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Advancing Heat Pump Adoption in Ukraine's Low-Carbon Energy Transition

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Abstract: The European Union established a legislative framework to facilitate the transition to low-carbon energy sources. As Ukraine aspires to join the EU, it is progressively adopting similar legislation. The extensive damage to Ukraine's fossil fuel-based heat generation infrastructure necessitates the reconstruction of heating and cooling supply systems, with a focus on low-carbon energy sources, particularly heat pumps. Notably, Poland achieved the highest growth in installed heat pump capacities in Europe, offering valuable insights for Ukraine's energy transition. This study employs the TIMES-Ukraine model to assess the potential proliferation of heat pumps within the country. The findings suggest that, if capital costs for heat pumps decrease, their adoption could accelerate more rapidly than biomass-fired heating systems, particularly in urban single-family homes and buildings lacking central heating systems, over the next decade. While high investment costs may slightly diminish the attractiveness of this technology for space heating, heat pumps consistently outperform biomass heating appliances and potential biomethane-sourced gas boilers.

Keywords: heat pumps; Ukraine; Poland; energy modelling; TIMES-Ukraine

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1. Introduction

As a result of the unfortunate geopolitical events, thermal generation in Ukraine, which played a crucial role in providing balancing and maneuverability for the energy system, has been particularly affected by hostile attacks. Despite the predominant use of coal and natural gas and the phenomenon of the "green-coal paradox", the importance of Ukraine's thermal generation cannot be underestimated. Thermal generation suffered significant damage, and the country has no choice but to rebuild it using advanced technologies and extensive implementation of renewable energy sources. It will provide several significant advantages, including decentralizing the energy system, making it more flexible and less attractive for hostile attacks. Additionally, renewable energy sources will help avoid dependency on imported energy carriers. Heat pumps are one of the most promising energy technologies for heat supply.

Heat pumps are devices that allow the use of distributed thermal energy stored in the ground, groundwater, air, or waste heat generated in manufacturing and other processes for heating purposes [1]. Although they have been known since 1852, when William Thomson (Lord Kelvin) described in detail the principles of their operation and proved that they could be used for heating, the development of cooling and heating technology occurred only as a result of the spread of access to electricity, which is most often used to power them [2]. Further impulses that led to increased interest in this technology in heating were shortages of energy carriers caused by the outbreak of World War II and, in the 1970s, by the oil crisis and the sharp rise in fuel prices. However, the most significant growth was in the late 20th and early 21st centuries, especially in North America and some European countries. The intensive development of low-temperature systems is taking place mainly because they are already available for small-scale developments, such as single-family houses, housing estates, holiday or welfare homes, office buildings, churches, factories, etc. The heat pump segment in Europe has been one of the most rapidly growing in the heating and installation market in recent years. The number of heat pumps in operation in European Union countries in 2022 was 50.8 million, up more than 272% from 2012 [3].

Ukraine is located in the mid-latitudes with a moderately continental climate. Each year, the heating season lasts from October to April. "Air-to-air" and "air-to-water" heat pumps effectively provide heating at temperatures as low as −15 °C. January temperatures average from −6.5 °C to −8 °C, and July averages +15.5 °C to +20.5 °C [4]. In Ukraine, some factors define the need not only for heating, but also for cooling. Such a necessity is determined by the climatic conditions, particularly the hot summers. Due to climate change, the occurrence of heat waves is increasing every year; thus, the demand for cooling increases. Additionally, most of the population in Ukraine lives in urban areas. In cities, the heat island effect is observed. Thus, both commercial and residential buildings have a high demand for cooling. We may expect an increase in demand for cooling technologies and respective supply growth in the future.

Ukraine ranks among the European countries most affected by air pollution, being the ninth highest in Europe. In 2019, air pollution contributed to 42,900 premature deaths, accounting for about 10% of total morbidity and mortality. In Ukraine's major cities, bringing air quality to "good" standards could prevent up to a third of all strokes and cases of chronic obstructive pulmonary disease [5]. HPs may bring environmental and health benefits to Ukrainians in rural and urban areas, as less fossil fuels could be used for heat generation. Yet, the extent of these benefits requires separate studies.

In Ukraine, in 2018, 4.6 MW of heat pumps were installed [6]. Ground, air, water, and/or sewage collectors could be the heat source. In 2020, heat pumps produced 52 thsd toe of energy in Ukraine (of which aerothermal energy—36 thsd toe, geothermal—10 thsd toe, and hydrothermal—6 thsd toe). To compare, we can say that due to martial law, the exact data on the new or existing installed capacities in heating are unknown, but it is known that more than 500 MW of new solar PV was installed in only eight months of 2024. The heat potential of ground in Ukraine is 6293 thsd toe/year, and the energy potential of air is 6307 thsd toe/year [6]. Buildings in Ukraine are designed for heat transfer agent temperatures of 70–150 °C for large systems and 70–95 °C for smaller systems. Heat pumps operate with a heat output temperature of 35–65 °C, using up to 80% renewable energy and the remaining 20% of electricity to heat water and the premises [6], which is only possible for new or deeply modernized buildings. Another essential precondition for heat pump operation is the availability of a stable and reliable electricity supply. In Ukraine, several manufacturers of heat pumps are united in the National Association of Ukraine for Heat Pumps. Foreign-made pumps, including Mitsubishi Electric, Daikin, Viessmann, Buderus, etc, dominate the domestic market. Heat pumps require relatively high investments: EUR 10–15 thousand for heating 100–300 m^2 [7] (or average USD 285–715/kW depending on the technology [6]). Drilling works are costly as well. As of 2024, this option was appropriate for apartment buildings, social infrastructure (schools, kindergartens, and hospitals), and social facilities (shopping malls, etc.), yet they can be used for individual households in urban or rural areas. In Ukraine, 79.2% of the population is urban [8], but not all urban areas have central heating. Thus, both urban and rural areas may host HP.

In Ukraine, some general measures need to be implemented first, aimed at the renovation of heat transmission infrastructure, increased energy efficiency, improved payment discipline, etc. [9]. The reform of the heat supply sector is to take into account international climate commitments, and the framework of Ukraine's European integration aspirations, and the measures are to include:

- Improving the quality of heat supply, reducing losses in the DH system, introducing innovative technologies in monitoring and accounting of heat supply;
- Reforming the tariff system. The existing Ukraine tariff system and cross-subsidization do not provide actual coverage of costs for heat supply services. The current tariffing

system does not cover all costs, mainly operating costs, which may change significantly in the short term, and tariffing rules do not allow for flexible responses to such changes;
- Improving the energy efficiency of buildings. Reforming the tariff system based on market pricing will lead to an increase in tariffs for final consumers. At the same time, the modernization of the housing stock should increase the energy efficiency of buildings, allowing more efficient use of the unit of heat and, accordingly, less consumption. Improving energy efficiency will lead to lower fees for heat supply services, which, to some extent, compensates for the increase in tariffs for end users. Focusing primarily on investing in energy efficiency of buildings will also increase the efficiency of heating networks, as this will allow for a better redesign of existing networks in accordance with existing needs;
- Social support. The introduction of market-based pricing principles for DH services requires the adaptation of the system of subsidies and social support to low-income households to new market conditions.

The main challenges for HP spread in Ukraine, especially in comparison to other low-carbon energy sources are the following:

- The high cost of the technology and tight state budget for capital grants, even for the most promising technologies. The capital expenditures for solar PV are declining fast, being the most widespread renewable energy technology in Ukraine, whereas such a cost decline is not yet observed for HPs;
- Ensuring the uninterrupted electricity supply;
- Lack of widespread practical experience, and, thus, insufficient people with high expertise in installing and maintaining HP. It is worth noting that nowadays, Ukraine experiences a severe deficit of people in all spheres of life and all technologies;
- And banking institutions' reluctance to provide loans for HPs to individual households. The bankability of projects using solar or wind is clear in Ukraine, and some banks may provide loans. However, this is not yet the case for HPs.

The opportunities include, but are not limited to, Ukraine's need to rebuild its entire heating supply system. Biomass-fired technologies are, to some extent, competitors to HPs, yet the latter are more accessible to operate; they do not require the creation of dedicated infrastructure for fuel supply and presume easier maintenance (e.g., no need to clean the ashes). Commercializing biomethane boilers remains questionable in the near future, whereas HPs have the possibility of commercialization.

Since the spread of HPs in Ukraine remains limited to date, it is essential to analyze Poland's experience in implementing heat pumps, as Poland is the fastest-growing heat pump market in Europe and a global leader in this field, according to the International Energy Agency, to investigate the international trends in low-carbon heating supply; to review the challenges of Ukraine in heating supply; and to explore the possibilities of expanding the use of heat pumps in Ukraine. In particular, it is essential to consider price sensitivity through making several scenarios on the dynamics of capital expenditures for heat pumps (optimistic, neutral, and pessimistic) and investigate the role of technologies in providing heating changes in the course of achieving a net-zero economy, with which they compete; taking one neutral price assumption and investigating the change in the role of heat pumps depending on the change in other factors that can affect the heat supply (biomass potential, and the given share of central heating). All these questions constitute the aim of the study.

Literature Review

Current studies increasingly identify the important role of heat pumps in achieving the goals of the decarbonization policy. In their flagship report [10], IEA identifies heat pumps among the three most important measures (together with energy efficiency retrofits and EVs) that households can adopt to accelerate clean energy transitions. They state that heat pumps have already become nearly cost-competitive over their lifetime in advanced economies, even without incentives. Additionally, not just climate commitments would make heat pumps become the primary means of decarbonizing space and water heating, but also energy security concerns. According to the WEO 2022 Special Report [11], heat pumps may account for nearly half of the global reductions in fossil fuel use for building heating by 2030. Various authors widely studied other possible implications of accelerated heat pump deployment. Schöniger et al. argue that beyond providing heat, heat pumps can enhance flexibility in future energy systems by leveraging the thermal storage potential of building structures and buffer tanks. This allows electricity demand to be shifted to periods when renewable energy production is high [12]. A major factor hindering the replacement of fossil fuels with heat pumps is their high economic cost, especially the upfront capital investment required; that is why researchers pay great attention to the availability of heat pump technology to stay on track to decarbonize home heating. The related issue of household subsidies and other support measures is widely debated [13]. While there is considerable potential for innovation to reduce initial costs, it seems unlikely that heat pump installation costs will match those of gas boilers in the near term. However, by minimizing operational expenses and providing subsidies and accessible financing, the total cost of a heat pump for the average household can be made more affordable than a gas boiler. Reaching this goal is crucial to making heat pumps accessible to all households and preventing any increase in fuel poverty [14]. Finally, the upscaled use of heat pumps is traditionally analyzed through the scope of public health and new job creation. Lysenko et al. summarize [15] that the adoption of heat pumps and other common solutions for a green and climate-friendly transition aligns with efforts to reduce harmful pollutants and improve air quality, yielding substantial economic benefits. This progress supports multiple sustainable development goals. Non-cost barriers to widespread use of heat pumps are also analyzed in the literature, such as restrictions on new installations, lack of reliable information, and split incentives between building owners and tenants. To increase the incentive for landlords to invest in heat pumps and other clean energy technologies, some governments passed special legislation to speed up the process [16]. Accelerating the deployment of heat pumps could also be constrained by the existing manufacturing capacity, availability of materials and components, the business and investment environment, and regulatory and legal restrictions. Several studies, for example, [17], focus on the ability of the heat pump manufacturing sector to increase heat pump deployment.

2. Materials and Methods

2.1. TIMES-UA Model Description

TIMES-Ukraine is a linear optimization energy system model from The Integrated MARKAL-EFOM System (TIMES) model family [18]. It offers a technology-rich, bottom-up representation of Ukraine's energy system, designed for long-term energy dynamics projections [19]. The model was developed by the Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine.

The model structure is harmonized with Eurostat and International Energy Agency methodology with approximately 2050 technologies. In the model, the energy system of Ukraine is divided into seven sectors, which include all energy flows from the extraction of primary energy resources to their final consumption with intermediate stages of processing and transformation, import, export/stocks, and supply to consumers. The latter is achieved by combining the following dimensions: four seasonal periods (winter, spring, summer, and autumn) and 24 daily time intervals (hours). TIMES-Ukraine includes international energy trade, accounting for electricity imports and exports with the European Network of Transmission System Operators for Electricity. Assumptions regarding net transfer capacities between Ukraine and the EU are based on Ukrenergo's conservative case scenario [20]. The TIMES-Ukraine model offers detailed coverage of Ukraine's energy system, representing 2064 processes and 822 commodities. It encompasses the IPCC sectors "Energy" and "Industrial processes and product use", with projections extending to 2060.

The model has one region representing the entire Ukraine, and each year is split into 96 time slices. Figure 1 represents an overview of the energy system in the TIMES-Ukraine model.

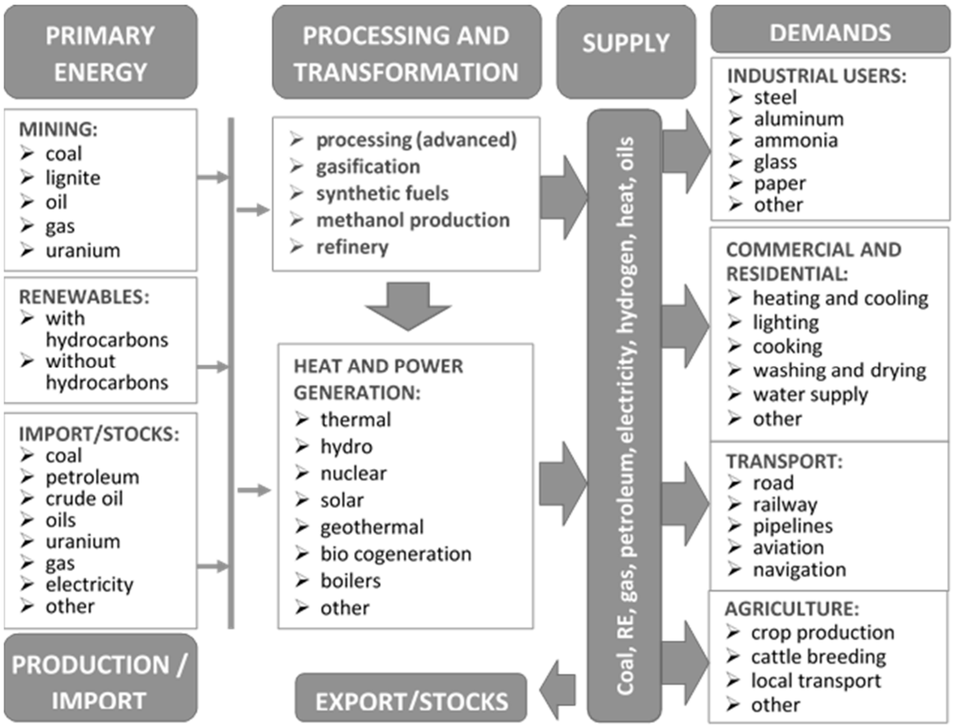


Figure 1. Reference energy system in TIMES-Ukraine model [21].

The database of the TIMES-Ukraine model is filled with economic and energy data for 2005–2020, as well as estimates of the corresponding data for 2022–2023 (there is a significant data gap due to the martial law in Ukraine), taking into account their changes in the future. We assume that in 2026, the war ends and Ukraine regains control over all occupied territories, which is reflected in the demand projections. The primary sources of the database are statistical observations of the State Statistics Service of Ukraine, the National Bank of Ukraine, data from Ukrainian ministries and departments, housing and communal enterprises, energy generation and supply companies, specialized associations, academic institutions, etc. In addition, data from international organizations (IEA, IAEA, OECD, IMF, World Bank, UN, etc.) are used in energy and economic development forecasting. Data from the IEA, the Danish Energy Agency (DEA), the National Renewable Energy Laboratory (NREL), and specialized associations in Ukraine serve as data sources for economic, technical, and other characteristics of the new (future) technologies.

In recent years, in cooperation with US national laboratories, in particular, with the PNNL, NREL, ANL, and LBNL as part of the Net Zero World initiative, the model was improved for developing the National Energy and Climate Plan of Ukraine [22] and Long-term Low-Emission Development Strategy (in progress). The model was employed to develop strategic documents for the Government of Ukraine, including [23–27]. TIMES models adhere to the methodological guidelines set forth by the Secretariat of the United Nations Framework Convention on Climate Change for creating energy and environmental forecasts [28].

The model assumptions regarding macroeconomic forecast, demographic projection, international fuel prices, carbon pricing, and technology costs have been discussed and validated on a high level and can be found in Section 4.1 and Appendix 3 Table D 3.1. of the NECP document [22].

In this research, we employed the model to explore two sensitivity analyses. The first is price sensitivity, where we consider three scenarios of the different forecasts on capital expenditures for heat pumps (optimistic, neutral, and pessimistic) and investigate their role in providing space heat while achieving a net-zero emissions in Energy and IPPU in 2050. Currently, there are four main types of heat pumps (HPs) presented in the TIMES-Ukraine model:

1. Solar assisted heat pumps (space heat and hot water);
2. Ground-sourced heat pumps (space heat and hot water);
3. Air-to-air heat pumps (space heat and cooling);
4. And large-scale district heating air-sourced heat pumps.

Their availability to segments of the buildings sector (residential buildings: urban single houses, rural single houses, multi-apartment buildings; and commercial buildings: small, large) varies. All single houses and all commercial buildings could be equipped with 1–3 types of individual HPs. No individual heat pumps are available for multi-apartment buildings. Still, they could benefit from large-scale district heating (DH) HPs and all other types of buildings, except rural ones with no central heating. No backup device exists for the listed individual HPs. Although previously existing CAPEXes for HP technologies in our model lie within respective ranges for most countries, we have chosen to refer to the Danish Energy Agency data from the energy technology catalogue on investment cost forecast for all technologies [29]. The data on the cost assumptions come from the Danish Technology Catalogue, which provides information on average European cost projections. There are differences in cost parameters for the installation of HPs in new/rebuilt property vs. retrofit. For instance, in Germany, the weighted average costs of HP installations are 40–50% higher in new buildings [30]. Once we observe the increase in the HP market, a more detailed study on implementation in new/rebuilt property vs. retrofit in Ukraine is yet to be conducted. In our modelling, the medium estimation values will supersede existing data for the core scenarios, and lower and upper estimations provided by DEA will be used as pessimistic and optimistic forecasts for parametric sensitivity scenarios (Table 1).

Table 1. The dynamics of capital expenditures of heat pumps in the TIMES-Ukraine model scenarios.

Nominal Investment	2020	2025	2030	2040	2050
DH HP, EUR/kW; COP = 3.5					
Lower estimation	670	670	670	670	670
Medium estimation	860	860	860	860	860
High estimation	1140	1140	1140	1140	1140
Ground-sourced HP (for existing building), EUR/unit; COP = 3.3					
Lower estimation	11,812	11,221	10,631	10,099	8812
Medium estimation	14,506	13,780	13,055	12,402	11,750
High estimation	17,181	16,322	15,463	14,690	14,687
Air-to-air HP (for existing building), EUR/unit; COP = 3					
Lower estimation	2887	2816	2746	2614	2128
Medium estimation	3804	3709	3618	3445	3273
High estimation	5051	4928	4805	4574	4346
Solar-assisted HP (for existing building), EUR/unit; COP = 4.1					
Lower estimation	9308	8651	7994	7429	6965
Medium estimation	12,402	11,516	10,631	9874	9121
High estimation	15,767	14,635	13,505	12,541	11,339

The CAPEX of an air-to-air heat pump considers the cost of multiple units to cover the full demand of an average household presented in our model, which consists of 2.24 rooms. It can also be considered a ducted system. The value for the upper estimation for 2050 has been calculated manually since, in the catalogue, it was higher than in 2025, which contradicts every other technology trend, where the upper estimation for 2050 is lower than in 2025. The CAPEX of solar-assisted HPs is calculated as an air-to-water HP CAPEX plus half of the equipment costs of solar heating.

For the second sensitivity, we take the medium price estimation for HPs and investigate the change in their role depending on the change in another factor that can significantly affect the heat supply—the available/harvested biomass potential, as the modelling for NECP shows significant contribution of biomass in achieving the national renewable energy targets and economy decarbonization. In particular, we consider two scenarios in this sensitivity group: 50% of the default biomass potential availability and only 10%. Note that woody biomass potential is already well developed and utilized, so these changes do not affect it. Additionally, the value of biogas use is not lower than 3.7 PJ. In Table 2, we present the default estimations on the biomass potential. The rationale for this kind of sensitivity is that there can be different utilizations of biomass potential (which may depend on a wide array of factors, such as affordability, availability, convenience of use, etc.).

Table 2. The default estimations on the biomass potential in the TIMES-Ukraine model, PJ.

Type of Biomass	2020	2023	2050
Corn and sugar beet for ethanol	60.3	60.3	66.4
Bioenergy crops	104.7	94.2	104.7
Landfill biogas	16.7	10.0	18.8
Sewage biogas	2.9	1.9	2.9
Municipal solid waste	10.4	6.3	11.7
Rapeseed for biodiesel	16.7	16.7	20.1
Manure and sludge	94.9	74.0	109.8
Corn silage	176.5	158.8	176.5
Solid field residues	582.8	446.1	746.3
Woody biomass	128.7	102.0	125.1

2.2. European Strategies for Low-Carbon Heat Supply

Globally, DH supplies only 9% of heat. About 90% of fossil fuels are used to produce heat (45%—coal, 40%—natural gas, and 3.5%—oil in 2020) [31]. This means that the global DH sector requires significant attention in terms of both its dissemination and switching to low-carbon energy sources. DH (as opposed to individual heating), if it already exists, is challenging to decarbonize, but it presumes the economy of scale and ensures heating at a lower cost; if created from scratch, it allows deploying renewables and modern energy technologies.

IEA distinguishes the directions of innovations that modern heating systems could deploy. They include, but are not limited to, the following:

- Integration of secondary heat sources (from data centres, industry, nuclear power plants, and electrolyzers);
- Support of those with renewables, heat pumps, and storage systems;
- Renovation of the existing networks;
- Implement digital solutions to enable more efficient use of heat [31].

In the European Union, about 50% of the final energy consumed is used for heating or cooling, and no significant changes are forecast in this regard in quantitative terms [32–34]. However, measures to reduce greenhouse gas (GHG) emissions are necessary for this sector due to the need to mitigate climate change. The most effective way to decarbonize heating and cooling is to replace conventional fuels used for these purposes with energy obtained from renewable sources. In 2004–2020, the share of renewables used for heating and cooling grew from 11.72% to 23.09% [35]. Negotiated at the 21st Paris Climate Convention summit (COP21 December 2015), the agreement commits parties to "pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels" [36]. In addition, while the Paris provisions leave it up to countries to choose the path by which this goal will be achieved, the need to promote renewable energy sources is already stated in the document's introduction. The need to fulfil the EU's obligations under the Paris Agreement was the main determinant for the adoption of the Clean Energy for All Europeans package; the so-called "Winter Package" [37]. It sets seven priorities and a legal framework for EU climate and energy policy until 2030. From the heating and cooling sector's point of view, the most important are Directives 2018/844 [38], 2018/2002 [39], and 2018/2001 (RED II) [40]. The first two of these directives relate to energy efficiency. The rationale for their adoption is best expressed by the statement "energy efficiency first" [38]. The regulations contained therein established a target of minimum 32.5% energy efficiency improvement in 2030 compared to 2007. With buildings accounting for about 40% of final energy consumption, the country was required to develop strategies to reduce energy consumption in this sector to almost zero, mainly by accelerating the pace of thermal upgrading and spreading the use of smart energy management technologies. Directive 2018/2001 sets a target of at least 32% of energy from renewable sources in gross final energy consumption in 2030. For heating and cooling, it requires member states to assess the potential of renewable energy and waste heat and cooling that can be used in the sector and promote their use. Complementing the Winter Package also for the heating and cooling sector is the EC statement "Europe that protects: clean air for all" [41]. Air pollution contributes to chronic and severe health conditions, including cardiovascular disease, asthma, and lung cancer, leading to an estimated 300,000 premature deaths annually. In 2019, residential, commercial, and institutional energy consumption was the main source of coarse particulate matter (PM10) and fine particulate matter (PM2.5) [42].

Even more ambitious targets for reducing GHG emissions are included in the Clean Planet for All strategy, in which the European Commission outlined a long-term vision for reaching net zero emissions in 2050 [43]. Among other things, it proposed a complete phase-out of coal use and significant reductions in oil and gas consumption [44]. These declarations were confirmed in the European Green Deal [45] and "Fit for 55" [46], which are integral parts of the strategy developed by the Commission to implement the UN 2030 Agenda for Sustainable Development [47].

The European Green Deal establishes ambitious targets in various fields to respond to deteriorating environmental conditions and climate change. It enforces European commitment to carbon neutrality by 2050, set out in climate law in 2021 [48]. To ensure high emission reductions by 2050, the EU introduced the Emission Trading System and a mechanism to ensure emissions reductions in sectors beyond the Emission Trading Scheme. To ensure the proper ambition in the emission reductions amongst the international partners of the EU, Carbon Border Adjustment Mechanism will be introduced with three years preceding period.

In energy, member states are to regularly submit their energy and climate plans, setting ambitious targets in energy and climate, respectively. Renewables are to play a crucial role in the energy sector, coupled with energy efficiency measures, to achieve decarbonization cost-effectively. The issue of energy poverty is to be addressed through financial programs aimed at home renovation. Despite the fact that Europe is already a global leader in the use of renewables in the DH [31], the latter is to be furthermore improved (in 2020, energy input of renewables reached 8%, primarily through the use of biomass). The interim target of the Green Deal of 55% of GHG emissions reduction by 2030 is embodied in the Fit for 55 Package of the EU. The plan includes establishing a Social Climate Fund, with EUR 72.2 billion allocated from 2025 to 2032 to mitigate the uneven effects of the Emissions Trading System on the transport and construction sectors. EU member states will create Social Climate Plans, and the Fund will support vulnerable groups, such as households and micro-enterprises, by promoting energy efficiency in buildings, decarbonizing heating and cooling systems, enhancing renewable energy integration, and increasing renewable energy use [49].

In the Green Deal itself, one of the critical areas of its attention is the topic of energy-efficient buildings renovation. The communications indicate that buildings account for 40% of the energy consumed, while the renovation rate of the building stock needs to be accelerated. The increased energy efficiency of buildings' "renovation wave" and climate-proofing of residential and commercial buildings are key pillars of the entire process, aiming to lower energy bills, diminish energy poverty, facilitate the construction industry, and create local jobs. It is recognized that the DH needs to be more digitalized. The waste heat should be more used, enabling more efficient and sustainable use of energy. The new Energy Efficiency Directive is a key factor indicating the amount of emissions possible.

The documents cited above also raise the issue of energy poverty [50–52]. In 2018, 6.8% of people in private households across the EU were unable to fully pay their utility bills, including energy costs, putting them at risk of disconnection. Additionally, 7.3% of the EU population experienced home temperatures outside comfortable limits [53]. A study in 2020 shows that this rate increased to 8%, with the main reasons being a high proportion of heating expenses in relation to the income received, energy inefficient buildings, and heating equipment with low efficiency [54]. In 2021, the problem of poverty is exacerbated due to a significant increase in the price of energy resources and energy [55]. Hence, the European Commission's recommendations to member states are "to give Union consumers, including households and businesses, secure, sustainable, competitive and affordable energy" [54].

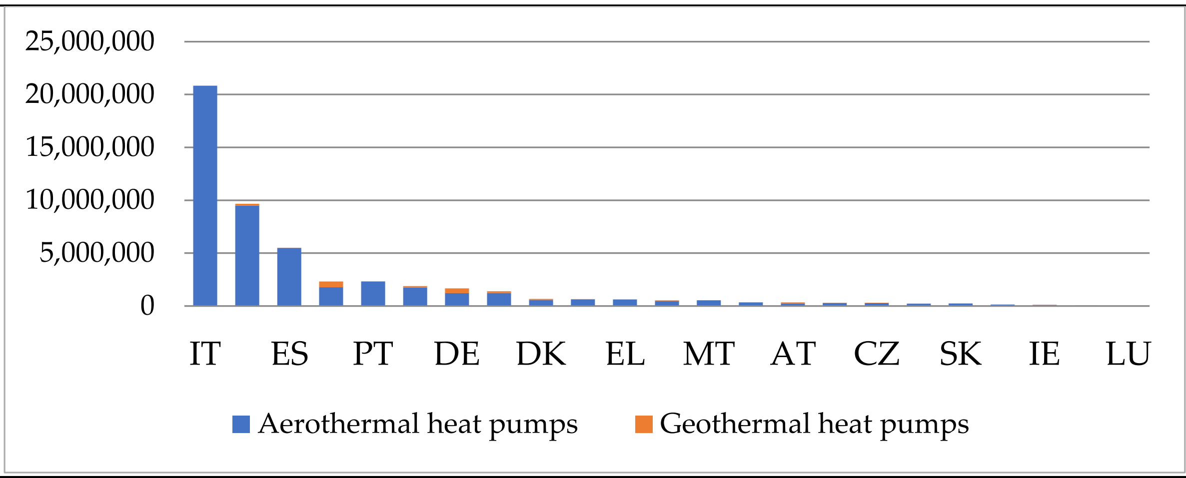
Studies from both macroeconomic [55,56] and microeconomic [57–59] perspectives demonstrate that fuel and energy prices are key factors influencing energy poverty, in addition to household income, needs, and habits, building energy characteristics, type of technology used, climatic conditions, and social policies. In addition, the phenomenon varies regionally, being more common in peripheral areas, mainly in rural areas of Southern and Eastern European countries [60]. An example of such a country is Poland, where the problem will intensify in the coming years due to the need to abandon the use of coal in heating. Hence, questions are increasingly being asked not only about technology, but also about the cost of replacing traditionally used conventional energy sources, since affordability is a major determinant of the rate of GHG emission reductions in this sector.

A very large potential for decarbonizing heating systems lies in the use of electricity as an energy carrier, primarily to power heat pumps [61–67]. This can be supported by the rapidly growing share of energy from renewable sources in gross electricity consumption. Between 2004 and 2020, this ratio increased from 15.9 to 37.5%. During the same period, the share of energy from renewable sources in total energy consumption increased from 9.6 to 22.1% [68]. The fact that the heat pumps will be a key technology for achieving the EU's goals for reliable, affordable, and sustainable heat supply was already pointed out in Directives 2009/28/EU, 2009/125/EU, and 2010/31/EU of the European Parliament and Council [67], and further confirmed in the 2020 communicate: Powering a climate-neutral economy: An EU Strategy for Energy System Integration [69]. According to this document, "In the residential sector, the share of electricity in heating demand should grow to 40% by 2030 and 50–70% by 2050; in the services sector, these shares are expected to be around 65% by 2030 and 80% by 2050". The primary factor in the popularity of heat pumps in many European countries is the relatively low capital expenditure. This is due to the fact that they are devices that use the heat contained in atmospheric air, which does not require additional expenditures, as is the case with the installation of heat exchangers in the ground. For installations with smaller capacities, the cost of making such intakes not infrequently exceeds the cost of purchasing the heat pumps themselves and then becomes the main item in the cost of the entire investment. From the data in Figure 2a, it can be seen that, in the countries of Southern Europe, mainly pumps using energy from the air were installed. In Italy, France, Spain, and Portugal, their share exceeded 95.0% of the total installed. In Central and Northern European countries, e.g., Germany and Sweden, it oscillated around 75.1%, and in Poland below 85.1%. In the period under review, the largest increase more than fivefold was recorded in Spain, Belgium, and France. The review of HPs spread in the EU-27 per capita (Figure 2b) reveals Malta as a leader in HP installation; Italy, Finland, Portugal, Sweden, and Estonia follow. This might indicate different approaches within these countries to promoting HPs, but it requires more studies on other factors that directly affect HPs, such as the lack/availability of other heating/cooling sources, price competition, and many other factors.

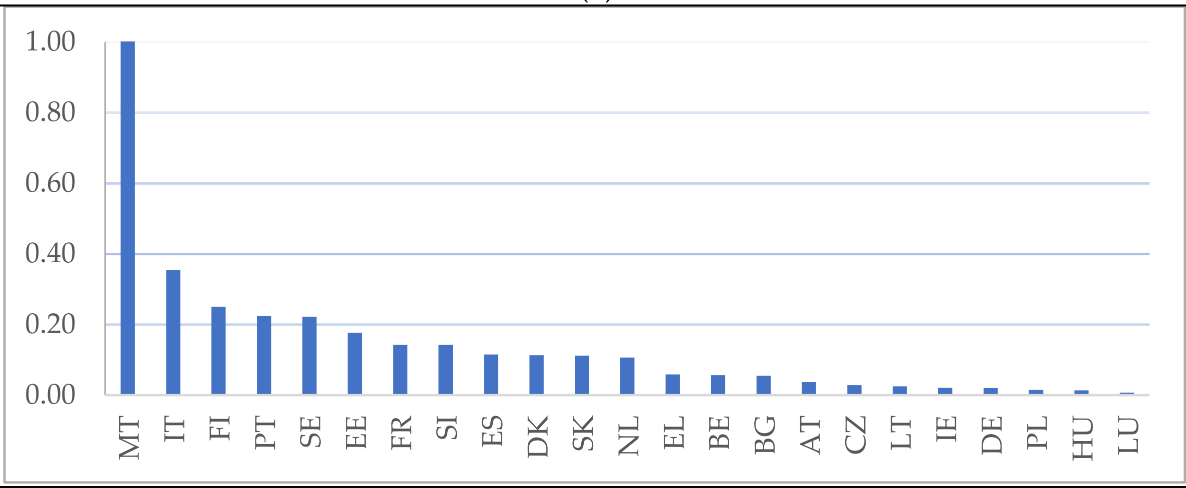
Despite notable quantitative growth, the share of heat pumps in the energy consumption structure for the heating and cooling sector in the EU27 in 2020 was only 2.94%. There was considerable variation, with values near zero in Romania, Lithuania, and Hungary, while Malta reached 15.2%, and Portugal, Sweden, Cyprus, and Greece saw around 10% (Figure 3a).

Per capita energy consumption from heat pumps for heating and cooling, as shown in Figure 3b, reveals that the highest consumption was recorded in relatively cold countries, such as Sweden, Finland, Denmark, and Austria, with Portugal as an exception. This may indicate that heat pumps are most efficient when used primarily for heating.

Due to the enforcing trend of urbanization, it is important to apply modern trends in urban and rural areas. In particular, the measures could include transitioning from one source of heat to multiple sources, from fossil fuels to renewables and waste heat, and from high temperatures to lower temperatures. Other measures should include the use of climate-neutral refrigerators, thermal storage, and waste heat recovery.



(**a**)



(**b**)

Figure 2. Total number of heat pumps in operation in 2022 in the European Union (**a**) and per capita (**b**). Own calculations.

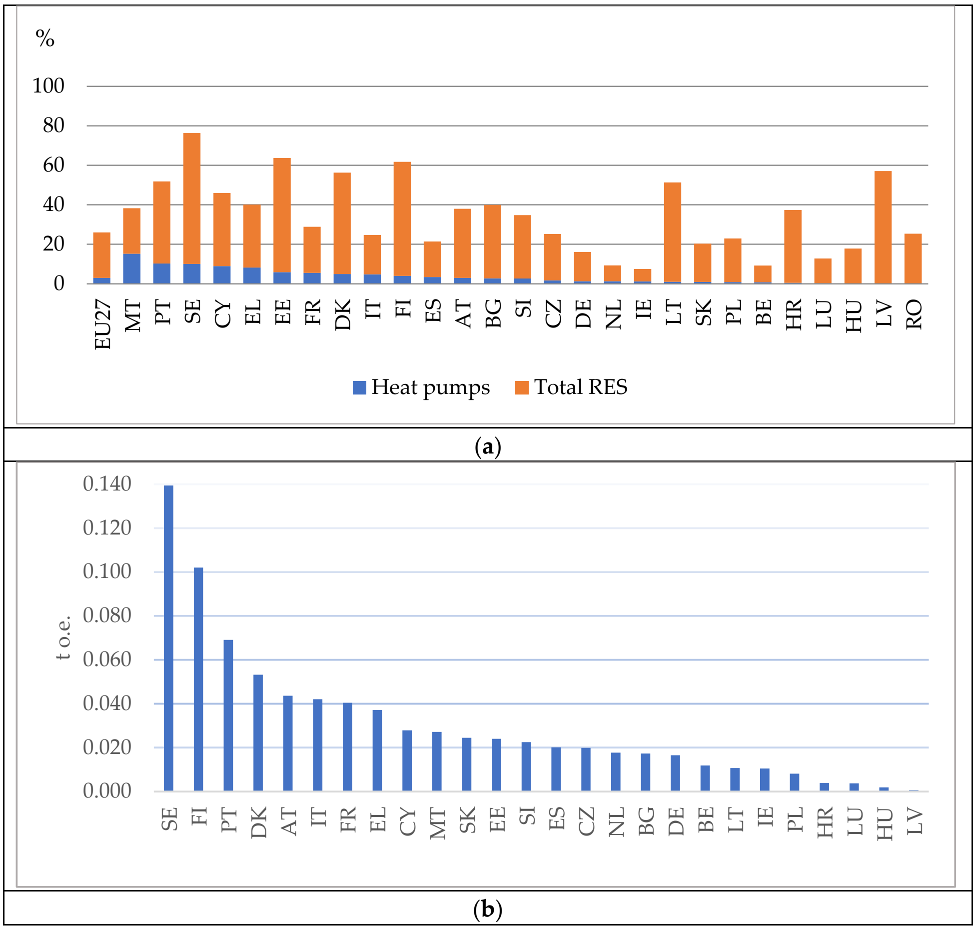


Figure 3. Share of energy from renewable sources for heating and cooling, with particular emphasis on heat pumps in 2020 (**a**) and per capita (**b**). Own elaboration based on [70].

3. Results

3.1. The Experience of Poland with the Heat Pumps

The implementation of ambitious plans as enshrined in, among others, the European Green Deal or "Fit for 55", involves the almost complete elimination of GHG emissions in the energy sector, which may pose a very big challenge for some member states. This also applies to Poland's energy system, which has one of the highest CO_2/TES emission rates from fuel combustion among the EU27 countries (Figure 4).

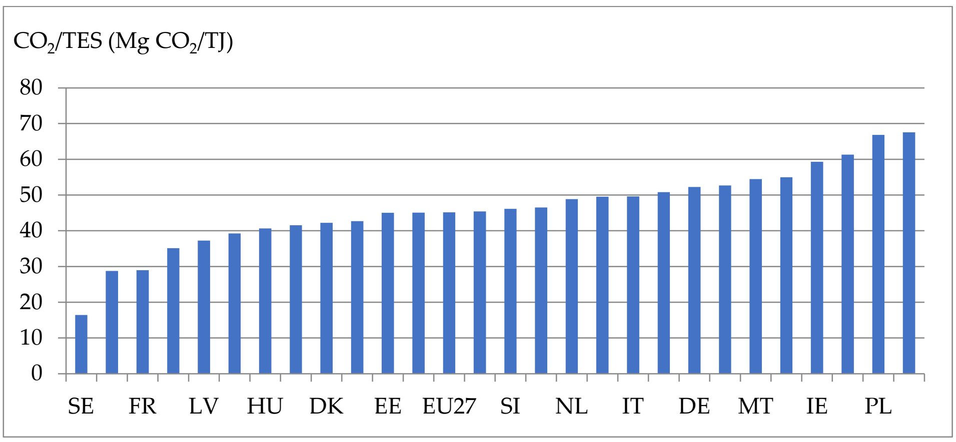


Figure 4. CO_2 emission factors per unit of total energy supply (TES) in 2019 (Mg CO_2/TJ). Own elaboration based on [71].

This is primarily because of the large proportion of domestic raw materials, such as hard coal and lignite, in the energy mix [72]. In 2019, these fuels accounted for 42.2% of the total energy demand, the highest share among the EU27 countries (Figure 5) [73].

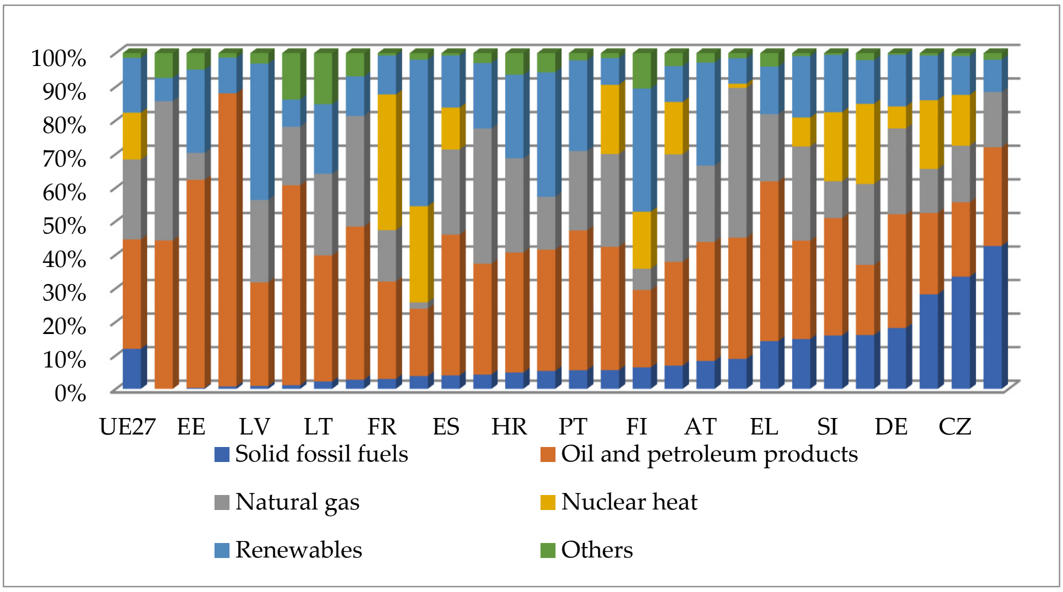


Figure 5. Total energy supply by product in 2019. Own elaboration based on [73].

In the context of the need to reduce GHG emissions, Polish households, which in 2019 accounted for more than 75% of the solid fossil fuels (mainly coal) consumed in this sector in the EU27, face a very big challenge (Figure 6).

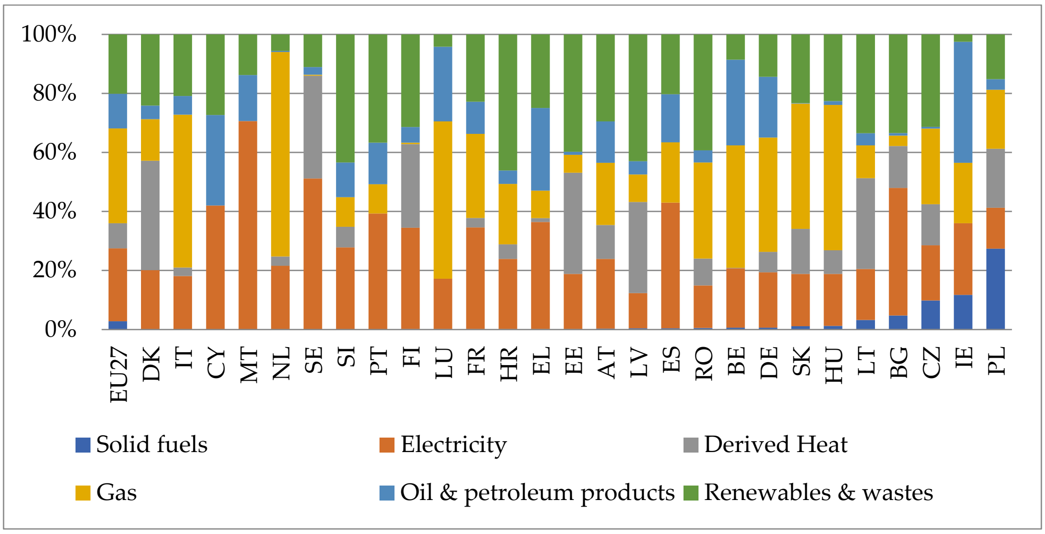


Figure 6. Share of fuels in the final energy consumption in the residential sector, 2019 [74].

In the "Energy Policy of Poland until 2040", it is stipulated that "If in a given area there is no possibility of connection to the district heating network, heating needs should be covered by individual sources with the lowest possible emissions, especially: installations of non-combustible RES (including heat pumps), electric heating, gas installations, installations using non-smoke fuels" [75]. Given the low access to transmission infrastructure for DH and gas networks in rural areas, which in 2017 was 1.7% (share of heat sales) and 23.3%, respectively [76], in these areas, heat pumps should be one of the main sources supplying heating systems in both individual and collective housing as well as in the service and manufacturing sectors.

Spreading the use of such a system can significantly reduce the concentration of particulate matter levels (PM10 and PM2.5) and benzo(a)pyrene in the air, which poses a serious threat to public health. Poland is still one of the European Union countries with the worst air quality. Maximum average annual concentrations of particulate matter were nearly double the permissible limits. Due to persistently high particulate matter levels in the air, the European Commission took legal action against Poland in the EU Court of Justice in 2015 for failing to address poor air quality. The Commission determined that the legislative and administrative measures implemented to date were insufficient to curb these emissions. As of 1 December 2020, there were 31 infringement proceedings pending against 18 member states for either exceeding concentration limits or inadequate monitoring of air pollutants. Ten of these cases were referred to the Court of Justice of the European Union, five of which (including Poland) resulted in rulings [77,78]. The latest Clean Air Outlook report indicates that member states will need to intensify efforts to meet their 2030 emission reduction targets under the NEC Directive [79]. To meet these targets, Poland and some other countries will need to reduce their PM2.5 emissions by half compared to 2018 levels [80].

In Poland, despite a more than twelvefold increase in the number of heat pump installations between 2011 and 2022, heat production from these systems increased more than fivefold (Table 3).

Table 3. Number of operating heat pumps in Poland in 2011–2022 [70,81,82].

Specification	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Aerothermal	3450	5445	6699	9007	21,982	45,361	61,731	81,636	112,950	167,075	257,458	466,032
Ground	15,500	20,621	25,763	31,038	36,605	41,995	47,655	53,486	60,196	65,818	71,468	78,989
Total	18,950	26,066	32,462	40,045	58,587	87,356	109,386	135,122	173,146	222,893	328,926	545,021
Output of ambient heat [TJ]	2337	2854	3627	4577	5566	6570	7683	8958	10,681	12,481	15,496	21,757
Consumption of energy by heat pumps [TJ]	872	1057	1333	1823	2521	2979	3508	4112	4898	5720	7101	9949
Seasonal Coefficient of Performance	2.68	2.70	2.72	2.51	2.21	2.20	2.19	2.18	2.18	2.18	2.18	2.19
Share of heat pumps in obtaining energy from RES (H&C) [%]	1.1	1.3	1.6	2.2	2.5	2.8	3.2	2.4	3.0	3.5	4.2	6.2
Share of heat pumps in the H&C sector [%]	0.15	0.18	0.23	0.31	0.38	0.42	0.48	0.52	0.65	0.78	0.98	1.34

A key factor was the evolving composition of installed equipment. While in 2011, the share of pumps using air as the lower heat source was 18.2%, by 2022, this figure had risen to 85.6%. However, the Polish heating sector remained significantly different from the rest of Europe in terms of pump types, with a much lower proportion of installations utilizing distributed thermal energy stored in ambient air for heating. As a result of these changes, the seasonal energy efficiency coefficients decreased by approximately 20%. This suggests that pumps utilizing atmospheric air for heating purposes are less efficient under Polish conditions compared to those using thermal energy stored in the ground or groundwater.

In 2019, the program "My Electricity" [82] was launched in Poland, offering subsidies for solar PV; in 2022, energy storage and solar thermal collectors were added. In 2023, heat pumps were added, and the program remains valid. The program allows a subsidy of EUR 12,322 per project. In 2022, the prices for coal for heating purposes in Poland went up fivefold, accompanied by high demand and depleting stock; similar was the case with natural gas. It made people look for substitutes for fossil fuels.

In 2018, the "Clean Air" [83] program started in Poland, presuming to upgrade coal stoves to more environmentally friendly energy technologies and improve house insulation. It anticipated grants up to EUR 15446, covering up to 50% of the upfront costs (the lower the household income, the higher the subsidy amount) [84]. Seven banks provided loans for the thermo-modernization of the houses. Notably, the urban population benefited from the program, yet the dissemination among the rural population was lower. As a result of the program, many households installed more advanced coal heaters, natural gas heaters, and heat pumps. The program made the payback period for the heat pumps about three years. Earlier in 2021, another program, "Polish Deal", was introduced, aimed at combatting the pandemic effects on the economy and creating the preconditions to strengthen the middle class. From 2018 to 2022, more than USD 30 billion was invested in Poland to implement low-carbon technologies. As of 2024, Poland aims to become a manufacturing hub for heat pumps, with Bosch, Daikin, and others launching factories to produce heat pumps in Poland. Shortage of heat pumps is a significant factor that restricts the market development. Additionally, in 2024, Poland made the requirements to obtain the lone stricter, favouring heat pumps produced in Europe [85].

According to the International Energy Agency, energy-related CO_2 emissions of Poland in 2022 reached 285 Mt CO_2 [86], while respective emissions of Ukraine reached 101 Mt CO_2 [87]. Although Ukraine has nuclear energy and Poland does not, comparing the two countries is possible due to their geographic proximity, similar population before 2022, similar climatic conditions, and reliance on fossil fuels for heating and electricity generation. For instance, in the total energy supply in 2022, the ratio "shares of coal/oil/natural gas" was "36.1%/32.6%/16.2%", while in Ukraine, it was "21.7%/18.6%/25.1%". Poland and Ukraine adopted their National Energy and Climate Plans until 2030 (in 2019 and 2024, respectively), reflecting their carbon strategies. To date, Poland continues to rely on coal, yet strives to increase the share of renewables, enhance energy efficiency, and increase carbon absorption by forests. Despite Poland's carbon intensity being 172% above the EU's average, it decreases much faster than the EU [88]. Due to the European integration aspirations, Ukraine attempts to align its carbon policy with the respective European legislation, e.g., it adopted the target of reaching carbon neutrality by 2050 [89]. Ukraine's energy intensity of economy decreased by 51% in 2023 compared to 2020; the country is developing renewable energy and attempting to implement energy efficiency measures. In 2023, Poland's energy independence was estimated at 53.4% [90]; Ukraine's data are unknown due to martial law. Both countries have skilled workforces to operate energy facilities, yet Ukraine faces a severe deficit of people.

3.2. Challenges of Heat Supply in Ukraine

DH in Ukraine is one of the good legacies of the former Soviet Union. Since then, numerous measures have been undertaken to maintain its condition. However, DH faces an extensive array of daily problems and challenges. The biggest challenge is the destruction of 93% of CHPs, 42% of block thermal power plants, and 72% of non-block thermal power plants (as of May 2024).

The other challenges have been accumulating for many years before 2024. Below, we consider these challenges in greater detail:

- Obsolete equipment of heat supply companies and worn-out heating networks. They were periodically repaired, but without noticeable effect. The vast majority of the equipment was installed during the existence of the USSR. Therefore, the equipment is inefficient: it consumes more energy, is expensive to repair, and pollutes the environment. All energy enterprises need to be modernized and replaced with more modern equipment. It is also the case for the heating networks. Pipes are periodically changed in small areas but must be replaced. Such works require significant investments, which are currently insufficient. On the part of heat supply companies, these are obsolete networks and constant breakthroughs, and as a result, consumers are very often disconnected from the service. Due to heat losses on the main and distribution pipelines, the efficiency of Ukrainian CHPs is 40–45% [91]. About 75% of Ukraine's housing stock was built in the 1990s when energy efficiency requirements were not given due attention. More than one-third of residential buildings needed thermal modernization and major repairs [92];
- High cost of heat, which is reflected in the bills during the heating season. Even though natural gas of domestic extraction is used in Ukraine for DH, overall, this energy source becomes less and less affordable every year;

- Paternalistic moods and lack of tradition to care for common areas in Ukraine mostly lead to the lack of proper care for both the house and engineering systems, coupled with social factors such as interference with the heating system and replacement of radiators [92];
- The insufficient number of heat metering devices and lack of technical capacity for consumers to manage thermal energy consumption. Additionally, the energy intensity of services is 2.5–3.0 times higher than that in developed countries [91];
- Inconsistency of actual temperature schedules of heat supply to the designed temperature schedules. Designed schedules are inscribed in the regime maps of equipment operation; these temperature graphs determine the parameters of the heating system when issuing technical conditions for connection to networks, installation of heat meters, and individual heating points. At the same time, most DH systems operate on low relative to the design temperature schedules. Still, the actual coolant temperatures of heating networks do not meet even these conditions [91].

All the mentioned factors lead to the popularity of individual heating in apartments. However, it is not a good solution because, in old houses, the exhaust can be taken out into the street, which worsens the environmental situation in cities. Over the last 15 years, 45% of district heating in Ukraine has been lost [93].

Several financial programs are active in Ukraine as of 2024 to enable changes in heat supply. The one most relevant to the heat pumps is called "Green DIM" (Green House), anticipating the installation of heat pumps by the Homeowners Associations and Construction and Housing Cooperatives. Within the program, 70% of the equipment investment costs are reimbursed, and the reimbursement amount does not exceed EUR 43,367 per project. However, reimbursement is possible only after the equipment has been installed. This means that this instrument does not really cover the problem of the lack of funds; additionally, only a quarter of multiapartment buildings in Ukraine organized homeowners associations [93].

3.3. Modelling Results

We modelled five scenarios of the above sensitivity groups as follows: Scenario #1—lower estimation of the HP CAPEX, Scenario #2 (core)—medium estimation of the HP CAPEX, Scenario #3—higher estimation of the HP CAPEX, Scenario #4—50% of the default biomass potential availability and core HP CAPEX, and Scenario #5—10% of the default biomass potential availability and core HP CAPEX (as in the matrix below, presented in Table 4).

Table 4. Scenario matrix.

	Lower Estimation on HP CAPEX	**Medium Estimation on HP CAPEX**	**Higher Estimation on HP CAPEX**
Default biomass potential	Scenario #1	Scenario #2	Scenario #3
50% of the default biomass potential		Scenario #4	
10% of the default biomass potential		Scenario #5	

3.3.1. Implications for the Energy System

In all our five modelling scenarios, we use the exogenous concave GHG emissions reduction trajectory, which envisages net zero emissions by 2050 in the energy and IPPU (industrial processes and product use) sectors, considering more mitigation efforts are applied in the first two decades (Figure 7).

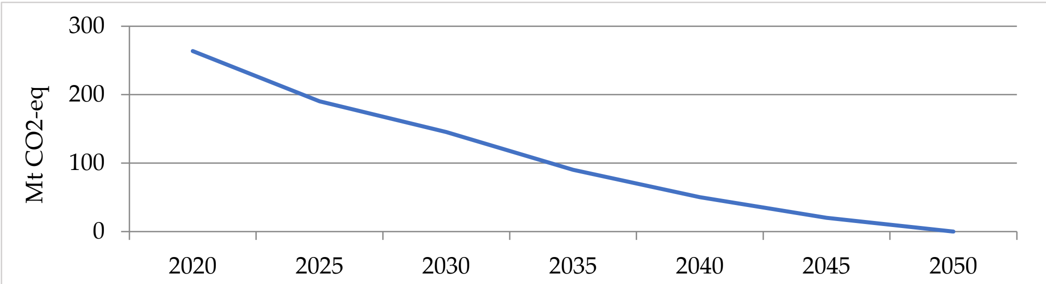


Figure 7. The GHG reduction trajectory in all scenarios, Mt CO_2-eq.

Reaching such ambitious mitigation targets requires significant energy system transformation in all cases. There is a need for 28 to 30 Mt of CO_2eq of negative emissions in 2050, which in scenarios #1–4 are supplied to a large extent by bioenergy and carbon capture and storage (BeCCS) plants (−24 to −19.7 Mt) and −6.4 to −7.6 Mt by CCS in hard to abate industries. In #5, however, BeCCS supplies only −0.76 Mt, while in industry, CCS has to provide −16.4 Mt and raise DAC an additional −12 Mt of CO_2eq.

Results show a substantial growth in electricity generation and installed capacities (Figure 8). Across CAPEX sensitivity scenarios (#1–3), the difference in dynamics is in place. Still, it is negligible, whereas biomass sensitivities demonstrate 11.4% and 26.5% higher electricity generation in #3 and #4, respectively, compared to the core scenario and 6% to 8% more capacities due to shortage of biomass. The difference in capacities between #1–3 and #4–5 is mainly caused by the commissioning of new big nuclear reactors (up to 5.5 GW in #4 and 20.7 GW in #5) and more energy storages and offshore wind as economy demands significantly more power in light of the absence of biomass and the renewable potentials of photovoltaics and onshore wind, which are set in exogenous manner for each period, are fully utilized in all scenarios (85 GW of PV and 44 GW of onshore wind). Small modular reactors in the size of 6.4 GW, which is an exogenous limit, are appearing in all scenarios. Decarbonization of the heat and power sector in #1–3 occurs after 2030, in #4 after 2035, and in #5 after 2040, signalling the importance of biomass in this process.

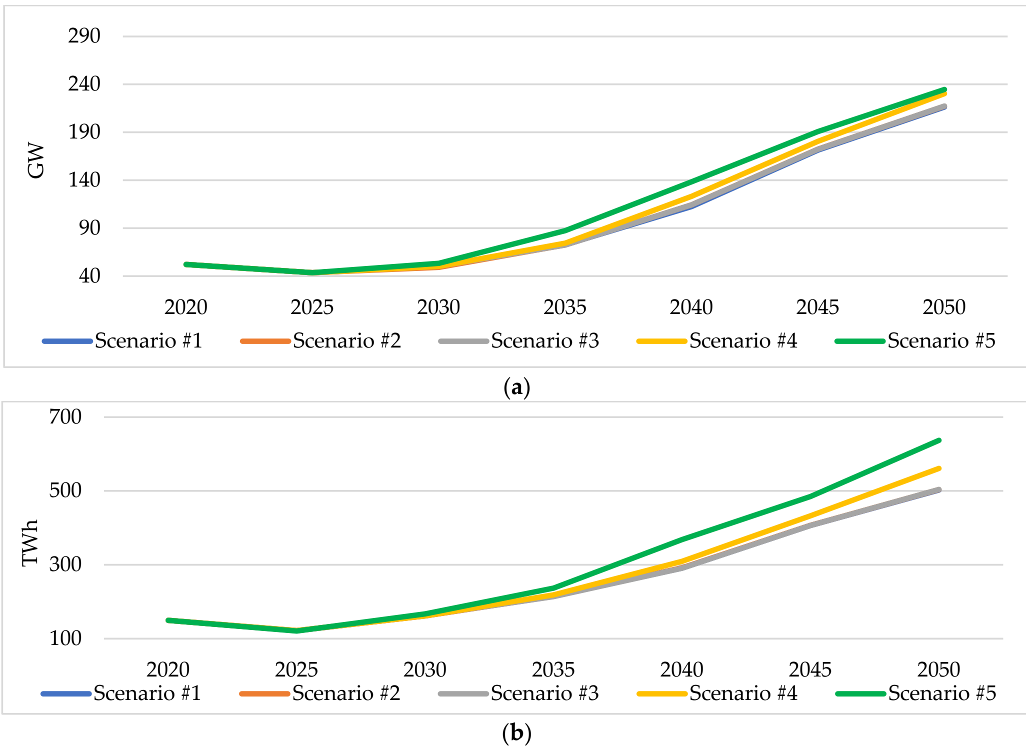


Figure 8. Electricity generation, TW (**a**) and installed capacities and (**b**) dynamics across all scenarios.

A shortage of available biomass might result in up to 10% lower final energy consumption in 2050 compared to scenarios where it can be freely utilized owing to electrification and more extensive energy efficiency measures, including heat pumps. Less than 1 Mtoe of fossil fuels is left in #5's final energy consumption and about 2 Mtoe in #2 (Figure 9).

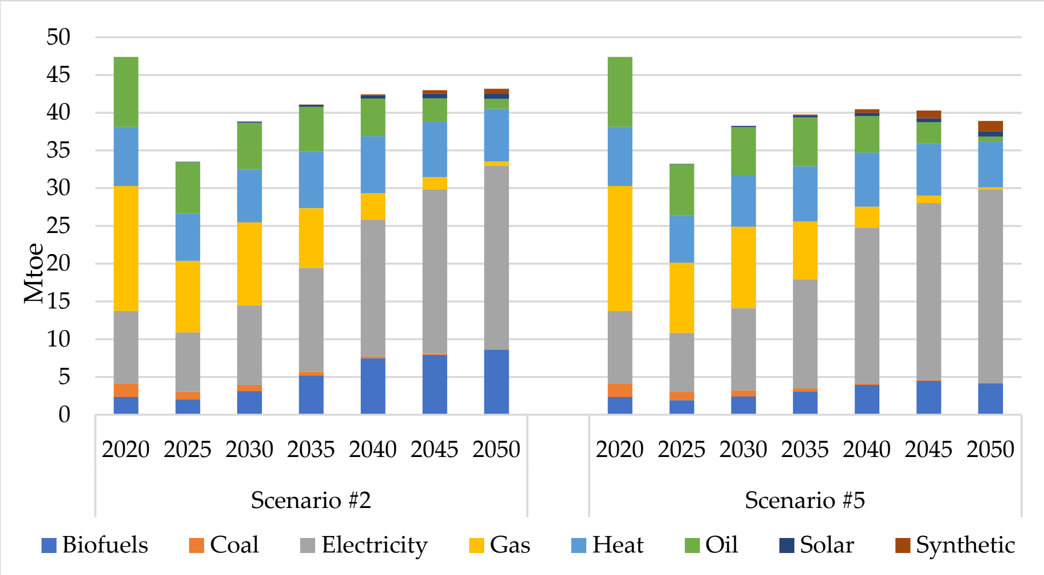
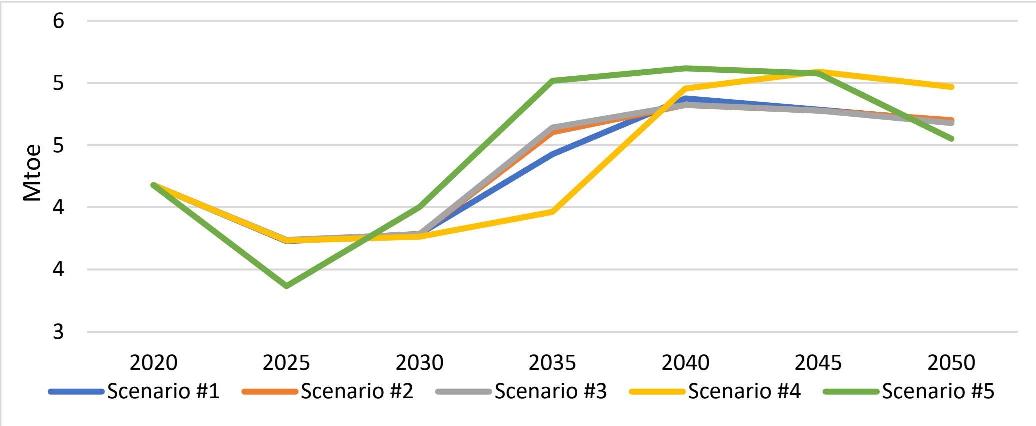


Figure 9. Final energy consumption by fuels in scenarios #2 and #5, Mtoe.

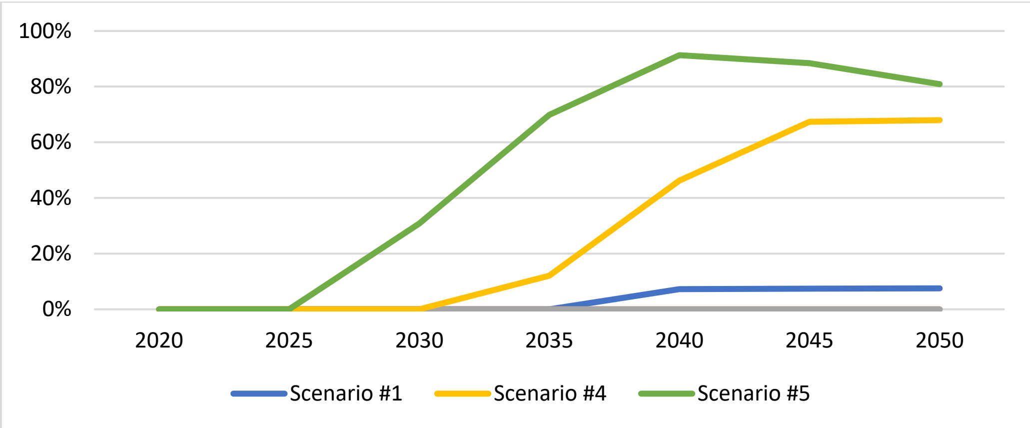
3.3.2. Heat Pumps in DH

Total district heat generation by all sources is shown in Figure 10a. The trajectory for #1–3 rises by about 12% compared to 2020, and in 2035, minor deviations occur. Of the first sensitivity group, DH HPs appear only in #1 with the lowest capital expenditure assumption, superseding some portion of the biomass heat-only plants' share and reaching 7% of the total heat production (Figure 10b). In the other two scenarios of this group, the DH mix is dominated by biomass-fuelled heat-only plants and CHPs. The second sensitivity group, on the other hand, demonstrates very different dynamics, which is explained for #5 by lower biomass-based generation in 2025, rapid commissioning of DH HPs plants in 2030–2040, and lower heat output from gas CHP and TPP in 2050 (which by that time operate on biomethane) compared to #4. The commercial buildings sector consumes less district heat in #5, and with more extensive thermomodernization, it results in a drop in total generation in 2050. The DH HPs share in total heat generation in #4 and #5 are incomparably higher compared to #1, which means that it would be a pretty complicated task for large DH HPs to maintain competitiveness with bioenergy-based district heat-producing technologies, especially cogeneration plants in case if biomass is utilized with no obstructions.

Direct substitution of CHP with HPs in DH is hardly possible because CHP works at much higher temperatures than HPs. Our findings indicate that the DH system would continue to exist in Ukraine without further significant growth, though. The new buildings that have not been previously connected to DH would have a possibility of using HPs; thus, integration of HPs into DH is not anticipated to be a widespread practice. In case such a necessity emerges, significant investments are needed to enhance energy efficiency and update the infrastructure, such as the renewal of insulation and pipelines to enable them to work at lower temperatures.



(**a**)



(**b**)

Figure 10. Total district heat generation by all sources (**a**) and share of DH heat pumps in it (**b**).

3.3.3. Heat Pumps Individual in Building Subsectors

Overall, in absolute and relative numbers, space heating covered by individual heat pumps grows in every building subsector in every scenario (Figure 11); however, it grows slightly differently (Figure 12). Across all scenarios, commercial buildings in relation to the heat pump penetration show rather an insensitive picture (Figure 12 upper left and right). The massive uptake of HPs is only expected for large commercial buildings if biomass is scarce. In small commercial buildings, the penetration of HPs could reach a maximum of 16.5% and a bit less if the CAPEX is higher. However, the share declines to 10% as ultimately more attractive for all commercial buildings with the centralized heating. Albeit this is where DH HPs could take part, given HPs obtain supportive mechanisms or the biomass market is underdeveloped.

Residential single-family buildings display the same conceptually insensitive response to the changing parameters (Figure 12 lower left and right). In the case of low capital expenditures, the uptake of heat pumps might be more rapid than in all other cases, and urban single houses are keener to implement this in the coming decade. On the contrary, high investments needed cannot change too much the attractiveness of this technology for space heat in the course of low-carbon development, given that central heating covering will not expand. The heat pumps outperform biomass heating appliances and possible biomethane-sourced gas boilers even in scenarios where biomass is available. From Figure 13, we can grasp the scale of energy efficiency implementation and change in the structure of commodities consumed to satisfy the space heating demand in the building sector in the core scenario and #5. Compared to 2020, energy consumption can be 32% lower in the core scenario and 40% lower in scenario #5, and in both cases, it consists only of electricity and district heat complemented with a 3% share of solar input by the moment of achievement of carbon neutrality. In both cases, the share of space heat in the total final energy consumption in 2050 equals 16% compared to 22% in 2020.

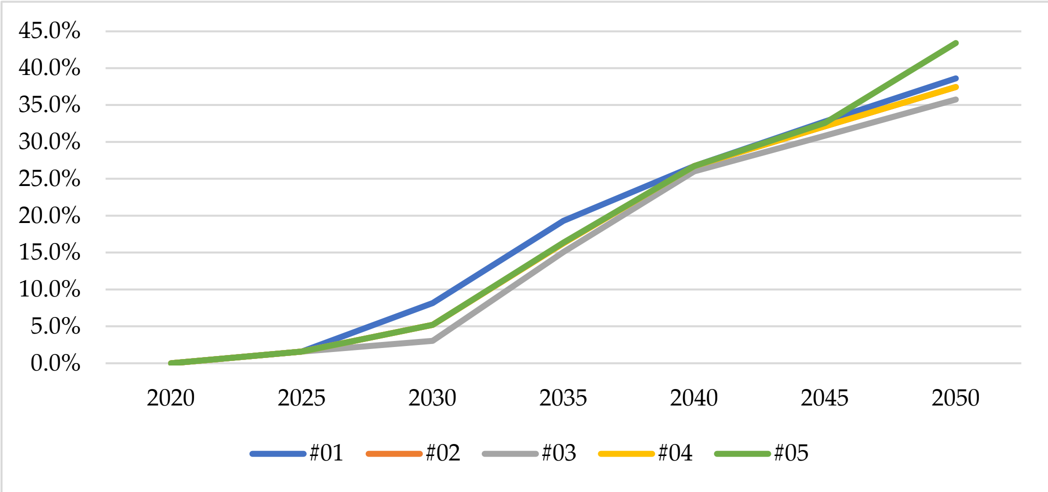


Figure 11. Share of covered space heating demand by individual heat pumps in building sector overall.

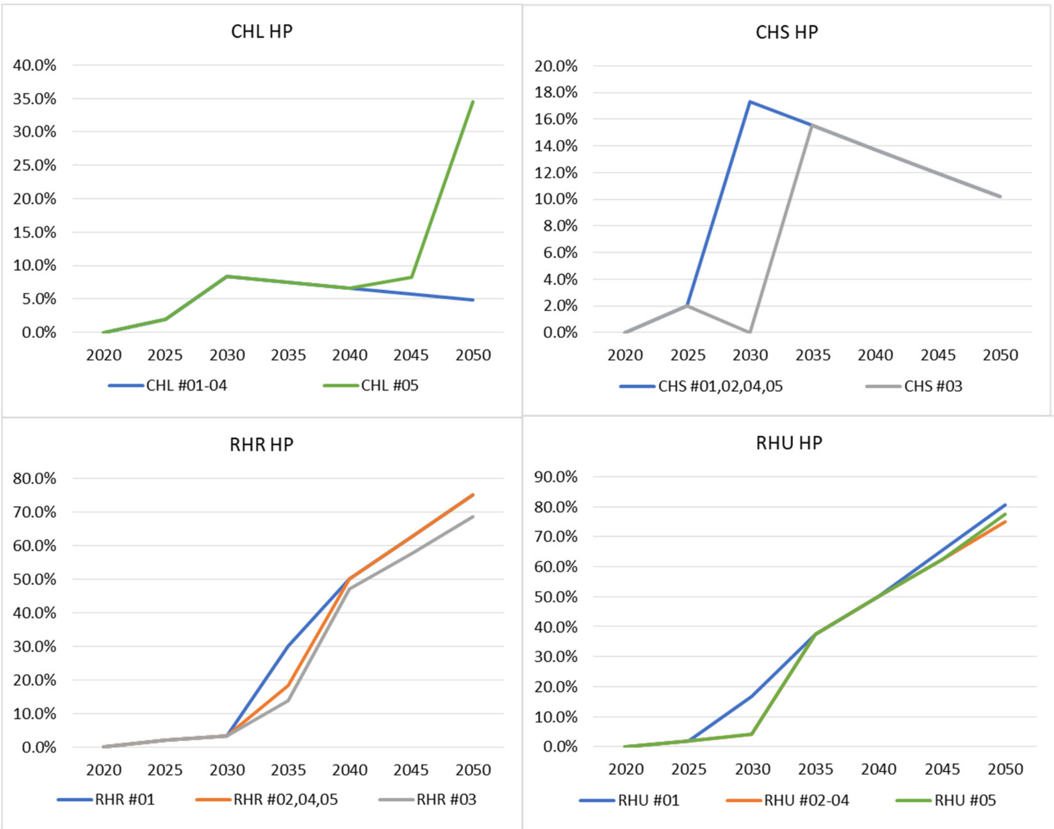


Figure 12. Share of covered space heating demand by individual heat pumps in building subsectors: commercial large buildings (**upper left**), commercial small buildings (**upper right**), residential rural single houses (**lower left**), and residential urban single houses (**lower right**).

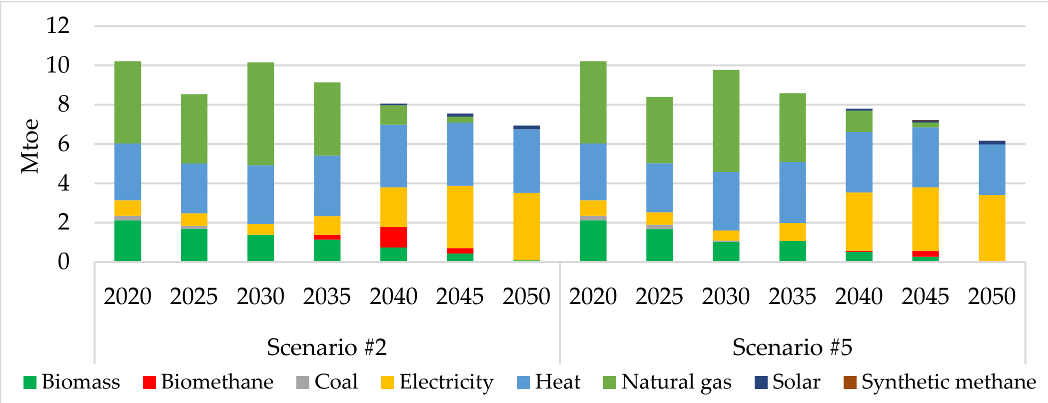


Figure 13. Final energy consumption in the buildings sector for space heating only by fuels in scenarios #2 and #5, Mtoe.

4. Discussion

In scenario #5, heat generation by nuclear plants grows fivefold to 732 Mtoe in 2050, which is 16% of the total DH production. Small reactors account for about 25% of the total, and we can theoretically assume their installation near potential consumers, but it is unclear whether there would be so much heating demand in satellite cities of large reactor plants.

The findings of this study are directly related to the current energy policies in Ukraine and the EU. As mentioned in Section 2.2, the EU set an ambitious legislative framework to transition to low-carbon energy sources. Ukraine attempts to align its legislation with the energy acquis. The study confirms that using HPs is possible in Ukraine, especially in the long run, and it fully aligns with EU legislation. The deployment of HPs may decrease dependence on imported fossil fuels, which is crucial for Ukraine's integration into the EU energy markets and essential to Ukraine's EU integration aspirations.

The significance of the research in the broader context of low-carbon energy transition in Europe is that Ukraine has the ambition to join the EU and reach carbon neutrality, which meets the European aspirations of decarbonization. Abandoning fossil fuels and meeting the energy demands for heating would enhance the security of Ukraine's energy supply and Europe in general. With the spread of renewables, heat pumps may operate using electricity from renewables. Even though the conducted study focuses on Ukraine, it can be well-embedded into the European energy transition towards low-carbon energy and economy.

Skills and supply chain development are crucial for developing the HPs market in Ukraine. The skills development system could anticipate, but not be limited to, teaching engineers and constructors to build HPs; professional education is needed to train people to install and maintain the equipment. Specialist certification is required to confirm the proficiency of experts. Supply chain development is crucial for the import and domestic output of equipment. Both require investment in expertise and the development of logistics infrastructure.

There are many potential directions for future economic studies on the spread of HPs in Ukraine. These may include, but are not limited to, the adoption of air-to-ground HPs in Ukraine (as this technology is more costly than air-to-air systems); the most effective support schemes for HPs (such as capital grants, loan interest rate reimbursement, tax rebates, or combinations thereof); the impact of HPs on energy security, along with an analysis of factors that may negatively affect energy security (e.g., interrupted electricity supply); social and environmental benefits, such as the monetization of improved health and reduced expenditures on sick leave and work incapacity; regional differences in technology adoption; and other related areas.

5. Conclusions and Policy Recommendations

One of the priorities not only of the European Green Deal and the "Fit for 55" package, but also of global climate agreements, is the decarbonization of heating and cooling by, among other things, replacing conventional fuels used for these purposes with energy from renewable sources. National and international scientific consortia research shows that the most significant potential for decarbonizing heating lies in using electricity as an energy carrier, primarily to power heat pumps. It concerns not only GHG, but also particulate matter (PM10 and PM2.5) and ana(a)pyrene, which pose a severe threat to public health.

In general, decisions on the choice of the heating method are made based on economic attractiveness, and this depends on the available technologies, the capital expenditure incurred for their implementation, their operating costs, and the support mechanisms promoting both the use of renewable energy sources and energy efficiency. To enable poles to switch to heat pumps, the government of Poland offers a generous subsidy, allowing the HPs to pay back in three years. The quick spread of heat pumps became possible due to growing prices for fossil energy sources, coupled with geopolitical risks. The government introduced several efficient financial programs, offering significant subsidies for the new equipment, including the heat pumps. Lowering the investment costs became a substantial impetus for households considering the installation of heat pumps.

Modelling results indicate substantial growth in electricity generation and installed capacities in Ukraine by 2050. The decarbonization of the heat and power sectors is projected to occur after 2030–2040, depending on the scenario, highlighting the critical role of biomass in this process. A shortage of available biomass could lead to up to 10% lower final energy consumption by 2050, compared to scenarios where biomass is readily available, as electrification and energy efficiency measures, including heat pumps, are more widely adopted.

In DH, large district heating heat pumps are not expected to compete with bioenergy-based heat production technologies, especially cogeneration plants, if there are no restrictions on biomass use. For individual heating, whether in urban or rural areas, space heating with individual heat pumps grows across all building subsectors in every scenario. However, a significant uptake in heat pumps is only expected for large commercial buildings if biomass becomes scarce. In small commercial buildings, heat pump penetration could reach a maximum of 16.5%, though this drops to around 10% if capital expenditures are higher, as centralized heating becomes more attractive. Residential single-family buildings exhibit a relatively stable response to varying parameters. In cases of low capital expenditure, heat pump adoption could accelerate more quickly, particularly among urban single-family houses in the coming decade. Conversely, high investment costs do little to reduce the appeal of this technology for space heating in the context of low-carbon development, as central heating coverage is unlikely to expand. Heat pumps outperform biomass heating appliances and potential biomethane-sourced gas boilers, even in scenarios where biomass is available.

The following recommendations could be suggested to ensure the broader deployment of heat pumps in Ukraine:

- Conduct broad information campaigns about their benefits and the long-term financial program.
- Introduce a special (reduced) rate for electricity for heat pumps.
- Simplify the permitting procedures to replace the heating system.
- Conduct information campaigns on the benefits of new technologies and the available options.
- Improve the statistics and data gathering, disclose not time-sensitive statistics.
- Promote research and development (R&D) in the energy sector, encouraging institutes within the Academy of Science of Ukraine, research centres of universities, and private companies to explore potential studies in modern technologies and local climate adaptation, especially the technical and economically feasible potential of modern technologies; adjustment of the imported equipment to the local climatic conditions in

Ukraine, especially bearing in mind the climate change (as the DH equipment has a relatively long exploitation time).

Supplementary Materials: The following supporting information can be downloaded at: https://docs.google.com/spreadsheets/d/1-wH2T5bnElgPdqnvthVEPKZLpvqf06Pt/edit?gid=1444791333#gid=1444791333 (accessed on 14 November 2024).

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