Contributions to National CO2 Reduction and Energy Security (RQ3)

RQ3. To what extent can widespread self-sufficiency in single-family buildings contribute to national CO_2 emissions reduction and enhance energy security by 2050?

Research Question 3 studies how widespread building self-sufficiency would contribute to Poland's national CO_2 emissions reductions and energy security by 2050. Hypothesis H3 predicted a direct contribution to both goals. To test it, simulations of aggregated single-family building stock were carried out for different scenarios.

Under an Ambitious scenario (considering deep renovations), total operational CO_2 emissions from single-family buildings fall from about 66.7 million tonnes (Mt) in a Frozen retrofit scenario to 49.8 Mt in 2050, when a fossil-fuel-dominated grid energy mix from 2025 is evaluated. When rooftop PV is added, emissions drop dramatically to roughly 0.03 Mt with PV and just 0.02 Mt with PV plus batteries (2025 grid mix). That gives a 99.9% reduction per house relative to the frozen scenario (no PV or battery). Even assuming a decarbonised 2050 grid, the pattern remains the same, as total emissions drop from about 4.1 Mt (frozen, no PV or battery) to nearly zero with PV and storage. While these buildings cannot be said to achieve net-zero independently, they show a pathway for systemic decarbonisation, aligning with national climate targets. In other words, scaling up energy self-sufficiency across all homes could almost eliminate that sector's CO_2 emissions by 2050, contributing to achieving the net-zero emissions target from the EU Green Deal (European Commission 2019).

In terms of established metrics, "energy conservation" represents a total useful energy decrease through retrofits of 126 TWh from 2025 to 2050. Furthermore, in the ambitious scenario with PV and batteries, the net total useful energy needed by households from the grid falls from roughly 176 TWh (frozen, no PV) to only about 0.05 TWh. This is caused by a parallel thermomodernisation effort and total annual prosumer PV energy generation of 49.95 TWh in

2050. Practically speaking, this means that single-family homes would generate nearly all their electricity, removing that part of the demand from the central energy system. Such a shift significantly enhances not only climate mitigation but also energy security: the country would be far less exposed to supply disruptions or fuel price volatility because households are almost entirely self-reliant, which aligns with energy security goals listed by the Energy Policy of Poland until 2040 (Ministry of Climate and Environment 2021). Decreasing reliance on imported fossil fuels and improving resilience to supply chain disturbances is particularly important to Poland, given geopolitical uncertainties such as those following Russia's invasion of Ukraine in 2022 (Sovacool et al. 2023).

Benchmarking emissions and energy conservation values against existing literature and policy plans is challenging, as the figures often refer either to the entire residential sector (including multi-family buildings) or to cumulative values. For example, the KAPE strategy for Polish single-family buildings projects a cumulative primary energy saving of 964.2 TWh over the years 2020–2050, corresponding to a CO_2 reduction of 310.2 Mt (KAPE, 2024). While not directly comparable, the scale of avoided emissions and grid energy demand in this study, based on hourly modelling of end-use energy demand, suggests that the Ambitious scenario approaches or even exceeds the long-term targets outlined in national policy when applied consistently across the stock.

To summarise, building autonomy directly supports climate mitigation by reducing energy need and usage of fossil-fuel-generated electricity, but also boosts national energy security, since less external supply is needed, confirming H3. This underscores the crucial role of the building sector in national decarbonisation efforts, as also emphasised by the IPCC (2023) and the EU's RePowerEU strategy, which identifies buildings to have substantial climate mitigation and energy security boosting potential (European Commission 2022).

Implications for Scaling Energy Self-Sufficiency (RQ4)

RQ4. What are the implications required to scale energy self-sufficiency in Poland's single-family housing stock by 2050?

The fourth question considers what it would take to scale energy self-sufficiency across the entire single-family stock by 2050, based on taken assumptions and existing literature. It doesn't aim to deliver policy recommendations, but rather shape the environment needed to achieve the studied case. Surely, raising energy independence levels requires multisectoral cooperation, including different technology penetration like PV, energy storage or complete heat electrification, thermomodernisation and ambitious building codes, and an adequate policy environment or even grid improvements.

First, ambitious retrofitting programmes are necessary to reduce energy demand across the building stock. This aligns with the Directive (EU) 2024/1275 (EPBD), which mandates zero-emission buildings by 2050, and the new draft of Poland's Long-Term Renovation Strategy, which targets an annual thermomodernisation rate of 3.8% (Ministry of Climate and Environment 2024). Following the Ambitious scenario, 65% of buildings would need to achieve the status of energy-plus buildings (Advanced New or Advanced Retrofitted), as indicated in Table 4-2, and the share of the least efficient buildings (Standard), with energy demand over 10,000 kWh/year, would drop from 82.8% in 2025 to 14.3% in 2050. The exact trajectory of changes in energy efficiency levels is shown in Figure 4-2.

It is crucial to underline that an efficiency-first strategy gives great overall environmental benefits, as without decreasing energy demand, it would be difficult to achieve a net-zero energy balance in 2050 without significantly outscaling PV panels and placing them also on façades or next to buildings (Gstöhl and Pfenninger 2020). Also, simulations show that deep retrofits amplify the impact of solar and storage, as for the same PV installation and battery, a highly efficient home achieves far higher autonomy than an inefficient one. This emphasises that demand reduction and renewable supply must go hand in hand to maximise energy self-sufficiency.

Additionally, to make it possible for each of the 8.45 million single-family buildings in 2050 to have 5,910 kWh solar generation on site, each of them should install a PV system sized around 6 kWp, which aligns with the average installed PV system in Polish single-family buildings (Olczak et al. 2021). Furthermore, total prosumer energy generation would need to be 49.95 TWh in 2050, which is over five times more than the energy delivered to the grid by prosumer PV installations in 2024, at 8.5 TWh (Energy Regulatory Office 2025). This translates to added capacity of 41.45 TWh over 26 years. Following the same logic as for PV, total storage capacity in 2050, assuming each of the ~8.45 million buildings have a 14 kWh battery, is approximately 118.31 GWh. Considering that in 2024 Polish prosumers had installed a total of 0.672 GWh of battery storage capacity, to achieve the 2050 goal, an additional 117.62 GWh would need to be installed in 26 years (Wysokie Napięcie 2024). This means a

176-fold increase from the 2024 level, and while it looks ambitious, it is important to acknowledge that end-of-meter batteries started to penetrate the market just recently, and their growth has an extraordinary exponential trend.

Since every building would have PV and a battery, the grid infrastructure must be upgraded to accommodate increased distributed generation and ensure stability, as highlighted by challenges in integrating high levels of prosumers into the existing grid (Obuseh et al. 2025; Hung et al. 2016). To ease the impact of many PV installations transmitting electricity at the same time, policymakers and scholars already emphasise the role of increasing energy self-consumption, in other words, the share of total energy generated that is consumed on site without feeding into the grid (National Fund for Environmental Protection and Water Management 2024). As shown in Table 4-1, energy self-consumption is highest for the most inefficient buildings, since they can use more energy to cover higher demand. For systems with only PV, the most efficient building (Advanced New) self-consumes only about one-third of the generated energy, while the most inefficient self-consumes over half. With PV+battery systems, Advanced New buildings' self-consumption rises to over half, while for Standard buildings, three-quarters of the total generated energy is consumed on site. As shown, adding a battery improves self-consumption by around 21–24 percentage points, and therefore, storage is one of the main solutions applied to mitigate grid constraint problems, especially around midday, when the number of prosumers causes significant issues.

Policy and financing are other challenges to making energy self-sufficiency widespread by 2050, since the upfront cost of retrofits plus PV/storage for millions of homes would be enormous and require ground-breaking subsidies, low-interest loans, or cooperative ownership models. Policies to incentivise the installation of PV and battery systems are crucial. Programmes like Poland's "Czyste Powietrze" (Clean Air), which offers financial support for retrofitting and renewable energy installations, and the "My Electricity" programme, which subsidises PV with mandatory storage systems, provide a foundation for such efforts. However, these initiatives must be expanded and sustained to meet the Ambitious scenario's requirements. What is important, to deliver on energy democracy, is that policy must include mechanisms ensuring that no one is left behind, like community-owned solar and storage systems or grants for low-income homes, so that all citizens can actively participate in the energy transition, not only those who can afford installation (Di Lorenzo et al. 2021; Mundaca et al. 2018; Hoicka et al. 2021). Ensuring equitable access to these technologies is crucial to prevent energy poverty, as the utility death spiral might most affect those unable to cover high upfront costs (Kleinebrahm et al. 2023). Additionally, the structure of grid charges should be rethought, since highly self-sufficient households won't contribute much to grid maintenance costs (Chen et al. 2023).

Near-complete decarbonisation of single-family energy is technically possible in the presented scenario, but real-world barriers, such as upfront costs, technological limits, and behavioural diversity, mean actual outcomes might be more modest. Finally, if every home becomes a power plant, this fundamentally changes the energy landscape: the roles of utilities, regulators, and consumers must evolve. The presented transition gives the promise of cleaner, more autonomous energy, but it also shows a need for new business models, grid-management tools, and inclusive policies to ensure broad and just participation.

Research Limitations

The generalisability of the findings in this study is subject to several limitations. The simulations are based on five representative building archetypes and assume uniform deployment of PV and battery technologies across vintages. In reality, retrofitting, PV and battery system sizing, user behaviour, and local climate or grid conditions will vary, potentially affecting performance outcomes. This simplification compresses the real diversity of building characteristics and should therefore be interpreted with caution. A second major limitation lies in the assumption of highly idealised conditions. The study assumes full penetration of PV and battery storage across the single-family building stock, along with highly ambitious levels of thermomodernisation. It also follows assumptions of complete system electrification and excludes potential impacts from ageing or temperature-induced efficiency losses. Similarly, battery operation was simplified, using basic load flow formulas and not accounting for the technical nuances of real-world battery performance. The modelling also assumes full grid flexibility, meaning curtailment or export limits are not considered, which does not fully reflect the operational characteristics of a grid with high prosumer penetration. Nevertheless, the study's methodology could be extrapolated to other types of buildings, such as multi-family or commercial, or applied to other countries. Additionally, following its steps while narrowing the geographical scope could support infrastructure planners in predicting potential grid flows. Furthermore, it is also important to add that CO_2 avoidance calculations are not temporally determined. They assume an annual balance and do not account for the timing of grid imports.

This matters because, even in a partially decarbonised grid, buildings draw electricity at times when their generation is insufficient, often corresponding periods when the grid mix is more carbon-intensive (Miller et al. 2022). Therefore, annual emissions metrics risk overestimating real emission reductions.

Furthermore, the simulations in the Ambitious Scenario have not been thoroughly validated against the characteristics of the existing building stock or official 2050 government policies and strategies, which may result in discrepancies between the simulated outcomes and real-world developments. Another notable limitation is the assumption of low summer cooling demand. While this reflects current conditions in Poland, it may shift over time as average temperatures rise, increasing the relevance of cooling loads, something not fully captured in the present modelling. Next, the appliances, cooking and lighting energy demand were assumed not to change over time, which might highly affect the results, since more energy-efficient technologies are pushed to the market. On the top of that rebound effects observed along energy efficiency improvements were not accounted for (Sorrell et al., 2020).

Lastly, while energy self-sufficiency is a useful measure of autonomy, it lacks temporal granularity. A household may reach a high annual SS level yet still depend on the grid during critical periods such as prolonged winter darkness or cold snaps. These nuances are important when considering resilience and system-level impacts.

6. CONCLUSIONS

This thesis explored the technical limits of energy self-sufficiency (SS) in Poland's single-family housing stock by 2050, using an "efficiency-first + PV + battery" approach. It determined what level of energy self-sufficiency Polish single-family houses can reach by 2050, how demand reduction shapes autonomy, and what the aggregated impact of SS means for climate mitigation, energy security, resilience, and energy democracy in Poland. This was achieved by simulating two customised retrofit scenarios, Frozen and Ambitious, using the High-Efficiency Building (HEB) model, developing hourly energy flows with a tailored Python script, and further data analysis.

Hour-by-hour simulations across five building vintages show that deep retrofits, combined with rooftop PV (annual yield: 5910 kWh) and 14 kWh of storage, support hypothesis H1 that SS levels around 70–80% are achievable, but only where energy demand is low, since it varied from 42% in Standard homes to 77% in Advanced New. The outcomes also strongly support H2, showing a clear and consistent relationship between reduced demand and higher self-sufficiency, especially when storage is added, as each 1000 kWh cut in annual demand raises self-sufficiency by roughly two percentage points in PV-only systems, and up to 6.7 in PV + battery systems. Low-demand buildings were also shown to be more climate-resilient and energy self-reliant, which enhances energy democracy. Furthermore, aggregating results at the national scale confirms H3, as widespread deployment of the Ambitious scenario would nearly eliminate residential electricity emissions and drastically reduce grid reliance, cutting operational CO_2 emissions from 66.7 Mt to near zero and decreasing useful energy demand up to 176 TWh in 2050. Taken together, these outcomes illustrate that high energy self-sufficiency is technically feasible, but conditional. It is not the result of a single technology, but rather their combination. Installing PV enables the discussion about self-sufficiency, as the consumer becomes a prosumer; and installing a battery significantly enhances self-reliability, but low energy demand enables high levels of energy self-sufficiency without overscaling PV installation. The thesis also showed that homes with lower demand not only reach higher self-sufficiency but are better positioned for resilience during outages and more able to participate as equal actors in a democratised energy system.

The study fills a gap by carrying out a national-scale analysis of single-family buildings by 2050, showing how efficiency, renewables, and storage can work together to shape the energy self-sufficiency landscape in Poland. Its novelty lies in integrating demand-side efficiency with supply-side renewables in long-term simulation, and quantifying their systemic benefits, potentially guiding future studies on energy transitions in similar contexts. It also evaluates the technology growth needed to achieve study outcomes, such as a 176-fold increase in required storage capacity and a 5.8-fold increase in required PV generation, figures not previously assessed at a national scale in Poland. The quantified and demonstrated nonlinear link between demand reduction and self-sufficiency (PV+battery) represents an important preliminary finding that, after more detailed study and validation, can inform future research, particularly regarding planning, investment strategies, and equity in the energy transition.

In practical terms, the analysis points to several clear implications. First, achieving energy autonomy at scale requires mass renovation: 65% of homes would need to reach advanced energy efficiency levels, while the share of inefficient homes must fall drastically. Prosumer energy generation must grow by over 41 TWh, and battery storage capacity by 117 GWh by 2050, which shows an ambitious but technically feasible goal, dependent on high levels of financing, supply chain development, and infrastructure readiness. This means that widespread energy self-sufficiency requires long-term support for thermomodernisation, enormous investments in rooftop solar and residential storage, and rethinking grid infrastructure to handle high levels of distributed generation. Equally important is ensuring fair access, as without specific mechanisms, such as substantial subsidies for low-income households or shared ownership models, there is a risk that the transition will deepen inequalities, letting only wealthier households participate in and benefit from the energy transition.

The findings of this study have far-reaching implications for both policy and research. Practically, they show that achieving high levels of energy self-sufficiency in Poland’s single-family housing stock is technically feasible by 2050, but only through an integrated approach combining deep energy retrofits, rooftop photovoltaics, and battery storage. This underlines the need for comprehensive national renovation strategies and targeted subsidies, particularly for low-income households, to ensure an inclusive transition. From a policy perspective, the results suggest that household-scale interventions, when implemented at scale, can play a central role in delivering climate targets, reducing dependency on imported fossil fuels, and increasing households' resilience. The quantified benefits for emissions reduction, energy autonomy, and grid independence support the case for integrating distributed energy resources into long-term energy security planning. Academically, the study contributes to the growing literature on decentralised energy transitions by linking energy efficiency with self-sufficiency, and identifying a nonlinear relationship between demand reduction and autonomy gains. This opens pathways for further research on optimising retrofit and PV-battery configurations, as well as socio-technical studies on equitable access and behavioural adoption in energy self-sufficient systems.

The thesis critically reflects on its process by acknowledging limitations. The modelling assumes idealised conditions: unified PV generation yields unaffected by weather, perfect battery performance, full heating electrification, fixed user behaviour, and unrestricted grid interaction. Real-world factors like system degradation, shading, varying occupancy schedules, different heat sources, or grid export limits were not accounted for. Additionally, it does not consider potential changes and reductions in appliance, cooking, and lighting demand, which could differ significantly over the next 26 years. As a result, absolute self-sufficiency values may be optimistic. Future work could improve this by incorporating real weather data, more detailed and varied energy-use profiles, and, importantly, dynamic grid constraints. Furthermore, the assumption of full electrification is highly ambitious, considering the heavy reliance on fossil fuels for heating in Polish single-family buildings. While this aligns with EU policy on phasing out fossil fuels from household heating, future studies should also examine self-sufficiency not only in electricity but also in combined electricity and heat systems (e.g. district heating) to reflect a more realistic picture.

To further explore how to maximise energy self-sufficiency, six main directions could be studied:

- Collective energy models, to explore how prosumers can be coordinated through local energy communities or peer-to-peer energy sharing schemes (e.g.McKenna et al. 2017);
- Seasonal energy storage, like hydrogen, to address seasonal imbalances (e.g. Lokar and Virtič 2020);

- Vehicle-to-Home (V2H) storage as an alternative for static battery end-of-meter storage (e.g. Gstöhl and Pfenninger 2020);
- Photovoltaic-thermal (PVT) collectors, which have been proven to significantly improve energy self-sufficiency (e.g. Gagliano et al. 2021);
- Grid stability conditions, by showing self-consumption and grid exports under extreme PV generation, to highlight stress on the grid (e.g. Gautier et al. 2018).
- Socio-economic impacts of widespread energy self-sufficiency, which would offer deeper insights into optimising policy design (e.g. Mutani and Todeschi 2021).

In conclusion, this research demonstrates that by 2050, Polish single-family homes can achieve significant levels of energy self-sufficiency through a combination of deep retrofitting, PV installations, and battery storage. It shows how technical decisions at the household level can scale up to deliver systemic benefits: cutting CO_2 emissions, enhancing energy security, improving household resilience, and promoting energy democracy. The findings highlight the critical role of energy efficiency in enabling high self-sufficiency and the need for integrated, ambitious policy measures to support retrofitting and renewable energy adoption. Beyond the technical results, this study also underscores a broader societal shift. To be energy self-reliant as a household means more than simply generating electricity, it represents a transformation from passive consumption to active participation in the energy transition. From a bottom-up perspective, self-sufficiency is not only a technological goal, but an act of resilience, empowering citizens to take control of their energy. Prioritising energy efficiency, in respect to planetary boundaries gives a great gain in an era of climatic, economic, and geopolitical uncertainty. Each self-reliant household becomes a small but significant force in reducing emissions, stabilising energy demand, and strengthening societal resilience. Taken together, such homes form a cornerstone of a just and sustainable energy future.

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APPENDIX

Simulations were carried in Python Script available here: Python Script.

High Efficiency Buildings (HEB) model

The 3CSEP High Efficiency Buildings (HEB) model is free, publicly available software, and all its documentation can be found in the public GitHub repository.

HEB simulations were run using the open-source Python package *py3csepheb* (v1.2.x) by Chatterjee et al. (2022). First, the prepared input data or tables were fed into the model. In the next step, custom scenarios were selected to evaluate the progression of the building's vintage floor area. The overall HEB workflow, including input data and calculations, is shown in Figure 1. Here, HEB performs its computations by disaggregating buildings according to their detailed categories over time.

HEB Calculations

Floor Area Calculations

The first step involves computing the building's floor area, which serves as a fundamental input for all subsequent energy calculations. In the model, this is done by multiplying the building's footprint area by the number of floor levels. For example, if *building_length* and *building_width* define the footprint dimensions (in metres), and *number_of_floors* represents the number of storeys, then the total floor area, *floor_area* (in m²), is calculated as:

$$A_{floor} = building\_length \times building\_width \times number\_of\_floors$$

This computed *A_floor* (*floor_area*) represents the building's gross floor area. The HEB documentation underscores that determining floor area is a crucial step in building energy models, as it directly influences the scale of a building's energy requirements.

The HEB model dynamically disaggregates Poland's single-family building stock into five vintages, capturing changes in construction, demolition, and retrofit rates over time while accounting for efficiency differences. This structure enables the model to track the annual evolution of both total and category-specific floor area, taking into account the growing average size of new homes and the gradual phase-out of older buildings.

Annual Energy Demand Calculation

With the floor area determined, the model proceeds to calculate the building's annual energy demand. This is done by multiplying the total floor area by the specific energy intensity. The calculation links building size directly to energy demand, with larger buildings or higher intensities resulting in proportionally greater energy requirements.

$$E_{annual} = A_{floor} \times I_{spec}$$

Where *Afloor* is the floor area (m²), and *Ispec* is the specific annual energy demand (kWh/m²·year). The result represents the total energy required by the building over a year (in kWh/year). Using this approach, the model applies a specific energy intensity (i.e. energy use per unit area) to the total floor aarea for each building category or end-use. In practice, the script defines an *energy_intensity* value (in kWh per m² per year) based on building characteristics or usage and multiplies it by *floor_area* to compute the annual energy demand.

Hourly Energy Demand Disaggregation

Because the HEB model operates on yearly aggregates, the code introduces an additional step to break down the annual demand into an hourly load profile. This disaggregation is essential for simulating interactions with PV generation and battery storage, which occur on an hourly basis. The code applies a typical hourly demand profile, a set of 8,760 values representing relative demand for each hour of the year, to distribute the total annual energy. These profile values reflect daily and seasonal usage patterns (for example, higher consumption during evenings or in winter, depending on the building type).

Let p_h be the normalized profile value for hour h. Each hour's energy demand is then computed as:

$$E_h = E_{annual} \times f_h$$

where E_h is the energy demand in hour h and f_h is the fractional hourly load (ensuring $\sum_{h=1}^{8760} f_h = 1$).

The outcome gives a realistic hourly demand curve for the building, reflecting peaks and troughs over days and seasons rather than assuming a flat demand.

Heb Model Inputs

The tables below present input data to the HEB model.

Building Stock

Table 5 Building Stock properties

		Ambitious	Frozen	
Variable Name	Description	2	3	source
Urban demolition rate	The rate at which buildings in urban areas are demolished is expressed as a percentage of the total urban building stock per year.	0.0065	0.0065	Statistics Poland (2021) and KAPE (2024)
Rural demolition rate	The rate at which buildings in rural areas are demolished annually.	0.0014	0.0014	Statistics Poland (2021) and KAPE (2024)
Starting retrofit rate for Residential	The initial rate at which residential buildings begin retrofitting is expressed as a percentage.	0.01	0.01	KAPE (2024)
The final retrofit rate for Residential	The final, or target, retrofitting rate for residential buildings by the end of the model's time horizon.	See Table 3	0.012	KAPE (2024)
Retrofit rate FinalYear	The overall retrofit rate across different building types by the final year of the analysis.	2027	2027	KAPE (2024)
Max retrofitted building rate	The maximum possible percentage of buildings that can be retrofitted, excluding buildings that are heritage-protected or otherwise exempt.	0.5916	0.5916	KAPE (2024)
FAPCInitialYear	Floor area per capita in a specific initial year.	2020	2020	HEB model input Chatterjee et al. (2022)
uSFInitial	The floor area per capita for urban single-family houses at the beginning of the model.	28.7	28.7	Statistics Poland (2023)
uSFFinal	The final floor area per capita for urban single-family houses by the end of the model's projection period.	52.3	52.3	HEB model input Chatterjee et al. (2022)
rSFInitial	Floor area per capita for rural single-family houses at the start of the model.	30	30	Statistics Poland (2023)
rSFFinal	Final floor area per capita for rural single-family houses by the end of the model.	52.3	52.3	HEB model input Chatterjee et al. (2022)

Scenario Setting

Scenario settings on values presented for ambitious scenarios for single-family buildings by KAPE (2024).

Table 6 Scenario settings for Ambitious and Frozen.

Column1		Ambitious	Frozen
SID		2	3
FullName		Poland	Poland
RetStartYearExp	Start the year of exponential growth in the share of advanced retrofit buildings within retrofitted buildings.	2025	2025
RetStartYear	Start year of linear growth (end year of exponential growth) in the share of advanced retrofit buildings.	2025	2025
RetEndYear	End year of linear growth in the share of advanced retrofit buildings within retrofitted buildings.	2030	2030
RetRateStartRes	Initial share of residential buildings that are retrofitted at the beginning of the uptake period.	0.00%	0.00%
RetRateEndRes	Maximum share of residential buildings that are retrofitted at the end of the uptake period.	100.00%	0.00%

RetRateExpEndRes	Maximum share of residential buildings that are retrofitted at the end of the exponential growth period.	0.00%	0.00%
RetRateStartCom	Initial share of commercial buildings that are retrofitted at the beginning of the uptake period.	11.54%	11.54%
RetRateEndCom	Maximum share of commercial buildings that are retrofitted at the end of the uptake period.	100.00%	11.54%
RetRateExpEndCom	Maximum share of commercial buildings that are retrofitted at the end of the exponential growth period.	11.54%	11.54%
NewStartYear	Year when the share of advanced new buildings within new buildings starts to increase.	2025	2025
NewEndYear	Year when the share of advanced new buildings within new buildings reaches its maximum.	2030	2035
NewRate	Maximum share of advanced new buildings within new buildings after the uptake period.	1	0
NewStartRate	Initial share of advanced new buildings within new buildings before the uptake period begins.	0	0
NewType	The growth between the start and end years can be either exponential or linear.	linear	linear

Retrofit rates for Scenarios

Retrofit rates were based on values presented by KAPE (2024).

Table 7 Retrofit rates for Scenarios

year	retrofit rates for ambitious	retrofit rates for Frozen
2020	1.20%	1.20%
2021	1.20%	1.20%
2022	1.20%	1.20%
2023	1.20%	1.20%
2024	1.20%	1.20%
2025	1.20%	1.20%
2026	1.80%	1.20%
2027	1.80%	1.20%
2028	1.80%	1.20%
2029	1.80%	1.20%
2030	2.20%	1.20%
2031	2.20%	1.20%
2032	2.20%	1.20%
2033	2.20%	1.20%
2034	2.20%	1.20%
2035	2.30%	1.20%
2036	2.30%	1.20%
2037	2.30%	1.20%
2038	2.30%	1.20%
2039	2.30%	1.20%
2040	2.10%	1.20%
2041	2.10%	1.20%
2042	2.10%	1.20%
2043	2.10%	1.20%
2044	2.10%	1.20%

2045	1.70%	1.20%
2046	1.70%	1.20%
2047	1.70%	1.20%
2048	1.70%	1.20%
2049	1.70%	1.20%
2050	2.00%	1.20%

GDP/population/urbanisation

Year	GDP	population	urbanisation
2020	0.564780883	37.941122	0.600426956
2021	0.585114886	37.8663472	0.60075041
2022	0.60544889	37.7915724	0.601335418
2023	0.625782893	37.7167976	0.602189975
2024	0.646116897	37.6420228	0.603295648
2025	0.6664509	37.567248	0.604661119
2026	0.683383072	37.457489	0.606294983
2027	0.700315244	37.34773	0.608179882
2028	0.717247416	37.237971	0.610341094
2029	0.734179587	37.128212	0.612734836
2030	0.751111759	37.018453	0.615386716
2031	0.767742425	36.888628	0.618280603
2032	0.78437309	36.758803	0.621432314
2033	0.801003756	36.628978	0.624812905
2034	0.817634421	36.499153	0.628444841
2035	0.834265087	36.369328	0.632298554
2036	0.847489645	36.2277936	0.636396935
2037	0.860714204	36.0862592	0.640699388
2038	0.873938762	35.9447248	0.645210946
2039	0.887163321	35.8031904	0.649918266
2040	0.900387879	35.661656	0.654816183
2041	0.911177495	35.5087994	0.659881526
2042	0.921967112	35.3559428	0.664932636
2043	0.932756728	35.2030862	0.669931757
2044	0.943546344	35.0502296	0.674908208
2045	0.954335961	34.897373	0.67983306
2046	0.963243669	34.7383392	0.684725516
2047	0.972151378	34.5793054	0.689585348
2048	0.981059086	34.4202716	0.694393718
2049	0.989966795	34.2612378	0.699169298
2050	0.998874504	34.102204	0.70389009

Table 8 Sources for GDP, Population and Urbanisation Rate

Metric	Source	Source Path
GDP	OECD statistics, World Bank	https://data.oecd.org/gdp/real-gdp-long-term-forecast.htm https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG
Population	UN	https://population.un.org/wpp/Download/Files/1_Indicators%20(Standard)/EXCEL_FILES/1_Population/ WPP2019_POP_F02_POPULATION_GROWTH_RATE.xlsx
Urbanisation rate	UN Population dynamics	https://population.un.org/wup/Download/Files/WUP2018-F01-Total_Urban_Rural. xls

Occupancy Schedule

Sourced from HEB model input data Chatterjee et al. (2022).

Hour	Weekdays	Saturday	Sunday
0	1	1	1
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	0.8831	1	1
8	0.40861	1	1
9	0.24189	1	1
10	0.24189	1	1
11	0.24189	1	1
12	0.24189	1	1
13	0.24189	1	1
14	0.24189	1	1
15	0.24189	1	1
16	0.29498	1	1
17	0.5531	1	1
18	0.89693	1	1
19	0.89693	1	1
20	0.89693	1	1
21	1	1	1
22	1	1	1
23	1	1	1

Hot water occupancy schedule

Sourced from HEB model input data Chatterjee et al. (2022).

Hour	Weekdays	Saturday	Sunday
0	0.006	0.0066	0.0066
1	0.003	0.0033	0.0033
2	0.001	0.0011	0.0011
3	0.001	0.0011	0.0011
4	0.003	0.0033	0.0033
5	0.021	0.0231	0.0231
6	0.075	0.0825	0.0825
7	0.079	0.0869	0.0869
8	0.076	0.0836	0.0836
9	0.067	0.0737	0.0737
10	0.061	0.0671	0.0671
11	0.05	0.055	0.055
12	0.042	0.0462	0.0462
13	0.038	0.0418	0.0418
14	0.033	0.0363	0.0363
15	0.038	0.0418	0.0418
16	0.043	0.0473	0.0473
17	0.058	0.0638	0.0638
18	0.068	0.0748	0.0748
19	0.065	0.0715	0.0715
20	0.06	0.066	0.066
21	0.047	0.0517	0.0517
22	0.041	0.0451	0.0451
23	0.024	0.0264	0.0264

Ambient temp

It was not displayed due to the big dataset, which was sourced from the HEB model input data of Chatterjee et al. (2022).

Hot water setting

Sourced from HEB model input data Chatterjee et al. (2022).

LID	FullName	whR	whC	ret	adv	con	st

36	Poland	1.32E+17	3.19E+16	1	2.12428264	1	0.8

Scenario Developments

The ambitious scenario was developed using data from KAPE (2025). It assumes that all buildings will reach net-zero status by 2050, wherever this is technologically and economically feasible. The scenario also projects a 1.5% annual growth in the building stock, alongside a 0.5% annual demolition rate, primarily targeting the least energy-efficient buildings.

Table 9 Energy: Useful, Final, Primary and Non-Renewable Primary and their transition factors KAPE (2025).

Year	Useful Energy (Purple) (kWh/m2/rok)	Final Energy (Black) (kWh/m2/rok)	Primary Total Energy (Red) (kWh/m2/rok)	Non-Renewable Primary Energy (Blue) (kWh/m2/rok)	useful/final	final/useful	useful/primary	final to primary
2020	175	205	230	165	0.8536585366	1.171428571	0.7608695652	1.12195122
2025	160	185	215	155	0.8648648649	1.15625	0.7441860465	1.162162162
2030	130	135	175	105	0.962962963	1.038461538	0.7428571429	1.296296296
2035	115	97	142	63	1.18556701	0.8434782609	0.8098591549	1.463917526
2040	95	62	135	33	1.532258065	0.6526315789	0.7037037037	2.177419355
2045	85	47	112	20	1.808510638	0.5529411765	0.7589285714	2.382978723
2050	75	33	90	10	2.272727273	0.44	0.8333333333	2.727272727

Energy distribution

As mentioned earlier, HEB calculates energy demand by disaggregating it across end uses, climate zones, levels of urbanisation, building types, and building vintages. To evaluate the total energy demand of a building, each vintage was modelled as a component of the overall energy use under a given scenario. Total energy consumption for heating, cooling, and hot water was then calculated using adjusted input parameters and assumptions aligned with Poland's specific climatic conditions and building typologies.

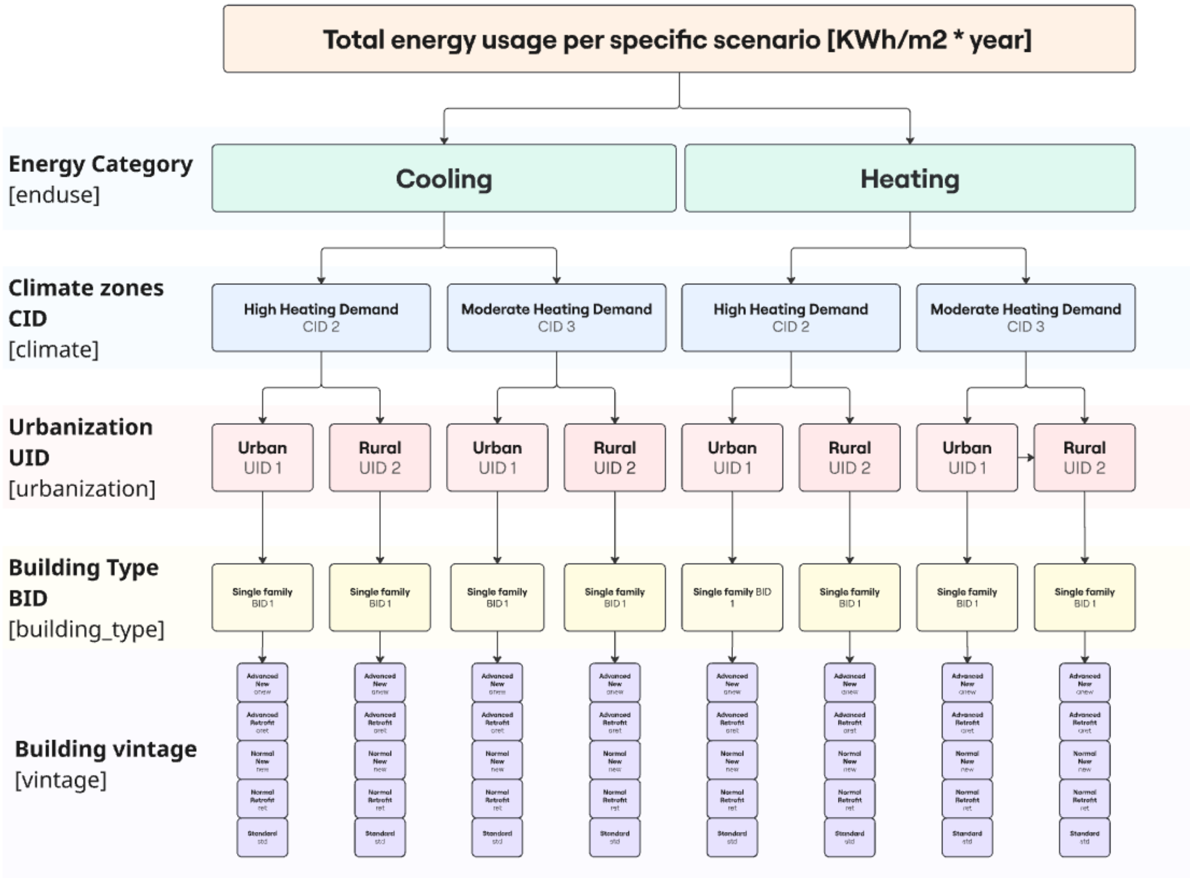

Figure A-1. Energy disaggregation workflow.

Establishing Building Vintages and Climate Zones

Initially, buildings were categorised into specific energy efficiency vintages based on the Polish Long-Term Building Renovation Strategy and HEB definitions (KAPE, 2024):

- Advanced New: EU0–EU1
- Advanced Retrofitted: EU2
- New: EU3
- Retrofitted: EU4
- Standard: EU5, EU6, EU7

Table 10 Transition of Polish Building categories into HEB methodology (KAPE, 2024).

Type	Definition	% buildings	Usable area [million m2]	Average energy consumption rate [kWh/m2/year]	% Buildings after aggregation
				useful	

EU0	Plus-energy building	0	-	53	advanced new	59,5	9,4495%	0
EU1	Zero-emission building	0	-	66	advanced new			
EU2	A building with almost zero energy consumption	0	-	74	advanced retrofit	74	11,7523%	0
EU3	Even division Buildings below compartment B and above compartment E.	0,29	209,6	110	new	110	17,4697%	0,29
EU4		0,29	209,6	142	ret	142	22,5518%	0,29
EU5	17% of buildings are more efficient than the EU6 range	0,17	125	187	standard	244,1627907	38,7768%	0,43
EU6	10% of buildings more efficient than the EU7 range	0,1	73,5	244	standard			
EU7	Least efficient 16% of buildings	0,16	117,7	305	standard			

Based on that, HEB vintages were assumed to have below energies;

Table 11 Energy type EU and HEB vintages

Legend single-family		
HEB	**Energy Type**	**Average energy consumption rate [kWh/m2/year]**
advanced new	EU0, EU1	59,5
advanced retrofit	EU2	74
retrofit	EU3	110
new	EU4	142
standard	EU5, EU6, EU7	244

Building progression was inspired by KAPE's (2024) ambitious scenario for single-family progression.

Table 12. Building types progression for the ambitious scenario for single-families KAPE (2024).

Year	EU0	EU1	EU2	EU3	EU4	EU5	EU6	EU7
2020	0%	0%	0%	29%	29%	17%	10%	16%
2025	0%	0%	10%	26%	26%	15%	9%	14%
2030	0%	8%	18%	32%	22%	12%	5%	3%
2035	0%	19%	24%	31%	17%	8%	1%	0%
2040	0%	36%	23%	29%	8%	3%	1%	0%
2045	1%	50%	20%	26%	3%	0%	0%	0%
2050	3%	61%	16%	20%	0%	0%	0%	0%

Climate zones in Poland from KAPE (2024) were consolidated into two main HEB climate categories (CID2 and CID3) based on their heating and cooling days:

- **CID2:** (colder climate, significant heating demand)
  - Zone V (Suwałki, Zakopane, Ełk)
- **CID3:** (moderate climate, balanced heating/cooling demands)
  - Zones I-IV (cities such as Warszawa, Krakow, Wrocław)

Table 13 Calculations of HHD and CCD for all fiPolishish climate zones to CID2 and CID3. Source: Meteostat data for 2022.

			%
CID 3, moderate heating HDD >= 1000 & < 3500	I zone - Szczecin,		
	HDD	2978,9	0,9921
	CDD	23,7	0,0079
	II zone - Poznań,		
	HDD	2910,1	0,9884
	CDD	34,2	0,0116
	III zone Warszawa		
	HDD	2923,59	0,9882
	CDD	34,8	0,0118
	IV zone- Olsztyn		
	HDD	3178	0,9976
	CDD	7,7	0,0024
	IV zone- Białystok		
	HDD	3344	0,9993
	CDD	2,5	0,0007
	IV zone- Biała_Podlaska		
	HDD	3121,29	0,9969
	CDD	9,69	0,0031
CID 2 High heating demand HDD>= 3500 & < 5000	V zone - Suwałki		
	HDD	3434,79	0,9988
	CDD	4,19	0,0012
	V zone - Zakopane		
	HDD	4018,6	0,9995
	CDD	1,9	0,0005

Calculation of Energy Intensity per Vintage and Climate Zone

Energy intensity values (kWh/m²·year) for heating, cooling, and hot water were derived by:

1. Obtaining average annual energy consumption from existing references (Table 10).
2. Calculating a weighted average energy intensity for each climate cluster (CID2, CID3), taking into account each climate zone's share in total floor area (weighted average of efficiency for each HEB climate).

Table 14 Number and total usable area of buildings by building category and climatic zone in which the building is located and average, minimum, maximum energy consumption of buildings by building category and climatic zone in which the building is located, and potential energy savings, source: KAPE(2024).

Building types	**Climate zone**	**HEB climate**	**Number [pcs]**	**Surface Floor area [m2]**	**Weight of the floor area (% of floor area in each climate zone, HEBaggregationn)**	**Average energy consumption (MWh)**	**Average energy consumption per floor area (MWh/m2)**	**WEIGHTED Average energy consumption per floor area (MWh/m2)**	**WEIGHTED Average energy consumption per floor area (kWh/m2)**		**weight in total residentials**	**WEIGHTED Average energy consumption per floor area (MWh/m2)**
Single-family building	I	CID 3	687948	80010694.6	0.10	14,603,552.00	0.1825200003	0.1830382027	183.0382027	single family CID3	0.6462390693	0.1757122797
	II	CID 3	1736301	201937923.7	0.25	36,631,539.40	0.1814000002					
	III	CID 3	3392711	394584211.1	0.50	72,397,159.30	0.1834770811					
	IV	CID 4	997450	116006969.6	0.15	21,432,809.70	0.1847545003					
								0.1879199982	187.9199982	single family CID2	0.01100293536	
	V	CID 2	116023	13493867.2	1.00	2,535,767.50	0.1879199982					
Multi-family building	I	CID 3	58873	43349034.2	0.10	6,934,701.40	0.1599736079	0.1620613914	162.0613914	multi-family CID3	0.2882777123	
	II	CID 3	141100	103893802.5	0.25	16,874,431.40	0.16242					
	III	CID 3	280175	206297472.2	0.50	33,775,022.10	0.1637199998					
	IV	CID 3	80672	59400325	0.14	9,337,578.80	0.1571974362		0			
								0.1585799968	158.5799968	multi-family CID2	0.05448028294	
	V	CID 2	10069	7413636.8	1.00	1,175,654.50	0.1585799968					

Table 15 Total energy share in CID2 and CID3

Share of the total energy used in each HEB climatzonees		
		Share
total energy consumption in HEB CID 2	3,711,422.00	0.01720654935
total energy consumption in HEB CID 3	211,986,794.10	0.9827934507

Share of heating, cooling, and hot water end-uses.

Calculated energy from Table 7 should be allocated among the heating, cooling, and hot water end-uses according to derived shares presented in Table 14.

Table 16 End use for heating/cooling, hot water, cooking appliances and light in 2021. Source: Polish Statistics 2022

Enduse	2021
Heating/Cooling	65,1
Hot water	17,3
Cooking	8,5
Appliances and Lighting	9,0
Cooling (assumed and benchmarked)	0,01

Table 17 Endues sources

	Source	Source Path
Enduse share in Poland	Glowny Urzad Statystyczny (Polish Statistics 2022)	https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/zuzycie-nosnikow-energii-w-gospodarstwach-domowych-w-2021-r-,13,1.html#:~:text=i%20Mieszka%C5%84%202021.-,W%202021%20r.,%2C5%20GJ%2F1%20mieszka%C5%84ca.

Based on the above proportional shares between heating, cooling, and hot water, those three values are divided like below:

Table 18 Share of heating, cooling, and hot water end-uses.

Enduse	2021
heating	78,06%
Cooling	1,20%
Hot water	20,74%

End-use Energy Shares (Heating, Cooling, Hot Water)

Hot water usage was fixed across all climate zones due to minimal differences in ground temperature influence. Based on project assumptions, hot water consumption was set at 20.74% of total heating/cooling/hot water energy consumption, consistent across all building vintages and climate zones.

Heating and Cooling

To distribute the remaining energy consumption (after removing hot water usage), the methodology involved evaluating heating degree days (HDD) and cooling degree days (CDD) from representative cities within each climate zone. The energy share for heating and cooling was then calculated based on the proportion of HDD and CDD within each climate zone, using the following formulas:

$$\text{Heating Share (\%)} = \frac{HDD}{HDD + CDD}\ x\ (100\% - Hot\ water\ share)$$

$$\text{Cooling Share (\%)} = \frac{HDD}{HDD + CDD}\ x\ (100\% - Hot\ water\ share)$$

Based on those calculations, shares of heating and cooling for each climate were established.

Table 19 Input data for calculations for vintages for heating, cooling and hot water.

SHARE OF END USE	
heating	78,06%
Cooling	1,20%
H +C	79,26%
Hot water	20,74%
CLIMATE CID 3	
HDD- CID3	0,9916
CDD- CID3	0,0084
CLIMATE CID 2	
HDD-CID 2	0,9995
CDD-CID 2	0,0005

$$\text{Heating end use for vintage} = \text{Average useful energy consumption rate(vintage)}\ x\ Total\ share\ of\ heating\ and\ cooling\ in\ end\ use\ (heating, cooling, hot\ water) x\ Share\ of\ heating\ in\ climate\ (climate)$$

$$\text{Cooling end use for vintage} = \text{Average useful energy consumption rate(vintage)}\ x\ Total\ share\ of\ heating\ and\ cooling\ in\ end\ use\ (heating, cooling, hot\ water) x\ Share\ of\ cooling\ in\ climate\ (climate)$$

$$\text{Hot water end use for vintage} = \text{Average useful energy consumption rate(vintage)}\ x\ Total\ share\ of\ hot\ water\ in\ end\ use\ (heating, cooling, hot\ water)$$

Based on that, the below tables with end energy usage were established for Single-Family Buildings, in division into:

- Heating, cooling and hot water
- Climate 2 and Climate 3

Table 20 Energy use for vintages for heating [kWh/m2/year]

	Heating	
	CID 2	CID 3
	SF	SF
anew	47,13538818	46,76049979
aret	58,62216345	58,15591571
new	112,4911785	111,5964869
ret	87,14105378	86,44798281
st	193,2947011	191,7573437

Table 21 Energy use for vintages for cooling [kWh/m2/year]

	Cooling	
	CID 2	CID 3
	SF	SF
anew	0,02228568097	0,3971740674
aret	0,02771664524	0,4939643864
new	0,05318599492	0,9478776063
ret	0,0412004186	0,7342713852
st	0,09139001944	1,628747436

Table 22 Energy use for vintages for hot water [kWh/m2/year]

	Hot water	
	CID 2	CID 3
	SF	SF
anew	12,34232614	12,34232614
aret	15,3501199	15,3501199
new	29,45563549	29,45563549
ret	22,8177458	22,8177458
st	50,61390887	50,61390887

Building on previous results, energy use by vintage was established below:

enduse	SID	LID	CID	UID	BID	PBID	anew	aret	new	ret	st
cooling	2	36	2	1	1	0	0.02228568097	0.02771664524	0.05318599492	0.0412004186	0.09139001944
cooling	2	36	2	1	3	0	0.02322205412	0.02884029302	0.04981505158	0.03857857378	0.09026637166
cooling	2	36	2	2	1	0	0.02228568097	0.02771664524	0.05318599492	0.0412004186	0.09139001944
cooling	2	36	3	1	1	0	0.3971740674	0.4939643864	0.9478776063	0.7342713852	1.628747436
cooling	2	36	3	1	3	0	0.4138620535	0.5139899696	0.8878008566	0.6875450243	1.608721853
cooling	2	36	3	2	1	0	0.3971740674	0.4939643864	0.9478776063	0.7342713852	1.628747436
heating	2	36	2	1	1	0	47.13538818	58.62216345	112.4911785	87.14105378	193.2947011
heating	2	36	2	1	3	0	49.11586667	60.99873764	105.3614559	81.59571399	190.9181269
heating	2	36	2	2	1	0	47.13538818	58.62216345	112.4911785	87.14105378	193.2947011
heating	2	36	3	1	1	0	46.76049979	58.15591571	111.5964869	86.44798281	191.7573437
heating	2	36	3	1	3	0	48.72522668	60.51358797	104.5234701	80.94674754	189.3996714
heating	2	36	3	2	1	0	46.76049979	58.15591571	111.5964869	86.44798281	191.7573437

To validate them and align with values from KAPE (2024), values were scaled with factor = 0.7.

Giving the final form of energy use by vintage

enduse	SID	LID	CID	UID	BID	PBID	anew	aret	new	ret	st
cooling	2	36	2	1	1	0	0.01559997668	0.01940165167	0.03723019644	0.02884029302	0.06397301361
cooling	2	36	2	1	3	0	0.01625543788	0.02018820511	0.03487053611	0.02700500165	0.06318646016
cooling	2	36	2	2	1	0	0.01559997668	0.01940165167	0.03723019644	0.02884029302	0.06397301361
cooling	2	36	3	1	1	0	0.2780218472	0.3457750705	0.6635143244	0.5139899696	1.140123205
cooling	2	36	3	1	3	0	0.2897034375	0.3597929787	0.6214605996	0.481281517	1.126105297
cooling	2	36	3	2	1	0	0.2780218472	0.3457750705	0.6635143244	0.5139899696	1.140123205
heating	2	36	2	1	1	0	32.99477173	41.03551442	78.74382495	60.99873765	135.3062908
heating	2	36	2	1	3	0	34.38110667	42.69911635	73.75301913	57.11699979	133.6426888
heating	2	36	2	2	1	0	32.99477173	41.03551442	78.74382495	60.99873765	135.3062908
heating	2	36	3	1	1	0	32.73234985	40.709141	78.11754083	60.51358797	134.2301406
heating	2	36	3	1	3	0	34.10765868	42.35951158	73.16642907	56.66272328	132.57977
heating	2	36	3	2	1	0	32.73234985	40.709141	78.11754083	60.51358797	134.2301406

Appliances cooking and lights calculations

To provide a complete picture of the final energy demand in residential buildings, the modelling approach includes energy consumed by appliances, cooking, and lighting with the assumption of equal distribution throughout the year.

Table 23 Calculation of average use of energy for appliances, cooking, and lighting per day per person per m2.

Average use of energy for appliances, cooking, and lighting per day per person per m2		
energy use per person in households in the year	24.6	GJ/year/person
	6833.39	kWh/year/person
share of energy used for cooking and appliances, lighting	17.5	%
energy use per person in households in the year for cooking and appliances	1195.84325	kWh/year/person
energy use per person in households during the day for cooking appliancesnces	3.276282877	kWh/day/person
urban: m2/person	28.7	m2/person
% of urban	0.6	%
rural: m2/person	30	m2/person
% of rural	0.4	%
average m2/person	29.22	m2/person
average use of energy for appliances, cooking, and lighting per day per person per m2	0.1121246707	kWh/m2 day
	40.92550479	kWh/m². ye r

Table 24 Source data for calculations of average use of energy for appliances, cooking, and lighting per day per person per m2

energy use per person in households in the year	GUS Zużycie nośników energii w gospodarstwach domowych w 2021 r.	https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/zuzycie-nosnikow-energii-w-gospodarstwach-domowych-w-2021-r-,13,1.html#:~:text=i%20Mieszka%C5%84%202021.-,W%202021%20r.,%2C5%20GJ%2F1%20mieszka%C5%84ca.
average m2/person	Statistical Yearbook of the Republic of Poland	https://stat.gov.pl/en/topics/statistical-yearbooks/statistical-yearbooks/statistical-yearbook-of-the-republic-of-poland-2023,2,25.html
Hourly distribution	Olczak et al. 2021	https://doi.org/10.1016/j.egyr.2021.07.038

Based on this, the average use of energy for appliances, cooking, and lighting per day per person per m2 is equal 0.1121246707kWh/m2 per day. The daily total was then disaggregated into hourly values using empirical load profiles from Olczak et al. (2021), which differentiate between weekdays and weekends. These profiles were normalised to ensure that hourly shares were summed to one over a 24-hour period.

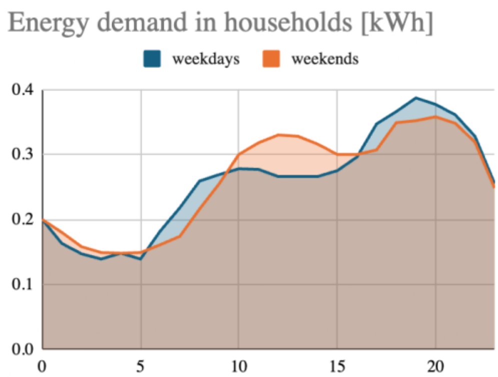

Table 25 Hourly E demand distribution for appliances, cooking and lights [kWh/m2]

	value		**normalised**		**Hourly E demand distribution [kWh/m2]**	
	weekdays	weekends	weekdays	weekends	weekdays	weekends
0	0.2	0.2	0.03221130617	0.03193357816	0.003611682096	0.003580541934
1	0.163	0.18	0.02625221453	0.02874022034	0.002943520908	0.003222487741
2	0.147	0.158	0.02367531003	0.02522752674	0.00265458634	0.002828628128
3	0.139	0.149	0.02238685779	0.02379051573	0.002510119057	0.002667503741
4	0.148	0.148	0.02383636656	0.02363084784	0.002672644751	0.002649601031
5	0.139	0.149	0.02238685779	0.02379051573	0.002510119057	0.002667503741
6	0.182	0.161	0.02931228861	0.02570653042	0.003286630707	0.002882336257
7	0.218	0.174	0.03511032372	0.027782213	0.003936733484	0.003115071483
8	0.259	0.216	0.04171364149	0.03448826441	0.004677128314	0.003866985289

9	0.269	0.255	0.0433242068	0.04071531215	0.004857712419	0.004565190966
10	0.278	0.3	0.04477371557	0.04790036724	0.005020238113	0.005370812901
11	0.277	0.318	0.04461265904	0.05077438927	0.005002179703	0.005693061675
12	0.266	0.33	0.0428410372	0.05269040396	0.004803537187	0.005907894191
13	0.266	0.328	0.0428410372	0.05237106818	0.004803537187	0.005872088772
14	0.266	0.316	0.0428410372	0.05045505349	0.004803537187	0.005657256256
15	0.275	0.3	0.04429054598	0.04790036724	0.004966062882	0.005370812901
16	0.296	0.3	0.04767273313	0.04790036724	0.005345289502	0.005370812901
17	0.347	0.307	0.0558866162	0.04901804247	0.006266268436	0.005496131869
18	0.366	0.349	0.05894669029	0.05572409388	0.006609378235	0.006248045675
19	0.387	0.352	0.06232887744	0.05620309756	0.006988604855	0.006301753804
20	0.377	0.358	0.06071831213	0.0571611049	0.00680802075	0.006409170062
21	0.361	0.348	0.05814140763	0.05556442599	0.006519086183	0.006230142965
22	0.328	0.319	0.05282654212	0.05093405716	0.005923158637	0.005710964385
23	0.255	0.248	0.04106941536	0.03959763692	0.004604894672	0.004439871998

As calculations assume the average floor area per building is 116.3m2, and the factor from useful to final energy is 0.44 (KAPE 2024), Hourly final energy values distributed through the day are:

Table 26 Hourly final energy demand distribution for appliances, cooking and lights [kWh/m2]

	Hourly E FINAL demand distribution per building [kWh]	
hour	weekdays	weekends
0	0.1848225701	0.1832290177
1	0.1506303946	0.1649061159
2	0.135844589	0.144750924
3	0.1284516862	0.1365056182
4	0.1367687019	0.1355894731
5	0.1284516862	0.1365056182
6	0.1681885388	0.1474993592
7	0.2014566014	0.1594092454
8	0.2393452283	0.1978873391
9	0.2485863568	0.2336169976
10	0.2569033725	0.2748435265
11	0.2559792596	0.2913341381
12	0.2458140182	0.3023278792
13	0.2458140182	0.300495589
14	0.2458140182	0.289501848
15	0.2541310339	0.2748435265
16	0.2735374038	0.2748435265
17	0.3206671591	0.2812565422

18	0.3382253033	0.3197346359
19	0.3576316732	0.3224830711
20	0.3483905447	0.3279799417
21	0.3336047391	0.3188184908
22	0.303109015	0.2922502832
23	0.2356487769	0.2272039819

PV generation calculations

The script takes a given PV system size and simulates its electricity production for each hour of the year based on solar availability. Consequently, photovoltaic (PV) generation is calculated based on the system's installed capacity and hourly solar factors:

$$P_{PV,h} = P_{PV,peak} \times g_h$$

Where:

- $P_{PV,peak}$ is the peak PV capacity (kW).
- g_h is the normalized hourly generation fraction (0 to 1).
- $P_{PV,h}$ is PV generation in hour h (kWh).

The code ensures that PV generation is calculated in parallel with demand on an hour-by-hour timeline. This produces an hourly PV supply profile that will be used to meet the building's demand whenever possible. It's worth noting that this generation modelling assumes the PV system is grid-connected (excess can be exported) and does not degrade over the year (no performance degradation or outage considered.

Table 27 Inputs for PV generation calculations.

Inputs	Description	Source	Source Path
Annual Solar Radiation	Annual photovoltaic (PV) generation was calculated by first setting a national cumulative PV target for 2050 that offsets the projected energy demand of single-family buildings, in line with Polish net-zero goals. This total generation was constrained by Poland's realistic technical PV potential (Molnár et al., 2024). It was then evenly distributed across all projected single-family buildings for 2050 using the HEB model, resulting in an assumed uniform annual yield of 5,911 kWh per building.	HEB model annual energy demand value	
Solar irradiation	Annual yield was broken down into an hourly time series using Poland's typical hourly solar irradiation profile, producing representative hourly PV generation data for each building. Da a was taken for the year 2022.	Meteostat	https://meteostat.net/en/place/pl/warsaw?s=12375&t=2022-01-01/2022-12-31

Limitations:

- Identical annual PV yield per building (5,911 kWh/year) ignores system variations

- Uniform hourly PV generation profile for all locations
- No accounting for system performance losses like temperature effects, shading, dust, or panel degradation.

PV generation linear growth was generated in MS Excel with the trend
Linear equation: PV_gen = 1601.21·Year + -3232538.19

Energy Storage Calculations

After obtaining hourly demand and PV generation, the script incorporates a battery storage model to simulate charging and discharging throughout the year.

Each building is equipped with a 14 kWh lithium-ion battery (5 kW charge/discharge power). Dispatch prioritises local use of surplus PV and discharges to meet demand when generation is insufficient. The model is based on maximising self-sufficiency calculations used in Moshovel et al. (2015).

Table 28 System Parameters and Assumptions

Symbol	Value	Description
C_{gross}	14 kWh	Total battery capacity.
SOC_{min}/SOC_{max}	10% / 90%	The battery only uses 10% to 90% of its capacity to avoid damage.
C_{usable}	12.6 kWh	Usable capacity = 14 kWh × (90% - 10%) = 12.6 kWh.
P_{max}	5 kW	Maximum power for charging or discharging (the speed of filling or emptying the battery).
η_{rt}	95%	Round-trip efficiency (5% energy is lost when storing and retrieving energy).
$\eta_{ch} = \eta_{dis}$	97.5%	One-way efficiency for charging or discharging ($\sqrt{0.95} \approx 0.975$).
Δt	1 hour	Simulations use hourly steps.
SOC_0	50%	Battery starts at 50% charge (6.3 kWh).

Hourly Dispatch Logic follows the following:

1. **Surplus PV (PV > Demand)** – If, in a given hour, PV generation exceeds the building's demand, that demand is met entirely by PV (no grid electricity is used during that hour). The excess PV energy (PV minus demand) is then directed to the

battery for charging. The code increases the battery's state of charge (SOC) by the surplus amount up to the battery's maximum storage capacity. If the battery is not yet full, it absorbs as much of the surplus as possible. Any remaining energy beyond the battery's capacity is either exported to the grid or considered unused, depending on the model's assumptions. This logic prioritises on-site use of PV: the building consumes PV directly first, then stores any extra generation in the battery.

2. **Deficit PV (PV < Demand)** – If, in a given hour, PV generation falls short of the building's demand, all available PV output is used immediately to partially meet that demand. This leaves a residual load (demand minus PV) that remains unmet. The code then checks the battery for available stored energy. If the battery has a positive SOC, it discharges to supply part or all of the remaining demand. The discharge is limited to the lesser of the unmet demand or the available energy in the battery, and the SOC is reduced accordingly. If the battery cannot fully cover the shortfall, or is empty, any remaining unmet demand is supplied by grid imports. This mechanism allows the battery to reduce grid consumption by shifting previously stored PV energy to periods of higher demand.

$$SOC_t = SOC_{t-1} + \eta_{ch} E_{charge,t} - \frac{E_{discharge,t}}{\eta_{dis}}$$

where η_{ch}, η_{dis} represent efficiencies, and $E_{charge,t}$, $E_{discharge,t}$ hourly charging and discharging energies.

The code ensures that the battery's state of charge (SOC) remains bound between 0 and its maximum capacity, preventing overcharging or discharging below empty. All battery energy flows are calculated in kilowatt-hours (kWh) for each hourly timestep and remain consistent with the modelled PV generation and demand. This battery modelling algorithm, implemented through *if/else* logic or loop conditions captures the hour-by-hour charging behaviour (in response to surplus PV) and discharging behaviour (in response to shortfalls).

Limitations include:

- No predictive control
- Battery degradation not modelled
- No tariff-based or economic dispatch

Energy Flow Calculations and Self-Sufficiency Metrics

Using the results of the hour-by-hour simulation, the code computes the overall energy flows and key performance indicators for the system. It aggregates relevant quantities over the full year and derives two central metrics: self-sufficiency and self-consumption.

The following terms are calculated:

- **Grid Import** – The total energy drawn from the electricity grid over the year to cover demand that could not be met by PV or the battery (kWh/year). This is effectively the sum of hourly shortfalls after PV generation and battery discharge have been accounted for. In every hour where the combined supply from PV and battery falls short of demand, the deficit is added to the grid import total.
- **Grid Export** – The total surplus PV energy fed into the grid over the year (kWh/year). This occurs during hours when PV generation exceeds demand, and the battery is either full or unable to absorb the remaining surplus.
- **Total PV Self-Consumed** – The amount of PV energy used on-site to meet the building's demand, either directly at the time of generation or indirectly after being stored in the battery and later discharged.

From these values, the model calculates two core performance metrics for on-site generation:

- **Self-Sufficiency Ratio (SS)** – The proportion of the building's total annual energy demand met by on-site PV, either directly or through battery storage.
- **Self-Consumption Ratio (SC)** – The share of total PV generation that is used on-site, whether immediately or via the battery.

For each vintage, the output includes:

- Hourly and annual values for demand, PV generation, grid imports, and exports
- Hourly battery charge/discharge and state of charge (SOC)
- Self-sufficiency and self-consumption indicators (both PV-only and PV + battery)

CO2 equivalent calculations

These assumptions are based on Poland's NECP, the EU Green Deal (targeting net-zero emissions by 2050), and energy transition reports (e.g. IEA; Aurora Energy Research). From 2025 onwards, each new home is assumed to be equipped with solar panels, reducing reliance on grid electricity for appliances, lighting, and, through heat pumps, for space heating and cooking. The RED III directive aims to increase the share of renewables to 70% by 2050. Electrification, primarily through heat pump adoption, drives electricity demand, even as the carbon intensity of the electricity supply continues to decline. Homes with solar installations are expected to reduce their dependence on district heating. Coal is to be phased out between 2035 and 2040 in line with the EU coal phase-out strategy. Natural gas demand falls as heat pumps become more widespread, and fossil fuel boilers are assumed to be banned after 2035. Primary energy (PE) factors remain unchanged for fossil fuels but decrease over time for electricity and district heat as the energy system decarbonises.

Assumed Energy Mix in 2050

The projected fuel mix for heating in 2050 is as follows:

- Heat pumps – 63.8%
- Biomass and biogas – 21.3%
- Non-emissive, non-renewable sources (e.g. nuclear energy, deep geothermal) – 15%
- Coal and gas – 0%

Electricity Sector Transition

In parallel, the share of renewable energy sources (RES) in Poland's National Power System (KSE) is expected to reach 95% by 2050, ensuring a near-zero-emission electricity supply for heat pumps and other electrical devices (KAPE 2024). CO_2 emission factors for heat and electricity were calculated using national fuel mix data and specific emission factors, as detailed in the CO_2 input table.

Table 29 Input data for CO2 calculations

Type of data	Source	Source path
Share of residential fuel consumption (2022)	Eurostat – Energy consumption in households	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households
Heat sources in Poland (2023)	Urząd Regulacji Energetyki – Energetyka cieplna w liczbach	https://www.ure.gov.pl/pl/cieplo/energetyka-cieplna-w-l/12424,2023.html
Electricity generation mix (2023):	IEA – Poland country profile	https://www.iea.org/countries/poland
Final-to-primary energy conversion factors:	Polish Regulation (Dz.U. 2023 No 697)	https://www.prawo.pl/akty/dz-u-2023-697%2C21818729.html
Average final-to-primary factor for district heat:	Audyty i Świadectwa – Analiza sieci ciepłowniczych w oparciu o wskaźnik WPC	https://www.audytyiswiadectwa.pl/index.php/analiza-sieci-cieplnych-w-oparciu-o-wskaznik-wpc
General conversion and emission factors:	SEAI – Conversion factors	https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors

Calculations for the 2050 grid

Conversion factor: useful/final 2050: 0,44 (KAPE 2024)

Frozen

		FROZEN (low efficiency, no PV and battery)				
2050			total final energy for single-family buildings (HEB)			
		66879,3	GWh			
share of fuels in residential in 2022		PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	7,00%	1,1	5149,7	1,85E+10	56,66	1,05E+09
electricity	75,00%	1,5	75239,2	2,71E+11	10	2,71E+09
renewables and biofuels	0,00%	0,1	0,0	0,00E+00	0	0,00E+00
oil and petroleum production	0,50%	1,1	367,8	1,32E+09	76,01	1,01E+08
heat	8,00%	1,2	6420,4	2,31E+10	10	2,31E+08
solid fossil fuels	0,00%	1,1	0,0	0,00E+00	95,83	0,00E+00
					Total CO2 [MtCO2]	4,09
					HEB buildings [number]	8450636
					CO2/building [kgCO2]	484

All electricity

2050				total final energy for single-family buildings (HEB)		
				49949,8		
share of fuels		PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	7,00%	1,1	3846,1	1,38E+10	56,66	7,85E+08
electricity	75,00%	1,5	56193,5	2,02E+11	10	2,02E+09
renewables and biofuels	0,00%	0,1	0,0	0,00E+00	0	0,00E+00
oil and petroleum production	0,50%	1,1	274,7	9,89E+08	76,01	7,52E+07
heat	8,00%	1,2	4795,2	1,73E+10	10	1,73E+08
solid fossil fuels	0,00%	1,1	0,0	0,00E+00	95,83	0,00E+00
					Total CO2 [MtCO2]	3,06
					HEB buildings [number]	8450636
					CO2/building [kgCO2]	362

PV only

Just PV **2050 grid**						
	imports from the grid	30,919	GWh			
share of fuels in residential in 2022		PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	7,00%	1,1	2,4	8,57E+06	56,66	4,86E+05
electricity	75,00%	1,5	34,8	1,25E+08	10	1,25E+06
renewables and biofuels	0,00%	0,1	0,0	0,00E+00	0	0,00E+00
oil and petroleum production	0,50%	1,1	0,2	6,12E+05	76,01	4,65E+04
heat	8,00%	1,2	3,0	1,07E+07	10	1,07E+05
solid fossil fuels	0,00%	1,1	0,0	0,00E+00	95,83	0,00E+00
					Total CO2 [MtCO2]	0,0019
					HEB buildings [number]	8450636
					CO2/building [kgCO2]	0,224

PV+ battery

PV+batteries **2050 grid**						
	imports from the grid	19,172	GWh			
share of fuels in residential in 2022		PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	7,00%	1,1	1,5	5,31E+06	56,66	3,01E+05
electricity	75,00%	1,5	21,6	7,76E+07	10	7,76E+05
renewables and biofuels	0,00%	0,1	0,0	0,00E+00	0	0,00E+00
oil and petroleum production	0,50%	1,1	0,1	3,80E+05	76,01	2,89E+04
heat	8,00%	1,2	1,8	6,63E+06	10	6,63E+04
solid fossil fuels	0,00%	1,1	0,0	0,00E+00	95,83	0,00E+00
					Total CO2 [MtCO2]	0,0012
					HEB buildings [number]	8450636
					CO2/building [kgCO2]	0,139

Calculations for the 2025 grid

Conversion factor: useful/final 2025: 1,15625 (KAPE 2024)

Frozen

			FROZEN		**total useful energy [GWh]**	**151998,38**
2050, but wno not changing the grid (from 2025)					useful->final for 2025	1,15625
					total final energy [GWh]	**175748,127**
	share of fuels in residential in 2022	PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	20,88%	1,1	40365,8	1,45E+11	56,66	8,23E+09
electricity	12,43%	2,5	54613,7	1,97E+11	167	3,28E+10
renewables and biofuels	26,49%	0,1	4655,6	1,68E+10	0	0,00E+00
oil and petroleum production	2,87%	1,1	5548,4	2,00E+10	76,01	1,52E+09
heat	17,51%	1,33	40928,8	1,47E+11	74,1	1,09E+10
solid fossil fuels	19,83%	1,1	38335,9	1,38E+11	95,83	1,32E+10

	Total CO2 [MtCO2]	66,73
	HEB buildings [number]	6614117
	CO2/building [kgCO2]	10089

All from grid

	ALL FROM THE GRID	**total useful energy [GWh]**	**113522,17**
2050, but without changing the grid (from 2025)		useful->final for 2025	1,15625
		total final energy [GWh]	**131260,009**

	share of fuels in residential in 2022	PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	20,88%	1,1	30147,8	1,09E+11	56,66	6,15E+09
electricity	12,43%	2,5	40789,0	1,47E+11	167	2,45E+10
renewables and biofuels	26,49%	0,1	3477,1	1,25E+10	0	0,00E+00
oil and petroleum production	2,87%	1,1	4143,9	1,49E+10	76,01	1,13E+09
heat	17,51%	1,33	30568,2	1,10E+11	74,1	8,15E+09
solid fossil fuels	19,83%	1,1	28631,7	1,03E+11	95,83	9,88E+09
					Total CO2 [MtCO2]	49,84
					HEB buildings [number]	6614117
					CO2/building [kgCO2]	7535

PV

	Just PV	**total useful energy [GWh]**	**70,2704545**
2050, but without a changing grid (from 2025)		useful->final for 2025	1,15625
		total final energy [GWh]	**81,2502131**

	share of fuels in residential in 2022	PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	20,88%	1,1	18,7	6,72E+07	56,66	3,81E+06
electricity	12,43%	2,5	25,2	9,09E+07	167	1,52E+07

renewables and biofuels	26,49%	0,1	2,2	7,75E+06	0	0,00E+00
oil and petroleum production	2,87%	1,1	2,6	9,23E+06	76,01	7,02E+05
heat	17,51%	1,33	18,9	6,81E+07	74,1	5,05E+06
solid fossil fuels	19,83%	1,1	17,7	6,38E+07	95,83	6,11E+06
					Total CO2 [MtCO2]	0,03
					HEB buildings [number]	6614117
					CO2/building [kgCO2]	5

PV+battery

			PV+batteries		**total useful energy [GWh]**	**43,5727273**
2050, but with without changing grid (from 2025)					useful->final for 2025	1,15625
					total final energy [GWh]	**50,3809659**
	share of fuels in residential in 2022	PE FACTOR	PRIMARY ENERGY BY SOURCE IN 2020 [GWh/year]	PRIMARY ENERGY BY SOURCE IN 2020 [MJ/year]	co2 factor [gCO2/MJ]	co2 [kgCO2]
natural gas	20,88%	1,1	11,6	4,17E+07	56,66	2,36E+06
electricity	12,43%	2,5	15,7	5,64E+07	167	9,41E+06
renewables and biofuels	26,49%	0,1	1,3	4,80E+06	0	0,00E+00
oil and petroleum production	2,87%	1,1	1,6	5,73E+06	76,01	4,35E+05
heat	17,51%	1,33	11,7	4,22E+07	74,1	3,13E+06
solid fossil fuels	19,83%	1,1	11,0	3,96E+07	95,83	3,79E+06
					Total CO2 [MtCO2]	0,02
					HEB buildings [number]	6614117
					CO2/building [kgCO2]	3