elementenergy

The Consumer Costs of Decarbonised Heat

Executive summary

for

BEUC

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Element Energy Limited
Suite 1, Bishop Bateman Court
Thompson's Lane
Cambridge
CB5 8AQ

Tel: 01223 852499

EU wide key messages

Introduction

- This study analyses the cost to consumers of low carbon heating options in the year 2040 in four European countries: Spain, Italy, Czechia, and Poland. We have investigated four archetypal homes in each country and present detailed results for two of these archetypes, typical older (pre-1970) single-family homes and more modern (post-1970) flats in multi-family homes. Detailed results are available in the companion reports prepared for each country as part of this project.
- We have examined four low carbon heating options within these archetypes: heat pumps, hybrid heat pumps, green hydrogen boilers, and low carbon district heat networks.
- 2040 electricity costs are predicted for each country using the Element Energy Integrated System Dispatch Model (ISDM), which predicts electricity system operation on an hourly basis, and utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system when high levels of variable renewables are connected. We assume the electricity grid in each country has significantly decarbonised by 2040 in line with 2050 net zero targets.
- Green hydrogen costs are estimated using Element Energy's green hydrogen costing tool. This includes country-specific renewable generation profiles and projections for the 2040 cost of hydrogen production technologies, as well as estimated costs for the distribution of hydrogen through the converted gas network.

Low carbon heating

- Heat pumps provide the most cost-effective route to decarbonisation of home heating across the countries and dwelling archetypes analysed.
- Across the four countries investigated, using hydrogen boilers for heating in single-family homes is estimated to be 60-120% more costly than using heat pumps and 50-80% more costly in multi-family homes.
- Hybrid heat pumps are more affordable than hydrogen boilers. The heat pump component is assumed here to meet 80% of the total heat demand, and the hydrogen boiler component is assumed to meet the remaining 20%, in the highest demand hours. In warmer countries like Spain and Italy, hybrid heat pumps tend to be more expensive than heat pumps by 30-40% in single-family homes, due to the low heat demand preventing the additional capex to be paid back. In colder countries like Czechia and Poland, hybrid heat pumps are expected to have similar annualised costs to heat pumps in single-family homes. In multi-family homes, hybrid heat pumps lead to an increase in costs by 20-40% compared to heat pumps across all countries investigated. Although usually more expensive, there may be a role for hybrid heat pumps in hard-to-decarbonise dwellings (most likely older and larger homes) which are connected to the gas network, provided that the technical challenges of retrofitting the gas grid to deliver hydrogen are overcome. There is also a risk that hydrogen used by hybrid heat pumps could be more expensive than estimated here if the majority of households adopt fully electric systems and the gas network is maintained although used by relatively few households.
- One limitation of using hydrogen for heating is that it is reliant on the existence of a hydrogen network. This could be a repurposed existing gas network or a new bespoke hydrogen network. No more than 40% of dwellings are currently connected to the gas grid in any of the countries analysed, with this number dropping to only 10% in Poland, highlighting a possible infrastructural risk for using hydrogen for heating on a large scale.

- Although heat pumps have a larger up-front cost than hydrogen boilers, we expect that the running costs of these will be significantly lower than other options for decarbonising heating. This means there may need to be some policy support in place (such as direct grants, affordable green loans and green mortgages) so that consumers are enabled and incentivised to purchase these high capex appliances.
- The results shown are consistent with the other two archetypes investigated in each country (post-1970 single family homes and pre-1970 multi-family homes). The archetypes are representative of typical homes but do not capture the full diversity of the European housing stock. Some segments of the housing stock may be unsuitable for heat pumps due to high heat loss and barriers to the installation of additional energy efficiency measures.

Energy efficiency

- Installing energy efficiency can provide cost savings to consumers in some cases, and comes with additional benefits for health, thermal comfort, and system flexibility.
- Deep retrofit is expected to be cost-effective in single-family homes in countries with low cost of heat demand saving in €/kWh such as Poland or Czechia. This is typically countries in colder climates but also includes other countries such as France or Germany.
- In some cases, energy efficiency retrofits will not pay back in energy bill savings alone. However, increasing the rate of energy efficiency rollout above current targets can reduce the total energy system costs (including the cost of energy efficiency) if combined with flexible operation of the electricity system.
- Policies may therefore be needed to enable and incentivise consumers to improve the fabric efficiency of their homes in order to realise the benefits to the wider energy system.
- Where deeper energy efficiency improvements are less cost-effective, installing domestic-scale thermal storage to enable flexible operation of heating enables a reduction in total electricity system costs.
- Consumer incentives through the market (e.g. ability to purchase lower cost electricity or rebates for providing flexibility) or policy supports (e.g. assistance covering the upfront cost of thermal storage) are likely to be needed to incentivise consumers to provide this service to the energy system.

Future cost of electricity and hydrogen

- Between today and 2040, electricity costs are expected to rise in some countries and fall in others, depending on the volume of high-carbon electricity sources remaining in the generation mix. Fossil fuel and carbon costs are the principal drivers of electricity cost in 2040. Hence Spain and Italy, which have less than 20% fossil generation, have retail electricity costs around €150/MWh. Czechia and Poland, with around 30% fossil generation, have retail electricity costs over €200/MWh.
- Hydrogen costs in the EU in 2040 could be in the €140-220/MWh range. This is generally of the same order or lower than electricity, but it is significantly more than natural gas costs to consumers today.

Smart and flexible heating

- Existing buildings within the countries analysed are not generally of sufficient fabric efficiency to be able to operate flexibly in response to the needs of the electricity grid. There are several routes to enabling a building to provide flexibility services to the electricity grid. Buildings that undergo deep retrofit to achieve a high level of building fabric efficiency can operate their heat pumps intermittently without impacting comfort. Alternatively, households may use a heat battery or a hybrid heat pump to enable flexible heat pump operation. In warmer countries, a shallow retrofit may be sufficient to allow dwellings to operate flexibly.

- Operating the energy system flexibly lowers the total energy system cost by 1-4% in a heat pump or hybrid heat pumps dominated future, equivalent to savings of €1-4bn/year in the countries analysed. The system cost decrease reaches 5-18% in a hydrogen-dominated world, equivalent to savings of €4-17bn/year. This requires investments in energy efficiency improvements in buildings to enable flexible operation of heating. Some investments which will not pay back if the building is considered in isolation may in fact be cost-effective if impact on the wider energy system is considered.
- Smart and responsive heating can reduce the annual consumer fuel cost, saving consumers up to 15% of the total fuel cost in single-family homes, and up to 10% in multi-occupancy buildings. In order to achieve such savings, consumers providing flexibility would need to be rewarded for providing flexibility, based on the whole system benefits they generate. Assuming all consumers benefit equally from the flexibility provided by some consumers, the fuel cost savings decrease to 1-4% for single-family homes and 2-3% in multi-family homes. There are no significant differences in how those savings are made between the countries analysed.
- By 2040, the cost of electricity will be largely driven by carbon prices in areas where the marginal generators are still supplied by fossil fuels. In these locations, smart heating can help to integrate further renewables, particularly solar, reducing carbon-intensive generation and peaking capacity. As the electricity system becomes fully decarbonised, we expect to see high cost savings from flexible heating due to reduced use of high-cost, low-carbon marginal generation, for example CCGTs using stored hydrogen. Smart and flexible heating also reduces the requirements for grid network reinforcement.

District heat networks

- Low carbon district heat networks can provide domestic heat at a comparable cost to building-level heating systems and offer a high level of demand flexibility. In many cases, heat networks will be simpler to decarbonise due to the relative ease of replacing centralised heating plant compared with disruption in hundreds or thousands of homes. Maintaining existing district heating networks and decarbonising them comes with significant consumer and carbon benefits if suitable consumer protections are in place.

Table of Contents

Authors

For comments or queries please contact:

Sam.Foster@element-energy.co.uk

Fiona.Hughes@element-energy.co.uk

Joachim.Dias@element-energy.co.uk

+44 (1223) 852 499

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Acronyms

CZ	Czechia
DH	District heating
DSR	Demand side response
ES	Spain
HP	Heat pump
HHP	Hybrid heat pump
kWh	kilo Watt hours
ISDM	Element Energy's Integrated system dispatch model
IT	Italy
MFH	Multi family home
MWh	Mega Watt hours
PL	Poland
SFH	Single family home
VRES	Variable renewable energy sources

1 Introduction

1.1 Context and objectives

Heat is recognised as one of the hardest sectors to decarbonise. Currently most consumers use fossil fuels to provide their heat, but to meet EU and national emissions targets they will have to swap to a cleaner technology. One possible solution is to electrify heating via heat pumps, however since the seasonality of heating is far greater than of electricity demand this may create a large winter peak in electricity demand causing issues for generators and the distribution network. Another possible option is to decarbonise the gas grid by converting it to carry hydrogen rather than natural gas. While this reduces the impact of heat on the electricity system, it creates challenges in producing zero carbon hydrogen and in ensuring all parts of the gas network are suitable for hydrogen. Since there is significant uncertainty around the costs and risks of these two methods of decarbonising heat, this study aims to understand the impacts of different future scenarios and particularly focuses on the possible impacts on consumers.

In addition to the technologies used to heat dwellings in the future, the installation of energy efficiency upgrades is considered. Currently, EU member states have an ambitious target for energy efficiency installation. This study aims to show both the benefits to the energy system of energy efficiency whilst also understanding the potential financial risks to consumers of these installations. We also consider the possible benefits of going beyond current energy efficiency installation targets for consumers.

This study considers the energy system in 2040. This date was chosen because it is sufficiently far in the future that significant steps towards the decarbonisation of heating will have been taken, but near enough to the present that high-resolution, hourly projections of the electricity generation mix can be found. We model that 80% of homes are using decarbonised heating by this date. The choice of this year will allow us to analyse with greater certainty the cost of different scenarios than we would be able to if choosing a year further into the future (for example, 2050) even though the system might be more decarbonised by then.

This study determines what the overall cost of heating will be to end users in Europe under different heating delivery scenarios (primarily electric heat pumps, green hydrogen boilers, and hybrid options, and including both individual building and district heating approaches). All costs are determined, including purchase, installation, and maintenance, and the fuel cost, which covers the commodity itself (gas or electricity) and the cost of the infrastructure required to deliver it to homes and to run a safe and secure energy system. The key aims of the study are to:

- Assess the costs of decarbonised heating options from a consumer perspective.
- Analyse the cost and benefit from building fabric energy efficiency measures to individual consumers and the energy system.
- Determine the impact of smart and responsive heating on the energy system and the financial benefits to heat consumers who provide flexibility to the energy system.
- Compare the costs of decarbonised district heating systems with individual dwelling level approaches.

The study has produced reports on four European Member states (Spain, Italy, Czechia, and Poland), as well as the current report, providing overall insights into EU-wide consumer impacts. Those four countries have been selected as country archetypes to represent a range of climates, building stock and heating systems, and cost of retrofits. Spain and Italy were chosen to represent archetypal warm countries, with expensive retrofit, while Poland and Czechia were chosen to represent colder countries with lower cost of retrofit. 13 European countries are seen to have a climate between that of IT/ES and PL/CZ, as displayed in Figure 1. 10 European countries have either colder or warmer climates. Across this report, the differences that exist between the warm and cold archetypes will be highlighted by comparing the results obtained for Poland and Spain, as representative cold and warm countries respectively. Where appropriate data for all four countries will be displayed.

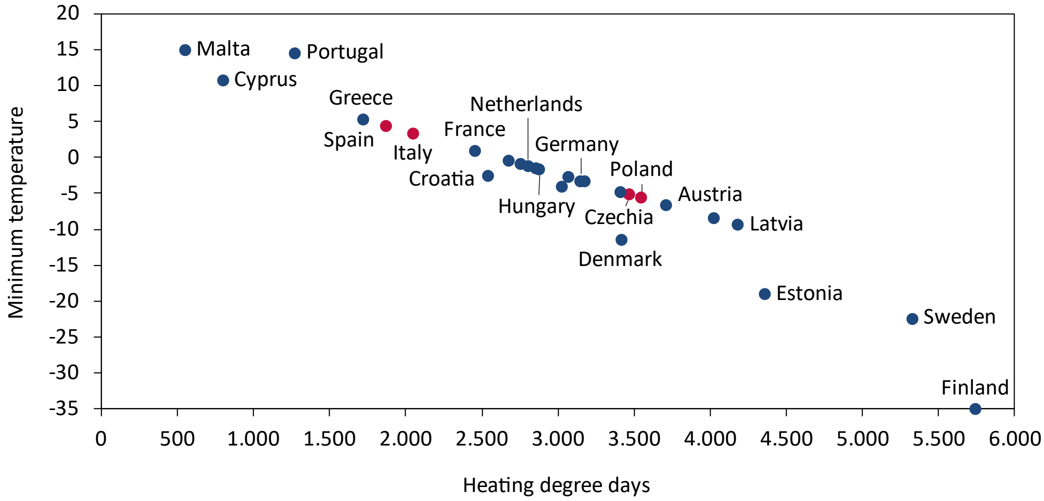

Figure 1 – Representation of EU countries climate by minimum temperature and heating degree days[1], showing the four selected countries as archetypal warm and cold climates

1.2 Technology scenarios

For this work, three technology deployment scenarios for 2040 were created. These three scenarios were focused on the deployment of a single technology as the main low carbon heating option. These were heat pumps (HP), hybrid heat pumps (HP + hydrogen boiler), and hydrogen boilers. The technology mix for each scenario in Poland and Spain is shown in Figure 2 and Figure 3 respectively. Across all scenarios, about 80% of the building stock is decarbonised by 2040. This is consistent across all four countries modelled. The main differences between those heating system uptake scenarios arise from the baseline fossil fuel and low carbon heating systems, which impact the total stock heating system fraction in 2040.

In the HP-focused scenario, across all countries, 30-45% of the stock is heated with HP. These have been modelled to reflect the characteristics of air-source heat pumps (ASHP) although in reality are likely to be a mix of ground and air-source heat pumps. In the Hybrid heat pump scenario, 20-27% of the stock is heated with hybrid heat pumps which combine an ASHP with a hydrogen boiler, and in the hydrogen scenario, 20-30% of the stock is heated with hydrogen boilers. These scenarios are used to analyse the likely cost of different

[1] Median HDDs over the years 1974-2016, typical minimum temperature, EUROSTAT database, https://ec.europa.eu/eurostat/web/main/data/database,

technology options under different possible futures and are not intended to be projections or predictions of the likely future technology mix.

In these scenarios, the hydrogen boiler and hybrid scenarios are based on the gas network transitioning to hydrogen. This is likely to be a phased process which will not be completed by 2040; hence some remaining natural gas boilers are included in the scenarios above. In these scenarios, hydrogen for heating is modelled as "green" hydrogen produced from electricity via electrolysis.

Spain has been modelled in a unique way due to its current lack of DH infrastructure, representing less than 1% of the baseline heating systems. As a result, for Spain only, two district heating uptake pathway scenarios have been modelled, leading to either 16% or 32% of DH penetration in the building stock. Both scenarios correspond to a high penetration of DH compared to the existing baseline. Those results are presented in Section 6.

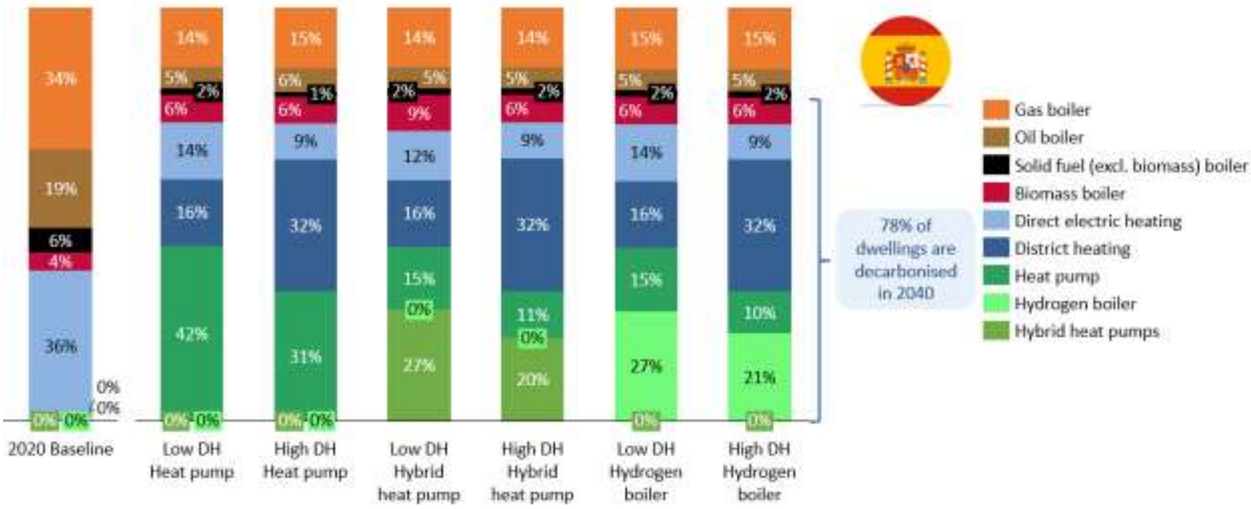

Figure 2 - Fraction of dwellings with each technology in 2040 in each scenario in Spain

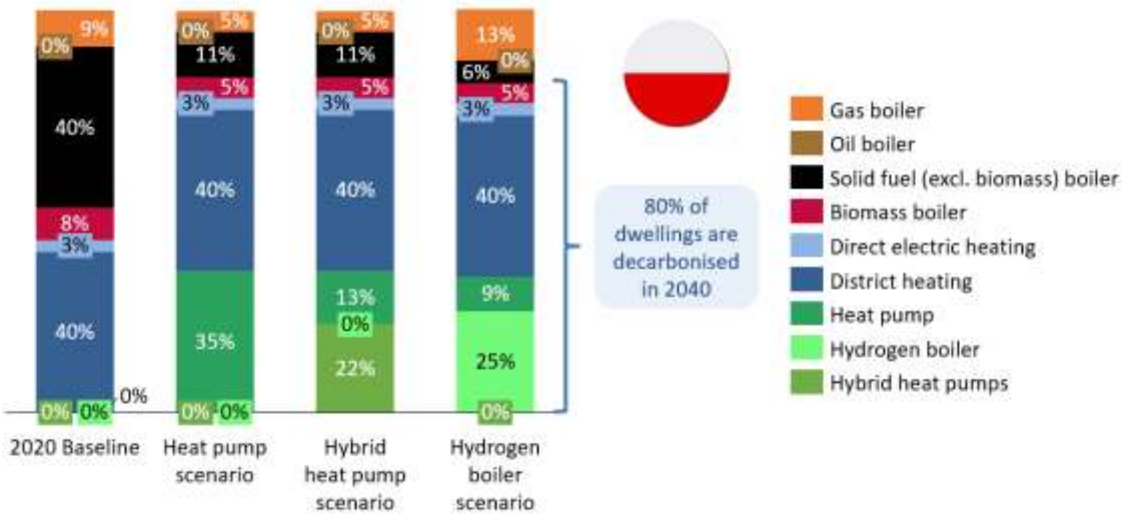

Figure 3 - Fraction of dwellings with each technology in 2040 in each scenario in Poland

Each of the three technology deployment scenarios are analysed in two ways:

1. The **Baseline-Passive** scenario, which includes fabric energy efficiency deployment at a rate of 2% of buildings per year, and energy demands such as heating continuing to operate in a passive way.
2. In the **Efficient-Smart** or **Flexible** scenario, for which a higher rate of fabric energy efficiency rollout is assumed, and heating systems behave in a flexible way, responding to the needs of the energy system as a whole. In the colder countries (CZ, PL), energy efficiency deployment rises to 4% of buildings per year, while in the warmer countries (ES, IT) it is deployed at about 2.7% of buildings per year.

In addition, in the Baseline-Passive scenario it is assumed that hydrogen is produced by grid-connected electrolysers, whereas in the Smart-Efficient scenario hydrogen is produced by dedicated renewables collocated with electrolysers and grid curtailment, to produce cheaper hydrogen with less impact on the overall energy system.

1.3 Case study buildings

The housing stock in the EU is made up of a large range of different buildings. To present results in this report, the key dwelling-level results for consumers are presented for two typical buildings. These typical buildings are a single-family home (SFH) built before 1970 and a multi-family home (apartment, MFH) built after 1970. These archetypes represent the average dwelling of that age group and type in each country and are chosen to illustrate the trends that consumers are expected to see. However, since all buildings are different there will be some variation from the trends presented for individual buildings. Across the countries, there is appreciable difference in the heating demand of our two key dwelling archetypes, particularly in the older, detached dwelling. Figure 4 below summarises the baseline average archetypes space heating and hot water demand across all four countries investigated. The climate was chosen to be representative of populated parts of each country, where consumers require significant winter heating: Prague, Madrid, Milan, and Warsaw respectively. While significant heat demand is required across all of Czechia and Poland, the level of heat demand is more variable across Spain and Italy, hence the focus here on the colder areas within these countries.

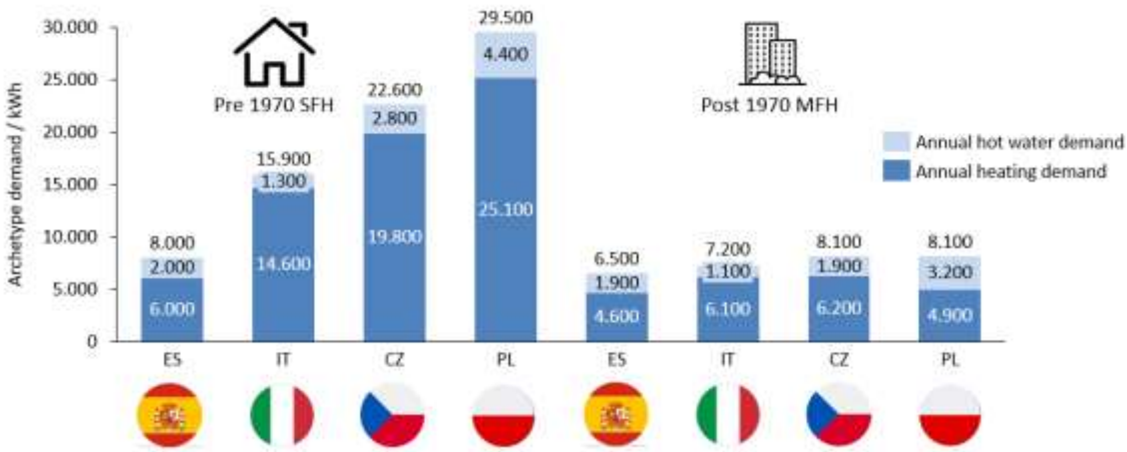

Figure 4 – Summary of baseline average archetypes space heating and hot water demand for each country

1.4 Method

An overview of the method is shown in Figure 5 below. The key steps in the modelling are described below and repeated for each country independently:

1. The archetype stock model calculates the heat demand and final energy consumption on an annual and hourly basis for domestic dwellings. The outputs are generated at the building level and at the country-level (i.e. including all buildings). Non-domestic buildings are included in the national demand although they are addressed with less detail than the residential stock.

2. Each residential building archetype undergoes a flexibility assessment to determine whether and how much its heating demand can be shifted to accommodate the needs of the wider electricity system.

3. The energy demands and flexibility potential of the heating system is used by the Integrated Supply and Demand Model (ISDM) in modelling the hourly behaviour of each country's energy system throughout 2040. The ISDM predicts the retail costs of electricity, which is used to calculate the green hydrogen cost. A more detailed description of the ISDM model is given below and shown in Figure 6.

4. The upfront and ongoing costs of heating are calculated by the consumer cost model for the selected building archetypes.

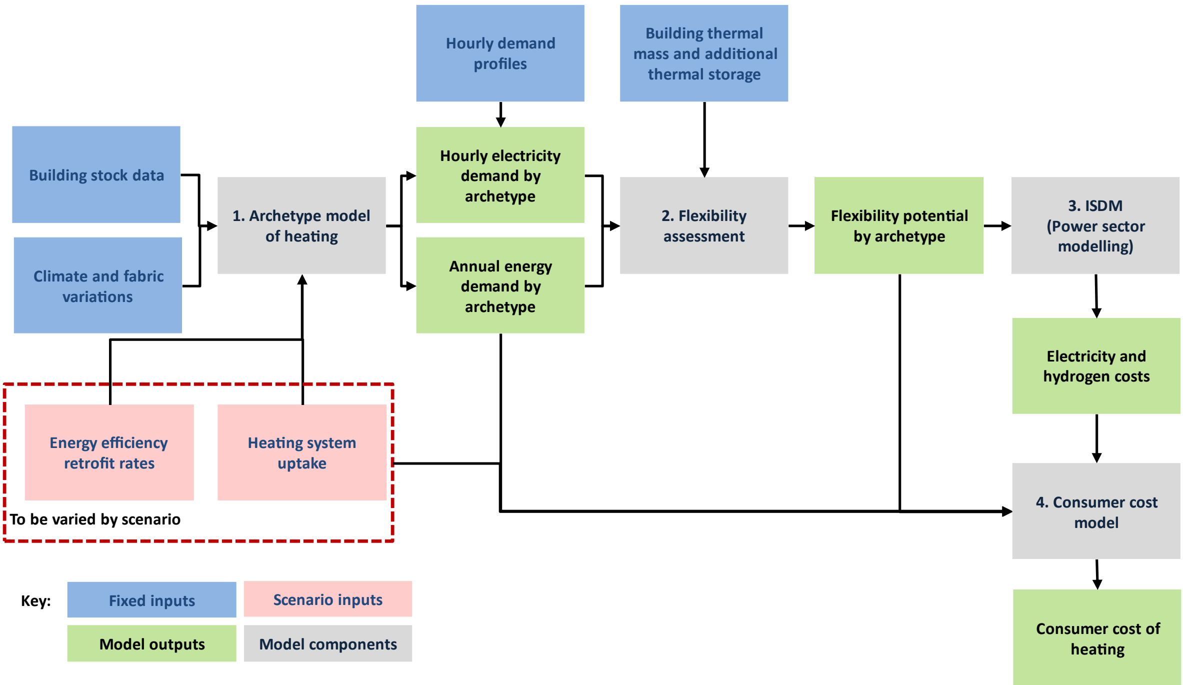

Figure 5 - Full heating system costing model flowchart

1.5 Energy system modelling

Element Energy's Integrated Supply and Demand Model (ISDM) was developed to overcome limitations of typical power system dispatch models when applied to zero carbon systems. Many such models continue to treat the power system as it currently is: highly dispatchable and reliant on thermal sources for flexibility on the supply side. Future low carbon systems, where variable renewable energy is dominant, will require flexibility on the demand side to support the integration of high levels of renewable energy, while minimising curtailment and reliance on backup thermal plant. The ISDM utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system. The main principles of whole system operation are summarised here.

The starting point for the modelling is a set of hourly energy demand profiles for each sector. Some demand profiles are fixed (no flexibility), while others are able to be shifted over defined periods. For heating, these demands are based on the building heat loss, heating technology and outside air temperatures. Transport demand is based on the number of electric vehicles, their efficiency, the daily usage, and arrival/departure times from home and work to generate a baseline electrified transport demand. Grid-responsive smart charging can schedule charging to times of most use to the grid, while still providing vehicles with sufficient charge for transport. Flexibility provided by thermal storage and thermal mass of buildings allows heat demand to move demand to times most useful to the grid, without reducing thermal comfort in homes and offices.

Hourly weather data is also used to generate hourly load factors for wind and solar production. Using the assumptions on the installed variable renewable energy sources (VRES) generation capacity, the model calculates the hourly VRES generation. By subtracting this from the demand profiles, initial net load curves are generated. Demand shifting, as enabled through smart EV charging and smart heating is deployed to minimise the peak system demand and therefore the required network capacity. Further demand shifting is then applied to reduce curtailment of renewables and fossil fuel use, by moving demand from hours of high demand to hours of low net demand. By reducing the peak net demand, demand shifting leads to a decreased requirement for dispatchable generation capacity.

The dispatchable generation fleet is then deployed in merit order to fill in the supply gap. Once all hourly demand is met, annual system performance metrics are evaluated, among them fuel and carbon cost, variable OPEX, VRES curtailment, peak demand (for determining the required network capacity), and peak net demand (for determining the required dispatchable generation capacity).

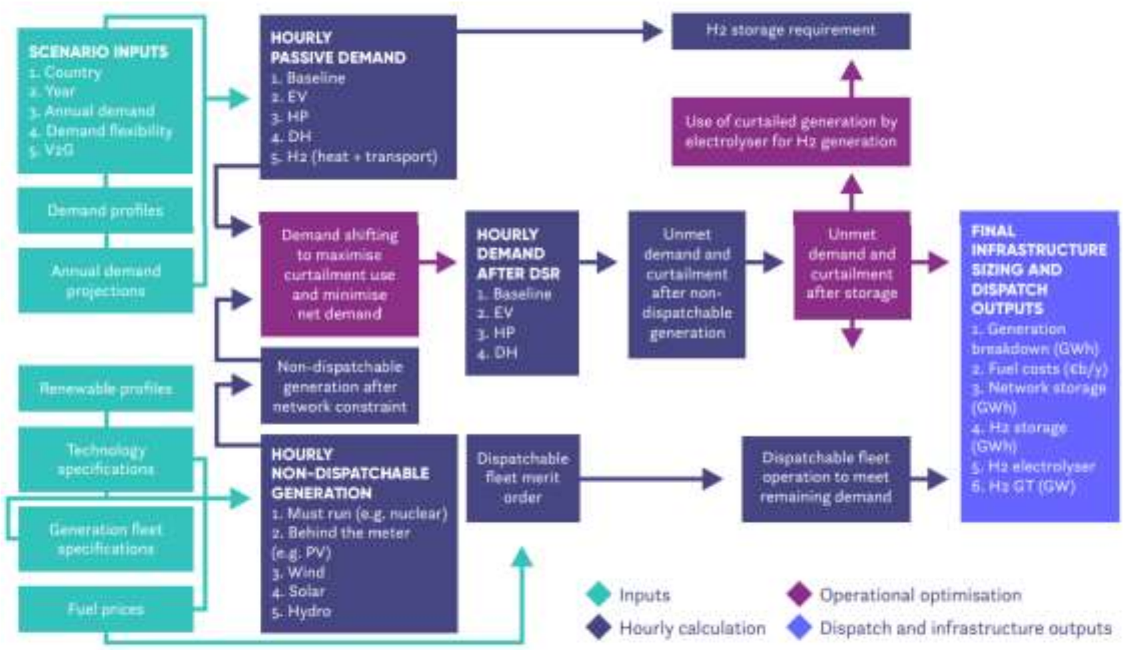

Figure 6 – Schematic of the calculation within the Integrated System Dispatch Model (ISDM)

2 Impact of ambitious energy efficiency deployment

2.1 Energy efficiency scenarios

Energy efficiency scenarios were defined for each country as annual rollout rates for each of the archetypes discussed earlier. Across the EU countries, there are significant differences in the absolute cost of retrofit. This may be due to differences in labour costs, the condition of the housing stock, typical dwelling size, and the level of supply chain and market development. There are also significant energy savings differences, due to varying initial condition of the housing stock and local climate. Figure 7 summarises those differences and highlights how the four countries selected represent most of the range of cost of heat demand saving in €/kWh seen across for the EU, where the €/kWh represents the upfront cost of the retrofit in € divided by the energy savings over 30 years in kWh. Across the EU, those costs of heat savings due to deep retrofit in single-family homes vary from 5 c/kWh to 45 c/kWh, or almost a factor of 10. Consequently, the cost-effectiveness of energy efficiency measures tends to be higher in countries with lower cost of retrofit and higher heat demand, such as Poland and Czechia, and lower in countries with higher cost of retrofit and lower heat demand, such as Spain and Italy. The energy efficiency rollout rate scenarios were defined based on those different characteristics.

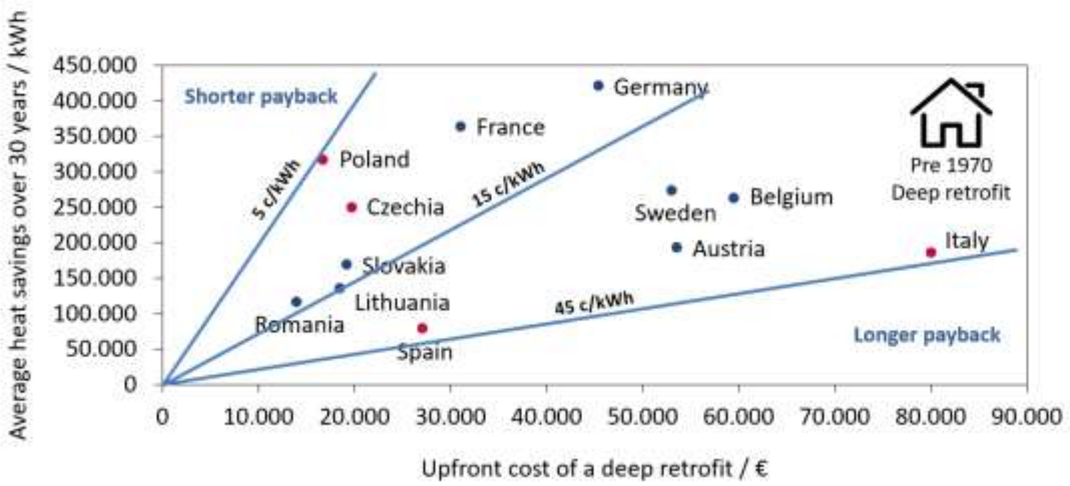

Figure 7 – Upfront costs and average heat savings of deep retrofit of pre-1970 SFH in European countries

Two energy efficiency rollout scenarios were analysed, one baseline scenario with rollout at the rate equivalent to existing targets and one more ambitious rollout rate combined with smart heating system operation. Energy efficiency rollout was analysed by using two packages, one shallow and one deep retrofit package. These packages each contain a set of measures that reduce heating demand. The rollout rate of these packages in the different scenarios and countries is shown in Figure 8**Error! Reference source not found.**.

In the efficient scenario in Spain and Italy, due to the large cost of retrofit, the additional retrofit packages were assumed to be rolled out only in stock where this allows the homes to become flexible due to a lower heat loss rate. In Spain, multi-family homes (MFH) are always flexible, and no additional packages are therefore installed there. Single-family homes (SFH) need to have shallow packages to become flexible, as a result, the renovation rate increases to 2.5% in the efficient scenario. In Italy, MFH and SFH need a shallow and deep package respectively to become flexible. The rate of deep packages installations in SFH is modelled as half of that in Czechia and Poland due to the high upfront capex.

In Poland and Czechia, shallow and deep retrofit rates are assumed identical for SFH and MFH.

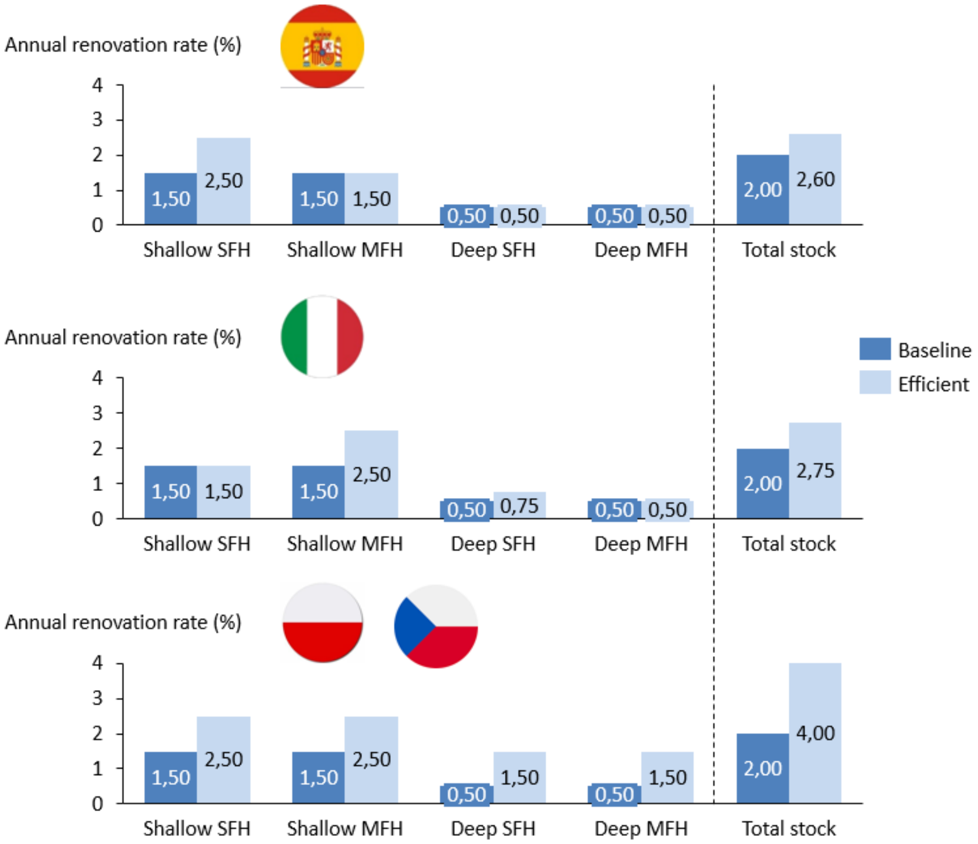

Figure 8 - Energy efficiency rollout rates in each country and archetype, in the baseline and efficient scenarios

2.2 Impact of energy efficiency on heat demand

Figure 9 shows the breakdown of the 2040 housing stock in the two energy efficiency rollout scenarios in Spain and Poland. In the efficient scenario, 3% and 13% more of the stock has had an energy efficiency retrofit than in the baseline scenario for Spain and Poland respectively.

Figure 10, shows the reduction in heating demand in buildings archetypes for Spain and Poland from a shallow and deep retrofit. Even though the percentage reduction in total heat demand can be large in both cases, the absolute heat demand savings are much larger in colder countries like Poland. Savings in heat demand also depend on size and age of the dwelling as well as the level of retrofit.

Figure 11 shows the heating demand changes between the current housing stock in 2020 and the housing stock in 2040, for both energy efficiency scenarios.

In Spain, the total stock heat demand in 2040 decreases by 4% in the baseline retrofit rate scenario compared to the 2020 stock, and this decreases by a further 1% in the efficient scenario, for a total of 6 TWh of energy savings. The small decrease in heat demand between both scenarios is due to the limited additional energy efficiency rolled out in the stock.

In Poland, the total stock heat demand in 2040 increases by 4% in the baseline retrofit rate scenario compared to the 2020 stock because 21% of the building stock in 2040 is made up of new buildings, contributing to a large increase in hot water demand. These new buildings are assumed to have a heating demand similar to or lower than a building which has undergone a deep retrofit. The efficient scenario has an 8% lower heating demand than the 2040 baseline.

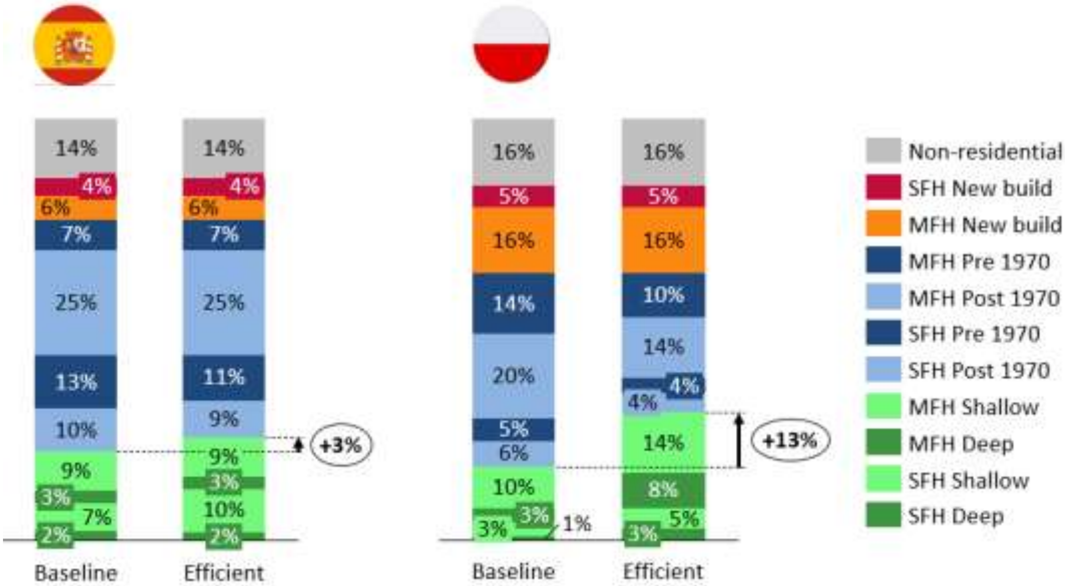

Figure 9 - 2040 housing stock in baseline and efficient scenarios

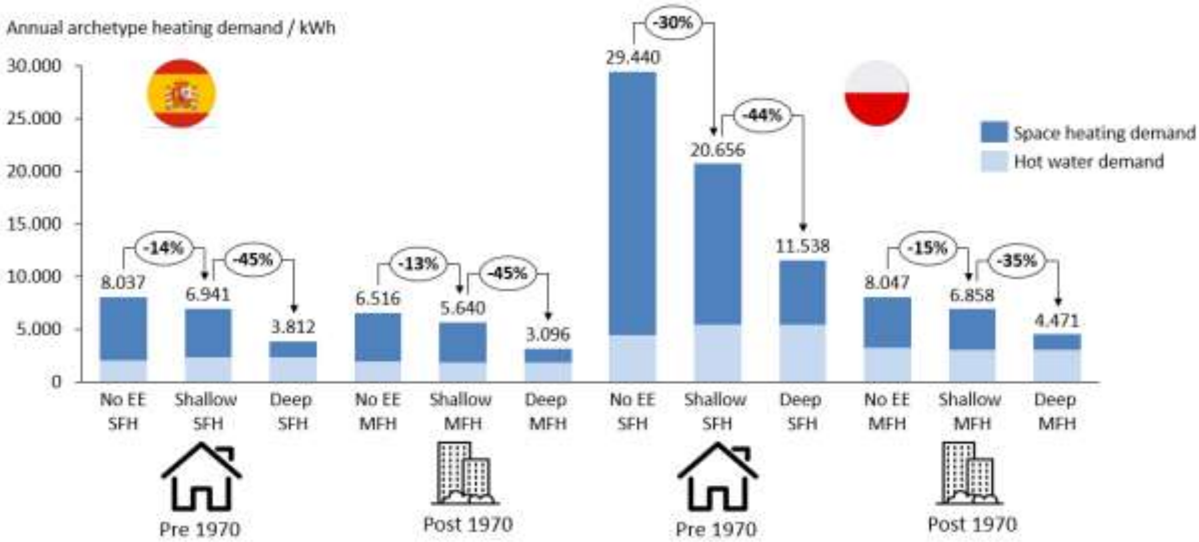

Figure 10 – Impact of shallow and deep energy efficiency packages on the space heating and hot water demand of building archetypes in Spain and Poland

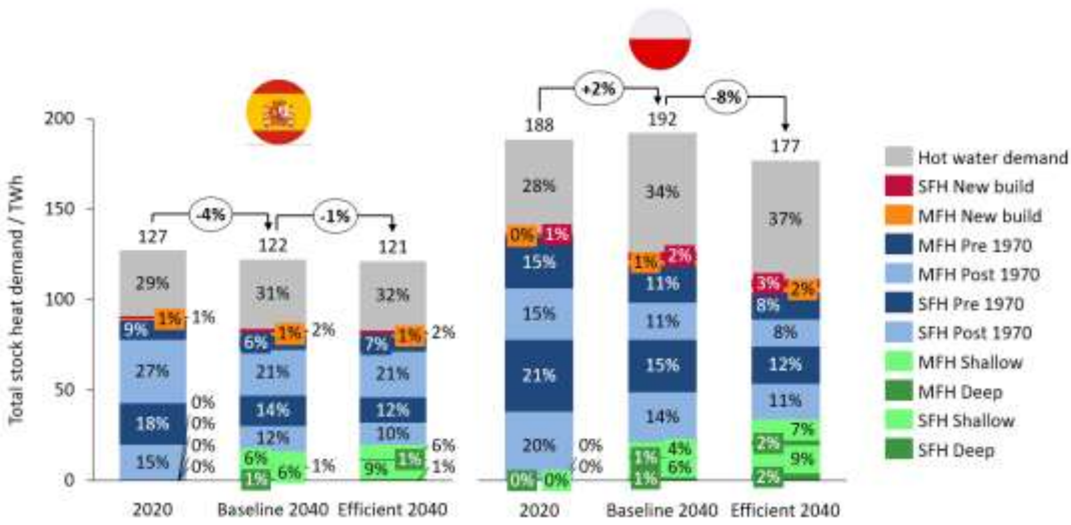

Figure 11 - Impact of energy efficiency scenario on residential heating demand for Spain and Poland

2.3 Impact of energy efficiency on the cost of heat

Figure 12 shows the building-level heating cost in € per year for the two key archetypes with shallow and deep energy efficiency packages installed in Spain. Despite the fuel cost savings from improved energy efficiency for both heating and cooling, the high additional annualised capex of energy efficiency installation in both large single-family homes and smaller multi-family homes result in a net increase in total heating system cost. However, consumers who do install energy efficiency measures despite their high capital cost will see lower fuel bills. Even in a case where a 50% grant is applied to the energy efficiency capex, as per Figure 13, Spanish consumers will still see a net increase in their cost of heating of approximately 10% for both archetypes for a shallow retrofit and 50% for a deep retrofit, highlighting the need for strong policy support of retrofit in Spain. The same is true for Italy, and is expected to apply for other countries in the EU with a high cost of heat demand savings in €/kWh.

Figure 14Figure 14 shows the building-level heating cost in € per year for the two key archetypes with different energy efficiency packages installed in Poland. In this case, the cost-effectiveness of energy efficiency is different between the single and the multi-family homes. In large single-family homes, where the fuel cost makes up a larger part of the total cost of heating than in smaller multi-family homes, the savings from energy efficiency in the fuel cost are greater than the additional annualised capex by around 20% for both shallow and deep retrofit. As such, the return on investment in deep energy retrofit is secure for single-family homes and investment in energy efficiency upgrades to achieve that level of performance should be fostered. However, in multi-family homes, where the fuel cost makes up a lower fraction of the total annual cost, there is no saving in total heating cost from installing energy efficiency due to the lower fuel cost savings.

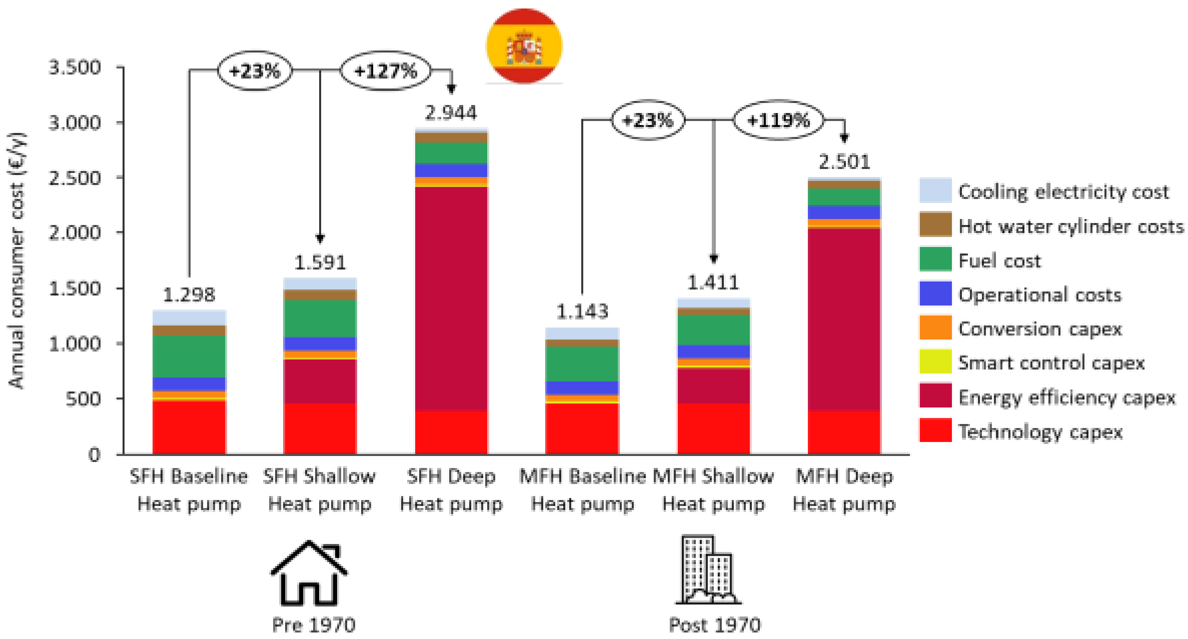

Figure 12 - Annual building level costs (€/y) and impact of energy efficiency in typical archetypes in Spain

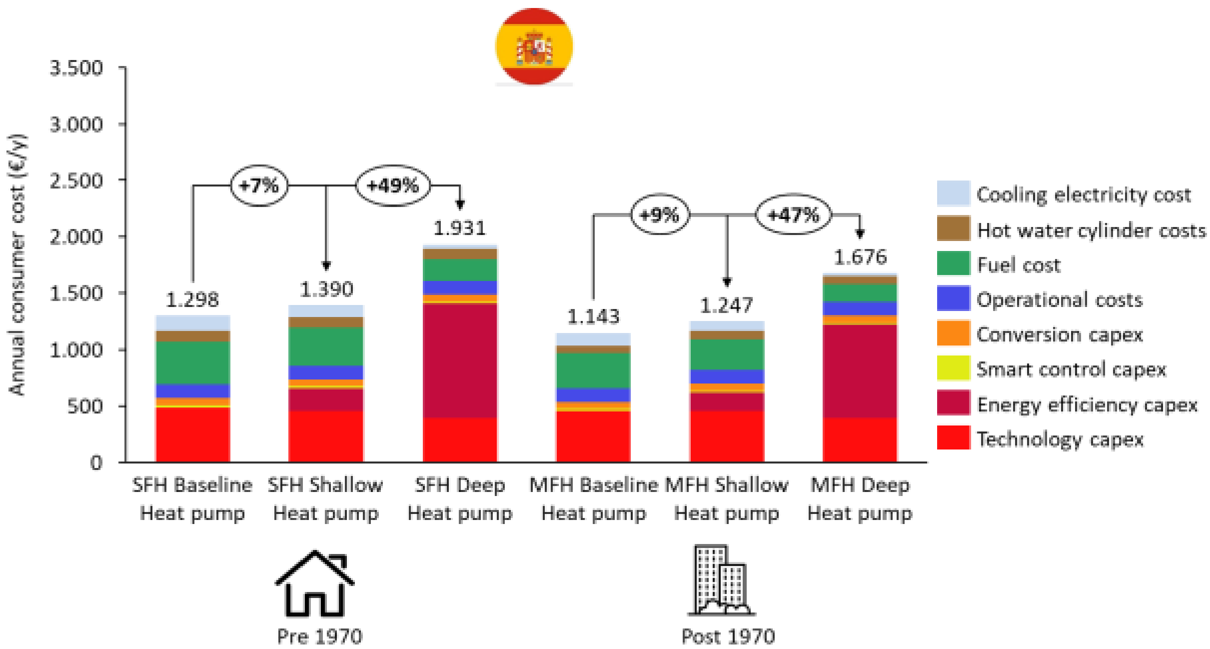

Figure 13 - Annual building level costs (€/y) and impact of energy efficiency in typical archetypes in Spain assuming a 50% energy efficiency capex grant

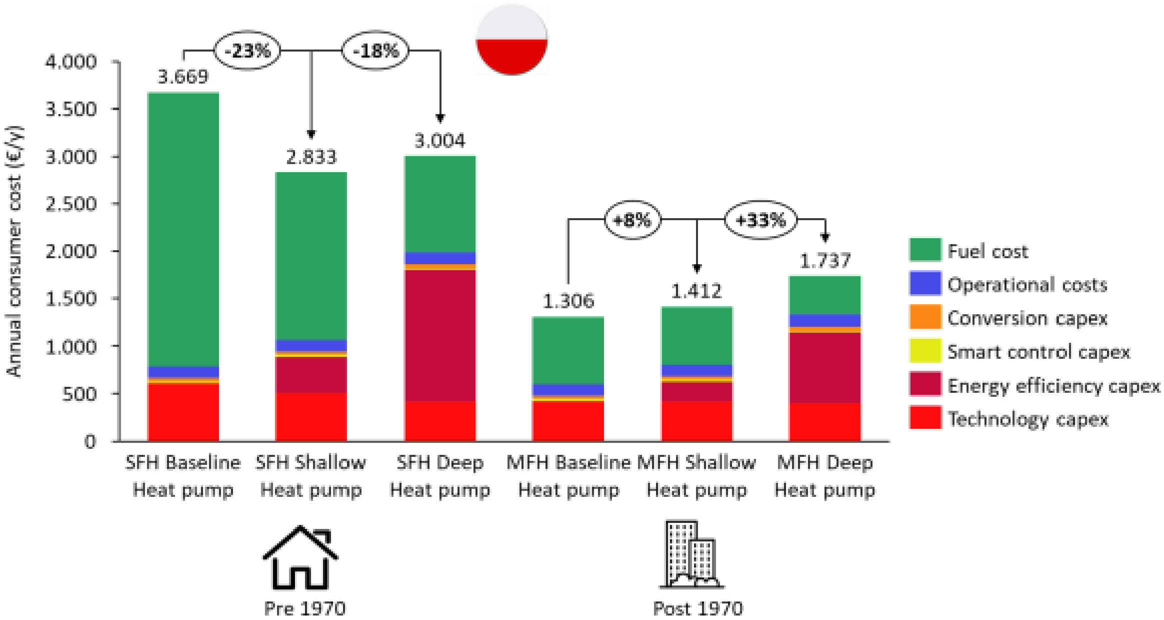

Figure 14 - Annual building level costs (€/y) and impact of energy efficiency in typical archetypes in Poland

Although energy efficiency measures may not be cost-effective at an individual building level for some consumers, the installation of these efficiency measures brings cost savings to the entire energy system. These savings depend on the type of renewable heating system deployed but are likely to be at least €0.8bn per year in Spain and €2.8bn per year in Poland, as highlighted in the cost difference between the baseline and efficient high heat pump rollout scenarios shown in Figure 15. In Spain, the total annual expenditure on energy efficiency measures would be €1.5bn in the baseline scenario, and €1.6bn in the efficient scenario. This €0.1bn increase in cost would lead to the €0.8bn savings. In Poland, the total expenditure would be €0.9bn in the baseline scenario, and €1.9bn in the efficient scenario. This €1bn increase in cost would lead to the €2.8bn savings

It is important to note that for the system to realise the full savings from energy efficiency rollout, policy support will be required to remove the significant upfront cost of energy efficiency from households such that they are incentivised to invest in reducing their dwelling's heating demand. For example, since there is no consumer cost saving from installing energy efficiency in a post 1970 multi-family home it is unlikely consumers would make this change without policy support.

Energy efficiency upgrades require significant capital outlay depending on the size and age of the home and the level of retrofit. Figure 16**Error! Reference source not found.** shows the upfront cost of energy efficiency retrofit in the two typical archetypes in both Spain and Poland.

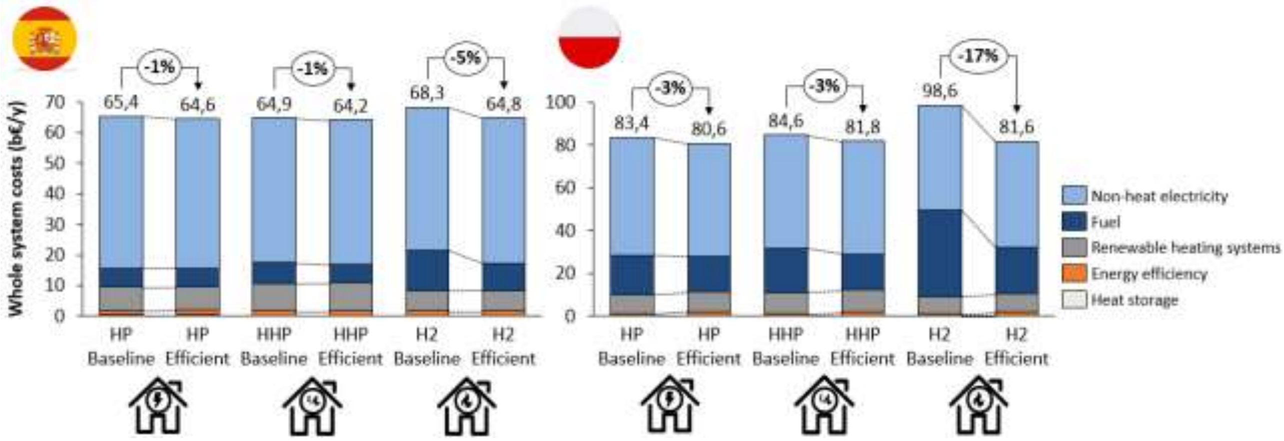

Figure 15 - Spain and Poland whole system costs highlighting savings in the efficient scenario compared to the baseline

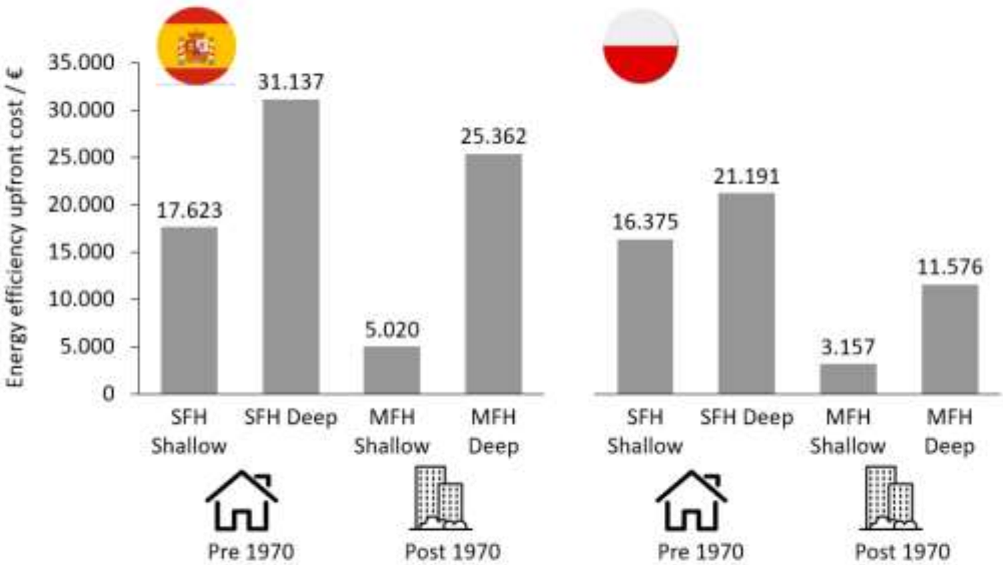

Figure 16 - Upfront cost of energy efficiency packages in Spain and Poland

2.4 Impact of energy efficiency across the EU

Across the EU, consumers in single-family homes are likely to benefit from cost-effective retrofit in countries with the lowest cost of heat savings, such as Poland and Czechia. Similarly, for countries like France or Germany, which benefit from large heat demand savings due to retrofit, and countries like Slovakia, Lithuania, and Romania, which benefit from low retrofit costs, retrofit can be expected to be cost-effective for consumers in single-family homes.

It is less likely that consumers in multi-family homes across the EU will be able to benefit from cost-effective retrofit. This is because the cost of heat savings in multi-family homes have lower absolute values, which do not necessarily payback for the investment in energy efficiency measures. Energy efficiency rollout in multi-family homes is nevertheless expected to bring significant whole-system benefits, as described in Section 5.

It is expected that consumers in typical single-family homes in countries with the highest cost of heat savings, such as Spain or Italy, would see an increase in costs due to energy efficiency. This indicates a possible need for strong policy support to incentivise consumers to take up energy efficiency measures, as that would lead to whole system benefits.

In the analysis performed in this study, the building stock has been simplified, and it is expected that both multi-family and single-family homes that are the most poorly insulated in any country will benefit from cost-effective retrofit, but those were not explicitly modelled here.

3 Consumer costs of low carbon heating options in 2040

The cost of heating systems to consumers has two parts. There is an upfront capital cost (capex) that is incurred when the heating system is replaced and there is an ongoing cost of fuel and maintenance. This section shows the total cost of heating made up of both of those components, and then looks at each component individually.

3.1 Total cost of heating for consumers

The total cost of heating for consumers is found by summing the annualised capital cost, at a 5% discount rate with a 15-year technology lifetime, with the annual operating cost. This represents the total cost for a consumer in each year for heating their dwelling with that technology. When comparing the annualised costs of heating systems in the three heating system scenarios defined, heat pumps are seen to be the cheapest option for consumers in both key archetypes across all countries investigates. Heating with hydrogen boilers relative to heat pumps could leave consumers paying approximately 50-60% more for their heat in both Spain and Poland, as shown in Figure 17 and Figure 18 respectively. Since the cheapest overall option, heat pumps, comes at a significant upfront cost premium compared to hydrogen boilers and counterfactual heating technologies, it is important that governments provide adequate support to consumers to switch their heating through incentives and financial products that address these high upfront costs in order for consumers to pay the least possible for their heat.

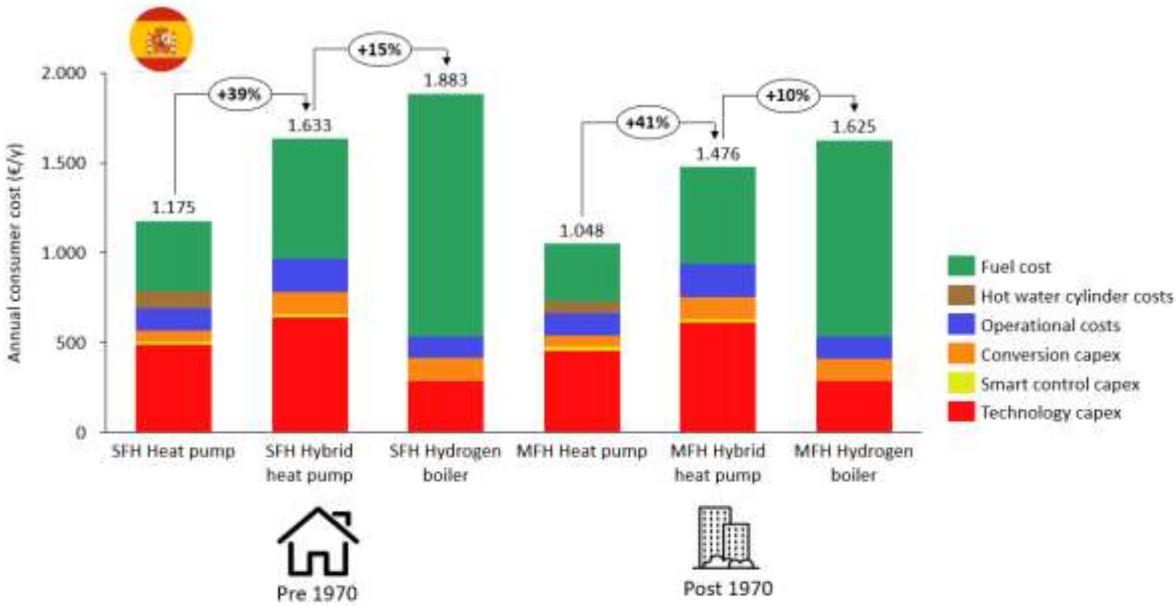

Figure 17 - Annual consumer cost of heat with the main technology in each scenario in Spain.

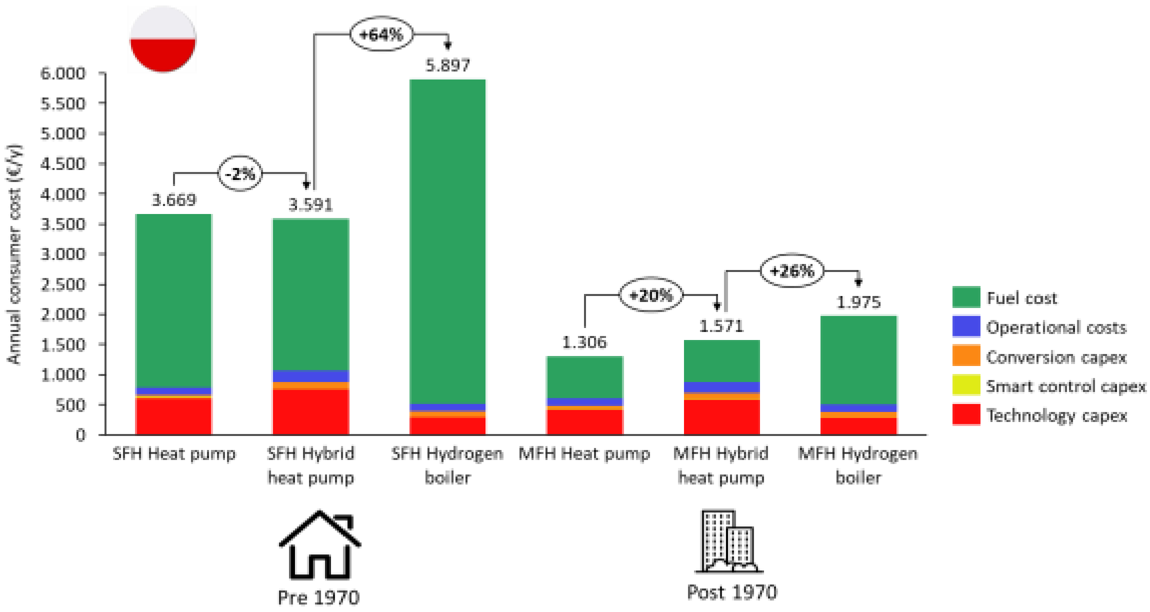

Figure 18 - Annual consumer cost of heat with the main technology in each scenario in Poland.

3.2 Ongoing costs of heating systems

Fuel costs are found from electricity system modelling based on the uptake of heating systems and energy efficiency for that scenario. The technologies considered here have different efficiencies of producing heat from their fuel, heat pumps can operate at 280% efficiency, whereas hydrogen boilers are 85% efficient. Since hydrogen is produced from electricity via electrolysis, using hydrogen boilers to produce heat typically uses 4.5 time as much electricity as producing the heat with a heat pump. Due to this, the operational costs of hydrogen boilers can be approximately 2-3 times larger than those of heat pumps, as shown for Spain in Figure 19 and Poland in Figure 20. This means that although hydrogen can be cheaper than electricity per kWh, the additional consumption outweighs this. Hydrogen is also likely to be significantly more expensive than gas is today for consumers.

In the current modelling, hybrid heat pumps were assumed to provide 80% of the heat output using the heat pump, with the remaining 20% using the boiler, which is assumed to use green hydrogen. This way, the hybrids' heat pumps can be operated outside of peak demand times, which would coincide with coldest temperatures and lowest efficiencies, and therefore have larger efficiency than simple heat pumps. For that reason, and due to the overall large heat demand in Poland, it is seen that hybrid heat pumps have actually lower fuel costs in single-family homes than heat pumps, leading to an overall 10% lower cost of operation than heat pumps in that archetype and country.

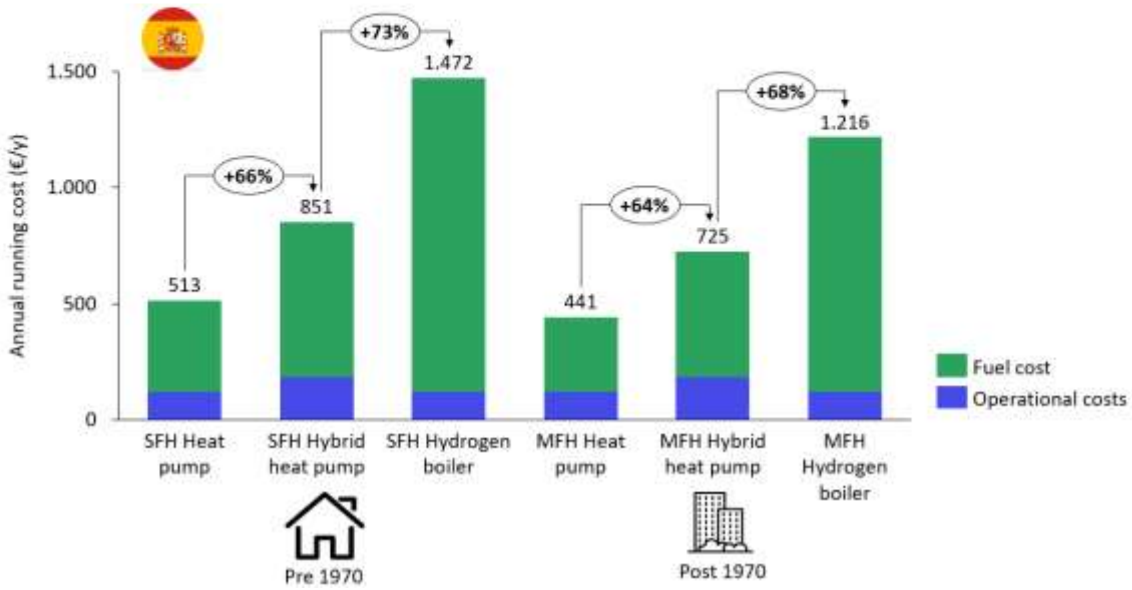

Figure 19 - Annual running costs of different heating systems in Spain

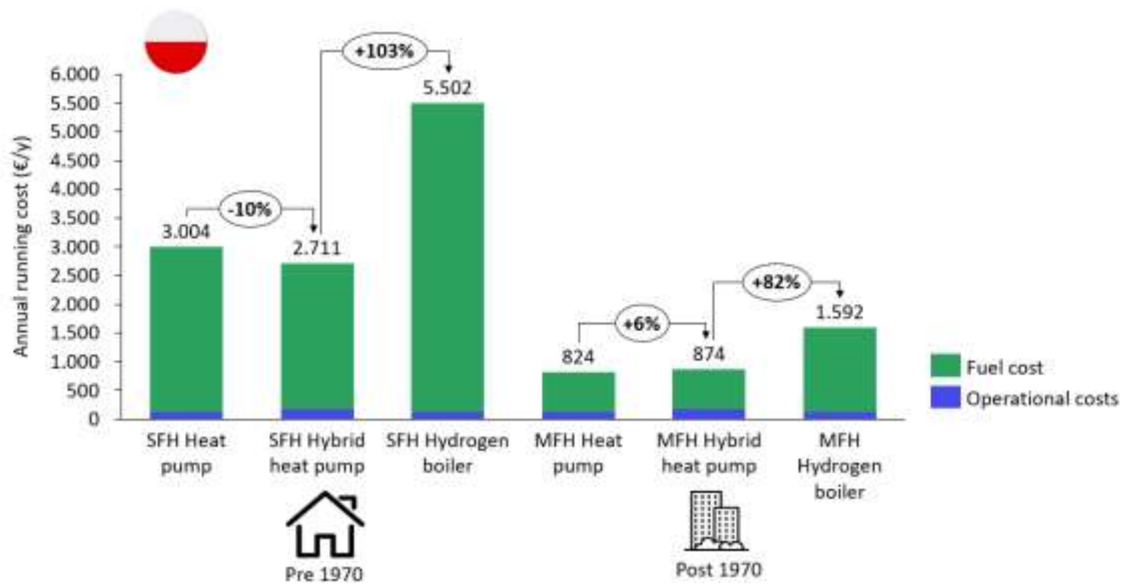

Figure 20 - Annual running costs of different heating systems in Poland

3.3 Capital cost of heating systems

Capital costs are found from the Element Energy database of heating system costs and include the cost of the heating system as well as the cost of hot water cylinders and smart controllers where appropriate. Hydrogen boilers have the lowest capital cost of the heating systems considered; hybrid heat pumps have the highest capital cost, as shown in Figure 21 and Figure 22 for Spain and Poland respectively.

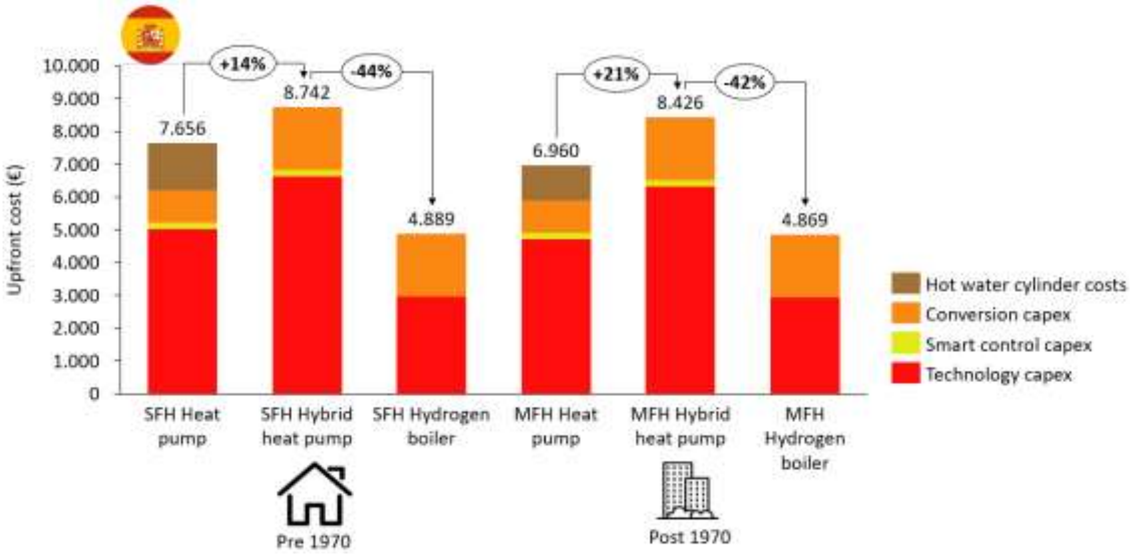

Figure 21 - Upfront costs of different heating systems for typical archetypes in Spain

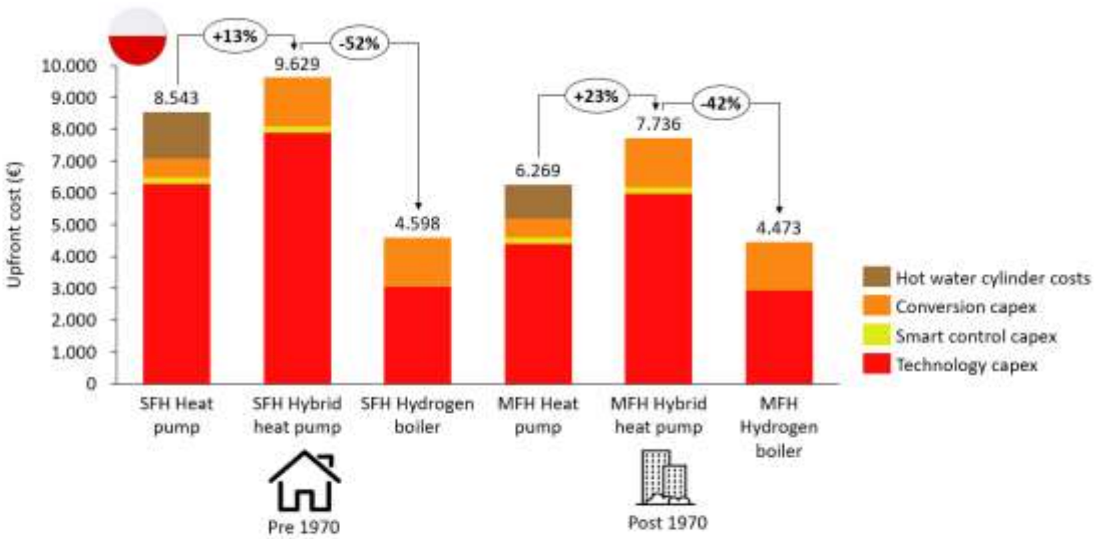

Figure 22 - Upfront costs of different heating systems for typical archetypes in Poland

3.4 Consumer costs of low carbon heating across the EU

The results presented above are expected to hold true across the EU countries, as no country is expected to have significantly different electricity or hydrogen fuel costs compared to the four countries investigated. There will be some differences in fuel costs due to different electricity generation mix, described in Sections 4 and 5, which will impact the consumer costs. Heat pumps are expected to be the cheapest option for heat decarbonisation in many archetypes and countries, and hydrogen boilers the most expensive one. The fuel cost variations between countries can make the difference in cost between those two options larger or smaller, and can in some cases, as it is in Poland, they can make hybrid heat pump cost-competitive with heat pumps.

Across all countries, there should be a focus to decarbonise existing DH, as they are expected to be cost-competitive with heat pumps, as described in Section 6.

4 Future cost of energy

Future energy retail prices in the four investigated countries have been derived from modelling the power system in 2040 in these countries. In this section we compare retail electricity and hydrogen prices and their breakdown today and in 2040. We then look at the reasons for why retail electricity prices are expected to rise in some of the countries but fall in others.

4.1 Future electricity retail prices and their breakdown

Figure 23 shows retail electricity prices in 2019 and as modelled in 2040 in the four investigated countries for the Baseline-Passive scenario of the Heat Pump scenario. Prices are expected to fall in ES and IT but rise in CZ and PL. While in 2019, retail prices are higher in ES and IT (210-230 €/MWh) than in CZ and PL (150-180 €/MWh), the opposite is true in 2040 with higher prices in CZ and PL (200-210 €/MWh) than in ES and IT (150-170 €/MWh).

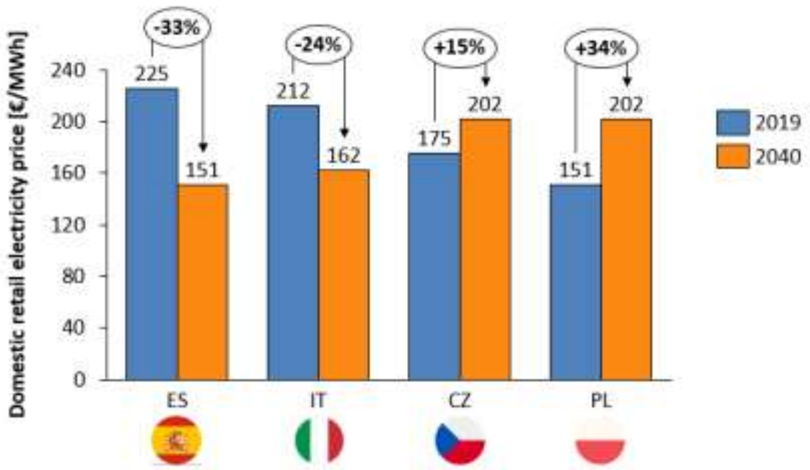

Figure 23: Retail electricity prices in 2019[2] and as modelled in 2040 in the four investigated countries

The breakdown of retail electricity prices in Figure 24 shows that the differences in retail prices between 2019 and 2040 are mostly driven by changes of the generation cost. Generation costs increase in CZ and PL but fall in ES and IT.

As seen in Figure 25, the breakdown of generation cost in 2040 differs significantly between the four countries: while it is dominated by fixed costs (capex and fixed opex) in ES and IT, it is dominated by variable costs (fuel and carbon - referring to the cost of emission trading scheme allowances) in CZ and PL. Furthermore, while fixed cost per MWh of electricity generated are slightly higher in ES and IT than in CZ and PL, the variable cost per MWh are many times higher in CZ and PL and thus the main driver of higher total generation costs there.

The reason for the different generation costs and their breakdown is the expected generation mix which differs significantly across the four countries as we will explore in the following section.

[2] From ACER Retail Monitoring Report 2020

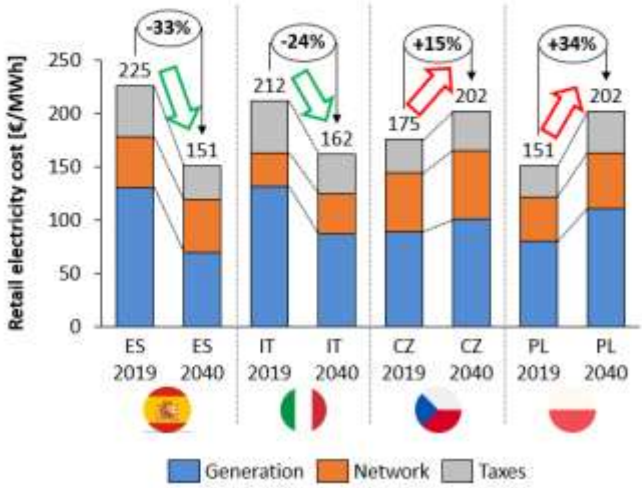

Figure 24: Breakdown of retail electricity costs in 2019 and 2040, with carbon costs (costs of emission trading scheme allowances) included in generation costs

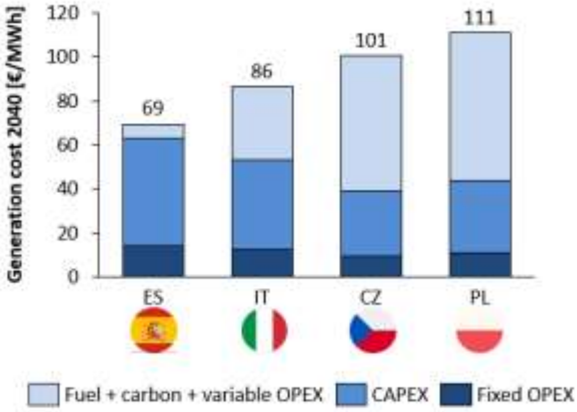

Figure 25: Breakdown of electricity generation costs in 2040

4.2 Future electricity generation mix and impact on prices

As shown in Figure 26, in ES and IT, the 2040 generation mix, referring to the total amount of electricity generated per year, is dominated by renewable generation of solar PV, wind, and hydro, which all have close to zero variable cost of generation. On the other hand, in CZ and PL, a significant share of generation is based on fossil fuels (coal, lignite or gas-fuelled).

This leads to high average fuel and carbon costs of electricity in CZ and PL as can be seen in the right part of Figure 26. The assumed carbon price of €188/tCO_2 in 2040, leads to carbon costs of €65 per MWh of electricity generated for a CCGT, €140/MWh for coal power plant, and €159/MWh for a lignite power plant[3]. Assumed prices for gas, coal, and lignite lead to fuel costs of €60/MWh, €22/MWh and €9/MWh for generation based on these fuels. The higher share of fossil fuelled generation is therefore the main driver of higher electricity costs in CZ and PL than in ES and IT.

[3] Assuming a 59% LHV efficiency for a CCGT plant, 45% for coal and lignite, and a carbon intensity of 0.204tCO_2/MWh for gas, 0.334t/MWh for coal, 0.381 tCO_2/MWh for lignite

The modelled 2040 generation mix is based on the assumed generation capacities as taken from the ENTSO-E TYNDP published in 2018. Since then, the EU Commission has adopted the European Climate Law which sets a binding goal to achieve net zero emissions by 2050 and a 55% reduction of emissions compared to 1990 by 2030[4]. These targets represent significant increases of emission reductions compared to those in place in 2018. In 2021, several European countries already adopted laws for accelerated power decarbonisation. It is thus likely that the level of decarbonisation as projected by the 2018 ENTSO-E TYNDP in 2040 will be achieved earlier. The reason why the 2018 ENTSO-E TYNDP data has been used is that it provides more detailed data for different weather in particular temperature conditions than the 2020 and 2022 versions.

Furthermore, it should be considered that the share of hydro (flexible as well as inflexible) generation will depend on future climatic conditions. Climate change is expected to lead to more frequent periods of droughts as well as flooding[5], both of which will reduce the availability of hydro capacity, in particular in the case of large-scale hydro dams. Such reduced availability of hydro generation would increase the need for alternative dispatchable low carbon generation, e.g. from plants fuelled by hydrogen or biomass, or fossil fuelled plants with CCS. These differ from hydro generation in that they have significant fuel and other variable cost (e.g. cost of capture, transport and storage of carbon in the case of CCS). Furthermore, their overall generation cost is likely to be more expensive than that of hydro.

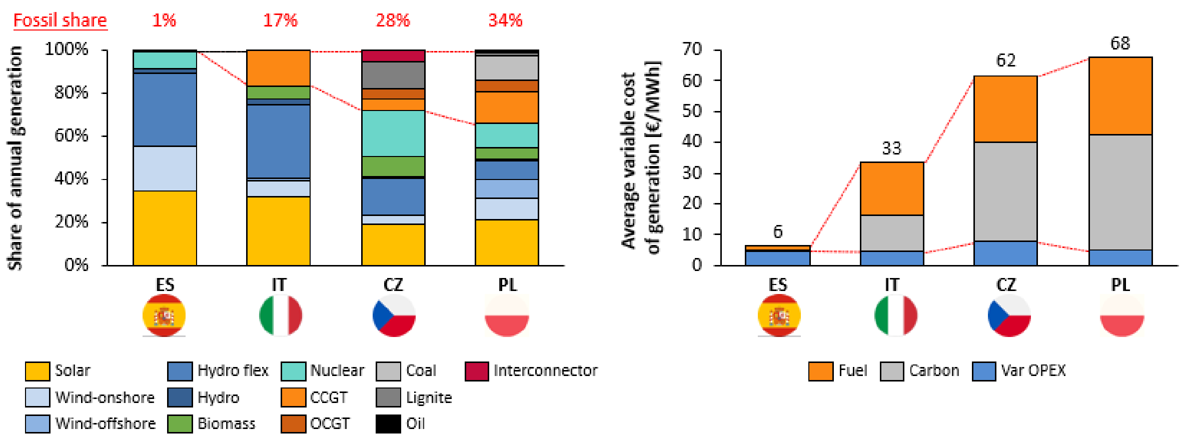

Figure 26: Generation mix (left) and breakdown of variable cost (right)

In general, it can be expected that in 2040, countries with higher fossil share in power generation will have higher electricity costs than those with lower fossil share, due to the significant increase of carbon prices[6]. However low availability of and/or reliance on low-cost renewable energy sources (such as wind, solar and hydro) can increase generation costs in countries with low fossil share, due to the high cost of low carbon dispatchable generation technologies such as hydrogen, biomass, and fossil-fuelled based with CCS. The high cost of dispatchable power in 2040 is likely to support the case for increased deployment of demand side response, in particular from electrified heating and transport, in order to minimise the need for such dispatchable power.

[4] https://ec.europa.eu/clima/eu-action/european-green-deal/european-climate-law_en

[5] https://www.dw.com/en/can-hydropower-withstand-a-future-of-extreme-weather/a-58968255

[6] EU ETS carbon prices have increased from €20-25/t in 2018 to up to €90/t in 2021: https://www.reuters.com/markets/commodities/eu-carbon-price-could-hit-100-euros-by-year-end-after-record-run-analysts-2021-12-08/

4.3 Future hydrogen retail prices and their breakdown

The cost of producing green hydrogen with electrolysers was modelled in this project. In the Baseline-Passive scenario, it was assumed that the electrolysers were connected to the electricity grid, and pay a wholesale price (excluding grid fees) for their electricity. The cost of hydrogen distribution and storage was then calculated based on a parameterised model of the gas grid and costs of converting the low-pressure distribution grid to hydrogen. The costs of hydrogen production and transmission used were taken from the BEIS hydrogen supply chain evidence base.

In the Flexible scenario, it was assumed that hydrogen electrolysers would not be connected to the electricity grid. Instead, hydrogen production electrolysers and renewable generation were assumed to be co-located and the production of hydrogen was found on an hourly basis to optimise the relative generation and electrolyser capacities for the cheapest hydrogen cost.

Country specific renewable generation profiles were calculated from NASA MERRA-2 data, and the cost of renewable generation was found from the BEIS 2020 cost of electricity generation report. In addition to this, the curtailed electricity produced from renewable generation for the rest of the electricity system was also used to produce hydrogen in the flexible case with a €0/MWh cost.

The consumer costs of hydrogen in the four countries in the Baseline and Flexible scenarios for the high hydrogen boiler rollout scenario are shown in Figure 27. To find the cost per MWh, the capex of generation and electrolysers was annualised over the expected lifetime of the technologies at a discount rate of 5% in the consumer cost case and a 3% discount rate in the system cost case, thus leading to a lower cost of hydrogen when looking at the whole energy system cost.

Both wind and solar generation to produce hydrogen were considered, and the cheapest option was selected in each country for the purpose of costing production in the Flexible scenario:

- Spain: solar
- Italy: offshore wind
- Czechia: onshore wind
- Poland: onshore wind

Two other factors impacting the cost of hydrogen in each country were investigated: the availability of natural storage and the extent of the existing gas grid that could be repurposed for hydrogen versus the need to build a bespoke hydrogen network.

It was estimated that both Spain and Poland have available salt cavern natural storage sites with enough capacity to provide interseasonal hydrogen storage for the whole hydrogen heating demand without additional storage requirements.[7] In both Czechia and Italy, no natural hydrogen storage sites are available, and storage was assessed as ammonia or liquid organic hydrogen carriers. In each country, the storage option leading to the lowest cost of hydrogen was selected as the only storage option for the costing of hydrogen fuel.

[7] Technical potential of salt caverns for hydrogen storage in Europe

In Poland, the limited extent of the existing gas grid means there will be a need for a bespoke hydrogen grid to be built, where in the three other countries investigated, the extent of the gas grid is sufficient to only require a conversion of the gas grid to become suitable for hydrogen use.

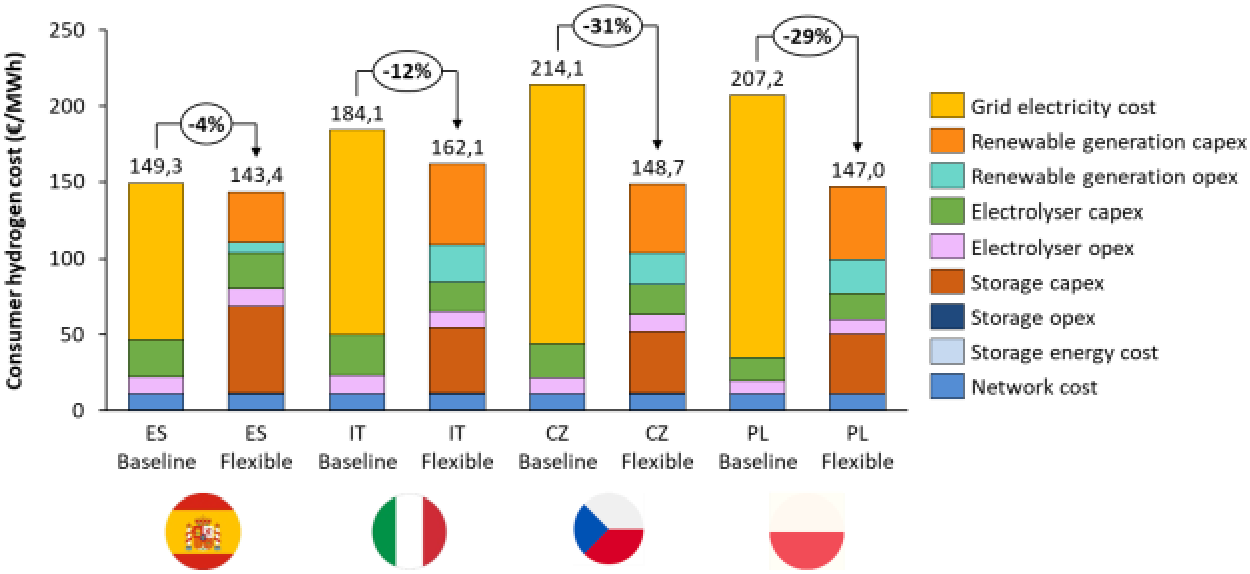

Figure 27 – Decrease in cost of hydrogen for consumers in the flexible compared to the baseline case

5 Benefit from smart and responsive low carbon heating

Two system operation scenarios are presented in this study. The Baseline-Passive scenario involves a passive/uncontrolled demand side, with supply operated such that it matches this passive demand. The Efficient-Smart or Flexible scenario involves a higher rate of energy efficiency and a more active and flexible demand side, shifting demand into periods of high renewable output and away from periods of high overall power demand. Each of these two scenarios has been run with the three different technology deployment scenarios, so in each case the impact of smart system operation can be quantified. In all scenarios, the smart operation of electric vehicle charging is assumed to take place.

5.1 Energy system benefit of smart operation

When heat pumps are operated in a smart way, they act to move electricity demand away from the system peak demand. This is achieved by pre-heating houses with high thermal mass relative to their heat loss rate, or by storing thermal energy in a phase change heat battery. We assume that by 2040, 50% of buildings with heat pumps that cannot be flexible through their thermal mass purchase a thermal battery. This allows a greater proportion of buildings to offer flexibility services, without implying an unrealistic rate of deep retrofit.

When heating is operated flexibly, the total demand for heating is unchanged, but the profile of electricity use is less “peaky”. The lower peaks mean that the total required capacity of electricity generation can be lower and less upgrade to higher capacity electricity networks is required, reducing the cost of the electricity system. In addition to the peak reduction, flexibility also allows demand to be better matched to high generation of renewable technologies. This means that technologies with zero marginal cost have higher load factors and less thermal generation is required, thus decreasing the system cost. Figure 28 shows the nationwide electricity demand in Spain and Poland over a typical winter week in 2040 in the scenario with high uptake of heat pumps. Under smart operation, heat demand is moved away from the peak demand hours, increasing demand at other hours of the day. This decreases the peak system demand and means less network capacity is required. In addition, heat demand can be moved into times where variable renewable electricity is available, reducing both the cost of electricity production and its carbon content. The model first moves demand that is flexible based on thermal mass, and then moves the demand that is flexible based on installing additional thermal storage. Figure 28 shows the change in the demand profile after the thermal mass flexibility and thermal storage are applied in Spain and Poland; in both cases, the majority of flexibility comes from additional thermal storage.

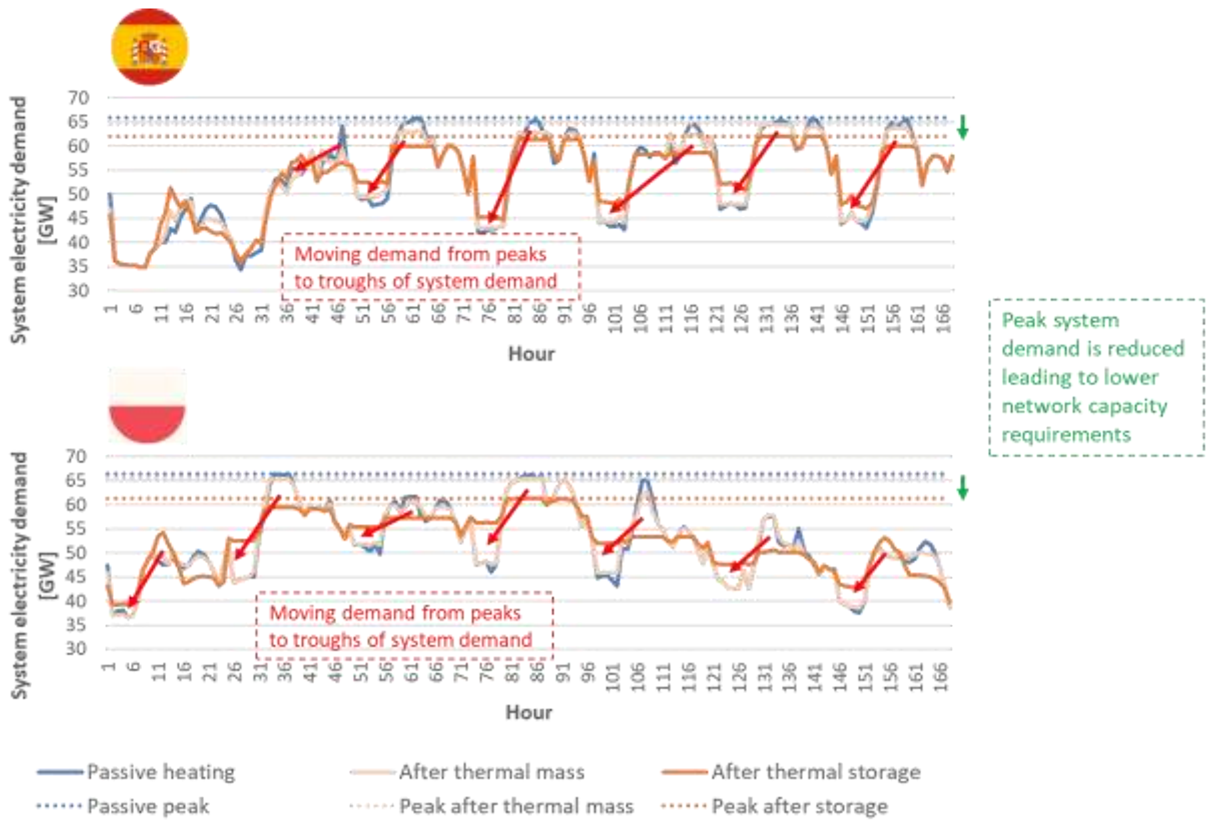

Figure 28 - Nationwide electricity demand in Spain and Poland for a typical winter week under the heat pump scenario with passive and smart heating system operation.

District heating also provides flexibility to the system through the use of larger-scale thermal storage, typically in the form of stored hot water. This allows the peaks and troughs of heating demand from buildings on a district heat network to be mitigated locally so the loads on the wider energy system are minimised. In the Flexible scenario, hydrogen is considered to be produced by co-located renewables and electricity that would otherwise be curtailed, so does not impact the wider electricity system relative to the baseline scenario where it is produced by grid connected electrolysers.

5.2 Electricity cost savings across countries

Modelled retail electricity costs in the Baseline and the Flexible scenarios are shown in Figure 29 for all technology deployment scenarios and investigated countries. For all technology deployment scenarios, the smart operation of heat pumps leads to cost reductions compared to the Baseline. The reductions range between 1-7% of the total electricity system costs.

In all countries, the electricity cost savings are highest in the case of high deployment of heat pumps, and lowest in the case of high deployment of hydrogen boilers. A key reason for this is that flexible heating comprises a lower share of total electricity demand in the case of high hydrogen boiler deployment as can be seen in Figure 30. With a higher share of heat pump heating systems, it is possible to displace a larger amount of electricity demand away from the peak demand hours, which therefore results in larger savings in the network reinforcement costs, shown in orange.

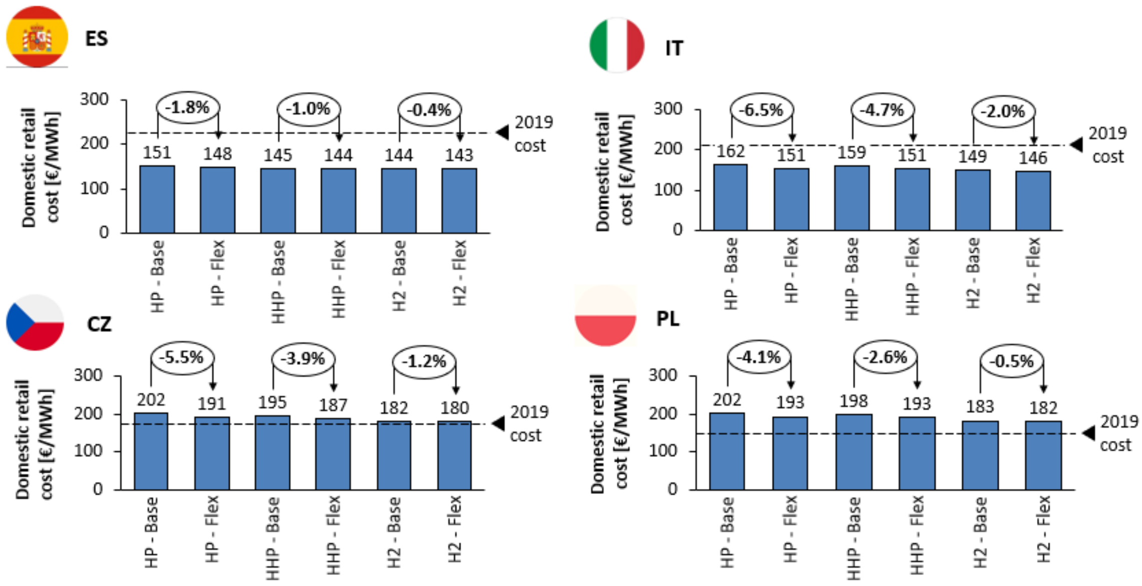

Figure 29: Modelled retail electricity prices in 2040 in the four investigated countries

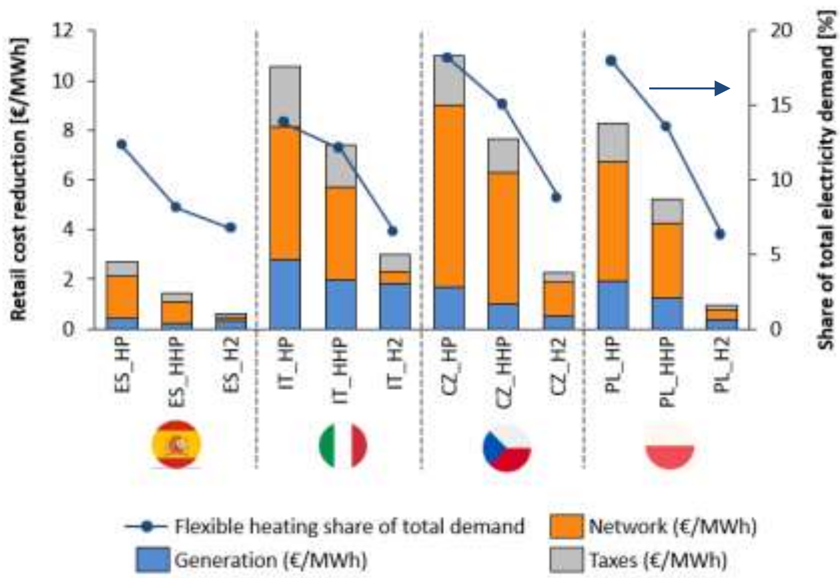

Figure 30: Retail cost reduction in the Flexible scenario compared to the Baseline scenario and flexible heating share of total electricity demand

Figure 31 shows that network fees are expected to increase in all countries, but to a lesser extent in Spain than in the other countries. Network fees have been modelled based on the "peakiness" of the aggregate national consumption profile, given by the ratio of peak demand (in MW) to annual demand (in MWh). As the network capacity needs to be sized according to peak demand, this ratio is a measure for the network capacity requirement per MWh of electricity demand.

As heat demand is highly seasonal, passive electrification of heat will typically increase the peak demand significantly and thus lead to increased peakiness and network costs. Since heat makes up a lower share of total demand in Spain than the other countries, the increase is less pronounced in Spain.

In all countries, flexible operation of heat pumps reduces the peak demand of the system and thus network costs.

Another factor driving the differences in network savings enabled by smart heating are the differences in baseline network costs between countries. Figure 32 shows that residential network fees in 2019 differ significantly between the four investigated countries. Such differences can be caused by a variety of reasons. They can be of technical nature (e.g. larger networks enable more economies of scale) as well as of regulatory nature (differences in what is covered by network fees, if injection as well as withdrawal from the grid is charged, how costs are distributed among different consumer groups)[8].

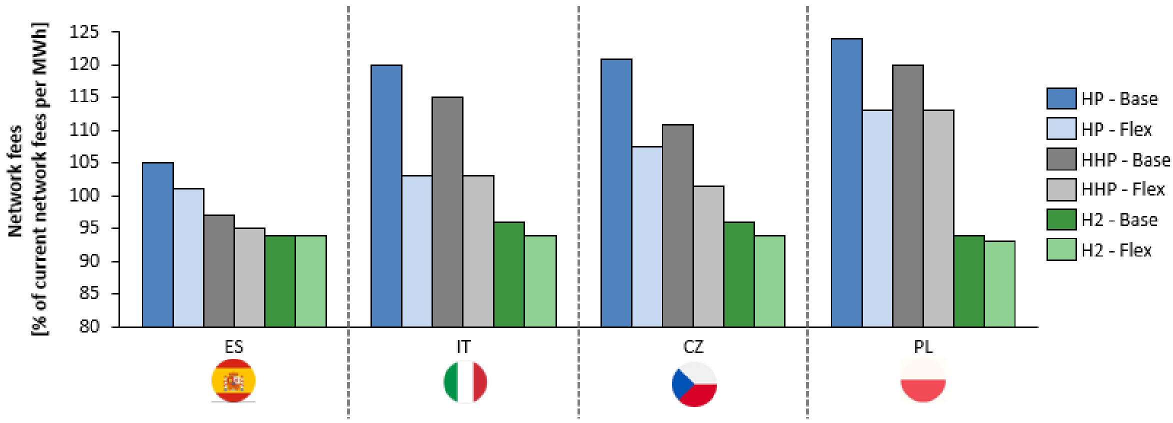

Figure 31: Network fees per MWh of electricity in 2040 relative to fees per MWh today

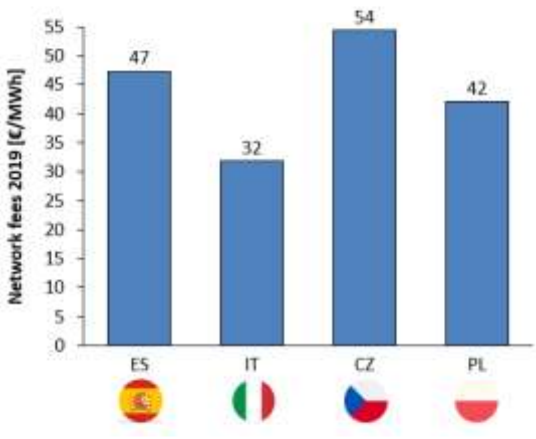

Figure 32: Network fees in 2019 in the four investigated countries[9]

5.3 Impact of smart heating on generation mix

Smart heating allows the system to increase utilisation of renewable energy and reduces the use of fossil fuels. Figure 33 shows for each technology the change in electricity generated when moving from passive to smart heating per MWh of flexible heating demand for the high heat pump scenario. In all countries smart heating increases renewable

[8] Cp. e.g. ACER 2021, Report on Distribution Tariff Methodologies in Europe

[9] ACER Retail Monitoring Report 2020

electricity generation while reducing fossil electricity generation, leading to fuel and carbon savings.

In Spain these savings are lower (per MWh of flexible heating demand) due to the high renewable penetration. Rather than replacing fossil generation, smart heating leads to replacing dispatchable renewable generation (flexible hydro, biomass) with variable renewable generation. While not providing carbon savings in this case, smart heating still improves system efficiency by increasing VRES utilisation and reducing utilisation of dispatchable renewable fuels (biomass, hydro).

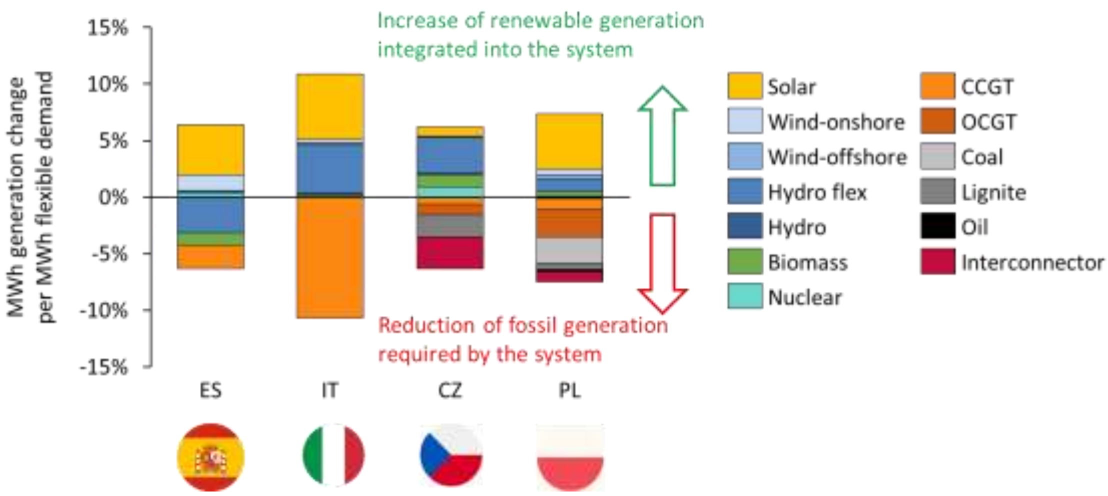

Figure 33: Change of generation mix due to smart heating

5.4 Impact of system characteristics on smart heating benefits

Smart heating enables carbon and fuel savings, and network and generation capacity savings. The level of benefits provided by smart heating will differ among countries depending on the electricity system characteristics. Figure 34 shows projected penetration levels of solar and fossil fuels in EU countries in 2040. In the case of ES, IT, CZ, and PL, this is based on the modelling performed in the project, for the other countries the projections are taken from the ENTSO-E 2018 TYNDP modelling results. The results in the four modelled countries exhibit a few general trends:

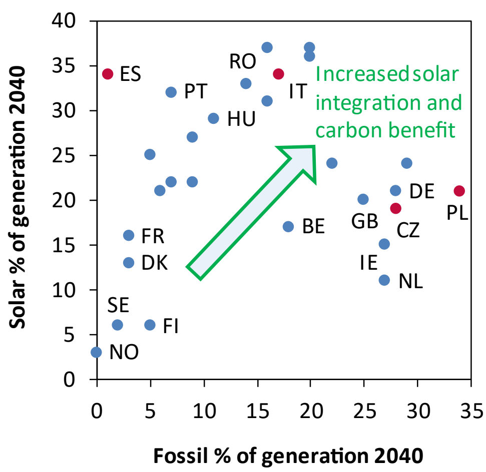

Figure 34: Projected share of fossil and solar generation in EU countries in 2040

Smart heating helps to replace carbon intensive and dispatchable generation. At high fossil shares of the power system, smart heating can help to replace carbon intensive generation from coal and gas plants with renewable generation, saving carbon and fuel. At a lower fossil fuel share, the potential for carbon savings is reduced but smart heating will still be essential to reduce expensive dispatchable low carbon generation such as H_2 gas turbines, CCS, biomass, and flexible hydro. Smart heating can help to reduce both the capacity requirement as well as the utilisation of dispatchable low carbon electricity. The former is only the case if smart heating leads to a reduction of the annual peak demand which is difficult to achieve, in particular since the peak demand depends on many factors outside the control of smart heating, e.g. the shape of electricity demand in periods of the year without need for heating. However, in light of high fuel and other variable costs of low carbon dispatchable technologies other than hydro, reduced utilisation will also be of significant value.

Daily flexibility of smart heating works well with diurnal solar pattern. Thermal mass and thermal storage allow the shifting of demand by up to 24 hours, i.e. within one day. This type of flexibility works particularly well with the diurnal pattern of solar generation (i.e. move demand from evening to midday when sun is shining). This is illustrated in Figure 33, where in most countries, solar is the technologies with the highest increase of generation due to smart heating.

IT, CZ, and PL have significantly higher fossil share than ES in 2040, meaning they will benefit from higher carbon savings from smart heating. Furthermore, the potential for solar integration is higher in IT than in CZ or PL due to higher solar share. A further key driver of the high saving in IT is the high amount of thermal storage assumed. This is due to the comparably high share of buildings with insufficient thermal mass to provide flexibility to the system in IT. Since we have assumed that 50% of such buildings will install thermal storage in all countries, the share of buildings with thermal storage installed is higher in IT in our modelling compared to other countries.

5.5 Costs and savings of flexibility for consumers

The total cost of the energy system, and therefore the energy costs to consumers, is reduced when heating systems are operated flexibly. The level of savings seen by different types of consumers will depend on the policies, tariff design, incentives for flexibility, taxation systems and market structures created to enable and incentivise smart operation of domestic heating. The cost savings may be passed on to the consumers that provide flexibility services, or they may be socialised across all electricity consumption. In practice, a mix of these two options is likely. While consumers may be incentivised to participate in demand-side response through time-of-use electricity tariffs or through regular discounts on bills, these incentives can be less than the total system cost savings.

The range of different annual heating costs that could be seen by consumers in the Flexible heat pump scenario relative to the Baseline-Passive scenario is shown in Figure 35 and Figure 36 for Spain and Poland respectively. The dashed bars show the fuel cost savings that consumers could see from flexible operation.

In Spain, if the benefits of flexibility are fully socialised, both flats and larger homes make negligible savings, less than €10/y. If savings are directed towards the households providing flexibility, large flexible households may save a further €120/y, for total savings of €125/y over the baseline case. Similarly, flexible flats may save up to €100/y. If all savings are passed along to households providing flexibility, those unable to operate flexibly will have fuel bills unchanged from the passive case.

In Poland, if the benefits of flexibility are fully socialised, larger homes may save around €120/y, with flats saving about €30/y. If electricity system savings are directed towards the households providing flexibility, large flexible households may save as much as €400/y over the baseline case. Similarly, flexible flats may save up to €50/y.

Due to Spain's lower absolute heat demand, the fuel cost savings from flexibility are comparatively lower than those in Poland, where they can reach 11% of the total fuel cost, or €420/y compared to 9% or €125/y in Spain.

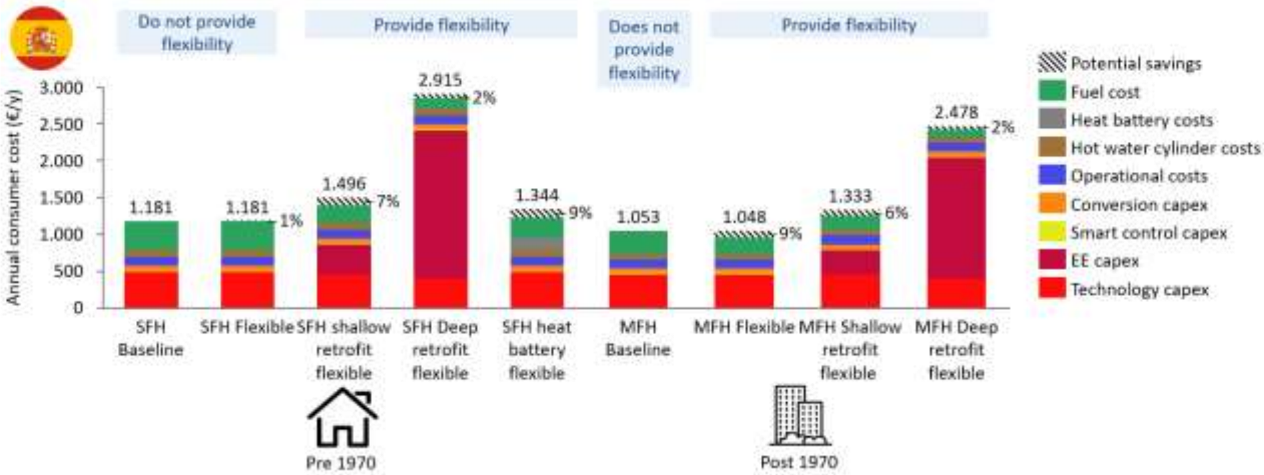

Figure 35 - Range of total annual consumer costs (€/y) possible in the Flexible scenario highlighting potential fuel savings due to flexible operation, in Spain

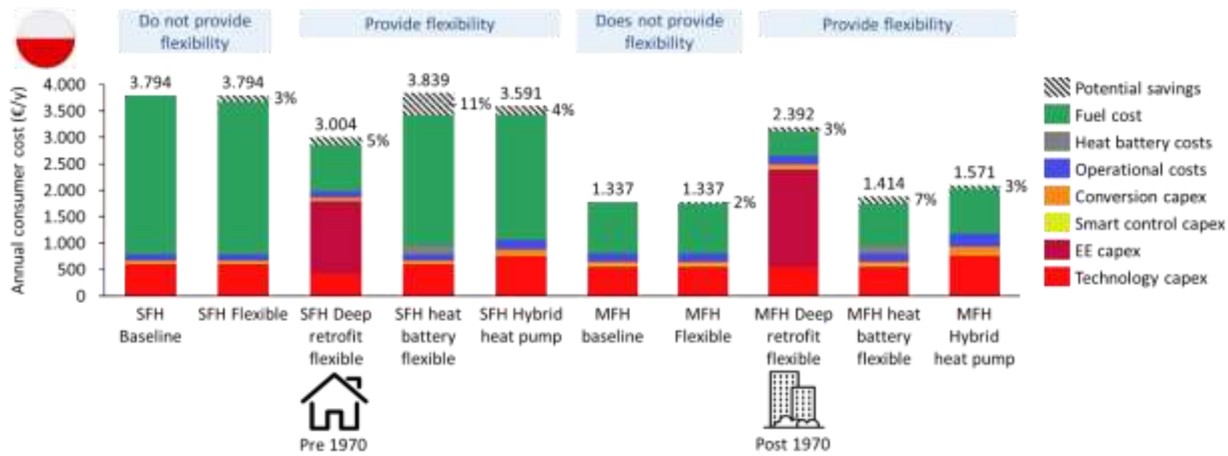

Figure 36 - Range of total annual consumer costs (€/y) possible in the Flexible scenario highlighting potential fuel savings due to flexible operation, in Poland

In Spain, as can be seen in Figure 35, both single-family and multi-family homes have higher annual costs in the cases where it is enabled to operate heating flexibly, despite the potential savings mentioned above, whereas in Poland, in Figure 36, that is only the case for multi-family homes. In older single-family homes in Poland, all consumers are better off with a flexible energy system, whether they purchase an energy efficiency retrofit, a heat battery, or a hybrid heat pump to provide flexibility.

It is therefore likely that policy support will be needed so consumers providing system flexibility, in multi-family homes in colder climates, or all consumers in warmer climates, do not pay higher costs overall. These supports may take the form of grants or other subsidies for energy efficiency measures, or enhanced payments for flexibility services.

5.6 System level savings from flexibility

This section considers savings at the system level from operating heating systems in a flexible way. This includes both the upfront additional cost of achieving flexibility and the final fuel savings resulting from the flexibility. Figure 37 shows the full system costs for each technology deployment scenario in both the Baseline and the Flexible scenarios across all countries investigated in this study. Across all scenarios and countries, the system cost is less in the Flexible scenario compared to the Baseline scenario. The Flexible heat pump scenario is seen to have the lowest full system costs across all countries. Considering only the heat sector and not the non-heat electricity, the heat pump scenario has a lower cost by at least €0.1bn in Czechia and up to €2bn in Italy than the hybrid heat pump scenario, which is the next lowest cost scenario.

When considering the components of the fuel cost which decrease in the Flexible scenario, the biggest decreases are from lower electricity generation costs where the lower peaks mean less investment in generation is required. The biggest savings come from the hydrogen scenario where making dedicated renewables that produce hydrogen at high load factors is significantly more cost effective than using grid connected electrolysers for hydrogen production.

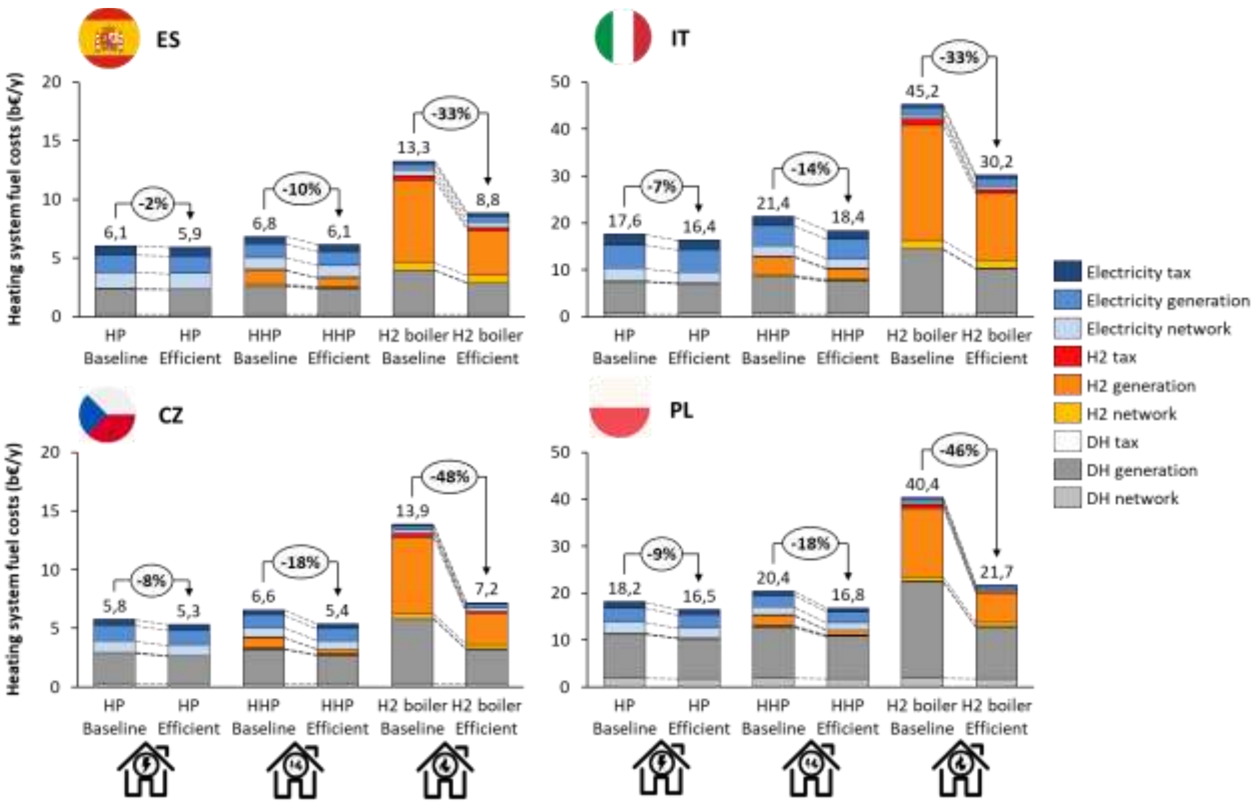

Figure 37 - Fuel cost savings from operating the electricity system in a flexible way

When the energy system is operated flexibly consumers will see a difference in their fuel bill. Some of the benefits of flexibility are likely to be passed on to the consumers that provide the flexibility, but some of the benefits are also likely to be socialised across all consumers. Since there is high uncertainty around how these savings will be shared in 2040, we show a range of possible savings for each consumer based on the maximum and minimum possible savings that they could be given by the system. Figure 38 shows the range of different costs that might be given to consumers in the Flexible scenario, the first and second bars represent the range of costs that a dwelling that doesn't provide flexibility might have, and the second and third bars show the range of costs that a consumer that does provide flexibility may have. In the extreme case of the third bar, all savings from flexibility are passed on to consumers who provide flexibility, and so consumers not providing flexibility would see the baseline electricity cost shown in the left-hand bar.

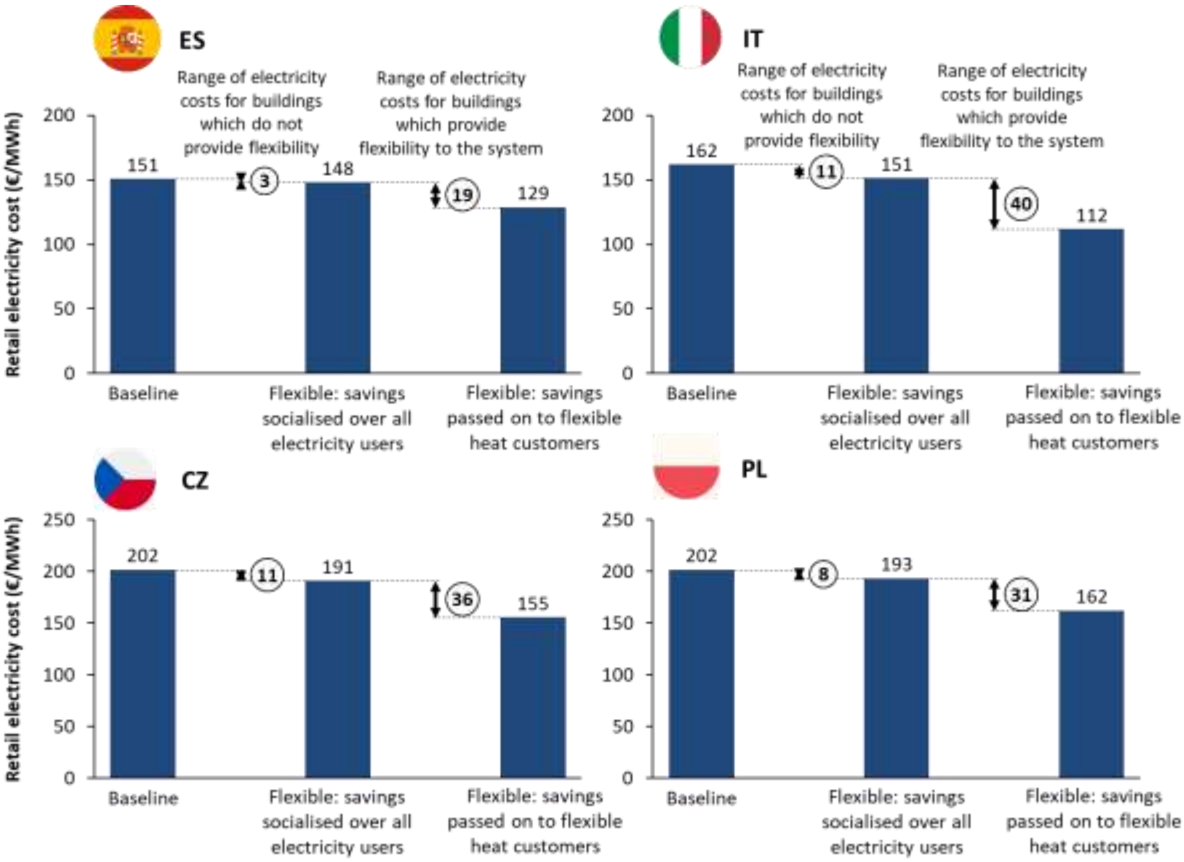

Figure 38 - The range of different electricity costs available to consumers in the four countries investigated in the Baseline and in the Flexible scenarios

5.7 Benefits of smart heating across the EU

The results shown above for the four countries investigated are expected to apply to all countries across the EU. It is expected that in countries like Poland, with either colder climates and/or lower cost of retrofitting, providing flexibility to the system can be cost-effective for consumers in single-family homes. Across the EU, some consumers providing flexibility, such as typical consumers in countries like Spain, or multi-family homes consumers in Poland, will benefit the overall energy system, and should be rewarded for providing this benefit, as it might not be cost-effective to do so if we assume a fully socialised cost benefit of electricity. Policies that could incentive consumers to provide flexibility could take the form of retrofit cost reductions, through grants for example, or could be a reduction in electricity cost through beneficial time of use tariff, or tariffs of similar type as a renewable heat incentive.

The largest amount of savings are expected to be made in countries with any of the following characteristics:

1. Countries with a high-cost marginal generation, such as coal or gas
2. Countries with a colder climate
3. Countries with a large share of solar generation in the energy mix

Beyond 2040, it is expected that the largest savings will be made when marginal generator cost is high, which is typically the case for fossil-fuel based generation. As can be seen in Spain in particular, with a very low marginal generation cost, the savings made by operating the grid flexibly are lower than for the other countries investigated.

Similarly, it is seen that in a hydrogen-focused future, the savings from operating flexibly are significant, due to the marginal generator in such cases is hydrogen-based and therefore has a high cost.

Thermal storage is also expected to provide valuable benefits, as highlighted by the decrease in electricity costs in Italy, despite a lower heat demand than Czechia and Poland.

6 Consumer costs of low carbon district heating

Spain and Poland have had a historical very different approach to district heating (DH). While in Spain, currently less than 1% of the building tock uses district heating, in Poland, they have been rolled out at scale, and approximately 40% of households are today on district heating. Due to the already high penetration of DH in Poland, we have assumed that the total building stock fraction on DH would stay at 40% by 2040. In Spain, we have modelled two scenarios, one with a high penetration of DH so that 32% of the building stock is on DH by 2040, and a lower ambition scenario, where 16% of the stock is on DH by 2040. This lower DH penetration in Spain is nevertheless a significant increase compared to the current level of DH in Spain.

The heat sources used by district heating are varied with the technology scenarios, as shown in Figure 39, with the further assumption that district heating is fully decarbonised by 2040. This means that gas, oil, and coal-fired systems, including combined heat and power, are not modelled as it is expected that these will be replaced with lower carbon alternatives. District heating systems can help accelerate decarbonisation since it is easier to replace a few large heat generators than the heating systems in many different dwellings. Although not modelled in this study, waste heat can be used as a cost-effective heat source for heat networks and should be considered where available.

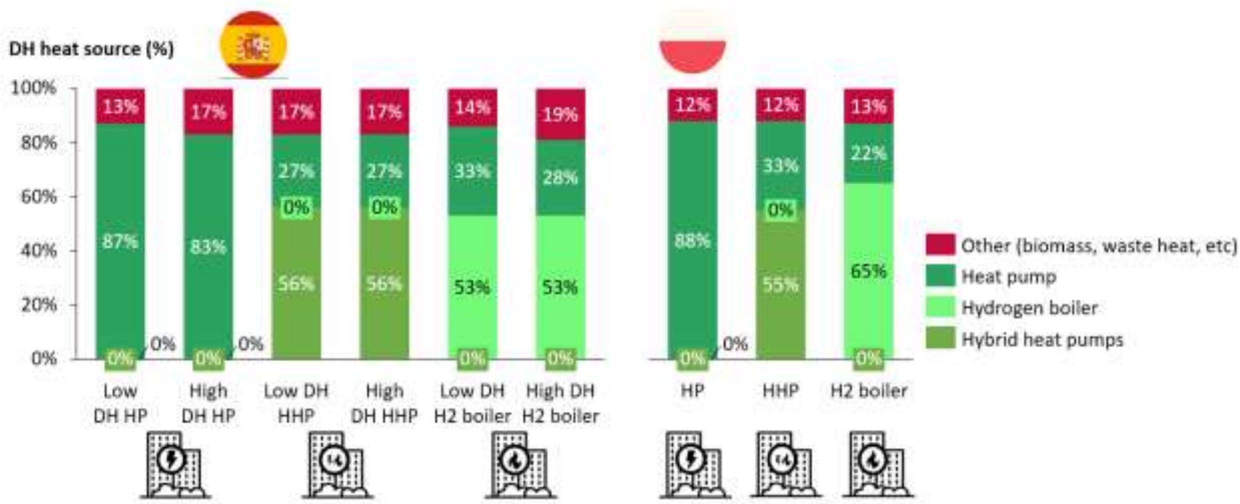

Figure 39 - Heat sources assumed for district heat in each technology scenario for Spain and Poland

While decarbonising district heating will bring benefits in terms of lower carbon emissions, it is important that adequate regulation is put in place to protect consumers on district heating networks. Because district heating is inherently a monopoly supply, and contracts are made over long time periods, consumers are at higher risk of high costs and poorly performing systems, and relatively less recourse to address these issues.

6.1 Cost of district heating networks for consumers

District heating networks are likely to have similar or lower costs for consumers than the dominant building-level technology in each scenario, as displayed in Figure 40 and Figure 41 for Spain and Poland respectively. However, the cost of any heat network is highly dependent on the local area in which it is installed and so drawing exact comparisons between district heating and building level technologies is difficult. For example, in Spain, the higher DH scenario has a higher average DH cost due to DH being taken up in areas with lower heat demand density, therefore leading to an increased average network cost. This analysis shows however that heat networks are likely to be a good option for consumers, particularly since their ease of decarbonisation is higher than building-level heating systems. In addition to that, they are a cost-effective way to help multi-family homes provide flexible heating, since installing a deep retrofit to provide flexibility is unlikely to lead to cost savings relative to the baseline. Those results are likely to apply to all European countries as the urban environments where DH would be cost-effective are similar. Table 1 summarises the main benefits and limitations of DH network schemes in the EU.

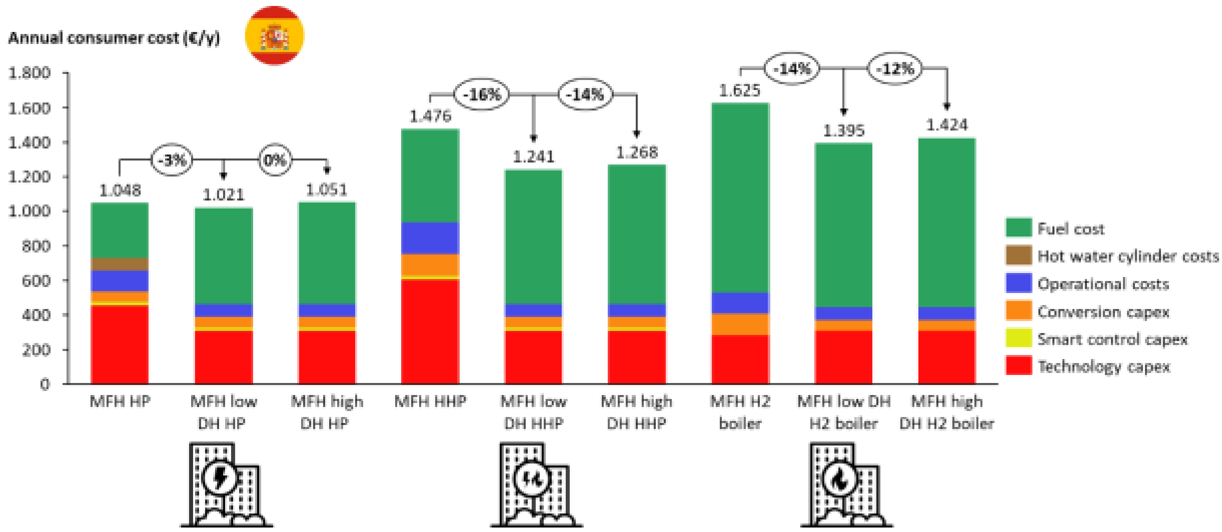

Figure 40 - Comparison between district heating and building level technology cost for consumers in each scenario in Spain. DH plant and network costs are included in the DH fuel cost

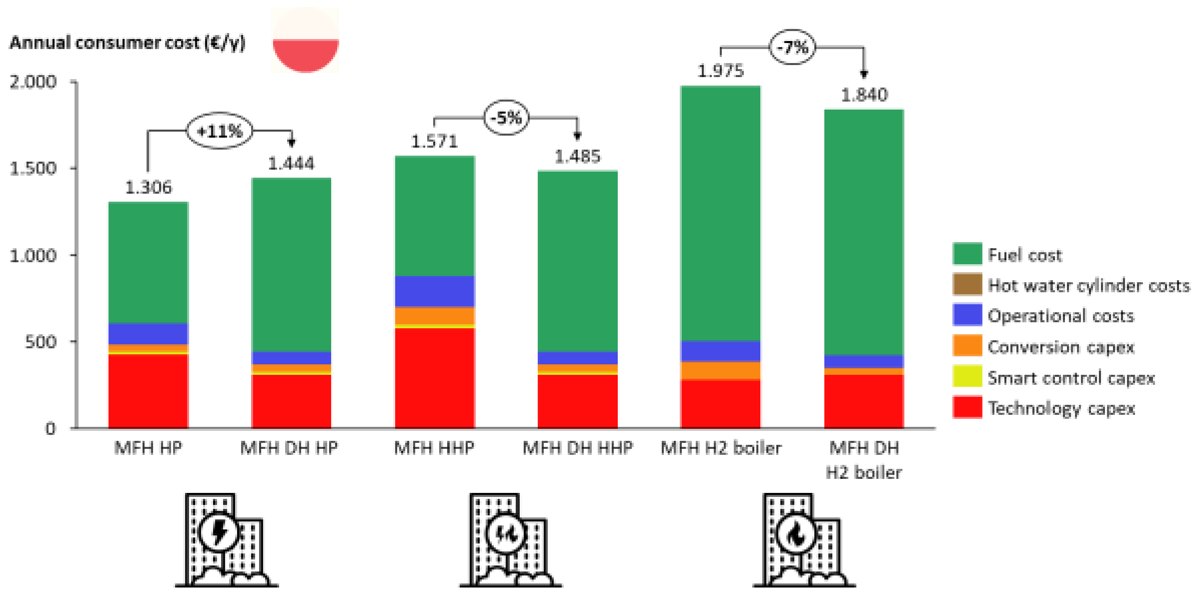

Figure 41 - Comparison between district heating and building level technology cost for consumers in each scenario in Poland. DH plant and network costs are included in the DH fuel cost

Table 1 - Summary of benefits and limitations of DH

District heating benefits	District heating limitations
DH can provide a significant level of flexibility by displacing large amount of heat demand in a centralised way.	Consumers are at risk of being locked in a costly heat contract over many years. Regulators need to ensure a fair pricing mechanism is available for all consumers connecting to a DH network.
DH causes minimal in-home disruption as it uses the same hot water flow temperature as current heating systems.	Development of DH schemes can be complicated as they require large upfront investment and coordination.
DH is technology agnostic and heat generation can be changed at heating system replacement points, which is especially useful when changing from fossil-based DH to renewables-based.	DH is only cost-effective in regions where the heat demand density is above the threshold needed to justify the large upfront investment needed.
DH networks have opportunities for extension once operational.	DH causes public disruption when they are installed.
DH allows removing all scope 1 heating emissions in the first year of operation, with the remaining emissions usually coming from grid electricity, allowing for fast decarbonisation of large heat demand centres.	
When waste heat is available, DH schemes can offer excellent business cases. In some cases, waste heat can be used directly, elsewhere, low temperature heat needs to be upgraded to appropriate temperatures.	

7 Conclusion

Decarbonisation of Europe's energy system will require wide-ranging changes in electricity generation, home heating, building fabric efficiency, and smart system interaction. While the evolution of the energy system will be different within each member state, there are several key trends likely to occur across Europe:

- Building energy efficiency improvements reduce peak and annual fuel demand, allow building heating systems to respond to the needs of the wider energy system, and provide improved comfort and health outcomes for occupants. Despite these many benefits, there are many situations where consumers cannot feasibly recover their initial investment through energy cost savings alone. This can be due to relatively small energy demand savings in milder climates but is also affected by the high cost of building retrofit. Coordinated policy to overcome the upfront cost barrier to energy efficiency can reduce whole-system energy costs if combined with smart, demand-responsive heating.
- Electric heating and green hydrogen are the primary options for widespread decarbonisation of domestic heating, while there are a range of other options likely to play smaller roles. The analysis presented above indicates that electrification of heat via heat pumps is likely to be the most affordable for the majority of consumers in the long run. Although heat pumps have a higher upfront cost than hydrogen boilers, the high running costs of hydrogen boilers result in a lifetime cost of heat significantly above that of heat pumps in all archetypes analysed. Policy support in the form of grants or low-cost loans enabling consumers to cover the initial capital cost of heat pumps will result in significant savings across the energy system.
- There are some cases, typically older and larger homes in colder countries, where hybrid heat pumps can be cost-competitive with heat pumps. Hybrid heat pumps may therefore be the preferred route to decarbonisation for some homes, provided that the technical challenges of retrofitting the gas grid to deliver hydrogen are overcome. There is also a risk that hydrogen used by hybrid heat pumps could be more expensive than estimated here if the majority of households adopt fully electric systems and the gas network is maintained although used by relatively few households.
- By 2040 the cost of electricity will be largely driven by carbon prices in areas where the marginal generators will still be supplied by fossil fuels. In these locations smart heating can help to integrate further renewables, particularly solar, reducing carbon-intensive generation and peaking capacity. As the electricity system becomes fully decarbonised, we expect to see high cost savings from flexible heating due to reduced use of high-cost, low-carbon marginal generation, for example CCGTs using stored hydrogen. Smart and flexible heating also reduces the requirements for grid network reinforcement.
- The co-location of electrolysers with dedicated renewable generation significantly reduces the cost of green hydrogen relative to use of grid electricity. Appropriate sizing of hydrogen storage infrastructure also contributes to a reduced hydrogen cost, especially in countries where geological storage is available.
- District heating can be cost competitive with other low carbon heating technologies. Decarbonising existing networks is likely to be more cost effective than converting existing district heating users to low carbon heat solutions at individual building level.

element energy

The Consumer Costs of Decarbonised Heat in Italy

Executive summary

for

BEUC

February 2022

Element Energy Limited
Suite 1, Bishop Bateman Court
Thompson's Lane
Cambridge
CB5 8AQ

Tel: 01223 852499

Key Messages

Low carbon heating

- This study analyses the cost to consumers of low carbon heating options in the year 2040 in Italy. We have investigated four archetypal homes and present detailed results for two of these archetypes, typical older (pre-1970) single-family homes and more modern (post-1970) flats in multi-family homes.
- We have examined four low carbon heating options within these archetypes: heat pumps, hybrid heat pumps, green hydrogen boilers, and low carbon district heat networks.
- 2040 electricity costs are predicted using the Element Energy Integrated System Dispatch Model (ISDM), which predicts electricity system operation on an hourly basis, and utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system when high levels of variable renewables are connected. We assume the Italian electricity grid has significantly decarbonised by 2040 in line with 2050 net zero targets.
- Green hydrogen costs are estimated using Element Energy's green hydrogen costing tool. This includes country-specific renewable generation profiles and projections for the 2040 cost of hydrogen production technologies, as well as estimated costs for the distribution of hydrogen through the converted gas network.
- Retail electricity costs are predicted to be about 150 €/MWh, while retail green hydrogen costs estimated to be between 160 and 180 €/MWh, depending on how hydrogen production interacts with the wider energy system.
- Heat pumps provide the most cost-effective route to decarbonisation of home heating in Italy across the dwelling archetypes analysed.
- The older single-family home using a heat pump is predicted to pay around €1.700/y for heating. With a hydrogen boiler, the same dwelling would see costs of nearly €3.800/y. The more modern flat is predicted to pay €1.100/y for heating with a heat pump, rising to around €2.000/y if heated with hydrogen. This includes the annualised cost of the heating system as well as maintenance and fuel.
- Hybrid heat pumps are more affordable than hydrogen boilers. The annual cost of heating with a hybrid heat pump is about €2.200 in the single-family home and €1.500 in the flat, an approximately 30% increase over the cost of heat with a heat pump in both cases. Although more expensive, there may be some role for hybrid heat pumps in hard-to-decarbonise Italian dwellings (most likely older and larger homes) which are connected to the gas network, provided that the technical challenges of retrofitting the gas grid to deliver hydrogen are overcome. There is also a risk that hydrogen used by hybrid heat pumps could be more expensive than estimated here if the majority of households adopt fully electric systems and the gas network is maintained although used by relatively few households.
- Although heat pumps have a larger up-front cost than hydrogen boilers, we expect that the running costs of these will be significantly lower than other options for decarbonising heating. This means there may need to be some policy support in place (such as direct grants, affordable green loans and green mortgages) so that consumers are enabled and incentivised to purchase these high capex appliances.
- The results shown are consistent with the other two archetypes investigated (post-1970 single family homes and pre-1970 multi-family homes). The archetypes are representative of typical Italian homes near Milan but do not capture the full diversity of the Italian housing stock of around 26 million dwellings. Some segments of the housing stock may be unsuitable for heat pumps due to high heat loss and barriers to the installation of additional energy efficiency measures.

Energy efficiency

- Installing energy efficiency can provide cost savings to consumers in some cases, and comes with additional benefits for health, thermal comfort and system flexibility.
- In some cases, energy efficiency retrofits will not pay back in energy bill savings alone. However, increasing the rate of energy efficiency rollout above current targets can reduce the total energy system costs (including the cost of energy efficiency) if combined with flexible operation of the electricity system.
- Policies may therefore be needed to enable and incentivise consumers to improve the fabric efficiency of their homes in order to realise the benefits to the wider energy system.
- Where deeper energy efficiency improvements are less cost-effective, installing domestic-scale thermal storage to enable flexible operation of heating enables a reduction in total electricity system costs.
- Consumer incentives through the market (e.g. ability to purchase lower cost electricity or rebates for providing flexibility) or policy supports (e.g. assistance covering the upfront cost of thermal storage) are likely to be needed to incentivise consumers to provide this service to the energy system.

Smart and flexible heating

- Italian households using heat pumps have several routes to providing flexibility services to the electricity grid. Buildings that undergo deep retrofit to achieve a high level of building fabric efficiency can operate their heat pumps intermittently without impacting comfort. In more modern flats, a shallow retrofit can also be sufficient to allow flexible heat pump operation. Alternatively, households may use a heat battery or a hybrid heat pump to enable flexible heat pump operation.
- Operating the energy system flexibly lowers the total energy system cost by 4% in a high heat pump scenario, an annual savings of €4,0 billion. This requires investments in energy efficiency improvements in buildings to enable flexible operation of heating. Some investments which will not pay back if the building is considered in isolation may in fact be cost-effective if impact on the wider energy system is considered.
- Smart and responsive heating can reduce the annual consumer cost of heating, saving consumers up to 9% for multi-occupancy buildings, and up 15% in single family homes.

District heat networks

- Low carbon district heat networks can provide domestic heat at comparable cost to building level heating systems and offer a high level of demand flexibility. In many cases heat networks will be simpler to decarbonise due to the relative ease of replacing centralised heating plant compared with disruption in hundreds or thousands of homes. Maintaining existing district heating networks and decarbonising them comes with significant consumer and carbon benefits if suitable consumer protections are in place.

Contents

Authors

For comments or queries please contact:

Sam.Foster@element-energy.co.uk

Fiona.Hughes@element-energy.co.uk

Joachim.Dias@element-energy.co.uk

+44 (1223) 852 499

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Acronyms

CZ	Czechia
DH	District heat
DSR	Demand side response
ES	Spain
HP	Heat pump
HHP	Hybrid heat pump
kWh	kilo Watt hours
ISDM	Element Energy's Integrated system dispatch model
IT	Italy
MFH	Multi family home
MWh	Mega Watt hours
PL	Poland
SFH	Single family home

1 Introduction

1.1 Context and objectives

Heat is recognised as one of the hardest sectors to decarbonise. Currently most consumers use fossil fuels to provide their heat, but to meet emissions targets they will have to swap to a cleaner technology. One possible solution is to electrify heating via heat pumps, however since the seasonality of heating is far greater than of electricity demand this may create a large winter peak in electricity demand causing issues for generators and the distribution network. Another possible option is to decarbonise the gas grid by injecting hydrogen rather than natural gas into it, this might reduce the impact of electrification on the electricity system, but creates challenges in producing zero carbon hydrogen, and converting the distribution network. Since there is significant uncertainty around the costs and risks of these two methods of decarbonising heat, this study aims to understand the impacts of different future scenarios and particularly focuses on the possible impacts on consumers.

In addition to the technologies used to heat dwellings in the future, the installation of energy efficiency upgrades is considered. Currently EU member states have an ambitious target for energy efficiency installation, this study aims to show both the benefits to the energy system of energy efficiency whilst also understanding the potential financial risks to consumers of these installations. We also consider the possible benefits of going beyond current energy efficiency installation targets for consumers.

This study considers the energy system in 2040, this is because it is sufficiently far in the future that significant steps towards the decarbonisation of heating will have been taken by then, we model that 80% of homes are using decarbonised heating by this date, but near enough to the present that accurate projections of the electricity generation mix can be found. The choice of this year will allow us to analyse with greater certainty the cost of different scenarios than we would be able to if choosing a year further into the future even though the system might be more decarbonised by then.

This study determines what the overall cost of heating will be to end users in Europe, under different heating delivery scenarios (primarily electric heat pumps, green hydrogen boilers and hybrid options, and including both individual building and district heating approaches). All costs are determined, including purchase, installation, and maintenance, and the fuel cost, which covers the commodity itself (gas or electricity) and the cost of the infrastructure required to deliver it to homes and to run a safe and secure energy system. The key aims of the study are to:

- Assess the costs of decarbonised heating options from a consumer perspective.
- Analyse the cost and benefit from building fabric energy efficiency measures to individual consumers and the energy system.
- Determine the impact of smart and responsive heating on the energy system and the financial benefits to heat consumers who provide flexibility.
- Compare the costs of decarbonised district heating systems with individual dwelling level approaches.

The study has produced reports on four European Member states (ES, IT, CZ, PL), as well as one overall report providing insights into EU-wide consumer impacts. This report summarises the key findings and conclusions about decarbonised heating in Italy, and makes recommendations around policies that should be implemented to protect consumers.

1.2 Technology scenarios

For this work three technology deployment scenarios for 2040 were created. These three scenarios were focused on the deployment of a single technology as the main low carbon heating option, these were air source heat pumps (ASHP), hybrid heat pumps (ASHP + hydrogen boiler), and hydrogen boilers. The technology mix for each scenario in Italy is shown in Figure 1. These scenarios are used to analyse the likely cost of different technology options in Italy under different possible futures and are not intended to be projections or predictions of the likely future technology mix.

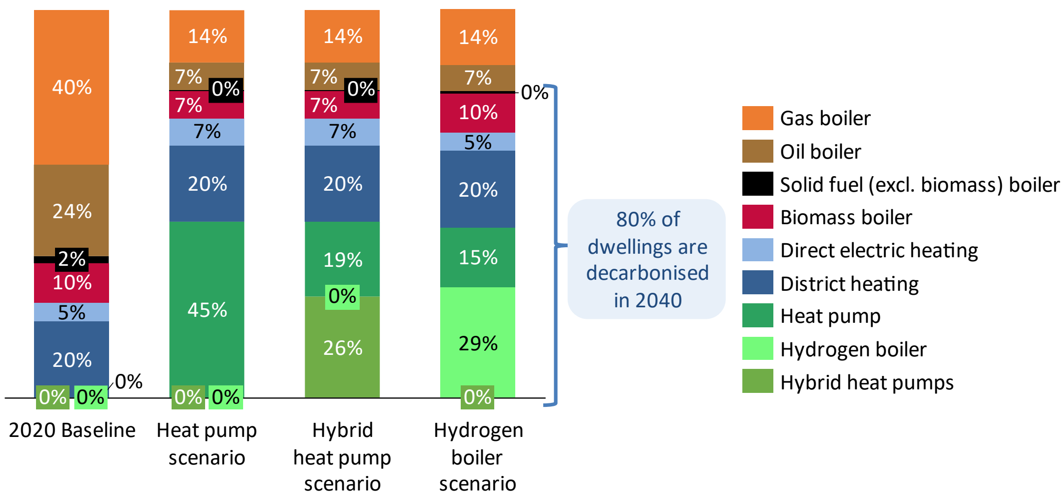

Figure 1 - Fraction of dwellings with each technology in 2040 in each scenario.

In these scenarios the hydrogen boiler and hybrid scenarios are based on the gas network transitioning to hydrogen. This is likely to be a phased process which will not be completed by 2040; hence some remaining natural gas boilers are included in the scenarios above[1]. In these scenarios hydrogen for heating is modelled as "green" hydrogen produced from electricity via electrolysis.

Each of the three technology deployment scenarios are analysed in two ways:

1. The **Baseline-Passive** scenario includes fabric energy efficiency deployment at a rate of 2% of buildings per year, and energy demands such as heating continuing to operate in a passive way.
2. In the **Efficient-Smart** or **Flexible** scenario a higher rate of fabric energy efficiency rollout of 2.7% of buildings per year is assumed, and heating systems behave in a flexible way, responding to the needs of the energy system as a whole.

In addition, in the Baseline-Passive scenario it is assumed that hydrogen is produced by grid-connected electrolysers, whereas in the Smart-Efficient scenario hydrogen is produced using dedicated renewables collocated with electrolysers, i.e. solar and wind installations that do not send their electricity to the grid but instead use it for hydrogen production. In addition, excess power from grid-connected renewables is also directed towards hydrogen production at times when it would otherwise be curtailed. Dedicated renewables and use of

[1] Hydrogen and natural gas are likely to co-exist in different areas of the distribution network during the period of transition to hydrogen.

grid curtailment allows production of cheaper hydrogen with less impact on the overall energy system.

1.3 Case study buildings

The housing stock in Italy is made up of a large range of different buildings. To present results in this report the key building level results for consumers are presented for two typical buildings. These typical buildings are a single-family home (SFH) built before 1970 and a multi-family home (apartment, MFH) built after 1970. These buildings are chosen to illustrate the trends that consumers are expected to see, however since all buildings are different there will be some variation from the trends presented for individual buildings. Table 1 shows the characteristics of the selected dwellings.

Table 1 Details of the two key archetypes that results are presented for in this report

Feature	Archetype 1[2]	Archetype 2[3]
Picture		
Type	SFH	MFH
Age	Pre-1970	Post-1970
Assumed climate	Milan	Milan
Floor area (m^2)	115	91
Annual heating demand (kWh)	14.624	6.107
Annual hot water demand (kWh)	1.349	1.062

1.4 Method

An overview of the method is shown in Figure 2 below. The key steps in the modelling are:

1. The archetype stock model calculates the heat demand and final energy consumption on an annual and hourly basis for domestic dwellings in Italy. The outputs are generated at the building level and at the country-level (i.e. including all

[2] Detached home near Milan, Google image search

[3] Vladimir Menkov, CC BY-SA 2.5 via Wikimedia Commons

buildings). Non-domestic buildings are included in the national demand although they are addressed with less detail than the residential stock.

2. Each residential building archetype undergoes a flexibility assessment to determine whether and how much its heating demand can be shifted to accommodate the needs of the wider electricity system.

3. The energy demands and flexibility potential of the heating system is used by the ISDM in modelling the hourly behaviour of Italy's energy system throughout 2040. The ISDM predicts the retail costs of electricity and green hydrogen. A more detailed description of the ISDM model is given below.

The upfront and ongoing costs of heating are calculated by the consumer cost model for the selected Italian building archetypes.

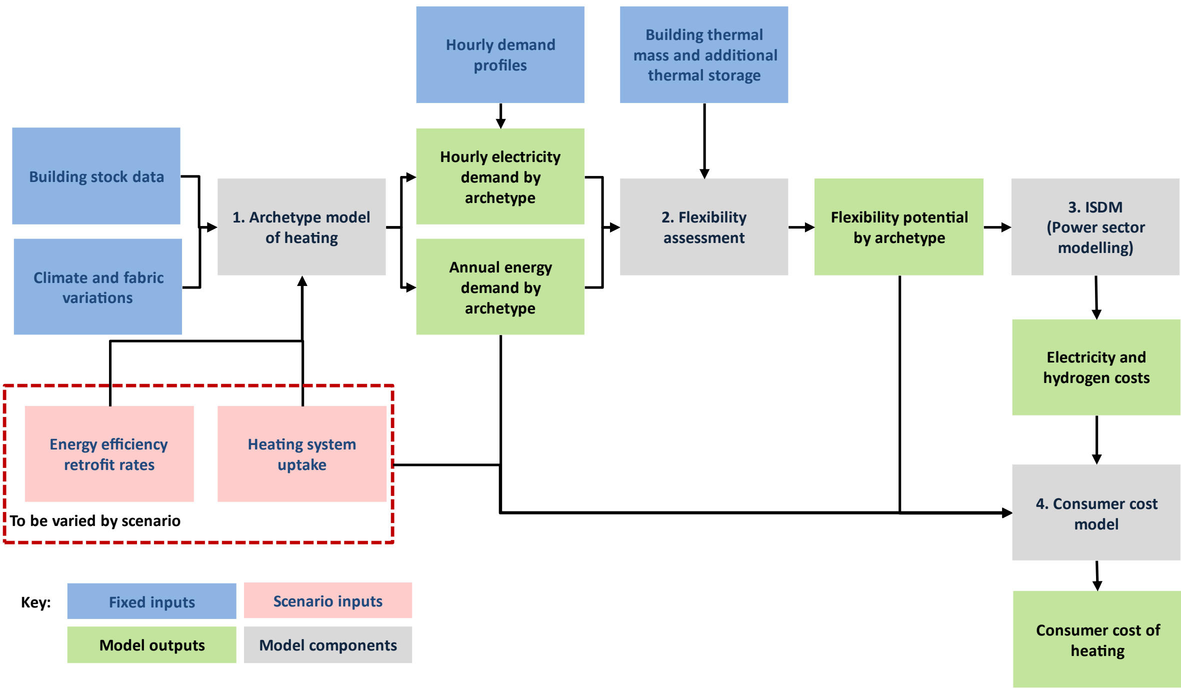

Figure 2 - Full heating system costing model flowchart.

1.5 Energy system modelling

Element Energy's Integrated Supply and Demand Model (ISDM) was developed to overcome limitations of typical power system dispatch models when applied to zero carbon systems. Many such models continue to treat the power system as it currently is: highly dispatchable and reliant on thermal sources for flexibility on the supply side. Future low carbon systems, where variable renewable energy is dominant, will require flexibility on the demand side to support the integration of high levels of renewable energy, while minimising curtailment and reliance on backup thermal plant. ISDM utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system.

The main principles of whole system operation are summarised here. The starting point for the modelling is a set of hourly energy demand profiles for each sector. Some demand profiles are fixed (no flexibility), while others are able to be shifted over defined periods. For heating, these demands are based on the building heat loss, heating technology and outside air temperatures. Transport demand is based on the stock of electric vehicles, their efficiency, the daily usage, and arrival/departure times from home and work to generate baseline electrified transport demand. Grid-responsive smart charging can schedule charging to times of most use to the grid, while still providing vehicles with sufficient charge for transport. Flexibility provided by thermal storage and thermal mass of buildings allows heat demand to move demand to times most useful to the grid, without reducing thermal comfort in homes and offices.

Hourly weather data is also used to generate hourly load factors for wind and solar production. Using the assumptions on the installed VRES generation capacity, the model calculates the hourly VRES generation. By subtracting this from the demand profiles, initial net load curves are generated. Demand shifting, as enabled through smart EV charging and smart heating is deployed to minimise the peak system demand and therefore the required network capacity. Further demand shifting is then applied to reduce curtailment of renewables and fossil fuel use, by moving demand from hours of high to hours of low net demand. By reducing the peak net demand, demand shifting leads to a decreased requirement for dispatchable generation capacity.

The dispatchable generation fleet is then deployed in merit order to fill in the supply gap. Once all hourly demand is met, annual system performance metrics are evaluated, among them fuel and carbon cost, variable OPEX, VRES curtailment, peak demand (for determining the required network capacity), and peak net demand (for determining the required dispatchable generation capacity).

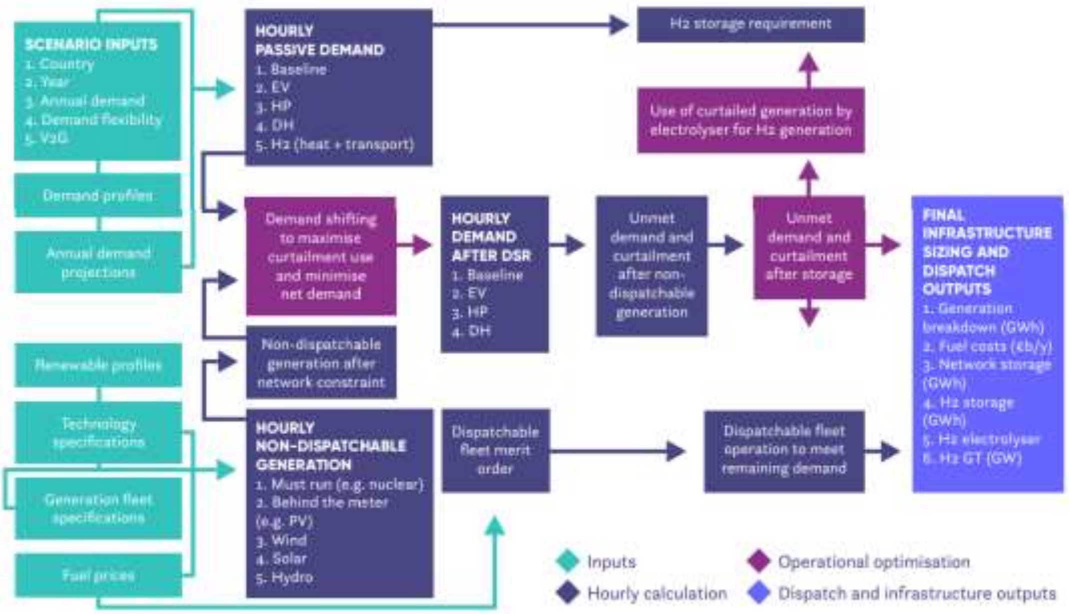

Figure 3 – Schematic of the calculation within the ISDM

1.6 Costing hydrogen for consumers

The cost of producing green hydrogen produced from electricity with electrolysis was modelled in this project. In the baseline case, it was assumed that the electrolysers were connected to the electricity grid, and pay a wholesale price (excluding grid fees) for their electricity. The cost of hydrogen distribution and storage was then calculated based on a parameterised model of the gas grid and costs of converting the low pressure distribution grid to hydrogen. The costs of hydrogen production and transmission used were taken from the BEIS hydrogen supply chain evidence base[4]. In the flexible case it was assumed that hydrogen production would not be connected to the electricity grid. Hydrogen production electrolysers were assumed to be collocated with renewable generation and the production of hydrogen was found on an hourly basis to optimise the relative generation and electrolyser capacities for the cheapest hydrogen cost.

Country specific renewable generation profiles were calculated from NASA MERRA-2 data, and the cost of renewable generation was found from the BEIS 2020 cost of generation report[5]. In addition, in the flexible case, hydrogen was also produced using renewable electricity that would otherwise be curtailed. The costs of hydrogen in the Baseline and Flexible scenarios for the high hydrogen scenario are shown in Figure 4. Both wind and solar generation to produce hydrogen were considered, but in Italy offshore wind was the cheapest way to produce hydrogen and this was used for the purpose of costing production in the flexible case. To find the cost per kWh the capex of generation and electrolysers was annualised over the expected lifetime of the technologies[6] at a discount rate of 5% in the consumer cost case and a 3% discount rate in the system cost case. Hydrogen storage was also costed, in Italy this storage was modelled as a liquid organic hydrogen carrier, with round trip efficiency and other energy use included in the costing.

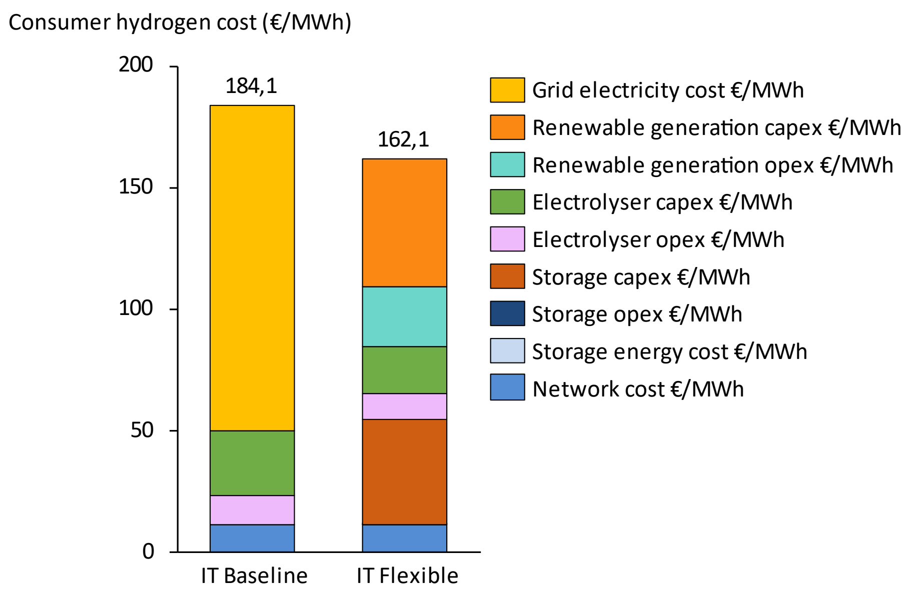

Figure 4 - Cost of hydrogen for consumers in the two cases.

[4]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf
[5] https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020
[6] We have assumed electrolyser lifetime of 20 years, and renewable generator lifetime of 40 years.

2 Impact of ambitious energy efficiency deployment

2.1 Energy efficiency scenarios in Italy

In Italy, two energy efficiency rollout scenarios were analysed, one baseline scenario with rollout at the rate equivalent to existing targets and one very ambitious rollout rate combined with smart heating system operation. Energy efficiency rollout was analysed by using two packages, one shallow and one deep retrofit, these packages each contain a set of measures that reduce heating demand. The rollout rate of these packages in the different scenarios is shown in Table 2.

Table 2 - Energy efficiency rollout rates in different scenarios.

Scenario	Shallow retrofit rate per year		Deep retrofit rate per year		Total retrofit rate
	SFH	MFH	SFH	MFH	
Baseline	1.5%	1.5%	0.5%	0.5%	2%
Efficient	1.5%	2.5%	0.75%	0.5%	2.7%

Figure 5 shows the breakdown of the 2040 housing stock in the two energy efficiency rollout scenarios in Italy. In the efficient scenario 4% more of the stock has had an energy efficiency retrofit than in the baseline scenario.

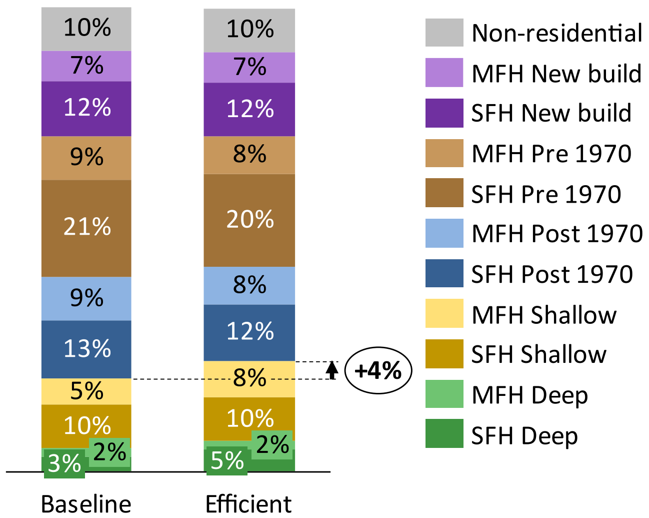

Figure 5 - 2040 housing stock in baseline and efficient scenarios (adds up to >100% due to rounding of numbers).

The next chart, Figure 6 shows the reduction in heating demand in typical buildings from a shallow and deep retrofit. Shallow packages reduce the heating demand by 29% in older single-family homes and 13% in newer multi-family homes. Deep packages give savings of 72% in the older single-family homes and 62% in newer multi-family homes.

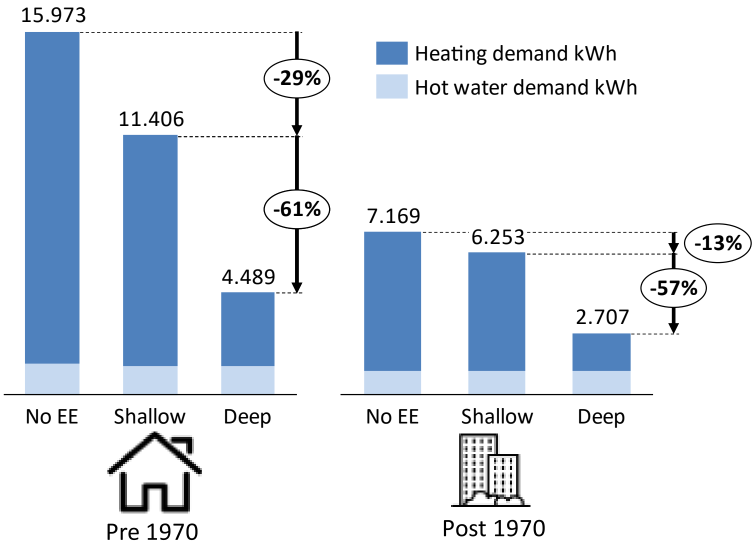

Figure 6 - Reductions in heating demand of typical buildings.

Energy efficiency upgrades require significant capital outlay depending on the size and age of the home and the level of retrofit. Figure 7 shows the upfront cost of energy efficiency retrofit in the two typical archetypes[7]. The costs are significant, particularly for deep retrofit. While the Ecobonus scheme has motivated uptake, the short-term nature of the scheme has caused a shortage of skilled installers and may be exacerbating the high costs of retrofit.

The total annual expenditure on energy efficiency measures would be €6.3bn in the baseline scenario, and €8.0bn in the efficient scenario.

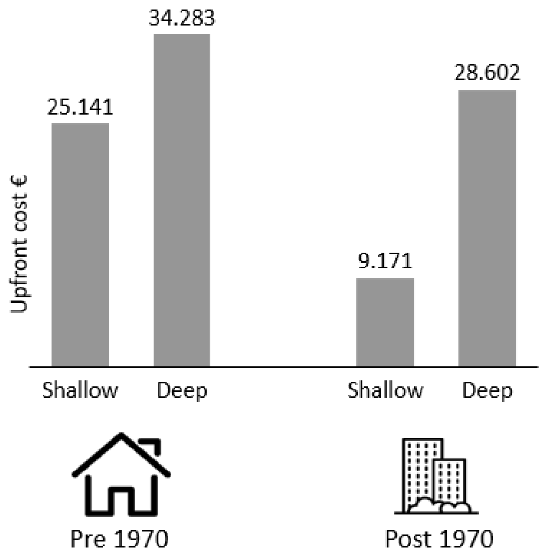

Figure 7 - Upfront cost of energy efficiency packages.

[7] Costs per square area and heat demand savings were taken from [ZEBRA2020: nearly zero-energy building strategy 2020] except for deep retrofit cost, taken from the [2020 Annual report on energy efficiency from the ministry of economic development]

Figure 8 shows the heating demand changes between the baseline 2020 housing stock and the two 2040 scenarios. The baseline scenario has 5% less heating demand than 2020 and the efficient scenario has 2% lower heating demand than the baseline. Both of these reductions are despite the fact that 19% of the building stock in 2040 is made up of new buildings. These are assumed to have heating demand similar to or lower than a building which has undergone a deep retrofit.

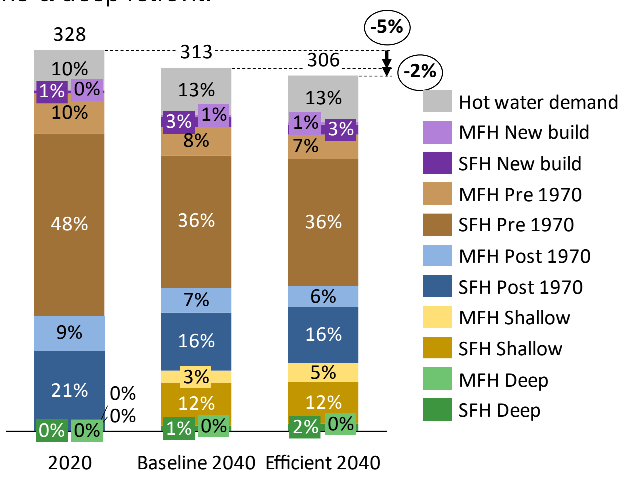

Figure 8 - Residential heating demand by scenario, in TWh.

Figure 9 shows the building level heating cost in € per year for the two key archetypes with different energy efficiency packages installed. This shows that despite the fuel cost savings from improved energy efficiency, the high annualised capex of energy efficiency installation in both large single-family homes and smaller multi-family homes result in a net increase in total heating system cost. This increase of annualised costs to consumers would occur without policy support, even though consumers who do install energy efficiency measures despite their high capital cost will see lower fuel bills. Throughout the study, we have analysed heat demand assuming the archetypal dwellings are located in Milan.

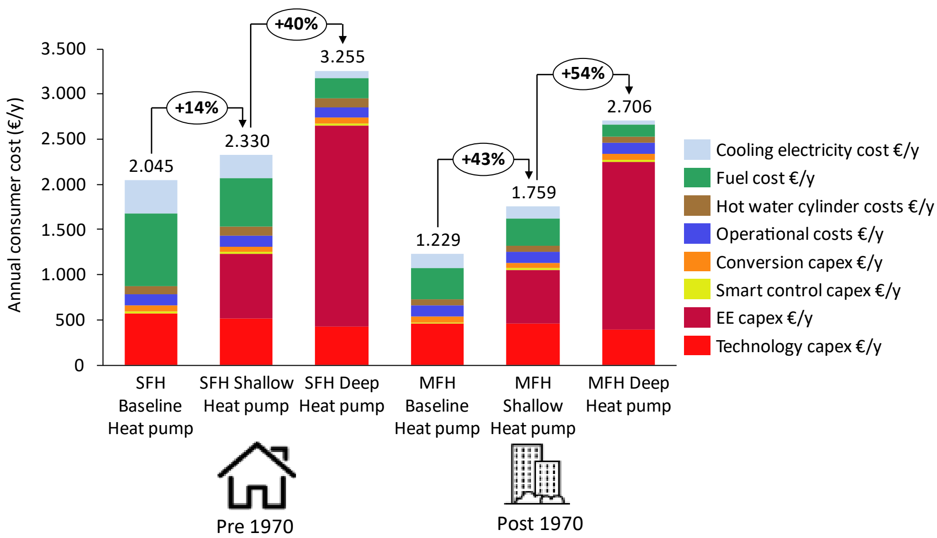

Figure 9 - Building level costs (€/y) of different levels of energy efficiency in typical archetypes.

Figure 10 and Figure 11 present the same annual consumer cost of heat with the addition of a public subsidy for energy efficiency, in the form of a 50% and 100% grant or rebate respectively, to defray the initial capital costs.

With a 50% grant support, a typical single family home benefits from reduced annual heating cost with a shallow retrofit and has a cost increase of less than 5% of the total annual cost with a deep retrofit. The annual cost impact for multi-family homes is still appreciable, with a 20% cost increase for shallow retrofit and a further 20% increase for deep retrofit.

With a 100% grant support, consumers are able to benefit fully from the fuel cost savings, leading to annual consumer heating costs reduction by close to 40% in single-family homes and close to 30% in multi-family homes for deep retrofit packages.

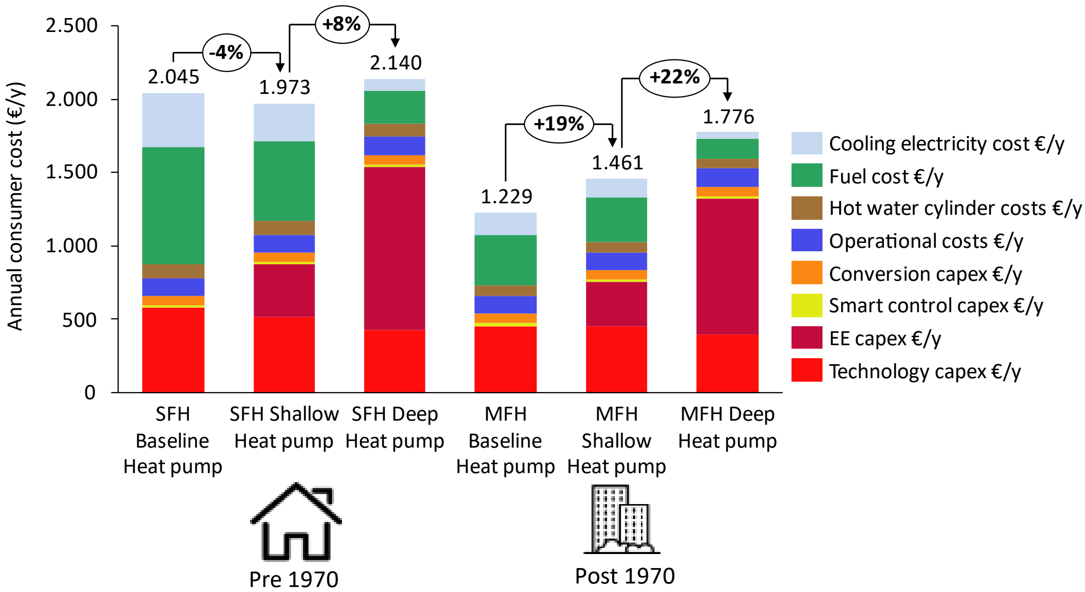

Figure 10 - Building level costs (€/y) and impact of energy efficiency in typical archetypes, with a 50% public subsidy supporting energy efficiency improvements.

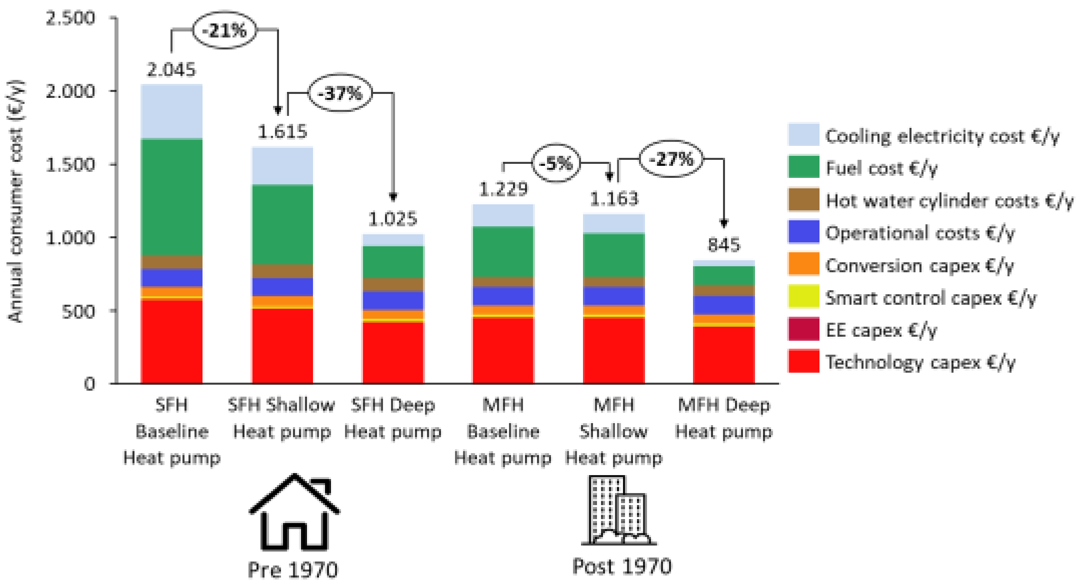

Figure 11 - Building level costs (€/y) and impact of energy efficiency in typical archetypes, with a 100% public subsidy supporting energy efficiency improvements.

Although energy efficiency measures may not be cost effective at an individual building level, particularly for consumers living in multi-unit buildings, the installation of these efficiency measures contribute to cost savings to the entire energy system. These savings depend on the type of renewable heating system deployed but are likely to be at least €4bn per year; the exact values are shown in Figure 12. It is important to note that for the system to realise the full savings from energy efficiency rollout, policy support will be required to remove the significant upfront cost of energy efficiency from households such that they are incentivized to invest in reducing their dwelling's heating demand. The current Ecobonus scheme for example, provides a tax deduction of 110% of any expenditure on fabric energy efficiency measures and seismic risk reduction.

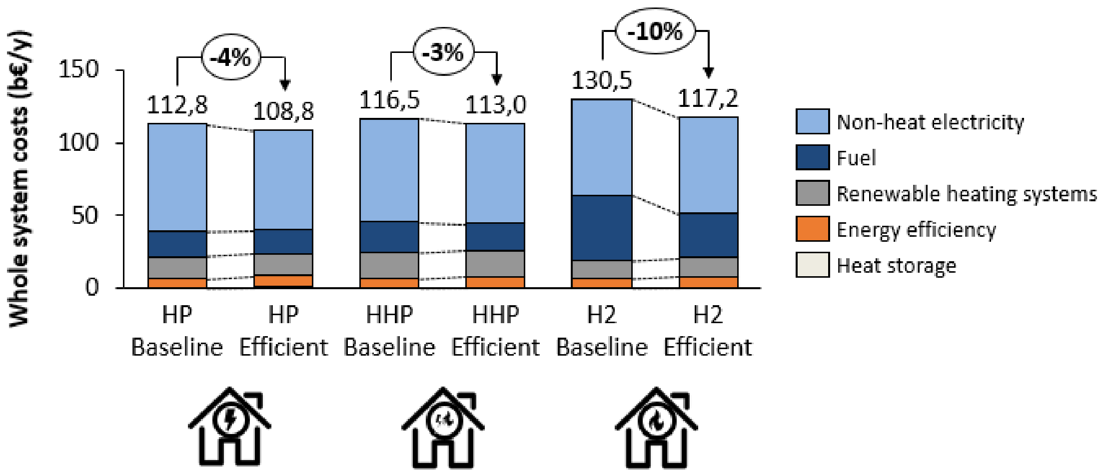

Figure 12 - The system cost saving from the efficient scenario.

3 Consumer costs of low carbon heating options in 2040

The cost of heating systems to consumers has two parts. There is an upfront capital cost (capex) that is incurred when the heating system is replaced and there is an ongoing cost of fuel and maintenance. This section shows the total cost of heating made up of both of those components, and then looks at each component individually.

3.1 Total cost of heating for consumers

The total cost of heating for consumers is found by summing the annualised capital cost, at a 5% discount rate with a 15-year technology lifetime, with the annual operating cost. This represents the total cost for a consumer in each year of heating their dwelling with that technology. This comparison shows that heating dwellings with heat pumps is the cheapest option for consumers in both key archetypes. A high rollout of hydrogen boilers relative to a rollout of heat pumps could leave consumers paying over twice as much for their heat. Since the cheapest overall option, heat pumps, come at a significant upfront cost premium to hydrogen boilers and gas boilers, it is important that government keeps providing adequate support to consumers to switch their heating through incentives and support measures such as the Ecobonus that address these high upfront costs.

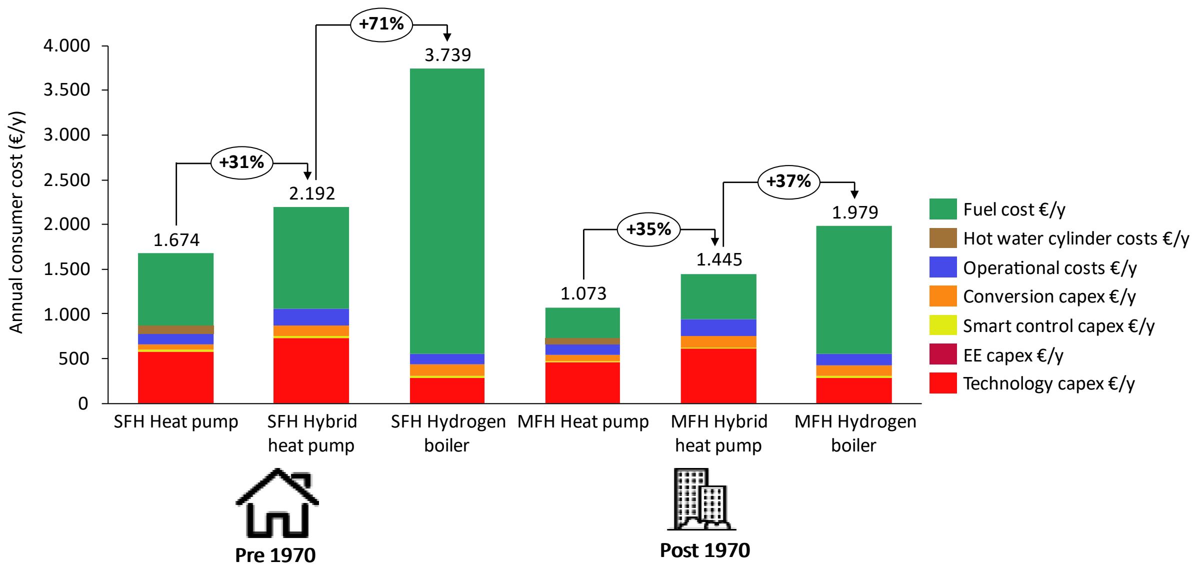

Figure 13 - Annual consumer cost of heat with the main technology in each scenario.

3.2 Ongoing costs of heating systems

Fuel costs are found from electricity system modelling based on the uptake of heating systems and energy efficiency for that scenario. The technologies considered here have different efficiencies of producing heat from their fuel. Heat pumps can operate at 280% efficiency, whereas hydrogen boilers are 85% efficient. Since hydrogen is produced from electricity via electrolysis, which is assumed to be 70% efficient, using hydrogen boilers to produce heat typically uses 4.5x as much electricity as producing the heat with a heat pump. Due to this, the operational costs of hydrogen systems can be 3x as large as those of heat pump systems. Even if hydrogen is cheaper than electricity per kWh, the significantly lower efficiency of heat generation with hydrogen boilers compared to heat pumps will lead to higher costs to consumers. In Italy, we anticipate that hydrogen costs will be comparable to electricity. This also indicates that hydrogen will be significantly more expensive than gas is today for consumers. Figure 14 shows the annual running costs for the different heating systems in the two main archetypes.

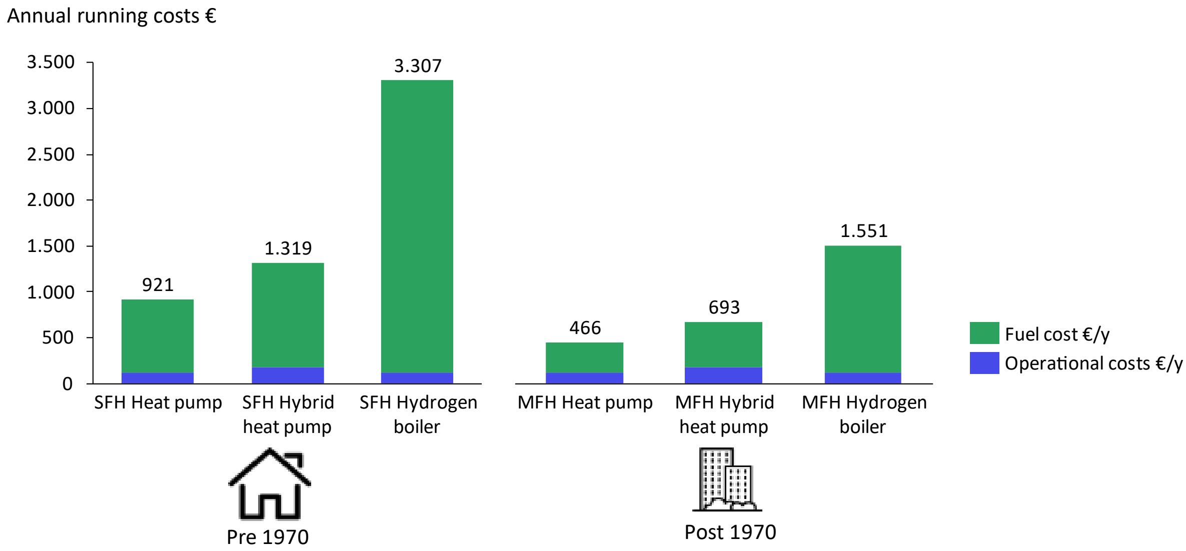

Figure 14 - Annual running costs of different heating systems.

3.3 Capital cost of heating systems

Capital costs are found from the Element Energy database of heating system costs and include the cost of the heating system as well as the cost of hot water cylinders and smart controllers where appropriate. Hydrogen boilers have the lowest capital cost of the heating systems considered; hybrid heat pumps have the highest capital cost.

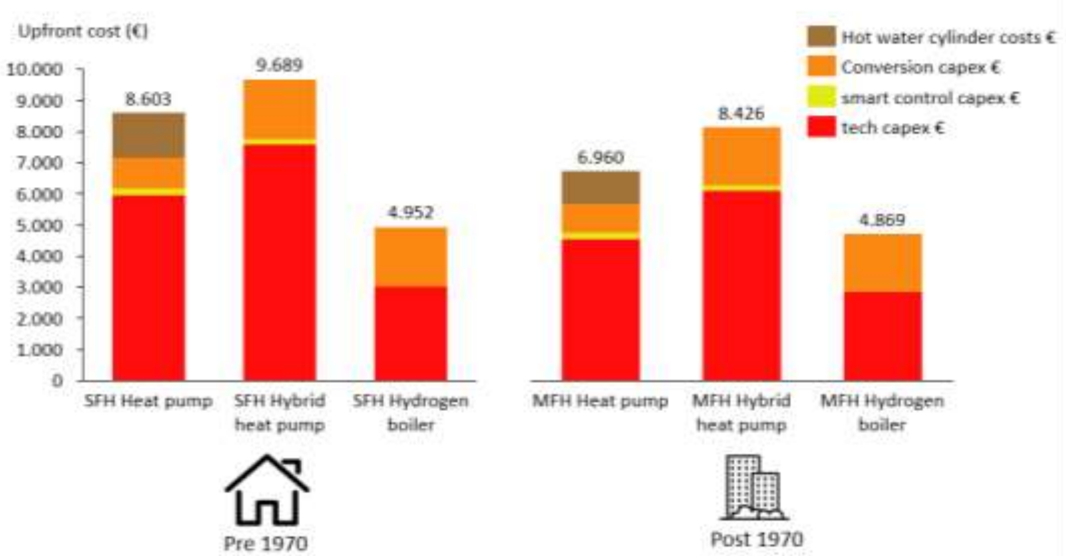

Figure 15 - Capital costs of different heating systems for typical archetypes.

4 Benefit from smart and responsive low carbon heating

Two system operation scenarios are presented in this study, the **Baseline-Passive** scenario involves passive operation of the energy system to meet demand, and the **Efficient-Smart** or **Flexible** scenario involves a higher rate of energy efficiency and operation of the energy system in a flexible way such that demand is changed to better match supply of power. Each of these two scenarios has been run with the three different technology deployment levels, so in each case the impact of smart system operation can be quantified. In all scenarios smart operation of electric vehicle charging is assumed.

4.1 Energy system benefit of smart operation

When heat pumps are operated in a smart way, they act to move demand away from the peak, this is achieved by pre-heating houses with high thermal mass relative to their heat loss rate, or by storing thermal energy in a phase change heat battery. Phase change batteries are commercially available heat storage systems that use a phase transition (e.g. solid to liquid) to store and release thermal energy when required. We assume that by 2040, 50% of buildings with heat pumps that cannot be flexible through their thermal mass purchase a thermal battery. This allows a greater proportion of buildings to offer flexibility services, without implying an unrealistic rate of deep retrofit.

When heating is operated flexibly, the total demand for heating is unchanged, but the profile of electricity use is less “peaky”. The lower peaks mean that the total required capacity of electricity generation can be lower and less upgrade to higher capacity electricity networks is required, reducing the cost of the electricity system. In addition to the peak reduction, flexibility also allows demand to be better matched to when there is high generation of renewable technologies. This means that some demand is shifted from times of low renewable electricity production, when gas peaking plants would be put in operation to satisfy this demand, to times of abundant renewable electricity production, when some renewable energy production would otherwise be curtailed. This causes an increase in load factor for those renewable generators and a decrease in thermal generation capacity required, thus decreasing the overall system cost. Figure 16 shows the nationwide electricity demand over a typical winter week in 2040 in the scenario with high uptake of heat pumps. Under smart operation, heat demand is removed away from the peak, increasing demand at other times of day. This decreases the peak system demand and means less network capacity is required. In addition, heat demand can be moved into times where variable renewable electricity is available, reducing both the cost of electricity production and its carbon content.

The model first moves demand that is flexible based on thermal mass, and then moves the demand that is flexible based on installing additional thermal storage, Figure 16 shows the change in the demand profile after the thermal mass flexibility and thermal storage are applied, the majority of flexibility comes from additional thermal storage.

In the flexible case, hydrogen is considered to be produced by collocated renewables and curtailment so does not impact the wider electricity system relative to the baseline scenario where it is produced by grid connected electrolysers.

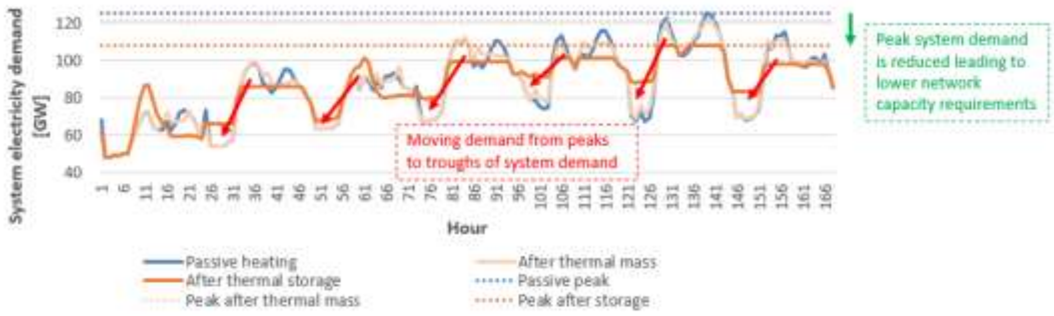

Figure 16 - Example of total electricity demand in Italy under the heat pump scenario with passive and smart heating system operation.

4.2 Costs and savings of flexibility for consumers

The total cost of the energy system, and therefore the energy costs faced by consumers, is reduced when heating systems are operated flexibly. The level of savings seen by different types of consumers will depend on the policies, tariff design, incentives for flexibility, taxation systems and market structures created to enable and incentivise smart operation of domestic heating. The cost savings may be passed on to the consumers that provide flexibility services, or they may be socialised across all electricity consumption. In practice, a mix of these two options is likely. While consumers may be incentivised to participate in DSR through Time-of-use electricity tariffs or through regular discounts on bills, these incentives may be less than the total system cost savings.

The range of different annual heating costs that could be seen by consumers in the smart and flexible heat pump scenario relative to the baseline passive scenario is shown in Figure 17 and Figure 18. The dashed bars show the range of different fuel costs that consumers might save in different circumstances. If the benefits of flexibility are fully socialised, larger homes may save around €50/y, with flats saving about €20/y.

If savings are directed towards the households providing flexibility, large flexible households may save a further €250/y, for total savings of €300/y over the baseline case. Similarly, flexible flats may save up to €120/y. If all savings are passed along to households providing flexibility, those unable to operate flexibly will have fuel bills unchanged from the passive case.

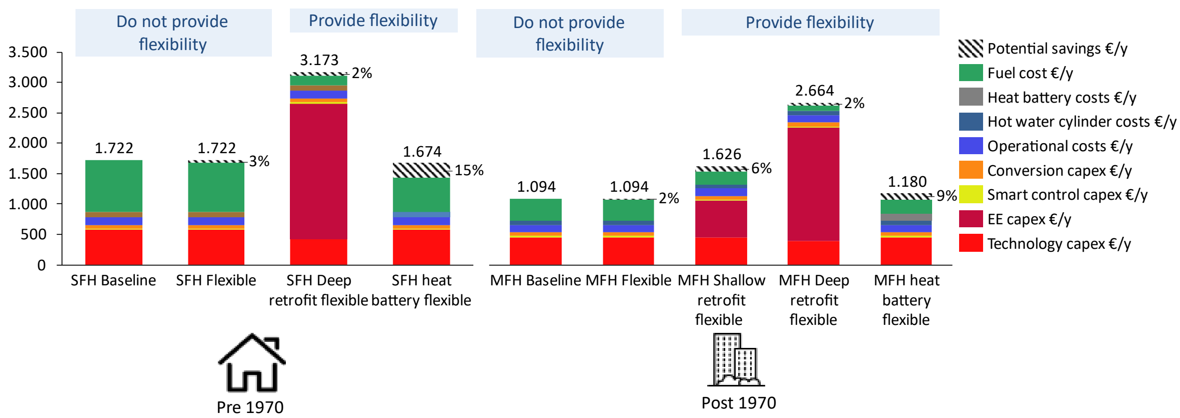

Figure 17 - The range of total consumer costs (€/y) possible in the Flexible Heat Pump scenario.

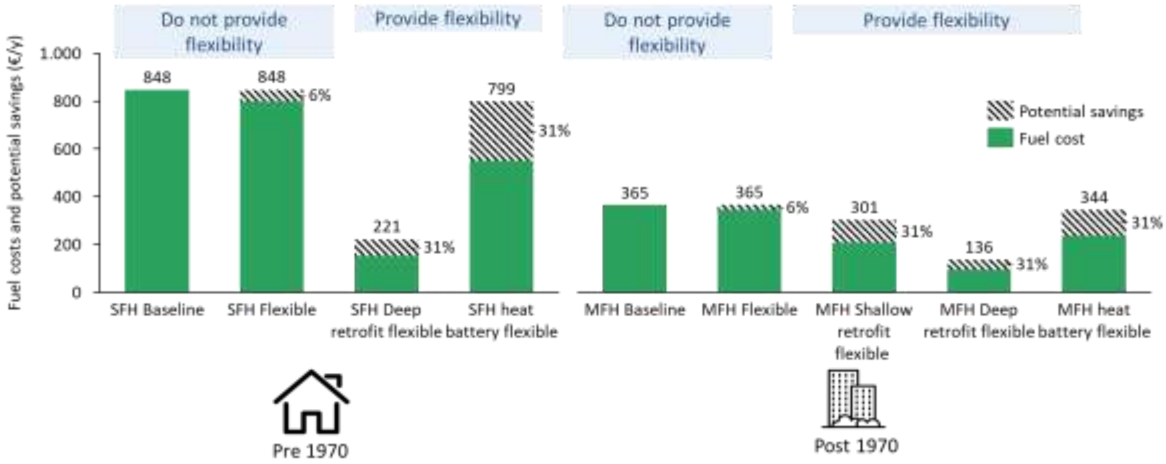

Figure 18 –The range of potential fuel costs savings (€/y) in the Flexible Heat Pump scenario

As shown in Figure 17 and Figure 18, the flexible scenario leads directly to energy cost savings for households which maintain their initial state and households which adopt additional thermal storage. However, homes which have undergone energy efficiency retrofit have higher total costs than the same dwelling in the passive baseline scenario, despite providing benefits to the wider energy system. It is therefore likely that policy support will be needed so consumers providing system flexibility do not pay higher costs overall. These supports may take the form of grants or other subsidies for energy efficiency measures, or enhanced payments for flexibility services.

When the energy system is operated flexibly consumers will see a difference in their fuel bill. Some of the benefits of flexibility are likely to be passed on to the consumers that provide the flexibility, but some of the benefit is also likely to be socialised across all consumers. Since there is high uncertainty around how these savings will be shared in 2040, we show a range of possible savings for each consumer based on the maximum and minimum possible savings that they could be given by the system. Figure 19 shows the range of different costs that might be given to consumers in the Efficient-Smart scenario. The first and second bars represent the range of costs that a dwelling that doesn't provide flexibility might have, and the second and third bars show the range of costs that a consumer that does provide flexibility may have. In the extreme case of the third bar, all savings from flexibility are passed on to consumers who provide flexibility, and so consumers not providing flexibility would see the baseline electricity cost shown in the left-hand bar.

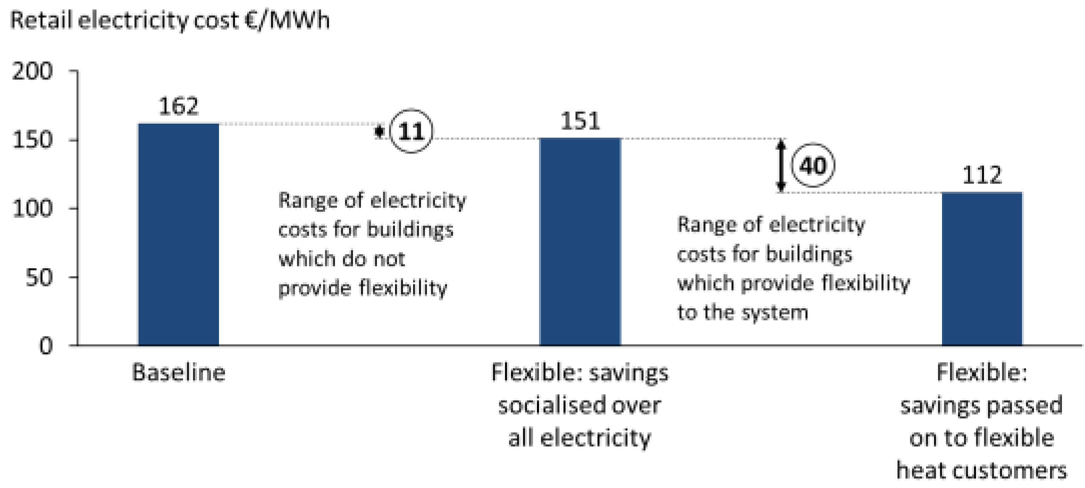

Figure 19 - The range of different fuel costs available to consumers in Italy.

4.3 System level savings from flexibility

This section considers savings at the system level from operating heating systems in a flexible way. This includes both the upfront cost of achieving flexibility and the final fuel savings resulting from the flexibility. Figure 12 shows the full system costs for each technology deployment scenario in both the baseline and efficient flexible cases. Across all scenarios the system cost is less in the flexible scenario compared to the baseline scenario. The efficient heat pump case has the lowest full system costs. Considering only the heat sector, the heat pump scenario is €4.2bn/y cheaper than the hybrid heat pump scenario, which is the next cheapest.

When considering the components of the fuel cost which decrease in the flexible case, the biggest decreases are from lower electricity generation costs where the lower peak demand mean less investment in generation capacity is required. The biggest savings are seen in the hydrogen scenario where making dedicated renewables that produce hydrogen at high load factors is significantly more cost-effective than using grid connected electrolysers for hydrogen production. Despite those savings, the hydrogen Efficient scenario leads to significantly higher costs than other Efficient scenarios, of 14 b€/y and 12 b€/y compared to the heat pump scenario and the hybrid scenario respectively.

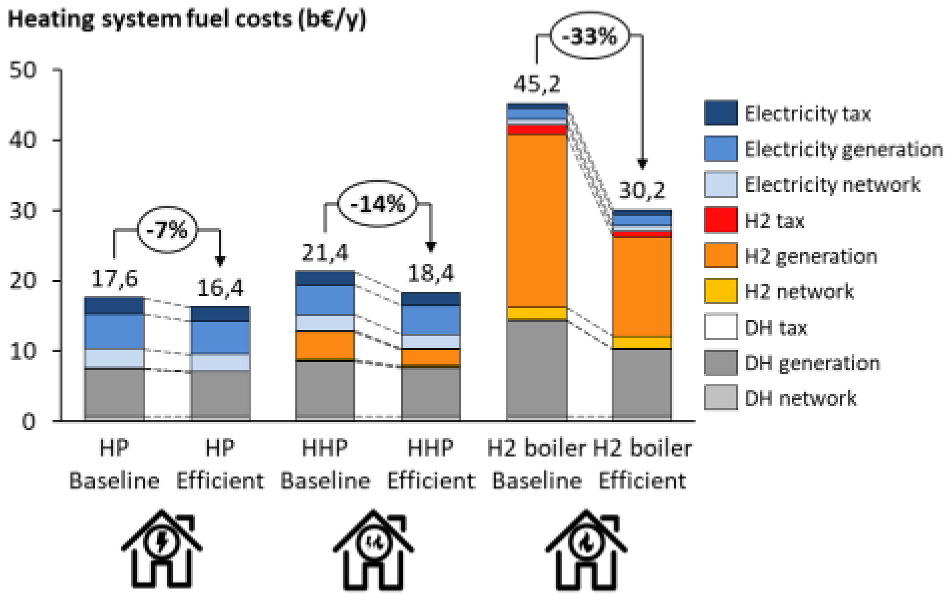

Figure 20 - Fuel cost savings from operating the electricity system in a flexible way (costs shown from system perspective).

5 Consumer costs of low carbon district heating

District heating in Italy is modelled at existing deployment rate, with 28% of domestic dwellings connected. The heat sources used by district heating are varied with the technology scenarios (see Table 3), with the further assumption that district heating is fully decarbonised by 2040. This means that gas, oil, and coal-fired systems (including combined heat and power) are not modelled as it is expected that these will be replaced with lower carbon alternatives. District heating systems can help accelerate decarbonisation since it is easier to replace a few large heat generators than the heat generators in many different dwellings. Although not modelled in this study, waste heat can be used as a cost-effective heat source for heat networks and should be considered where available.

Table 3 – Heat sources assumed for district heat in each technology scenario.

	Heat pump scenario	Hybrid heat pump scenario	Hydrogen scenario
Heat pumps	87%	37%	28%
Hybrid heat pumps	-	50%	-
Hydrogen boilers	-	-	53%
Other low carbon systems (biomass, waste heat)	13%	13%	19%

While decarbonising district heating will bring benefits in terms of lower carbon emissions, it is important that adequate regulation is put in place to protect consumers on district heating networks. Because district heating is inherently a monopoly supply, consumers are at higher risk of high costs and poorly performing systems, and have relatively less recourse to address these issues.

5.1 Cost of district heating networks for consumers

District heating networks are likely to have similar costs for consumers on average to the typical building level technology in each scenario. However, the cost of any heat network is highly dependent on the local area in which it is installed and so drawing exact comparisons between district heating and building level technologies is difficult. This analysis shows however that heat networks are likely to be a good option for consumers, particularly since their ease of decarbonisation is higher than individual heating technologies. District heating also provides flexibility to the system through use of larger-scale thermal storage (typically in the form of stored hot water). This allows the peaks and troughs of heating demand from buildings on a district heat network to be mitigated locally so the loads on the wider energy system are minimised.

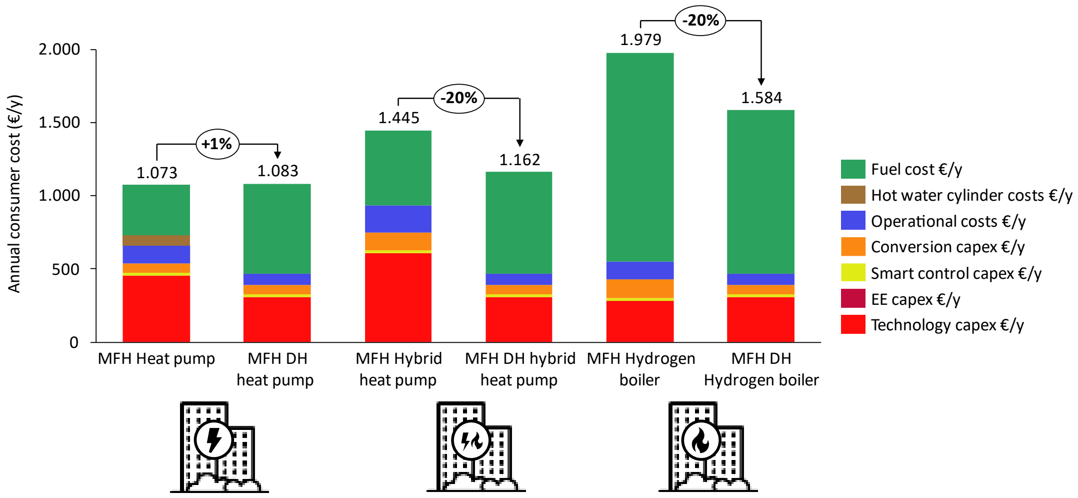

Figure 21 - District heating and building level technology cost for consumers, district heating plant and network costs are included in the fuel cost.

6 Conclusion

As in most European countries, fossil fuels play a significant role in domestic heating and in electricity generation in Italy today. Across the economy, electricity and heating contribute about 22% of Italy's carbon emissions[8]. Recent steps to reduce emissions include an increased target of 60% reduction in carbon emissions by 2030, which will need to be supported by sector-specific policy supporting the energy transition. Roughly 70% of homes in Italy are heated with fossil fuels, including about 24% heated with oil[9]. Efforts have been made to support energy efficiency improvements through the Italian Energy Efficiency Fund[10], but consumer uncertainty around the duration of the scheme and funding availability have limited uptake, and may also contribute to the high costs of energy efficiency measures seen above. By 2040, a significant shift towards renewable heating sources will be required to fulfil Italy and EU's commitments towards net zero emissions in 2050.

Electric heating and green hydrogen are the primary options for widespread decarbonisation of domestic heating, while there are a range of other options likely to play smaller roles. The analysis presented above indicates that electrification of heat via heat pumps is likely to be the most affordable for consumers in the long run. Although heat pumps have a higher upfront cost than hydrogen boilers, the high running costs of hydrogen boilers result in a lifetime cost of heat around 60% higher than that offered by heat pumps. Policy support in the form of grants or low cost loans enabling consumers to cover the initial capital cost of heat pumps will result in significant savings across the energy system. District heating can be cost competitive with other low carbon heating technologies. Decarbonising existing networks is likely to be more cost effective than a conversion to low carbon heat solutions at individual building level.

Building fabric efficiency is a key enabler of a smart, cost effective energy system in future. As shown above, energy efficiency retrofits in Italy could reduce demand for heating by 7% (22 TWh) by 2040 relative to today. Raising the ambition for energy efficiency deployment beyond 2% of dwellings per year could contributes to system-wide savings of €4bn despite the additional expenditure of €1.6bn on efficiency measures. This means that for every €1 spent on energy efficiency measures savings of €2.5 are achieved. However, insufficient fuel bill savings will mean a net increase in expenditure for individual households, so it is essential for financial incentives that support energy efficiency adoption, such as the Ecobonus, to be maintained for the system-wide savings to be realised. Smart and responsive operation of heating systems could reduce electricity costs by €10 to €50 per MWh. Households providing flexibility services may see yearly savings of between €120/year and €300/year, depending on home size and energy demand if appropriate rewards for flexible operation are in place.

[8] EU Parliament Briefing, Climate Action in Italy, 2021, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/690663/EPRS_BRI(2021)690663_EN.pdf
[9] EntraNZE European Buildings database, https://www.entranze.eu/pub/pub-data
[10] European Investment Bank, Italian Energy Efficiency Fund II, 2019, https://www.eib.org/en/projects/pipelines/all/20190722

elementenergy

The Consumer Costs of Decarbonised Heat in Poland

Executive summary

for

BEUC

February 2022

Element Energy Limited
Suite 1, Bishop Bateman Court
Thompson's Lane
Cambridge
CB5 8AQ

Tel: 01223 852499

Key Messages

Low carbon heating

- This study analyses the cost to consumers of low carbon heating options in the year 2040 in Poland. We have investigated four archetypal homes and present detailed results for two of these archetypes, typical older (pre-1970) single-family homes and more modern (post-1970) flats in multi-family homes.
- We have examined four low carbon heating options within these archetypes: heat pumps, hybrid heat pumps, green hydrogen boilers, and low carbon district heat networks.
- 2040 electricity costs are predicted using the Element Energy Integrated System Dispatch Model (ISDM), which predicts electricity system operation on an hourly basis, and utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system when high levels of variable renewables are connected. We assume the Polish electricity grid has significantly decarbonised by 2040 in line with 2050 net zero targets.
- Green hydrogen costs are estimated using Element Energy's green hydrogen costing tool. This includes country-specific renewable generation profiles and projections for the 2040 cost of hydrogen production technologies, as well as estimated costs for the distribution of hydrogen through the converted gas network.
- Retail electricity costs are predicted to be about 240 €/MWh, while retail green hydrogen costs estimated to be between 150 and 210 €/MWh, depending on how hydrogen production interacts with the wider energy system.
- Heat pumps provide the most cost-effective route to decarbonisation of home heating in Poland across the dwelling archetypes analysed.
- The older single-family home using a heat pump is predicted to pay around €3.700/y for heating. With a hydrogen boiler, the same dwelling would see costs close to €6.000/y. The more modern flat is predicted to pay €1.300/y for heating with a heat pump, rising to €2.000/y if heated with hydrogen. This includes the annualised cost of the heating system as well as maintenance and fuel.
- Hybrid heat pumps can provide a similar cost of heating as heat pumps in older single-family homes. In more modern flats we find the cost of heating from hybrid heat pumps is about 20% higher than for heat pumps alone. We therefore anticipate there is a role for hybrid heat pumps in older and larger Polish dwellings connected to the gas network, provided that the technical challenges of retrofitting the gas grid to deliver hydrogen are overcome. There is also a risk that hydrogen used by hybrid heat pumps could be more expensive than estimated here if the majority of households adopt fully electric systems and the gas network is maintained although used by relatively few households.
- Although heat pumps have a larger up-front cost than hydrogen boilers, we expect that the running costs of these will be significantly lower than other options for decarbonising heating. This means there may need to be some policy support in place (such as direct grants, affordable green loans and green mortgages) so that consumers are enabled and incentivised to purchase these high capex appliances.
- The results shown are consistent with the other two archetypes investigated (post-1970 single family homes and pre-1970 multi-family homes). The archetypes are representative of typical Polish homes but do not capture the full diversity of the Polish housing stock of around 15 million dwellings. Some segments of the housing stock may be unsuitable for heat pumps due to high heat loss and barriers to the installation of additional energy efficiency measures.

Energy efficiency

- Installing energy efficiency can provide cost savings to consumers in some cases, and comes with additional benefits for health, thermal comfort and system flexibility.
- In some cases, energy efficiency retrofits will not pay back in energy bill savings alone. However, increasing the rate of energy efficiency rollout above current targets can reduce the total energy system costs (including the cost of energy efficiency) if combined with flexible operation of the electricity system.
- Policies may therefore be needed to enable and incentivise consumers to improve the fabric efficiency of their homes in order to realise the benefits to the wider energy system.
- Where deeper energy efficiency improvements are less cost-effective, installing domestic-scale thermal storage to enable flexible operation of heating enables a reduction in total electricity system costs.
- Consumer incentives through the market (e.g. ability to purchase lower cost electricity or rebates for providing flexibility) or policy supports (e.g. assistance covering the upfront cost of thermal storage) are likely to be needed to incentivise consumers to provide this service to the energy system.

Smart and flexible heating

- Polish households using heat pumps have several routes to providing flexibility services to the electricity grid. Buildings that undergo deep retrofit to achieve a high level of building fabric efficiency can operate their heat pumps intermittently without impacting comfort. Alternatively, households may use a heat battery or a hybrid heat pump to enable flexible heat pump operation.
- Operating the energy system flexibly lowers the total energy system cost by 3% in a high heat pump scenario, an annual savings of €2,8 billion. This requires investments in energy efficiency improvements in buildings to enable flexible operation of heating. Some investments which will not pay back if the building is considered in isolation may in fact be cost-effective if impact on the wider energy system is considered.
- Smart and responsive heating can reduce the annual consumer cost of heating, saving consumers up to 7% for multi-occupancy buildings, and up 11% in single family homes.

District heat networks

- Low carbon district heat networks can provide domestic heat at comparable cost to building level heating systems and offer a high level of demand flexibility. In many cases heat networks will be simpler to decarbonise due to the relative ease of replacing centralised heating plant compared with disruption in hundreds or thousands of homes. Maintaining existing district heating networks and decarbonising them comes with significant consumer and carbon benefits if suitable consumer protections are in place.

Contents

Authors

For comments or queries please contact:

Sam.Foster@element-energy.co.uk

Fiona.Hughes@element-energy.co.uk

Joachim.Dias@element-energy.co.uk

+44 (1223) 852 499

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Acronyms

CZ	Czechia
DH	District heat
DSR	Demand side response
ES	Spain
HP	Heat pump
HHP	Hybrid heat pump
kWh	kilo Watt hours
ISDM	Element Energy's Integrated system dispatch model
IT	Italy
MFH	Multi family home
MWh	Mega Watt hours
PL	Poland
SFH	Single family home

1 Introduction

1.1 Context and objectives

Heat is recognised as one of the hardest sectors to decarbonise. Currently most consumers use fossil fuels to provide their heat, but to meet emissions targets they will have to swap to a cleaner technology. One possible solution is to electrify heating via heat pumps, however since the seasonality of heating is far greater than of electricity demand this may create a large winter peak in electricity demand causing issues for generators and the distribution network. Another possible option is to decarbonise the gas grid by injecting hydrogen rather than natural gas into it, this might reduce the impact of electrification on the electricity system, but creates challenges in producing zero carbon hydrogen, and converting the distribution network. Since there is significant uncertainty around the costs and risks of these two methods of decarbonising heat, this study aims to understand the impacts of different future scenarios and particularly focuses on the possible impacts on consumers.

In addition to the technologies used to heat dwellings in the future, the installation of energy efficiency upgrades is considered. Currently EU member states have an ambitious target for energy efficiency installation, this study aims to show both the benefits to the energy system of energy efficiency whilst also understanding the potential financial risks to consumers of these installations. We also consider the possible benefits of going beyond current energy efficiency installation targets for consumers.

This study considers the energy system in 2040, this is because it is sufficiently far in the future that significant steps towards the decarbonisation of heating will have been taken by then, we model that 80% of homes are using decarbonised heating by this date, but near enough to the present that accurate projections of the electricity generation mix can be found. The choice of this year will allow us to analyse with greater certainty the cost of different scenarios than we would be able to if choosing a year further into the future even though the system might be more decarbonised by then.

This study determines what the overall cost of heating will be to end users In Europe, under different heating delivery scenarios (primarily electric heat pumps, green hydrogen boilers and hybrid options, and including both individual building and district heating approaches). All costs are determined, including purchase, installation, and maintenance, and the fuel cost, which covers the commodity itself (gas or electricity) and the cost of the infrastructure required to deliver it to homes and to run a safe and secure energy system. The key aims of the study are to:

- Assess the costs of decarbonised heating options from a consumer perspective.
- Analyse the cost and benefit from building fabric energy efficiency measures to individual consumers and the energy system.
- Determine the impact of smart and responsive heating on the energy system and the financial benefits to heat consumers who provide flexibility to the energy system.
- Compare the costs of decarbonised district heating systems with individual dwelling level approaches.

The study has produced reports on four European Member states (ES, IT, CZ, PL), as well as one overall report providing insights into EU-wide consumer impacts. This report summarises the key findings and conclusions about decarbonised heating in Poland, and makes recommendations around policies that should be implemented to protect consumers.

1.2 Technology scenarios

For this work three technology deployment scenarios for 2040 were created. These three scenarios were focused on the deployment of a single technology as the main low carbon heating option, these were air source heat pumps (ASHP), hybrid heat pumps (ASHP + hydrogen boiler), and hydrogen boilers. The technology mix for each scenario in Poland is shown in Figure 1. Since there are already 40% of dwellings on district heating in Poland, no addition of district heating has been modelled for 2040. These scenarios are used to analyse the likely cost of different technology options in Poland under different possible futures and are not intended to be projections or predictions of the likely future technology mix.

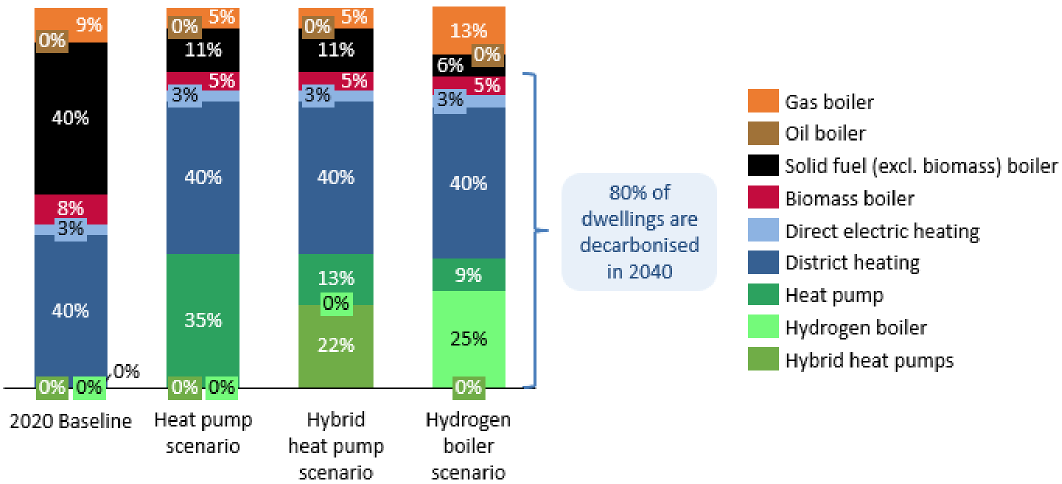

Figure 1 - Fraction of dwellings with each technology in 2040 in each scenario.

In these scenarios the hydrogen boiler and hybrid scenarios are based on the gas network transitioning to hydrogen. This is likely to be a phased process which will not be completed by 2040; hence some remaining natural gas boilers are included in the scenarios above. In these scenarios hydrogen for heating is modelled as “green” hydrogen produced from electricity via electrolysis.

Each of the three technology deployment scenarios are analysed in two ways:

1. The **Baseline-Passive** scenario includes fabric energy efficiency deployment at a rate of 2% of buildings per year, and energy demands such as heating continuing to operate in a passive way.
2. In the **Efficient-Smart** or **Flexible** scenario a higher rate of fabric energy efficiency rollout of 4% of buildings per year is assumed, and heating systems behave in a flexible way, responding to the needs of the energy system as a whole.

In addition, in the Baseline-Passive scenario it is assumed that hydrogen is produced by grid-connected electrolysers, whereas in the Smart-Efficient scenario hydrogen is produced by dedicated renewables collocated with electrolysers and grid curtailment to produce cheaper hydrogen with less impact on the overall energy system.

1.3 Case study buildings

The housing stock in Poland is made up of a large range of different buildings. To present results in this report the key building level results for consumers are presented for two typical buildings. These typical buildings are a single-family home (SFH) built before 1970 and a multi-family home (apartment, MFH) built after 1970. These buildings are chosen to illustrate the trends that consumers are expected to see, however since all buildings are different there will be some variation from the trends presented for individual buildings. Table 1 shows the characteristics of the selected dwellings.

Table 1 Details of the two key archetypes that results are presented for in this report

Feature	Archetype 1[1]	Archetype 2[2]
Picture		
Type	SFH	MFH
Age	Pre-1970	Post-1970
Assumed climate	Warsaw	Warsaw
Floor area (m^2)	78	56
Annual heating demand (kWh)	25.062	4.890
Annual hot water demand (kWh)	4.378	3.157

1.4 Method

An overview of the method is shown in Figure 2 below. The key steps in the modelling are:

1. The archetype stock model calculates the heat demand and final energy consumption on an annual and hourly basis for domestic dwellings in Poland. The outputs are generated at the building level and at the country-level (i.e. including all buildings). Non-domestic buildings are included in the national demand although they are addressed with less detail than the residential stock.

[1] Krysiul, CC-BY-SA-3.0-PL, via Wikimedia commons

[2] Szczebrzeszynski, PD-self, via Wikimedia Commons

2. Each residential building archetype undergoes a flexibility assessment to determine whether and how much its heating demand can be shifted to accommodate the needs of the wider electricity system.

3. The energy demands and flexibility potential of the heating system is used by the ISDM in modelling the hourly behaviour of Poland's energy system throughout 2040. The ISDM predicts the retail costs of electricity and green hydrogen. A more detailed description of the ISDM model is given below.

4. The upfront and ongoing costs of heating are calculated by the consumer cost model for the selected Polish building archetypes.

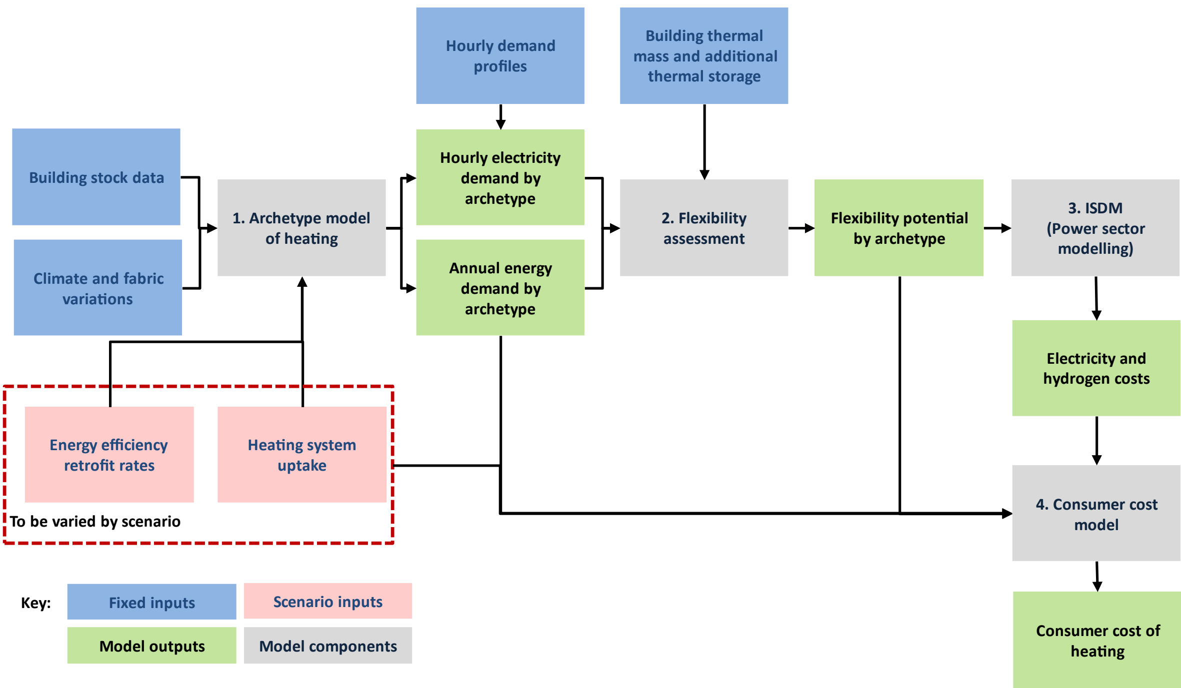

Figure 2 - Full heating system costing model flowchart.

1.5 Energy system modelling

Element Energy's Integrated Supply and Demand Model (ISDM) was developed to overcome limitations of typical power system dispatch models when applied to zero carbon systems. Many such models continue to treat the power system as it currently is: highly dispatchable and reliant on thermal sources for flexibility on the supply side. Future low carbon systems, where variable renewable energy is dominant, will require flexibility on the demand side to support the integration of high levels of renewable energy, while minimising curtailment and reliance on backup thermal plant. ISDM utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system.

The main principles of whole system operation are summarised here. The starting point for the modelling is a set of hourly energy demand profiles for each sector. Some demand profiles are fixed (no flexibility), while others are able to be shifted over defined periods. For heating, these demands are based on the building heat loss, heating technology and outside air temperatures. Transport demand is based on the stock of electric vehicles, their efficiency, the daily usage, and arrival/departure times from home and work to generate baseline electrified transport demand. Grid-responsive smart charging can schedule charging to times of most use to the grid, while still providing vehicles with sufficient charge for transport. Flexibility provided by thermal storage and thermal mass of buildings allows heat demand to move demand to times most useful to the grid, without reducing thermal comfort in homes and offices.

Hourly weather data is also used to generate hourly load factors for wind and solar production. Using the assumptions on the installed VRES generation capacity, the model calculates the hourly VRES generation. By subtracting this from the demand profiles, initial net load curves are generated. Demand shifting, as enabled through smart EV charging and smart heating is deployed to minimise the peak system demand and therefore the required network capacity. Further demand shifting is then applied to reduce curtailment of renewables and fossil fuel use, by moving demand from hours of high to hours of low net demand. By reducing the peak net demand, demand shifting leads to a decreased requirement for dispatchable generation capacity.

The dispatchable generation fleet is then deployed in merit order to fill in the supply gap. Once all hourly demand is met, annual system performance metrics are evaluated, among them fuel and carbon cost, variable OPEX, VRES curtailment, peak demand (for determining the required network capacity), and peak net demand (for determining the required dispatchable generation capacity).

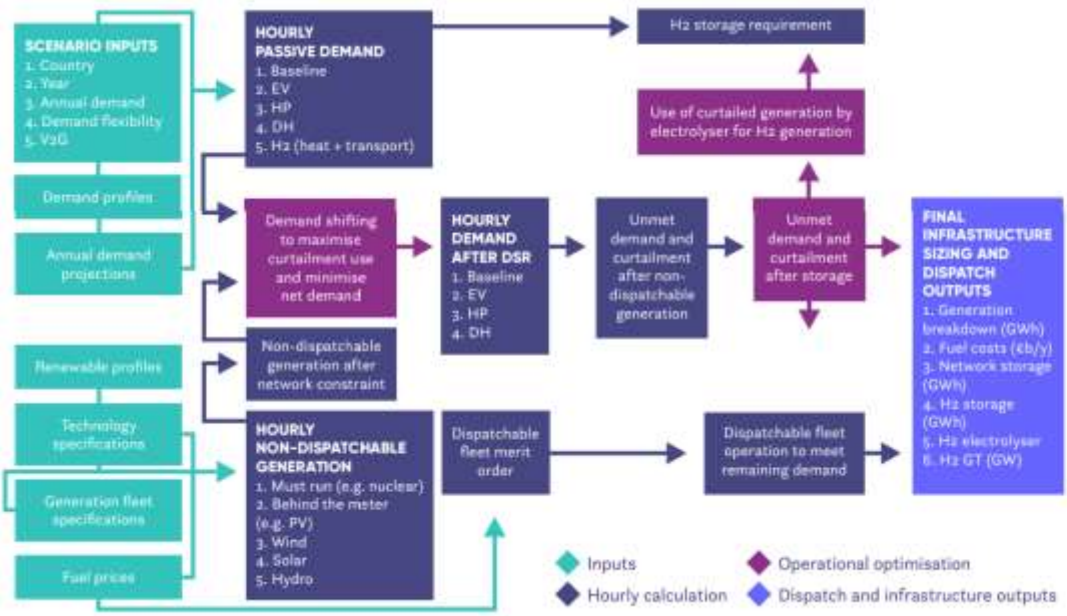

Figure 3 – Schematic of the calculation within the ISDM

1.6 Costing hydrogen for consumers

The cost of producing green hydrogen produced from electricity with electricity was modelled in this project. In the baseline case, it was assumed that the electrolysers were connected to the electricity grid, and pay a wholesale price (excluding grid fees) for their electricity. The cost of hydrogen distribution and storage was then calculated based on a parameterised model of the gas grid and costs of converting the low pressure distribution grid to hydrogen. The costs of hydrogen production and transmission used were taken from the BEIS hydrogen supply chain evidence base[3]. In the flexible case it was assumed that hydrogen production would not be connected to the electricity grid. Hydrogen production electrolysers and renewable generation were assumed to be collocated and the production of hydrogen was found on an hourly basis to optimise the relative generation and electrolyser capacities for the cheapest hydrogen cost.

Country-specific renewable generation profiles were calculated from NASA MERRA-2 data, and the cost of renewable generation was found from the BEIS 2020 cost of generation report[4]. In addition to this the curtailed electricity produced from renewable generation for the rest of the electricity system was also used to produce hydrogen in the flexible case at 0 cost for the electricity. The costs of hydrogen in the Baseline and Flexible scenarios for the high hydrogen scenario are shown in Figure 4. Both wind and solar generation to produce hydrogen were considered, but in PL onshore wind was the cheapest way to produce hydrogen and this was used for the purpose of costing production in the flexible case. To find the cost per kWh the capex of generation and electrolysers was annualised over the expected lifetime of the technologies at a discount rate of 5% in the consumer cost case and a 3% discount rate in the system cost case.

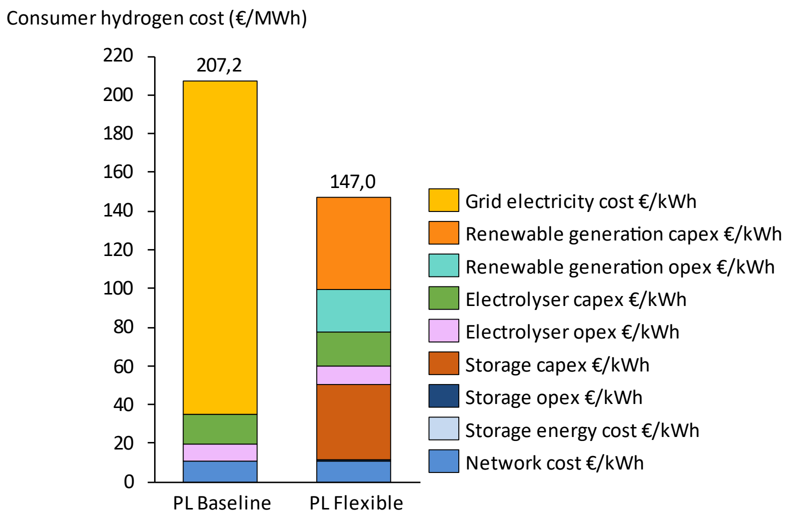

Figure 4 - Cost of hydrogen for consumers in the two cases.

3 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf

4 https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

2 Impact of ambitious energy efficiency deployment

2.1 Energy efficiency scenarios in Poland

In Poland, two energy efficiency rollout scenarios were analysed, one baseline scenario with rollout at the rate equivalent to existing targets and one very ambitious rollout rate combined with smart heating system operation. Energy efficiency rollout was analysed by using two packages, one shallow/medium (referred to below as the 'shallow' package) and one deep retrofit. In the 'shallow' package, the older single family home adopts a medium level of retrofit while the modern flat adopts a shallow level. The costs and energy savings of the two packages are based on the ZEBRA2020 study of energy efficiency in buildings across Europe[5]. The rollout rate of these packages in the different scenarios is shown in Table 2.

Table 2 - Energy efficiency rollout rates in different scenarios.

Scenario	Shallow retrofit rate	Deep retrofit rate	Total retrofit rate
Baseline	1.5% per year	0.5% per year	2%
Efficient	2.5% per year	1.5% per year	4%

Figure 5 shows the breakdown of the 2040 housing stock in the two energy efficiency rollout scenarios in Poland. In the efficient scenario 14% more of the stock has had an energy efficiency retrofit than in the baseline scenario. The next chart, Figure 6 shows the reduction in heating demand in typical buildings from a shallow and deep retrofit. Shallow packages reduce the heating demand by 13% in older single family homes and 10% in newer multi family homes. Deep packages give savings of 52% in the older single family homes and 44% in newer multi family homes.

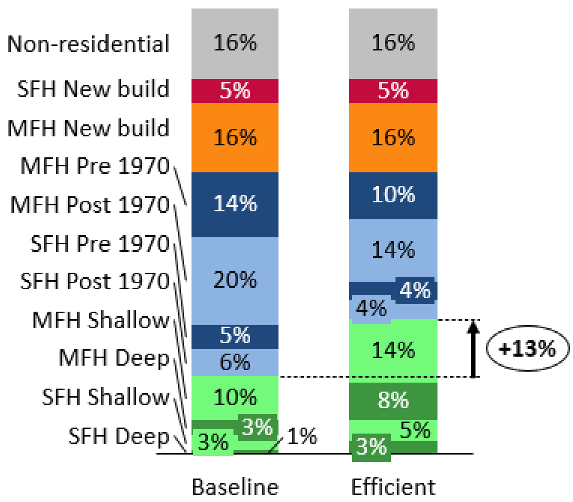

Figure 5 - 2040 housing stock in baseline and efficient scenarios.

[5] nZEB technology solutions, cost assessment and performance, ZEBRA2020: NEARLY ZERO-ENERGY BUILDING STRATEGY 2020, https://zebra2020.eu/publications/nzeb-technology-solutions-cost-assessment-and-performance/

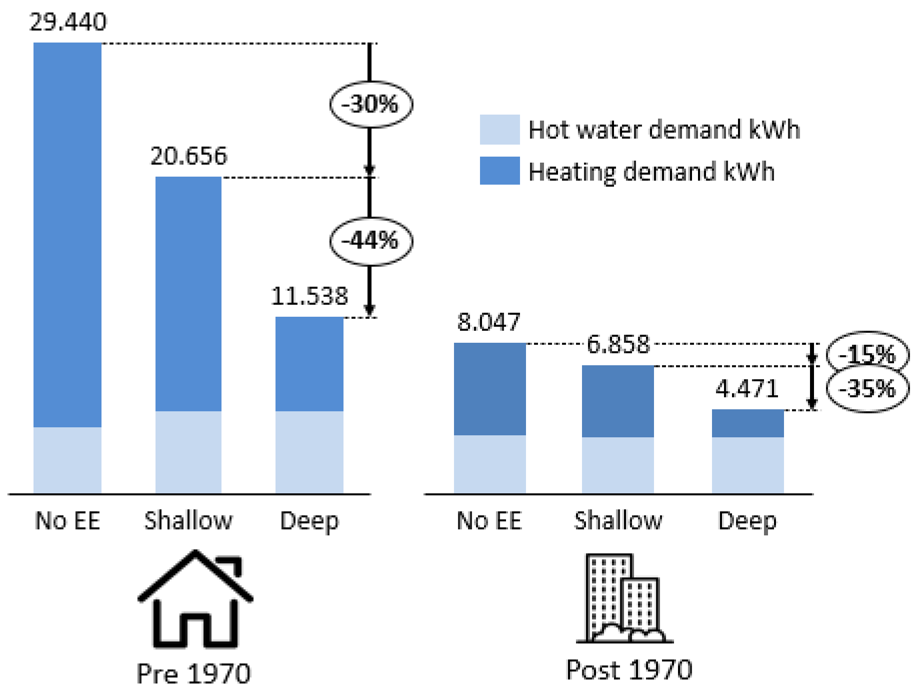

Figure 6 - Reductions in heating demand of typical buildings.

Figure 7 shows the heating demand changes between the baseline 2020 housing stock and the two 2040 scenarios. The baseline scenario has 2% more heating demand than 2020 due to the fact that 21% of the building stock in 2040 is made up of new buildings, contributing to a large increase in hot water demand. These are assumed to have heating demand similar to or lower than a building which has undergone a deep retrofit. The efficient scenario has 6% lower heating demand than the baseline.

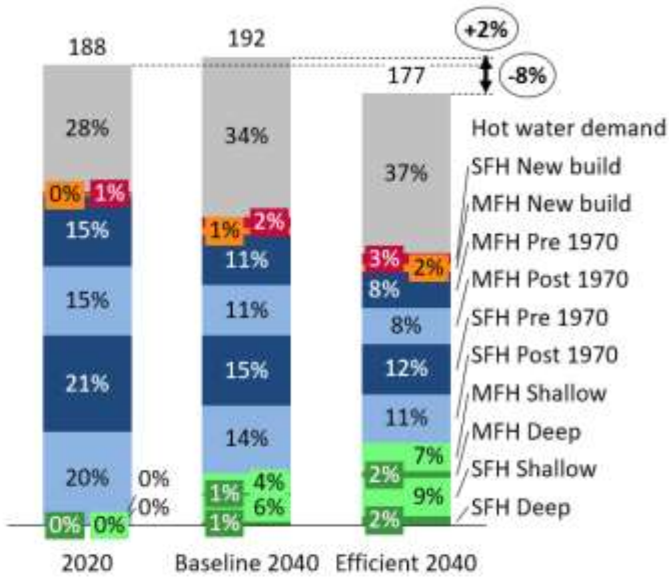

Figure 7 - Residential heating demand by scenario, in TWh.

Figure 8 shows the building level heating cost in € per year for the two key archetypes with different energy efficiency packages installed. This shows that in large single-family homes, where the fuel cost makes up a larger part of the total cost of heating than in smaller multi-family homes, the savings from energy efficiency in the fuel cost are greater than the additional annualised capex by around 20% for both shallow and deep retrofit. As such, the return on investment in deep energy retrofit is secure for single family homes and investment in energy efficiency upgrades to achieve that level of performance should be fostered. However in multi-family homes, because there fuel cost makes up less of the total there is no saving in total heating cost from installing energy efficiency due to the higher capex of energy efficiency installation. Consumers who do install energy efficiency measures despite their high capital cost will see lower fuel bills.

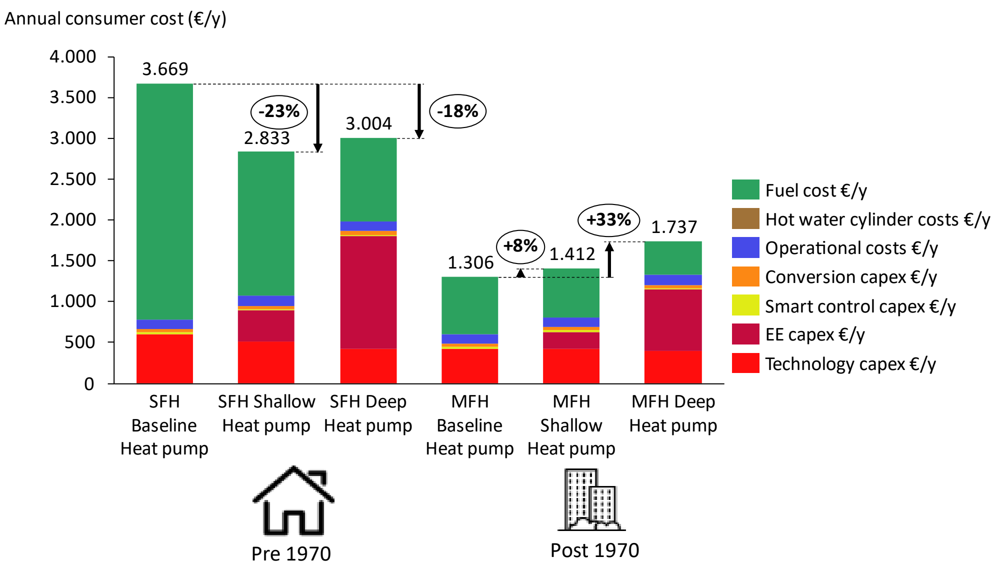

Figure 8 - Building level costs (€/y) and savings of energy efficiency in typical archetypes.

Although energy efficiency measures may not be cost effective at an individual building level for consumers living in multi-unit buildings, the installation of these efficiency measures brings about cost savings to the entire energy system. These savings depend on the type of renewable heating system deployed but are likely to be at least €3bn per year , the exact figures are shown in Figure 9. It is important to note that for the system to realise the full savings from energy efficiency rollout, policy support will be required to remove the significant upfront cost of energy efficiency from households such that they are incentivized to invest in reducing their dwelling's heating demand. For example since there is no consumer saving from installing energy efficiency in a post 1970 multi-family home it is unlikely consumers would make this change without policy support.

Energy efficiency upgrades require significant capital outlay depending on the size and age of the home and the level of retrofit. Figure 10 shows the upfront cost of energy efficiency retrofit in the two typical archetypes. The total annual expenditure on energy efficiency measures would be €0.9bn in the baseline scenario, and €1.9bn in the efficient scenario.

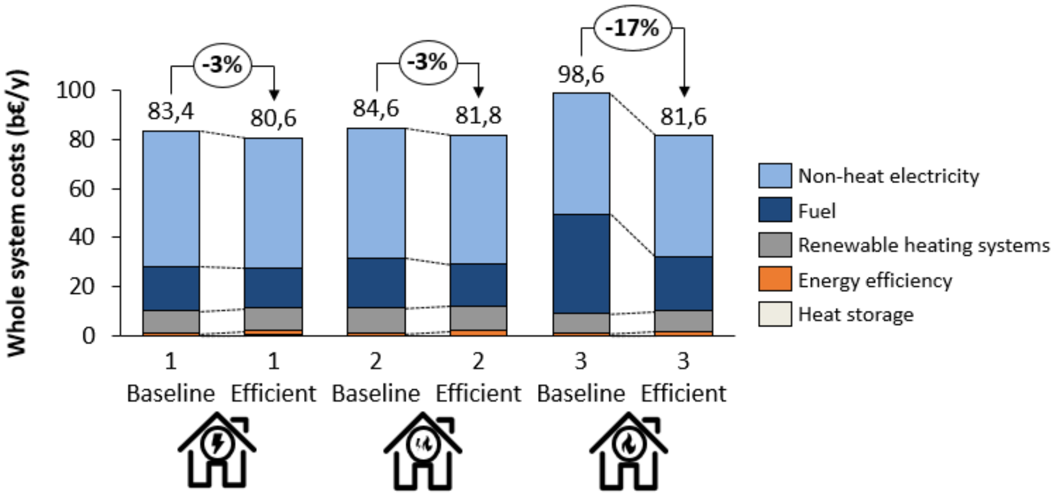

Figure 9 - The system cost saving from the efficient scenario.

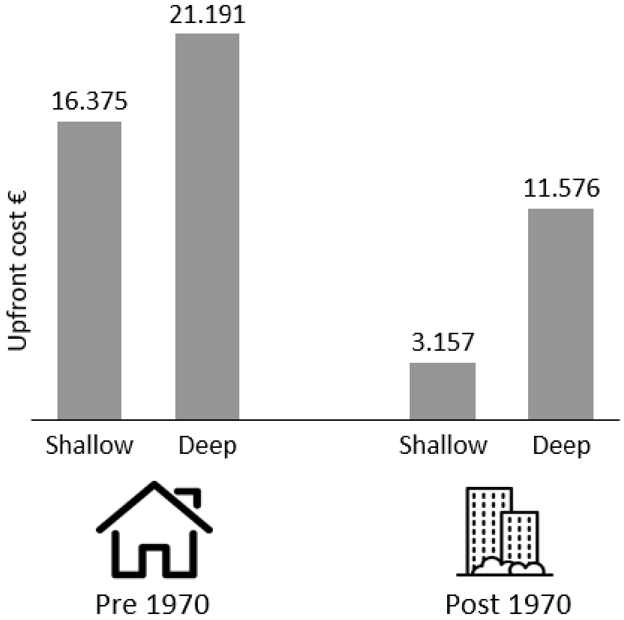

Figure 10 - Upfront cost of energy efficiency packages.

3 Consumer costs of low carbon heating options in 2040

The cost of heating systems to consumers has two parts. There is an upfront capital cost (capex) that is incurred when the heating system is replaced and there is an ongoing cost of fuel and maintenance. This section shows the total cost of heating made up of both of those components, and then looks at each component individually.

3.1 Total cost of heating for consumers

The total cost of heating for consumers is found by summing the annualised capital cost, at a 5% discount rate with a 15-year technology lifetime, with the annual operating cost. This represents the total cost for a consumer in each year of heating their dwelling with that technology. This comparison shows that for larger and older dwellings, heating with heat pumps and hybrid heat pumps is the cheapest option. In multi-family homes, heat pumps are around 20% less costly than hybrid heat pumps. In both archetypes, a high rollout of hydrogen boilers relative to heat pumps could leave consumers paying over 50% more for their heat. Since the cheapest overall option, heat pumps, come at a significant upfront cost premium to hydrogen boilers and counterfactual heating technologies, it is important that government provides adequate support to consumers to switch their heating through incentives and financial products that address these high upfront costs in order for consumers to achieve the possible savings.

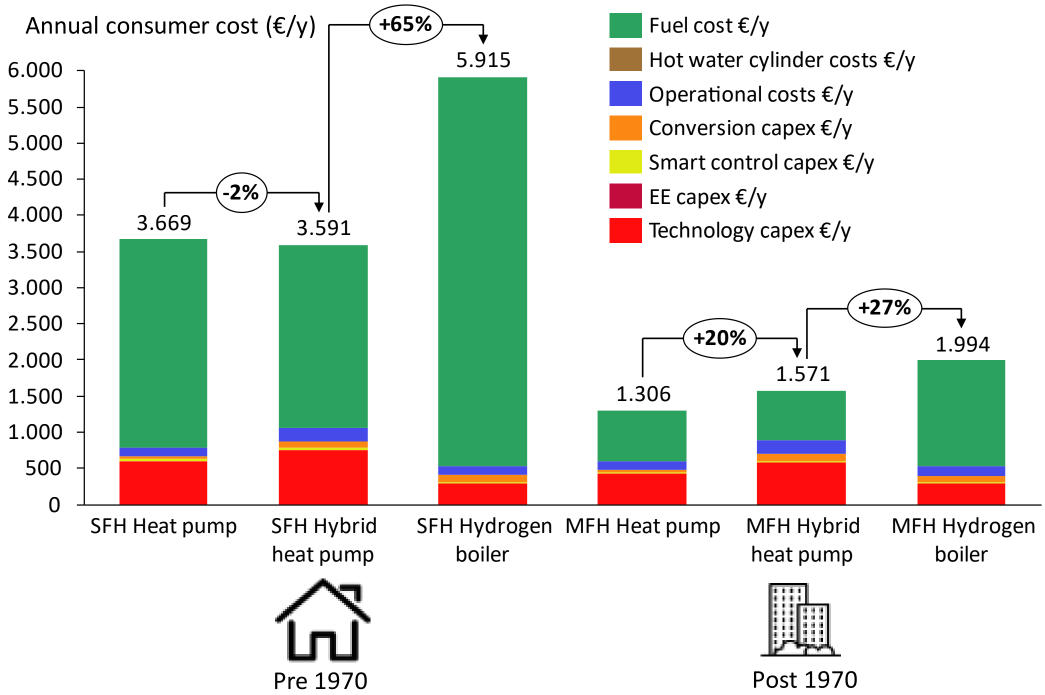

Figure 11 - Annual consumer cost of heat with the main technology in each scenario.

3.2 Ongoing costs of heating systems

Fuel costs are found from electricity system modelling based on the uptake of heating systems and energy efficiency for that scenario. The technologies considered here have different efficiencies of producing heat from their fuel, heat pumps can operate at 280% efficiency, whereas hydrogen boilers are 85% efficient. Since hydrogen is produced from electricity via electrolysis using hydrogen boilers to produce heat typically uses 4.5x as much electricity as producing the heat with a heat pump. Due to this the operational costs of hydrogen systems can be close to 2x as large as those of heat pump systems. This means although hydrogen can be cheaper than electricity per kWh the additional consumption outweighs this. Hydrogen is also likely to be significantly more expensive than gas is today for consumers. Figure 12 shows the annual running costs for the different heating systems in the two main archetypes.

Hybrid heat pumps provide 80% of heat output from the heat pump, with the remaining 20% from the boiler which is assumed to use green hydrogen. For single-family homes, hybrid heat pumps provide the lowest annual running costs, while pure heat pumps provide the lowest running cost in multi-family homes.

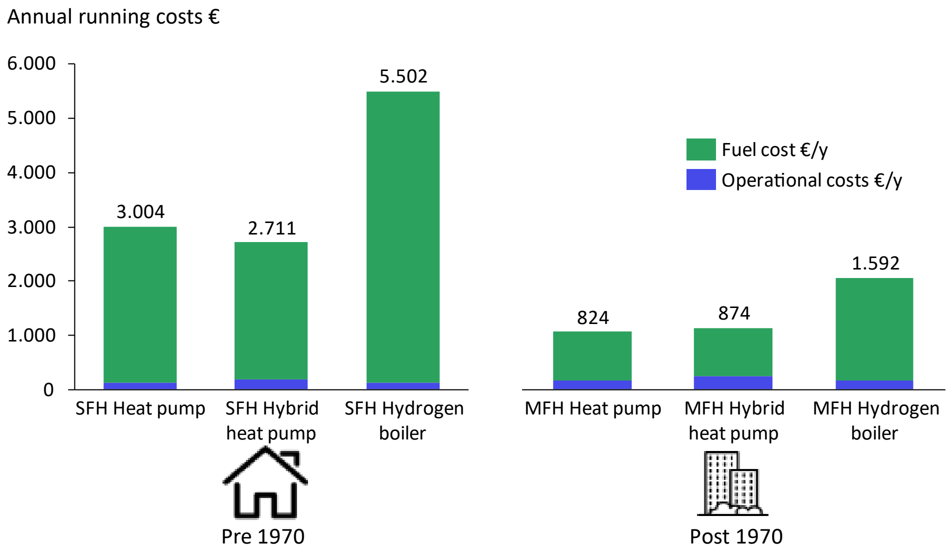

Figure 12 - Annual running costs of different heating systems.

3.3 Capital cost of heating systems

Capital costs are found from the Element Energy database of heating system costs and include the cost of the heating system as well as the cost of hot water cylinders and smart controllers where appropriate. Hydrogen boilers have the lowest capital cost of the heating systems considered; hybrid heat pumps have the highest capital cost.

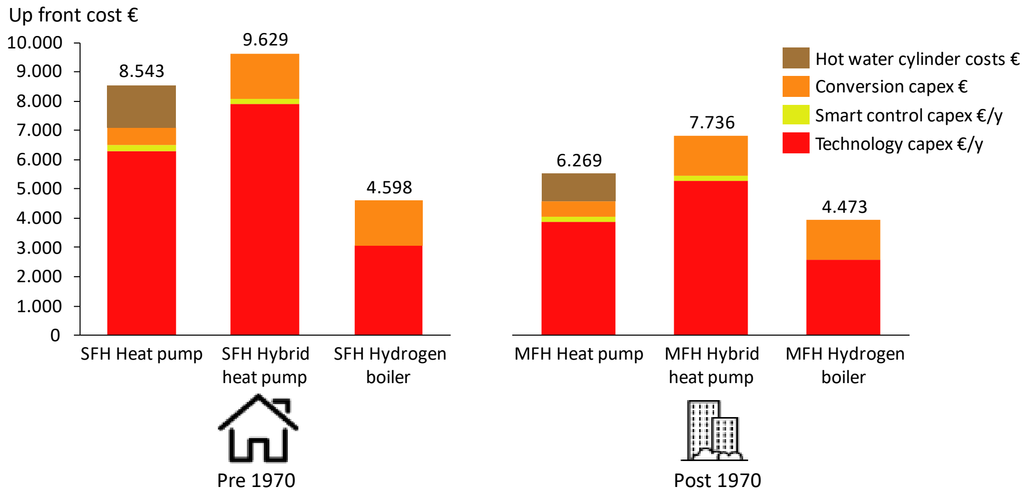

Figure 13 - Capital costs of different heating systems for typical archetypes.

4 Benefit from smart and responsive low carbon heating

Two system operation scenarios are presented in this study, the **Baseline-Passive** scenario involves passive operation of the energy system to meet demand, and the **Efficient-Smart** or **Flexible** scenario involves a higher rate of energy efficiency and operation of the energy system in a flexible way such that demand is changed to better match supply of power. Each of these two scenarios has been run with the three different technology deployment levels, so in each case the impact of smart system operation can be quantified. In all scenarios smart operation of electric vehicle charging is assumed.

4.1 Energy system benefit of smart operation

When heat pumps are operated in a smart way, they act to move demand away from the peak, this is achieved by pre heating houses with high thermal mass relative to their heat loss rate, or by storing thermal energy in a phase change heat battery. We assume that by 2040, 50% of buildings with heat pumps that cannot be flexible through their thermal mass purchase a thermal battery. This allows a greater proportion of buildings to offer flexibility services, without implying an unrealistic rate of deep retrofit.

When heating is operated flexibly, the total demand for heating is unchanged, but the profile of electricity use is less "peaky". The lower peaks mean that the total required capacity of electricity generation can be lower and less upgrade to higher capacity electricity networks is required, reducing the cost of the electricity system. In addition to the peak reduction, flexibility also allows demand to be better matched to when there is high generation of renewable technologies, this means those technologies with zero marginal cost have higher load factors and less thermal generation is required decreasing the system cost. Figure 14 shows the nationwide electricity demand over a typical winter week in 2040 in the scenario with high uptake of heat pumps. Under smart operation, heat demand is removed away from the peak, increasing demand at other times of day. This decreases the peak system demand and means less network capacity is required. In addition, heat demand can be moved into times where variable renewable electricity is available, reducing both the cost of electricity production and its carbon content. The model first moves demand that is flexible based on thermal mass, and then moves the demand that is flexible based on installing additional thermal storage, Figure 14 shows the change in the demand profile after the thermal mass flexibility and thermal storage are applied, the majority of flexibility comes from additional thermal storage.

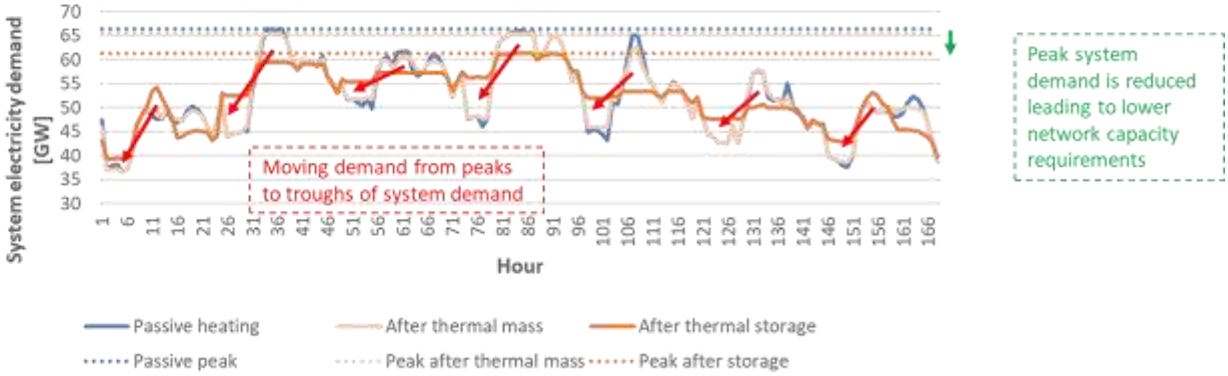

Figure 14 - Example of total electricity demand in Poland under the heat pump scenario with passive and smart heating system operation.

District heating also provides flexibility to the system through use of larger-scale thermal storage (typically in the form of stored hot water). This allows the peaks and troughs of heating demand from buildings on a district heat network to be mitigated locally so the loads on the wider energy system are minimised. In the flexible case hydrogen is considered to be produced by collocated renewables and curtailment so does not impact the wider electricity system relative to the baseline scenario where it is produced by grid connected electrolysers.

4.2 Costs and savings of flexibility for consumers

The total cost of the energy system, and therefore the energy costs faced by consumers, is reduced when heating systems are operated flexibly. The level of savings seen by different types of consumers will depend on the policies, tariff design, incentives for flexibility, taxation systems and market structures created to enable and incentivise smart operation of domestic heating. The cost savings may be passed on to the consumers that provide flexibility services, or they may be socialised across all electricity consumption. In practice, a mix of these two options is likely. While consumers may be incentivised to participate in DSR through Time-of-use electricity tariffs or through regular discounts on bills, these incentives may be less than the total system cost savings.

The range of different annual heating costs that could be seen by consumers in the smart and flexible heat pump scenario relative to the baseline passive scenario is shown in Figure 15. The dashed bars show the range of different fuel costs that consumers might save in different circumstances. If the benefits of flexibility are fully socialised, larger homes may save around €120/y, with flats saving about €30/y.

If electricity system savings are directed towards the households providing flexibility, large flexible households may save as much as €400/y over the baseline case. Similarly, flexible flats may save up to €50/y. If all savings are passed along to households providing flexibility, those unable to operate flexibly will have fuel bills unchanged from the passive case.

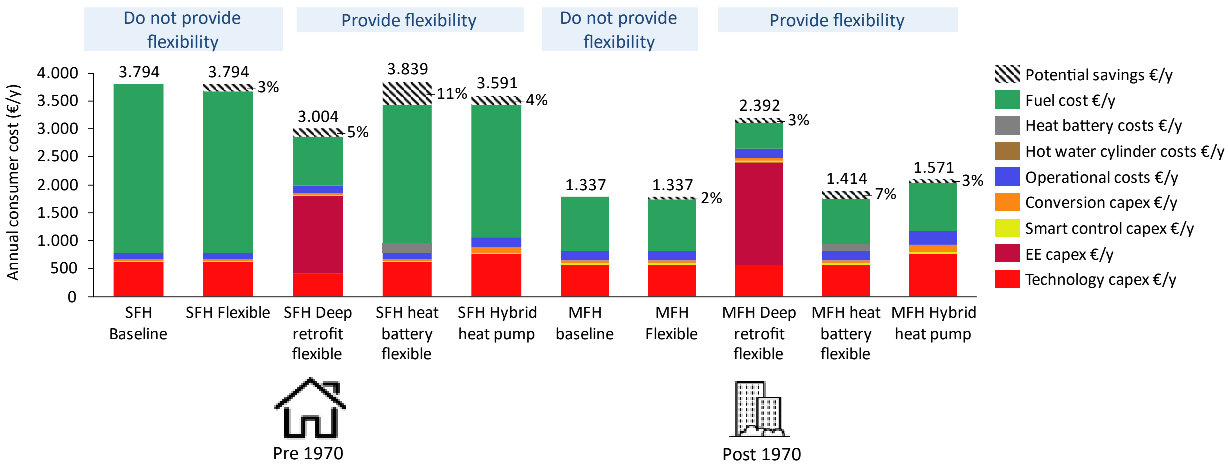

Figure 15 - The range of total consumer costs (€/y) possible in the flexible scenario.

In older single-family homes, all consumers are better off with a flexible energy system, whether they purchase an energy efficiency retrofit, heat battery, or hybrid heat pump to provide flexibility or remain in their initial state and do not provide DSR. Whereas in newer multi-family homes it is more difficult for consumers to see a saving on an individual level. For example, the post-1970 multi-family home in Figure 15 which has undergone a deep retrofit has higher total costs than the same dwelling in the passive baseline scenario, despite providing benefits to the wider energy system. It is therefore likely that policy support will be needed so consumers providing system flexibility do not pay higher costs overall. These supports may take the form of grants or other subsidies for energy efficiency measures, or enhanced payments for flexibility services.

4.3 System level savings from flexibility

This section considers savings at the system level from operating heating systems in a flexible way. This includes both the upfront cost of achieving flexibility and the final fuel savings resulting from the flexibility. Figure 9 shows the full system costs for each technology deployment scenario in both the baseline and efficient flexible cases. Across all scenarios the system cost is less in the flexible scenario compared to the baseline scenario. The efficient heat pump case has the lowest full system costs, considering only the heat sector and not the non-heat electricity, the heat pump scenario is €1.2bn cheaper than the hybrid heat pump scenario which is the next cheapest.

When considering the components of the fuel cost which decrease in the flexible case, the biggest decreases are from lower electricity generation costs where the lower peaks mean less investment in generation is required. The biggest savings come from the hydrogen scenario where making dedicated renewables that produce hydrogen at high load factors is significantly more cost effective than using grid connected electrolysers for hydrogen production.

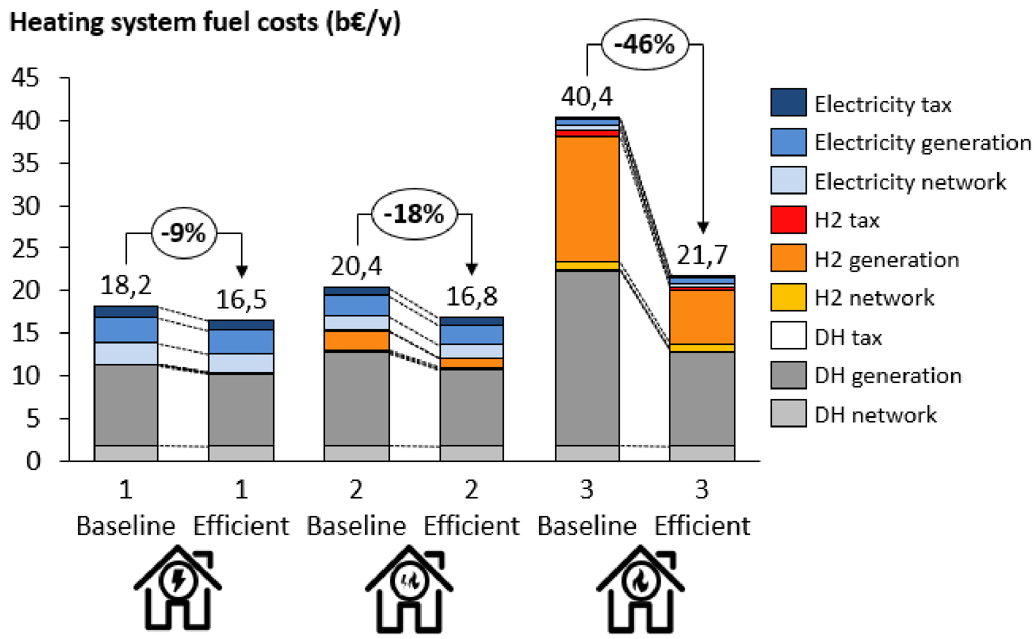

Figure 16 - Fuel cost savings from operating the electricity system in a flexible way (costs shown from system perspective).

When the energy system is operated flexibly consumers will see a difference in their fuel bill. Some of the benefits of flexibility are likely to be passed on to the consumers that provide the flexibility, but some of the benefit is also likely to be socialised across all consumers. Since there is high uncertainty around how these savings will be shared in 2040 we show a range of possible savings for each consumer based on the maximum and minimum possible savings that they could be given by the system. Figure 17 shows the range of different costs that might be given to consumers in the Efficient-Smart scenario, the first and second bars represent the range of costs that a dwelling that doesn't provide flexibility might have, and the second and third bars show the range of costs that a consumer that does provide flexibility may have. In the extreme case of the third bar, all savings from flexibility are passed on to consumers who provide flexibility, and so consumers not providing flexibility would see the baseline electricity cost shown in the left hand bar.

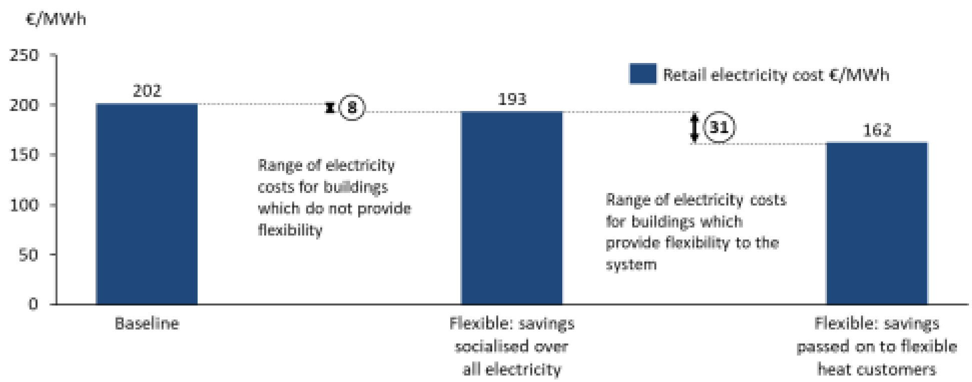

Figure 17 - The range of different fuel costs available to consumers in Poland.

5 Consumer costs of low carbon district heating

District heating in Poland is modelled as not changing from the current 40% of all domestic dwellings connected. The heat sources used by district heating are varied with the technology scenarios (see Table 3), with the further assumption that district heating is fully decarbonised by 2040. This means that gas, oil, and coal-fired systems (including combined heat and power) are not modelled as it is expected that these will be replaced with lower carbon alternatives. District heating systems can help accelerate decarbonisation since it is easier to replace a few large heat generators than the heat generators in many different dwellings. Although not modelled in this study, waste heat can be used as a cost-effective heat source for heat networks and should be considered where available.

Table 3 – Heat sources assumed for district heat in each technology scenario.

	Heat pump scenario	Hybrid heat pump scenario	Hydrogen scenario
Heat pumps	88%	33%	22%
Hybrid heat pumps	-	55%	
Hydrogen boilers	-	-	65%
Other low carbon systems (biomass, waste heat)	12%	12%	13%

While decarbonising district heating will bring benefits in terms of lower carbon emissions, it is important that adequate regulation is put in place to protect consumers on district heating networks. Because district heating is inherently a monopoly supply, consumers are at higher risk of high costs and poorly performing systems, and relatively less recourse to address these issues.

5.1 Cost of district heating networks for consumers

District heating networks are likely to have similar costs for consumers on average to the typical building level technology in each scenario. However, the cost of any heat network is highly dependent on the local area in which it is installed and so drawing exact comparisons between district heating and building level technologies is difficult. This analysis shows however that heat networks are likely to be a good option for consumers, particularly since their ease of decarbonisation is higher than building level technologies. In addition to that they are a cost effective way to help multi family homes provide flexible heating, since installing a deep retrofit to provide flexibility is unlikely to lead to cost savings relative to the baseline.

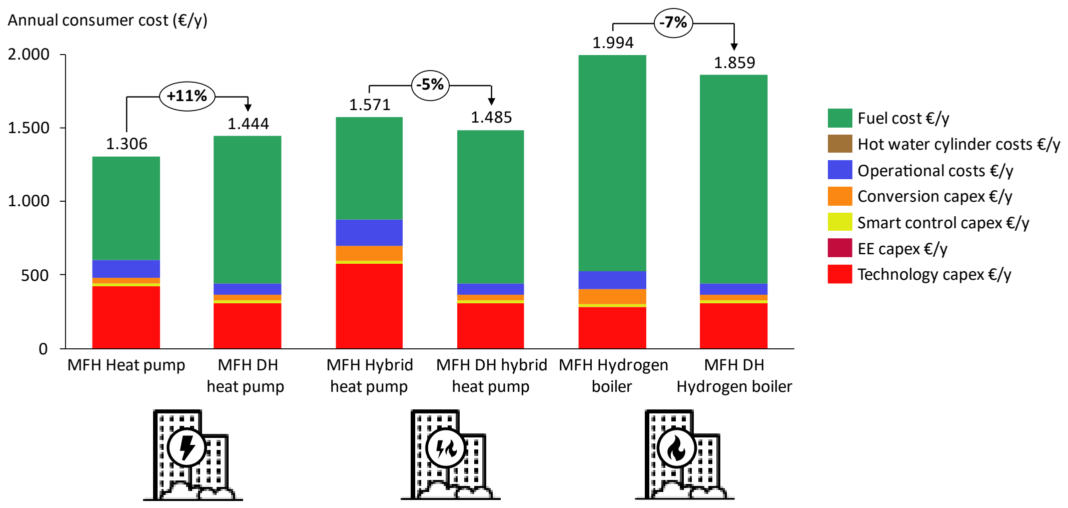

Figure 18 - District heating and building level technology cost for consumers, district heating plant and network costs are included in the fuel cost.

6 Conclusion

As in most European countries, fossil fuels play a significant role in domestic heating and in electricity generation in Poland today. Poland is unique in the fact that it relies strongly on coal, and its emissions have been stable since 2005, thus making the carbon intensity of the Polish economy currently the second highest in the EU and 170% above the EU average. Across the economy, electricity and heating contribute about 38% of Poland's carbon emissions[6]. Recent steps to reduce emissions include adoption of the EU's 2030 target for 55% reduction in carbon emissions from 1990 levels. These commitments will need to be supported by sector-specific policy supporting the energy transition. About 50% of Polish homes are heated with fossil fuels, with 80% of those being heated with coal[7]. By 2040, a significant shift towards renewable heating sources will be required to fulfil Polish and EU commitments towards net zero emissions in 2050.

Electric heating and green hydrogen are the primary options for widespread decarbonisation of domestic heating, while there are a range of other options likely to play smaller roles. The analysis presented above indicates that electrification of heat via heat pumps is likely to be the most affordable for consumers in the long run. Although heat pumps have a higher upfront cost than hydrogen boilers, the high running costs of hydrogen boilers result in a lifetime cost of heat over 90% higher than that offered by heat pumps. Policy support in the form of grants or low cost loans enabling consumers to cover the initial capital cost of heat pumps will result in significant savings across the energy system. District heating can be cost competitive with other low carbon heating technologies. Decarbonising existing networks is likely to be more cost effective than a conversion to low carbon heat solutions at individual building level.

Building fabric efficiency is a key enabler of a smart, cost effective energy system in future. As shown above, energy efficiency retrofits in Poland could reduce demand for heating by 6% (11 TWh) by 2040 relative to today. Raising the ambition for energy efficiency deployment beyond 2% of dwellings per year contributes to system-wide savings of €2.8bn (3% of total energy system costs) despite the additional expenditure of €1bn on efficiency measures. This means that for each €1 spent on energy efficiency measures and smart operation, system costs are reduced by €2.8. Again, consumers may need to be supported in adopting energy efficiency in order for the system-wide savings to be realised. Smart and responsive operation of heating systems could reduce electricity costs by €10 to €45 per MWh. Households providing flexibility services may see yearly savings of between €50/year and €40 0/year, depending on home size and energy demand if appropriate rewards for flexible operation are in place.

6 EU Parliament Briefing, Climate Action in Poland, 2021, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698766/EPRS_BRI(2021)698766_EN.pdf
7 https://data.europa.eu/data/datasets/building-stock-observatory?locale=en

elementenergy

The Consumer Costs of Decarbonised Heat in Czechia

Executive summary

for

BEUC

February 2022

Element Energy Limited
Suite 1, Bishop Bateman Court
Thompson's Lane
Cambridge
CB5 8AQ

Tel: 01223 852499

Key Messages

Low carbon heating

- This study analyses the cost to consumers of low carbon heating options in the year 2040 in Czechia. We have investigated four archetypal homes and present detailed results for two of these archetypes, typical older (pre-1970) single-family homes and more modern (post-1970) flats in multi-family homes.
- We have examined four low carbon heating options within these archetypes: heat pumps, hybrid heat pumps, green hydrogen boilers, and low carbon district heat networks.
- 2040 electricity costs are predicted using the Element Energy Integrated System Dispatch Model (ISDM), which predicts electricity system operation on an hourly basis, and utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system when high levels of variable renewables are connected. We assume the Czech electricity grid has significantly decarbonised by 2040 in line with 2050 net zero targets.
- Green hydrogen costs are estimated using Element Energy's green hydrogen costing tool. This includes country-specific renewable generation profiles and projections for the 2040 cost of hydrogen production technologies, as well as estimated costs for the distribution of hydrogen through the converted gas network.
- Retail electricity costs are predicted to be about 200 €/MWh, while retail green hydrogen costs estimated to be between 150 and 215 €/MWh, depending on how hydrogen production interacts with the wider energy system.
- Heat pumps provide the most cost-effective route to decarbonisation of home heating in Czechia across the dwelling archetypes analysed.
- The older single-family home using a heat pump is predicted to pay around €2.800/y for heating. With a hydrogen boiler, the same dwelling would see costs close to €4.700/y. The more modern flat is predicted to pay €1.300/y for heating with a heat pump, rising to €2.050/y if heated with hydrogen. This includes the annualised cost of the heating system as well as maintenance and fuel.
- Hybrid heat pumps can provide a similar cost of heating as heat pumps in older single-family homes. In more modern flats we find the cost of heating from hybrid heat pumps is about 20% higher than for heat pumps alone. We therefore anticipate there is a role for hybrid heat pumps in older and larger Czech dwellings connected to the gas network, provided that the technical challenges of retrofitting the gas grid to deliver hydrogen are overcome. There is also a risk that hydrogen used by hybrid heat pumps could be more expensive than estimated here if the majority of households adopt fully electric systems and the gas network is maintained although used by relatively few households.
- Although heat pumps have a larger up-front cost than hydrogen boilers, we expect that the running costs of these will be significantly lower than other options for decarbonising heating. This means there may need to be some policy support in place (such as direct grants, affordable green loans and green mortgages) so that consumers are enabled and incentivised to purchase these high capex appliances.
- The results shown are consistent with the other two archetypes investigated (post-1970 single family homes and pre-1970 multi-family homes). The archetypes are representative of typical Czech homes but do not capture the full diversity of the Czech housing stock of around 4.5 million dwellings. Some segments of the housing stock may be unsuitable for heat pumps due to high heat loss and barriers to the installation of additional energy efficiency measures.

Energy efficiency

- Installing energy efficiency can provide cost savings to consumers in some cases, and comes with additional benefits for health, thermal comfort and system flexibility.
- In some cases, energy efficiency retrofits will not pay back in energy bill savings alone. However, increasing the rate of energy efficiency rollout above current targets can reduce the total energy system costs (including the cost of energy efficiency) if combined with flexible operation of the electricity system.
- Policies may therefore be needed to enable and incentivise consumers to improve the fabric efficiency of their homes in order to realise the benefits to the wider energy system.
- Where deeper energy efficiency improvements are less cost-effective, installing domestic-scale thermal storage to enable flexible operation of heating enables a reduction in total electricity system costs.
- Consumer incentives through the market (e.g. ability to purchase lower cost electricity or rebates for providing flexibility) or policy supports (e.g. assistance covering the upfront cost of thermal storage) are likely to be needed to incentivise consumers to provide this service to the energy system.

Smart and flexible heating

- Czech households using heat pumps have several routes to providing flexibility services to the electricity grid. Buildings that undergo deep retrofit to achieve a high level of building fabric efficiency can operate their heat pumps intermittently without impacting comfort. Alternatively, households may use a heat battery or a hybrid heat pump to enable flexible heat pump operation.
- Operating the energy system flexibly lowers the total energy system cost by 4% in a high heat pump scenario, an annual savings of €1,0 billion. This requires investments in energy efficiency improvements in buildings to enable flexible operation of heating. Some investments which will not pay back if the building is considered in isolation may in fact be cost-effective if impact on the wider energy system is considered.
- Smart and responsive heating can reduce the annual consumer cost of heating, saving consumers up to 8% for multi-occupancy buildings, and up 12% in single family homes.

District heat networks

- Low carbon district heat networks can provide domestic heat at comparable cost to building level heating systems and offer a high level of demand flexibility. In many cases heat networks will be simpler to decarbonise due to the relative ease of replacing centralised heating plant compared with disruption in hundreds or thousands of homes. Maintaining existing district heating networks and decarbonising them comes with significant consumer and carbon benefits if suitable consumer protections are in place.

Contents

Authors

For comments or queries please contact:

Sam.Foster@element-energy.co.uk

Fiona.Hughes@element-energy.co.uk

Joachim.Dias@element-energy.co.uk

+44 (1223) 852 499

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Acronyms

CZ	Czechia
DH	District heat
DSR	Demand side response
ES	Spain
HP	Heat pump
HHP	Hybrid heat pump
kWh	kilo Watt hours
ISDM	Element Energy's Integrated system dispatch model
IT	Italy
MFH	Multi family home
MWh	Mega Watt hours
PL	Poland
SFH	Single family home

1 Introduction

1.1 Context and objectives

Heat is recognised as one of the hardest sectors to decarbonise. Currently most consumers use fossil fuels to provide their heat, but to meet emissions targets they will have to swap to a cleaner technology. One possible solution is to electrify heating via heat pumps, however since the seasonality of heating is far greater than of electricity demand this may create a large winter peak in electricity demand causing issues for generators and the distribution network. Another possible option is to decarbonise the gas grid by injecting hydrogen rather than natural gas into it, this might reduce the impact of electrification on the electricity system, but creates challenges in producing zero carbon hydrogen, and converting the distribution network. Since there is significant uncertainty around the costs and risks of these two methods of decarbonising heat, this study aims to understand the impacts of different future scenarios and particularly focuses on the possible impacts on consumers.

In addition to the technologies used to heat dwellings in the future, the installation of energy efficiency upgrades is considered. Currently EU member states have an ambitious target for energy efficiency installation, this study aims to show both the benefits to the energy system of energy efficiency whilst also understanding the potential financial risks to consumers of these installations. We also consider the possible benefits of going beyond current energy efficiency installation targets for consumers.

This study considers the energy system in 2040, this is because it is sufficiently far in the future that significant steps towards the decarbonisation of heating will have been taken by then, we model that 80% of homes are using decarbonised heating by this date, but near enough to the present that accurate projections of the electricity generation mix can be found. The choice of this year will allow us to analyse with greater certainty the cost of different scenarios than we would be able to if choosing a year further into the future even though the system might be more decarbonised by then.

This study determines what the overall cost of heating will be to end users In Europe, under different heating delivery scenarios (primarily electric heat pumps, green hydrogen boilers and hybrid options, and including both individual building and district heating approaches). All costs are determined, including purchase, installation, and maintenance, and the fuel cost, which covers the commodity itself (gas or electricity) and the cost of the infrastructure required to deliver it to homes and to run a safe and secure energy system. The key aims of the study are to:

- Assess the costs of decarbonised heating options from a consumer perspective.
- Analyse the cost and benefit from building fabric energy efficiency measures to individual consumers and the energy system.
- Determine the impact of smart and responsive heating on the energy system and the financial benefits to heat consumers who provide flexibility to the energy system.
- Compare the costs of decarbonised district heating systems with individual dwelling level approaches.

The study has produced reports on four European Member states (ES, IT, CZ, PL), as well as one overall report providing insights into EU-wide consumer impacts. This report summarises the key findings and conclusions about decarbonised heating in Czechia, and makes recommendations around policies that should be implemented to protect consumers.

1.2 Technology scenarios

For this work three technology deployment scenarios for 2040 were created. These three scenarios were focused on the deployment of a single technology as the main low carbon heating option, these were air source heat pumps (ASHP), hybrid heat pumps (ASHP + hydrogen boiler), and hydrogen boilers. The technology mix for each scenario in Czechia is shown in Figure 1. These scenarios are used to analyse the likely cost of different technology options in Czechia under different possible futures and are not intended to be projections or predictions of the likely future technology mix.

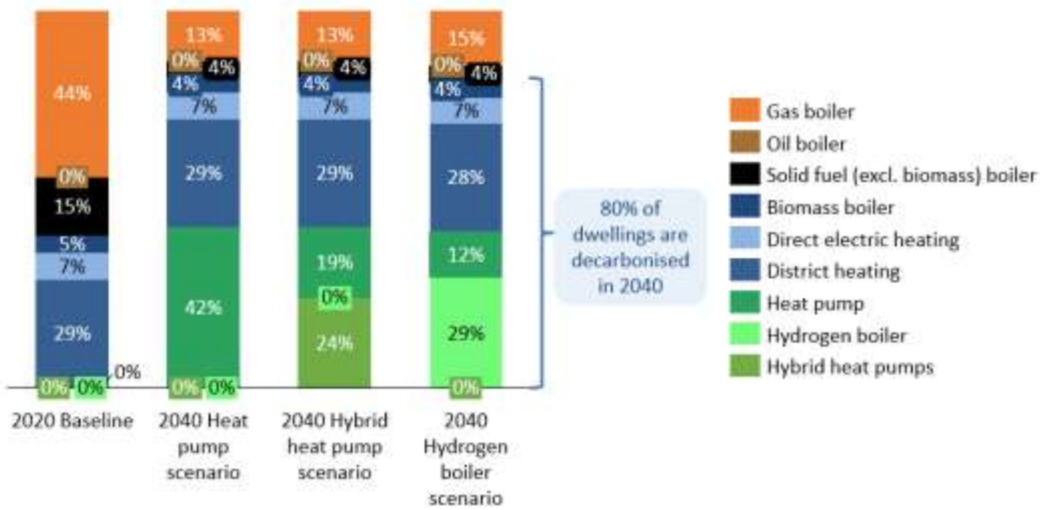

Figure 1 - Fraction of dwellings with each technology in 2040 in each scenario.

In these scenarios the hydrogen boiler and hybrid scenarios are based on the gas network transitioning to hydrogen. This is likely to be a phased process which will not be completed by 2040; hence some remaining natural gas boilers are included in the scenarios above. In these scenarios hydrogen for heating is modelled as "green" hydrogen produced from electricity via electrolysis.

Each of the three technology deployment scenarios are analysed in two ways:

1. The **Baseline-Passive** scenario includes fabric energy efficiency deployment at a rate of 2% of buildings per year, and energy demands such as heating continuing to operate in a passive way.
2. In the **Efficient-Smart** or **Flexible** scenario a higher rate of fabric energy efficiency rollout of 4% of buildings per year is assumed, and heating systems behave in a flexible way, responding to the needs of the energy system as a whole.

In addition, in the Baseline-Passive scenario it is assumed that hydrogen is produced by grid-connected electrolysers, whereas in the Smart-Efficient scenario hydrogen is produced by dedicated renewables collocated with electrolysers and grid curtailment to produce cheaper hydrogen with less impact on the overall energy system.

1.3 Case study buildings

The housing stock in Czechia is made up of a large range of different buildings. To present results in this report the key building level results for consumers are presented for two typical buildings. These typical buildings are a single-family home (SFH) built before 1970 and a multi-family home (apartment, MFH) built after 1970. These buildings are chosen to illustrate the trends that consumers are expected to see, however since all buildings are different there will be some variation from the trends presented for individual buildings. Table 1 shows the characteristics of the selected dwellings.

Table 1 Details of the two key archetypes that results are presented for in this report

Feature	Archetype 1[1]	Archetype 2[2]
Picture		
Type	SFH	MFH
Age	Pre-1970	Post-1970
Assumed climate	Prague	Prague
Floor area (m^2)	91	62
Annual heating demand (kWh)	19.790	6.240
Annual hot water demand (kWh)	2.824	1.909

1.4 Method

An overview of the method is shown in Figure 2 below. The key steps in the modelling are:

1. The archetype stock model calculates the heat demand and final energy consumption on an annual and hourly basis for domestic dwellings in Czechia. The outputs are generated at the building level and at the country-level (i.e. including all buildings). Non-domestic buildings are included in the national demand although they are addressed with less detail than the residential stock.

2. Each residential building archetype undergoes a flexibility assessment to determine whether and how much its heating demand can be shifted to accommodate the needs of the wider electricity system.

3. The energy demands and flexibility potential of the heating system is used by the ISDM in modelling the hourly behaviour of Czechia's energy system throughout

[1] Michal Klajban, CC BY-SA, via Wikimedia commons

[2] Kirk, CC BY-SA 4.0 via Wikimedia Commons

2040. The ISDM predicts the retail costs of electricity and green hydrogen. A more detailed description of the ISDM model is given below.

4. The upfront and ongoing costs of heating are calculated by the consumer cost model for the selected Czech building archetypes.

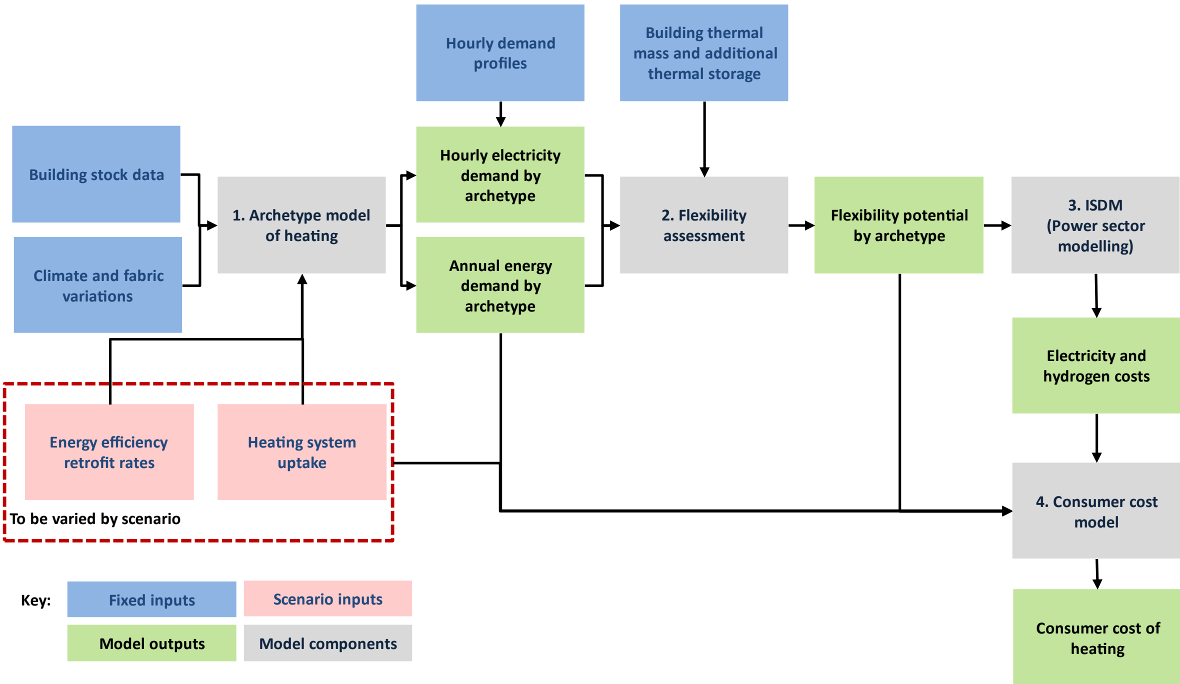

Figure 2 - Full heating system costing model flowchart.

1.5 Energy system modelling

Element Energy's Integrated Supply and Demand Model (ISDM) was developed to overcome limitations of typical power system dispatch models when applied to zero carbon systems. Many such models continue to treat the power system as it currently is: highly dispatchable and reliant on thermal sources for flexibility on the supply side. Future low carbon systems, where variable renewable energy is dominant, will require flexibility on the demand side to support the integration of high levels of renewable energy, while minimising curtailment and reliance on backup thermal plant. ISDM utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system.

The main principles of whole system operation are summarised here. The starting point for the modelling is a set of hourly energy demand profiles for each sector. Some demand profiles are fixed (no flexibility), while others are able to be shifted over defined periods. For heating, these demands are based on the building heat loss, heating technology and outside air temperatures. Transport demand is based on the stock of electric vehicles, their efficiency, the daily usage, and arrival/departure times from home and work to generate baseline electrified transport demand. Grid-responsive smart charging can schedule charging to times of most use to the grid, while still providing vehicles with sufficient charge for transport. Flexibility provided by thermal storage and thermal mass of buildings allows heat demand to move demand to times most useful to the grid, without reducing thermal comfort in homes and offices.

Hourly weather data is also used to generate hourly load factors for wind and solar production. Using the assumptions on the installed VRES generation capacity, the model calculates the hourly VRES generation. By subtracting this from the demand profiles, initial net load curves are generated. Demand shifting, as enabled through smart EV charging and smart heating is deployed to minimise the peak system demand and therefore the required network capacity. Further demand shifting is then applied to reduce curtailment of renewables and fossil fuel use, by moving demand from hours of high to hours of low net demand. By reducing the peak net demand, demand shifting leads to a decreased requirement for dispatchable generation capacity.

The dispatchable generation fleet is then deployed in merit order to fill in the supply gap. Once all hourly demand is met, annual system performance metrics are evaluated, among them fuel and carbon cost, variable OPEX, VRES curtailment, peak demand (for determining the required network capacity), and peak net demand (for determining the required dispatchable generation capacity).

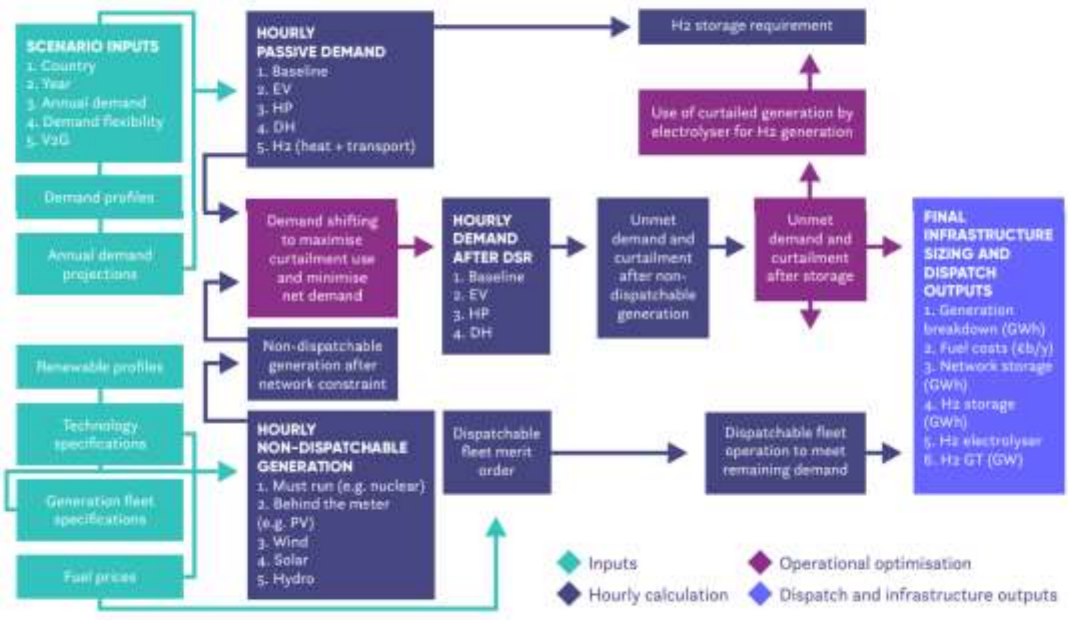

Figure 3 – Schematic of the calculation within the ISDM

1.6 Costing hydrogen for consumers

The cost of producing green hydrogen produced from electricity with electricity was modelled in this project. In the baseline case, it was assumed that the electrolysers were connected to the electricity grid, and pay a wholesale price (excluding grid fees) for their electricity. The cost of hydrogen distribution and storage was then calculated based on a parameterised model of the gas grid and costs of converting the low pressure distribution grid to hydrogen. The costs of hydrogen production and transmission used were taken from the BEIS hydrogen supply chain evidence base[3]. In the flexible case it was assumed that hydrogen production would not be connected to the electricity grid. Hydrogen production electrolysers and renewable generation were assumed to be collocated and the production of hydrogen was found on an hourly basis to optimise the relative generation and electrolyser capacities for the cheapest hydrogen cost.

Country-specific renewable generation profiles were calculated from NASA MERRA-2 data, and the cost of renewable generation was found from the BEIS 2020 cost of generation report[4]. In addition to this the curtailed electricity produced from renewable generation for the rest of the electricity system was also used to produce hydrogen in the flexible case at 0 cost for the electricity. The costs of hydrogen in the Baseline and Flexible scenarios for the high hydrogen scenario are shown in Figure 4. Both wind and solar generation to produce hydrogen were considered, but in CZ onshore wind was the cheapest way to produce hydrogen and this was used for the purpose of costing production in the flexible case. To find the cost per kWh the capex of generation and electrolysers was annualised over the expected lifetime of the technologies at a discount rate of 5% in the consumer cost case and a 3% discount rate in the system cost case. Hydrogen storage was also costed, in Czechia this storage was modelled as a liquid organic hydrogen carrier, with round trip efficiency and other energy use included in the costing.

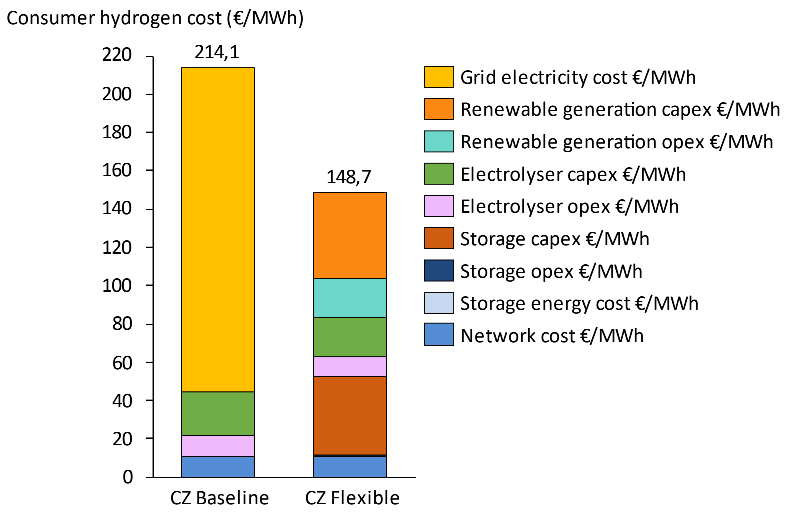

Figure 4 - Cost of hydrogen for consumers in the two cases.

3 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf

4 https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

2 Impact of ambitious energy efficiency deployment

2.1 Energy efficiency scenarios in Czechia

In Czechia, two energy efficiency rollout scenarios were analysed, one baseline scenario with rollout at the rate equivalent to existing targets and one very ambitious rollout rate combined with smart heating system operation. Energy efficiency rollout was analysed by using two packages, one shallow/medium (referred to below as the 'shallow' package) and one deep retrofit. In the 'shallow' package, the older single family home adopts a medium level of retrofit while the modern flat adopts a shallow level. The costs and energy savings of the two packages are based on the ZEBRA2020 study of energy efficiency in buildings across Europe[5].The rollout rate of these packages in the different scenarios is shown in Table 2.

Table 2 - Energy efficiency rollout rates in different scenarios.

Scenario	Shallow retrofit rate	Deep retrofit rate	Total retrofit rate
Baseline	1.5% per year	0.5% per year	2%
Efficient	2.5% per year	1.5% per year	4%

Figure 5 shows the breakdown of the 2040 housing stock in the two energy efficiency rollout scenarios in Czechia. In the efficient scenario 14% more of the stock has had an energy efficiency retrofit than in the baseline scenario. The next chart, Figure 6 shows the reduction in heating demand in typical buildings from a shallow and deep retrofit. Shallow packages reduce the heating demand by 13% in older single family homes and 10% in newer multi family homes. Deep packages give savings of 52% in the older single family homes and 44% in newer multi family homes.

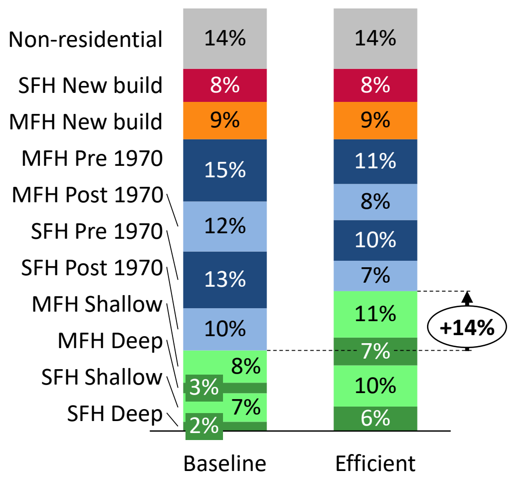

Figure 5 - 2040 housing stock in baseline and efficient scenarios.

[5] nZEB technology solutions, cost assessment and performance, ZEBRA2020: NEARLY ZERO-ENERGY BUILDING STRATEGY 2020, https://zebra2020.eu/publications/nzeb-technology-solutions-cost-assessment-and-performance/

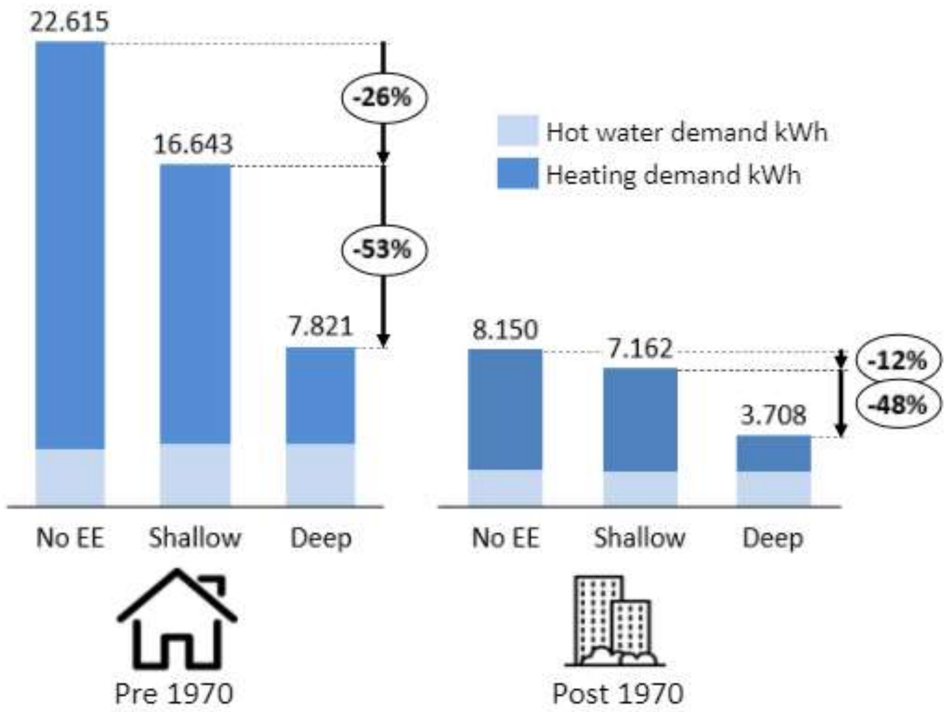

Figure 6 - Reductions in heating demand of typical buildings.

Figure 7 shows the heating demand changes between the baseline 2020 housing stock and the two 2040 scenarios. The baseline scenario has 3% less heating demand than 2020 and the efficient scenario has 9% lower heating demand than the baseline. Both of these reductions are despite the fact that 17% of the building stock in 2040 is made up of new buildings. These are assumed to have heating demand similar to or lower than a building which has undergone a deep retrofit.

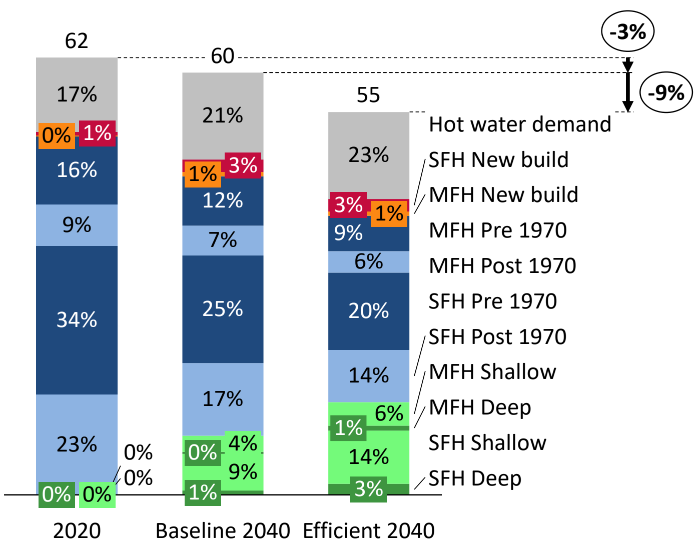

Figure 7 - Residential heating demand by scenario, in TWh.

Figure 8 shows the building level heating cost in € per year for the two key archetypes with different energy efficiency packages installed. This shows that in large single family homes, where the fuel cost makes up a larger part of the total cost of heating than in smaller multi family homes, the savings from energy efficiency in the fuel cost are greater than the additional annualised capex, resulting in annual savings for both deep and shallow retrofit of about 3% per year. However in multi family homes, because there fuel cost makes up less of the total there is no saving in total heating cost from installing energy efficiency due to the higher capex of energy efficiency installation. Consumers who do install energy efficiency measures despite their high capital cost will see lower fuel bills.

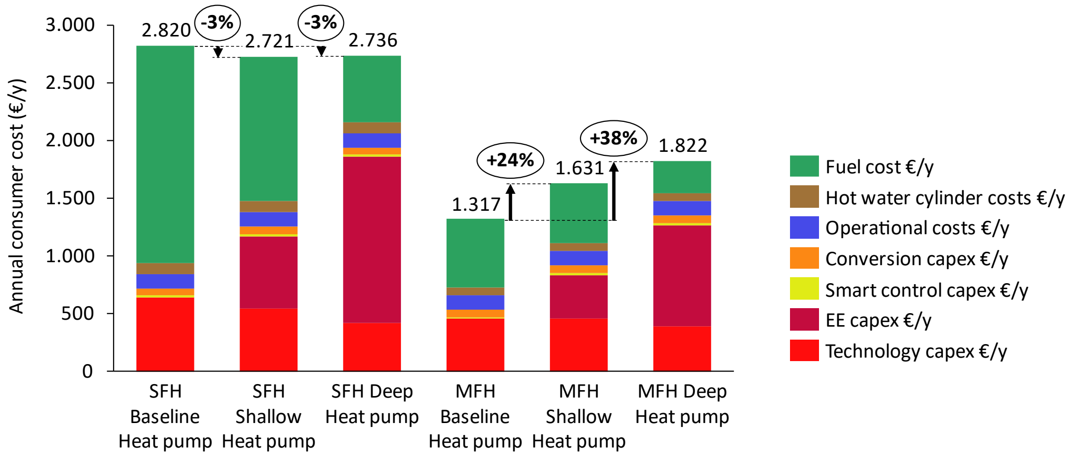

Figure 8 - Building level costs (€/y) and savings of energy efficiency in typical archetypes.

Although energy efficiency measures may not be cost effective at an individual building level for consumers living in multi-unit buildings, the installation of these efficiency measures brings about cost savings to the entire energy system. These savings depend on the type of renewable heating system deployed but are likely to be at least €1bn per year, the exact figures are shown in Figure 9. It is important to note that for the system to realise the full savings from energy efficiency rollout, policy support will be required to remove the significant upfront cost of energy efficiency from households such that they are incentivized to invest in reducing their dwelling’s heating demand. For example since there is no consumer saving from installing energy efficiency in a post 1970 multi family home it is unlikely consumers would make this change without policy support.

Energy efficiency upgrades require significant capital outlay depending on the size and age of the home and the level of retrofit. Figure 10 shows the upfront cost of energy efficiency retrofit in the two typical archetypes. The total annual expenditure on energy efficiency measures would be €0.4bn in the baseline scenario, and €0.8bn in the efficient scenario.

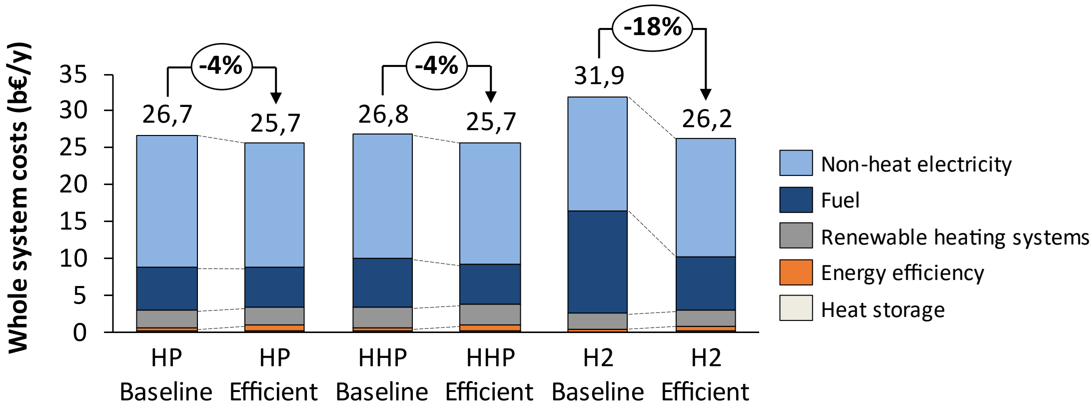

Figure 9 - The system cost saving from the efficient scenario.

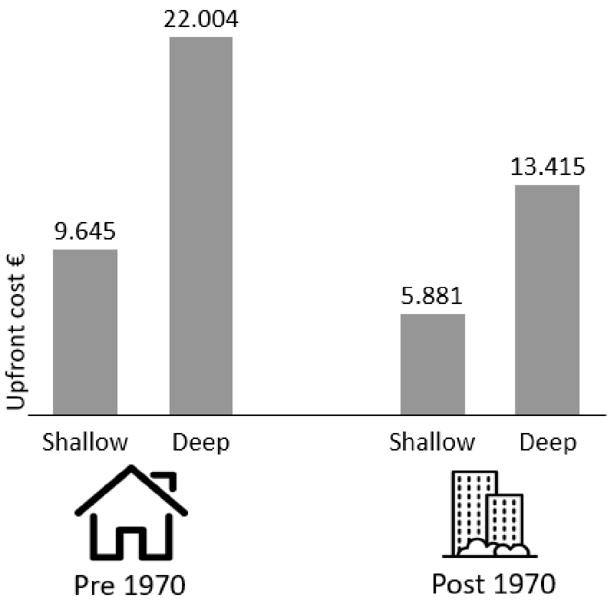

Figure 10 - Upfront cost of energy efficiency packages.

3 Consumer costs of low carbon heating options in 2040

The cost of heating systems to consumers has two parts. There is an upfront capital cost (capex) that is incurred when the heating system is replaced and there is an ongoing cost of fuel and maintenance. This section shows the total cost of heating made up of both of those components, and then looks at each component individually.

3.1 Total cost of heating for consumers

The total cost of heating for consumers is found by summing the annualised capital cost, at a 5% discount rate with a 15-year technology lifetime, with the annual operating cost. This represents the total cost for a consumer in each year of heating their dwelling with that technology. This comparison shows that heating dwellings with heat pumps is the cheapest option for consumers in both key archetypes. A high rollout of hydrogen boilers relative to a rollout of heat pumps could leave consumers paying between 55% and 70% more for their heat. Since the cheapest overall option, heat pumps, come at a significant upfront cost premium to hydrogen boilers and counterfactual heating technologies, it is important that government provides adequate support to consumers to switch their heating through incentives and financial products that address these high upfront costs in order for consumers to achieve the possible savings.

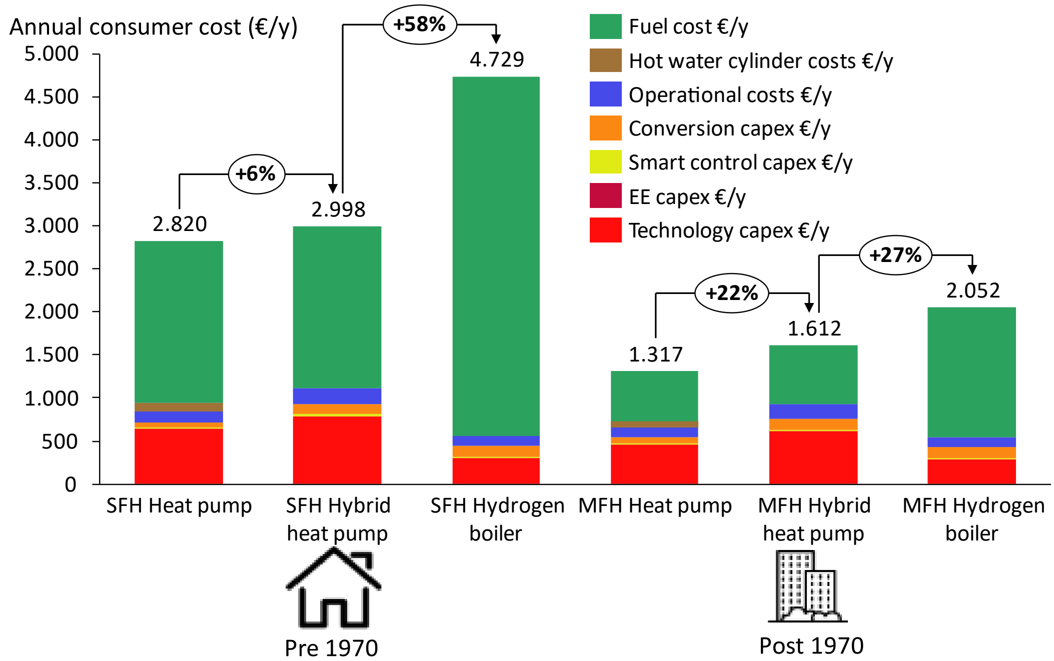

Figure 11 - Annual consumer cost of heat with the main technology in each scenario.

3.2 Ongoing costs of heating systems

Fuel costs are found from electricity system modelling based on the uptake of heating systems and energy efficiency for that scenario. The technologies considered here have different efficiencies of producing heat from their fuel, heat pumps can operate at 280% efficiency, whereas hydrogen boilers are 85% efficient. Since hydrogen is produced from electricity via electrolysis using hydrogen boilers to produce heat typically uses 4.5x as much electricity as producing the heat with a heat pump. Due to this the operational costs of hydrogen systems can be over 2x as large as those of heat pump systems. This means although hydrogen can be cheaper than electricity per kWh the additional consumption outweighs this. Hydrogen is also likely to be significantly more expensive than gas is today for consumers. Figure 12 shows the annual running costs for the different heating systems in the two main archetypes.

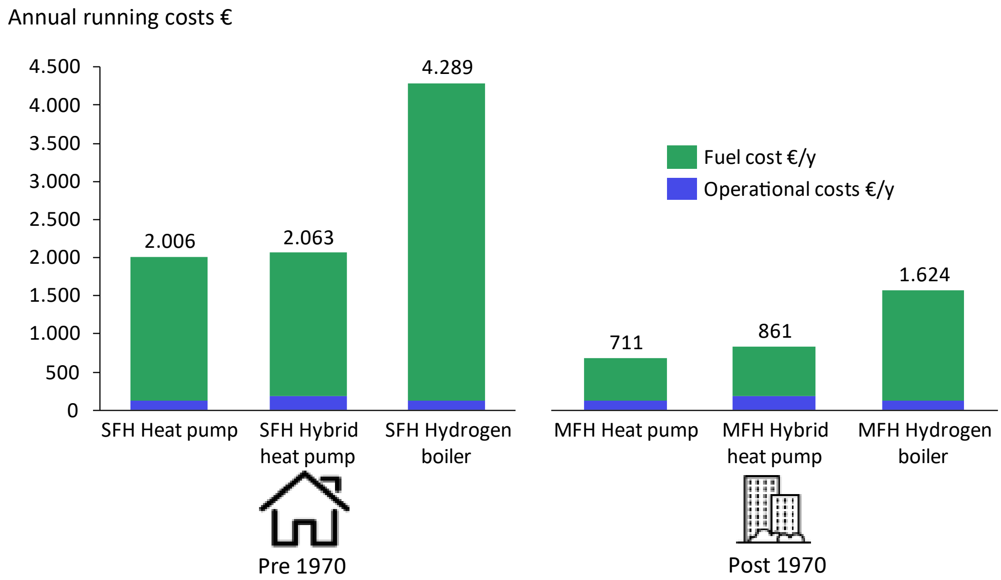

Figure 12 - Annual running costs of different heating systems.

3.3 Capital cost of heating systems

Capital costs are found from the Element Energy database of heating system costs and include the cost of the heating system as well as the cost of hot water cylinders and smart controllers where appropriate. Hydrogen boilers have the lowest capital cost of the heating systems considered; hybrid heat pumps have the highest capital cost.

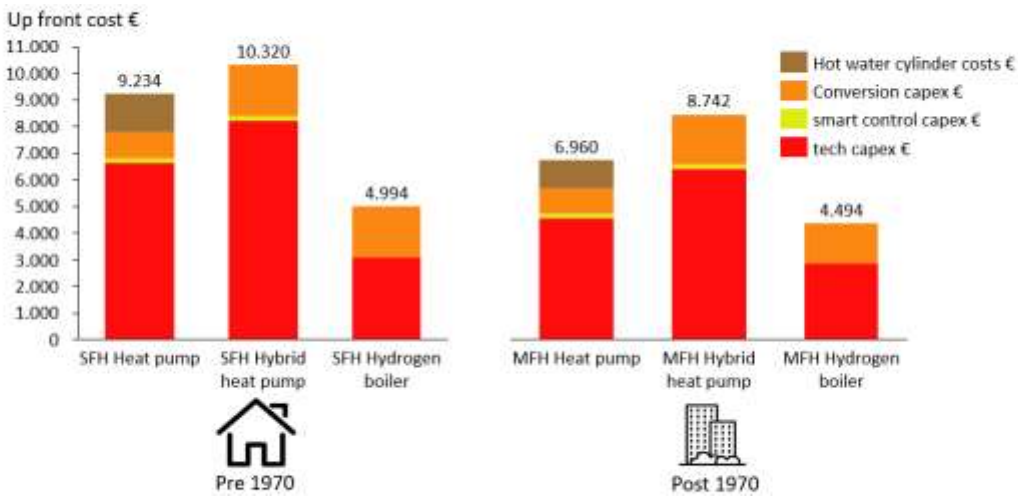

Figure 13 - Capital costs of different heating systems for typical archetypes.

4 Benefit from smart and responsive low carbon heating

Two system operation scenarios are presented in this study, the **Baseline-Passive** scenario involves passive operation of the energy system to meet demand, and the **Efficient-Smart** or **Flexible** scenario involves a higher rate of energy efficiency and operation of the energy system in a flexible way such that demand is changed to better match supply of power. Each of these two scenarios has been run with the three different technology deployment levels, so in each case the impact of smart system operation can be quantified. In all scenarios smart operation of electric vehicle charging is assumed.

4.1 Energy system benefit of smart operation

When heat pumps are operated in a smart way, they act to move demand away from the peak, this is achieved by pre heating houses with high thermal mass relative to their heat loss rate, or by storing thermal energy in a phase change heat battery. We assume that by 2040, 50% of buildings with heat pumps that cannot be flexible through their thermal mass purchase a thermal battery. This allows a greater proportion of buildings to offer flexibility services, without implying an unrealistic rate of deep retrofit.

When heating is operated flexibly, the total demand for heating is unchanged, but the profile of electricity use is less "peaky". The lower peaks mean that the total required capacity of electricity generation can be lower and less upgrade to higher capacity electricity networks is required, reducing the cost of the electricity system. In addition to the peak reduction, flexibility also allows demand to be better matched to when there is high generation of renewable technologies, this means those technologies with zero marginal cost have higher load factors and less thermal generation is required decreasing the system cost. Figure 14 shows the nationwide electricity demand over a typical winter week in 2040 in the scenario with high uptake of heat pumps. Under smart operation, heat demand is removed away from the peak, increasing demand at other times of day. This decreases the peak system demand and means less network capacity is required. In addition, heat demand can be moved into times where variable renewable electricity is available, reducing both the cost of electricity production and its carbon content. The model first moves demand that is flexible based on thermal mass, and then moves the demand that is flexible based on installing additional thermal storage, Figure 14 shows the change in the demand profile after the thermal mass flexibility and thermal storage are applied, the majority of flexibility comes from additional thermal storage.

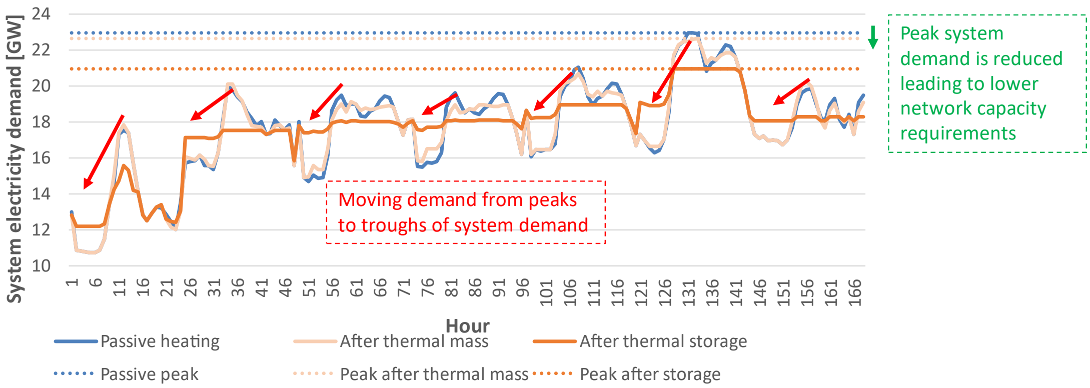

Figure 14 - Example of total electricity demand in Czechia under the heat pump scenario with passive and smart heating system operation.

District heating also provides flexibility to the system through use of larger-scale thermal storage (typically in the form of stored hot water). This allows the peaks and troughs of heating demand from buildings on a district heat network to be mitigated locally so the loads on the wider energy system are minimised. In the flexible case hydrogen is considered to be produced by collocated renewables and curtailment so does not impact the wider electricity system relative to the baseline scenario where it is produced by grid connected electrolysers.

4.2 Costs and savings of flexibility for consumers

The total cost of the energy system, and therefore the energy costs faced by consumers, is reduced when heating systems are operated flexibly. The level of savings seen by different types of consumers will depend on the policies, tariff design, incentives for flexibility, taxation systems and market structures created to enable and incentivise smart operation of domestic heating. The cost savings may be passed on to the consumers that provide flexibility services, or they may be socialised across all electricity consumption. In practice, a mix of these two options is likely. While consumers may be incentivised to participate in DSR through Time-of-use electricity tariffs or through regular discounts on bills, these incentives may be less than the total system cost savings.

The range of different annual heating costs that could be seen by consumers in the smart and flexible heat pump scenario relative to the baseline passive scenario is shown in Figure 15. The dashed bars show the range of different fuel costs that consumers might pay in different circumstances. If the benefits of flexibility are fully socialised, larger homes may save around €100/y, with flats saving about €35/y.

If savings are directed towards the households providing flexibility, large flexible households as much as €350/y over the baseline case, depending on how they provide flexibility. Similarly, flexible flats may save up to €100/y. If all savings are passed along to households providing flexibility, those unable to operate flexibly will have fuel bills unchanged from the passive case.

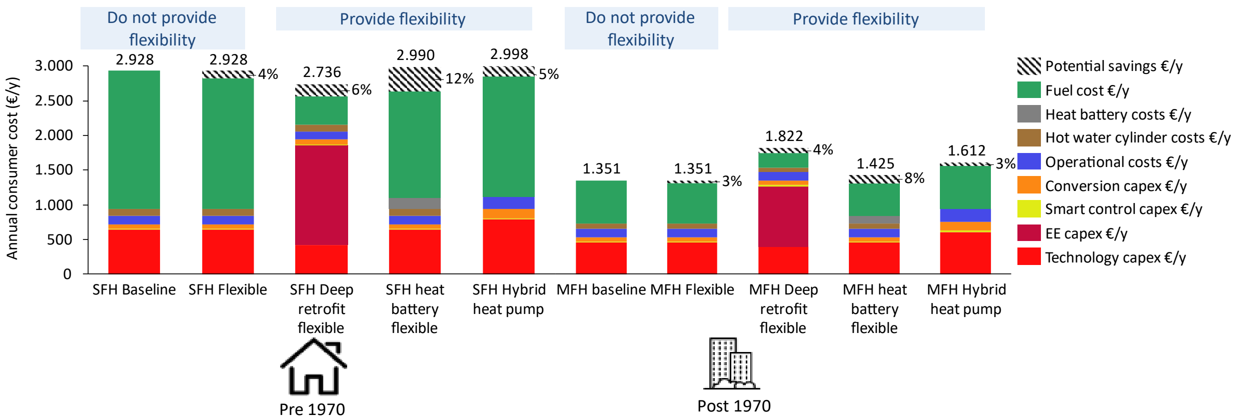

Figure 15 - The range of total consumer costs (€/y) possible in the flexible scenario.

In older single family homes, all consumers are better off with a flexible energy system, whether they purchase an energy efficiency retrofit or heat battery to provide flexibility or not. Whereas in newer multi family homes it is more difficult for consumers to see a saving on an individual level. For example, the post-1970 multi family home in Figure 15 which has undergone a deep retrofit has higher total costs than the same dwelling in the passive baseline scenario, despite providing benefits to the wider energy system. It is therefore likely that policy support will be needed so consumer providing system flexibility do not pay higher costs overall. These supports may take the form of grants or other subsidies for energy efficiency measures, or enhanced payments for flexibility services.

4.3 System level savings from flexibility

This section considers savings at the system level from operating heating systems in a flexible way. This includes both the upfront cost of achieving flexibility and the final fuel savings resulting from the flexibility. Figure 9 shows the full system costs for each technology deployment scenario in both the baseline and efficient flexible cases. Across all scenarios the system cost is less in the flexible scenario compared to the baseline scenario. The efficient heat pump case has the lowest full system costs, considering only the heat sector and not the non-heat electricity, the heat pump scenario is €0.1bn cheaper per year than the hybrid heat pump scenario which is the next cheapest.

When considering the components of the fuel cost which decrease in the flexible case, the biggest decreases are from lower electricity generation costs where the lower peaks mean less investment in generation is required. The biggest savings come from the hydrogen scenario where making dedicated renewables that produce hydrogen at high load factors is significantly more cost effective than using grid connected electrolysers for hydrogen production.

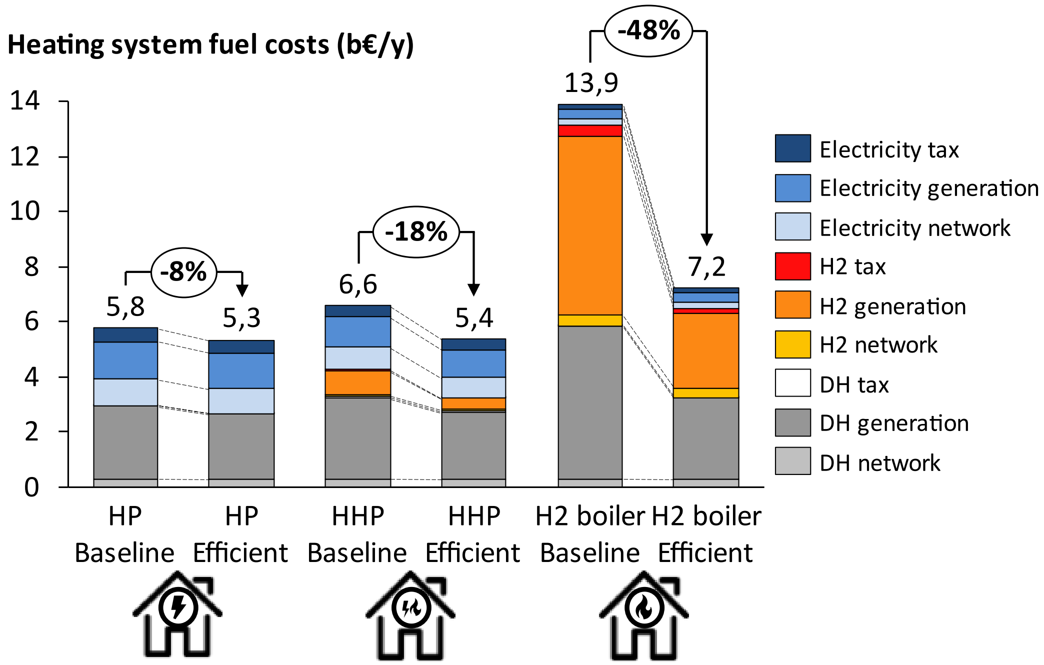

Figure 16 - Fuel cost savings from operating the electricity system in a flexible way (costs shown from system perspective).

When the energy system is operated flexibly consumers will see a difference in their fuel bill. Some of the benefits of flexibility are likely to be passed on to the consumers that provide the flexibility, but some of the benefit is also likely to be socialised across all consumers. Since there is high uncertainty around how these savings will be shared in 2040 we show a range of possible savings for each consumer based on the maximum and minimum possible savings that they could be given by the system. Figure 17 shows the range of different costs that might be given to consumers in the Efficient-Smart scenario, the first and second bars represent the range of costs that a dwelling that doesn't provide flexibility might have, and the second and third bars show the range of costs that a consumer that does provide flexibility may have. In the extreme case of the third bar, all savings from flexibility are passed on to consumers who provide flexibility, and so consumers not providing flexibility would see the baseline electricity cost shown in the left hand bar.

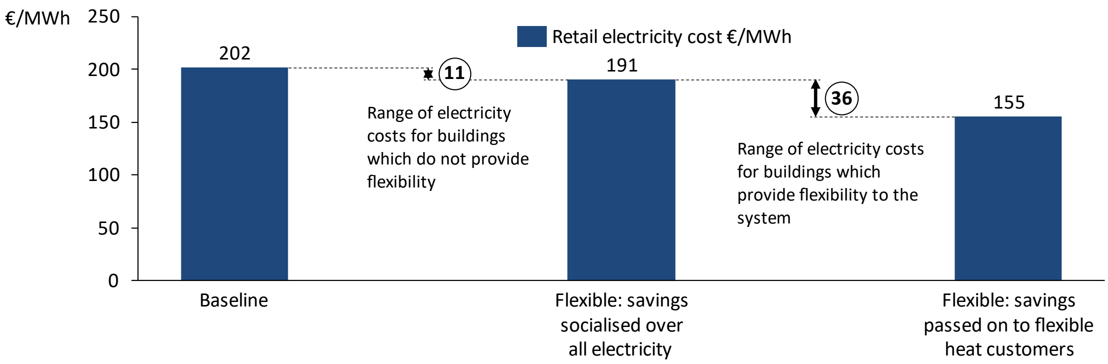

Figure 17 - The range of different fuel costs available to consumers in Czechia.

5 Consumer costs of low carbon district heating

District heating in Czechia is modelled at existing deployment rate, with 28% of domestic dwellings connected. The heat sources used by district heating are varied with the technology scenarios (see Table 3), with the further assumption that district heating is fully decarbonised by 2040. This means that gas, oil, and coal-fired systems (including combined heat and power) are not modelled as it is expected that these will be replaced with lower carbon alternatives. District heating systems can help accelerate decarbonisation since it is easier to replace a few large heat generators than the heat generators in many different dwellings. Although not modelled in this study, waste heat can be used as a cost-effective heat source for heat networks and should be considered where available.

Table 3 – Heat sources assumed for district heat in each technology scenario.

	Heat pump scenario	Hybrid heat pump scenario	Hydrogen scenario
Heat pumps	91%	40%	27%
Hybrid heat pumps	-	51%	
Hydrogen boilers	-	-	64%
Other low carbon systems (biomass, waste heat)	9%	9%	9%

While decarbonising district heating will bring benefits in terms of lower carbon emissions, it is important that adequate regulation is put in place to protect consumers on district heating networks. Because district heating is inherently a monopoly supply, consumers are at higher risk of high costs and poorly performing systems, and relatively less recourse to address these issues.

5.1 Cost of district heating networks for consumers

District heating networks are likely to have similar costs for consumers on average to the typical building level technology in each scenario. However, the cost of any heat network is highly dependent on the local area in which it is installed and so drawing exact comparisons between district heating and building level technologies is difficult. This analysis shows however that heat networks are likely to be a good option for consumers, particularly since their ease of decarbonisation is higher than building level technologies. In addition to that they are a cost effective way to help multi family homes provide flexible heating, since installing a deep retrofit to provide flexibility is unlikely to lead to cost savings relative to the baseline.

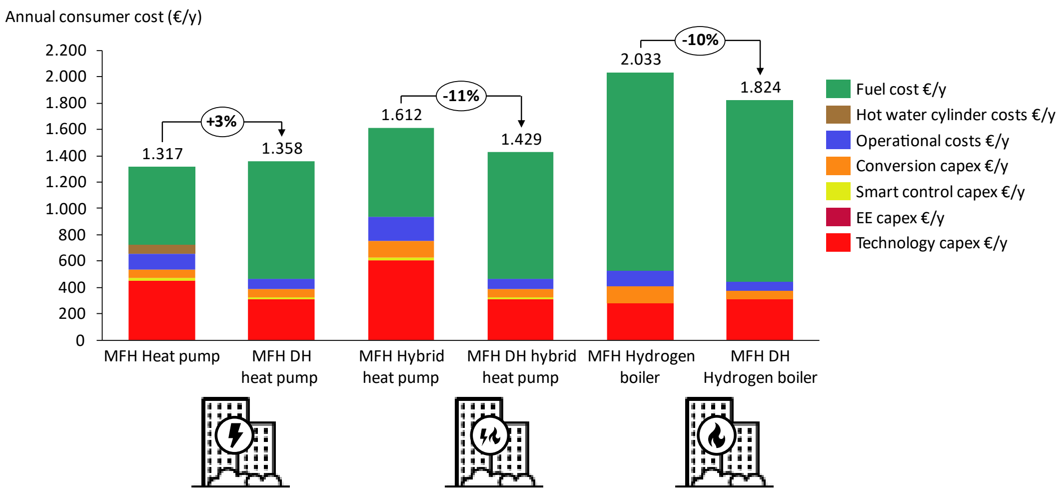

Figure 18 - District heating and building level technology cost for consumers, district heating plant and network costs are included in the fuel cost.

6 Conclusion

As in most European countries, fossil fuels play a significant role in domestic heating and in electricity generation in Czechia today. Across the economy, electricity and heating contribute about 40% of Czechia's carbon emissions[6]. Recent steps to reduce emissions include adoption of the EU's 2030 target for 55% reduction in carbon emissions from 1990 levels roadmap and the Czech utility ČEZ's goal of phasing out electricity production from coal by 2030[7]. These commitments will need to be supported by sector-specific policy supporting the energy transition. Over 60% of Czech homes are heated with fossil fuels, including about 15% heated with coal[8]. By 2040, a significant shift towards renewable heating sources will be required to fulfil Czech and EU commitments towards net zero emissions in 2050.

Electric heating and green hydrogen are the primary options for widespread decarbonisation of domestic heating, while there are a range of other options likely to play smaller roles. The analysis presented above indicates that electrification of heat via heat pumps is likely to be the most affordable for consumers in the long run. Although heat pumps have a higher upfront cost than hydrogen boilers, the high running costs of hydrogen boilers result in a lifetime cost of heat over 80% higher than that offered by heat pumps. Policy support in the form of grants or low cost loans enabling consumers to cover the initial capital cost of heat pumps will result in significant savings across the energy system. District heating can be cost competitive with other low carbon heating technologies. Decarbonising existing networks is likely to be more cost effective than a conversion to low carbon heat solutions at individual building level.

Building fabric efficiency is a key enabler of a smart, cost effective energy system in future. As shown above, energy efficiency retrofits in Czechia could reduce demand for heating by 12% (7 TWh) by 2040 relative to today. Raising the ambition for energy efficiency deployment beyond 2% of dwellings per year contributes to system-wide savings of €1,0bn (4% of total energy system costs) despite the additional expenditure of €0,4bn on efficiency measures. This means that for each €1 spent on energy efficiency measures and smart operation, system costs are reduced by €2.50. Again, consumers may need to be supported in adopting energy efficiency in order for the system-wide savings to be realised. Smart and responsive operation of heating systems could reduce electricity costs by €20 to €50 per MWh. Households providing flexibility services may see yearly savings of between €100/year and €350/year, depending on home size and energy demand if appropriate rewards for flexible operation are in place.

[6] EU Parliament Briefing, Climate Action in Czechia, 2021, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689329/EPRS_BRI(2021)689329_EN.pdf

[7] https://beyond-coal.eu/2021/05/20/cez-announces-plan-to-slash-coal-by-2030-ahead-of-czech-government-coal-exit-vote/

[8] EntraNZE European Buildings database, https://www.entranze.eu/pub/pub-data

elementenergy

The Consumer Costs of Decarbonised Heat in Spain

Executive summary

for

BEUC

February 2022

Element Energy Limited
Suite 1, Bishop Bateman Court
Thompson's Lane
Cambridge
CB5 8AQ

Tel: 01223 852499

Key Messages

Low carbon heating

- This study analyses the cost to consumers of low carbon heating options in the year 2040 in Spain. We have investigated four archetypal homes and present detailed results for two of these archetypes, typical older (pre-1970) single-family homes and more modern (post-1970) flats in multi-family homes.
- We have examined four low carbon heating options within these archetypes: heat pumps, hybrid heat pumps, green hydrogen boilers, and two levels of potential deployment of low carbon district heat networks.
- 2040 electricity costs are predicted using the Element Energy Integrated System Dispatch Model (ISDM), which predicts electricity system operation on an hourly basis, and utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system when high levels of variable renewables are connected. We assume the Spanish electricity grid has significantly decarbonised by 2040 in line with 2050 net zero targets.
- Green hydrogen costs are estimated using Element Energy's green hydrogen costing tool. This includes country-specific renewable generation profiles and projections for the 2040 cost of hydrogen production technologies, as well as estimated costs for the distribution of hydrogen through the converted gas network.
- Retail electricity costs are predicted to be about 150 €/MWh, while retail green hydrogen costs estimated to be about 145 €/MWh, depending on how hydrogen production interacts with the wider energy system.
- Heat pumps provide the most cost-effective route to decarbonisation of home heating in Spain across the dwelling archetypes analysed.
- The older single-family home using a heat pump is predicted to pay around €1.200/y for heating. With a hydrogen boiler, the same dwelling would see costs of nearly €1.900/y. The more modern flat is predicted to pay €1.050/y for heating with a heat pump, rising to around €1.600/y if heated with hydrogen. This includes the annualised cost of the heating system as well as maintenance and fuel.
- Hybrid heat pumps are more affordable than hydrogen boilers. The annual cost of heating with a hybrid heat pump is about €1.600 in the single-family home and €1.500 in the flat, an approximately 40% increase over the cost of heat with a heat pump in both cases. Although more expensive, there may be some role for hybrid heat pumps in hard-to-decarbonise Spanish dwellings (most likely older and larger homes) which are connected to the gas network, provided that the technical challenges of retrofitting the gas grid to deliver hydrogen are overcome. There is also a risk that hydrogen used by hybrid heat pumps could be more expensive than estimated here if the majority of households adopt fully electric systems and the gas network is maintained although used by relatively few households.
- Although heat pumps have a larger up-front cost than hydrogen boilers, we expect that the running costs of these will be significantly lower than other options for decarbonising heating. This means there may need to be some policy support in place (such as direct grants, affordable green loans and green mortgages) so that consumers are enabled and incentivised to purchase these high capex appliances.
- The results shown are consistent with the other two archetypes investigated (post-1970 single family homes and pre-1970 multi-family homes). The archetypes are representative of typical Spanish homes near Madrid but do not capture the full diversity of the Spanish housing stock of around 19 million dwellings. Some segments of the housing stock may be unsuitable for heat pumps due to high heat loss and barriers to the installation of additional energy efficiency measures.

Energy efficiency

- Installing energy efficiency can provide cost savings to consumers in some cases, and comes with additional benefits for health, thermal comfort and system flexibility.
- In some cases, energy efficiency retrofits will not pay back in energy bill savings alone. However, increasing the rate of energy efficiency rollout above current targets can reduce the total energy system costs (including the cost of energy efficiency) if combined with flexible operation of the electricity system.
- Policies may therefore be needed to enable and incentivise consumers to improve the fabric efficiency of their homes in order to realise the benefits to the wider energy system.
- Where deeper energy efficiency improvements are less cost-effective, installing domestic-scale thermal storage to enable flexible operation of heating enables a reduction in total electricity system costs.
- Consumer incentives through the market (e.g. ability to purchase lower cost electricity or rebates for providing flexibility) or policy supports (e.g. assistance covering the upfront cost of thermal storage) are likely to be needed to incentivise consumers to provide this service to the energy system.

Smart and flexible heating

- Spanish households using heat pumps have several routes to providing flexibility services to the electricity grid. Buildings that undergo deep retrofit to achieve a high level of building fabric efficiency can operate their heat pumps intermittently without impacting comfort. In more modern flats, a shallow retrofit can also be sufficient to allow flexible heat pump operation. Alternatively, households may use a heat battery or a hybrid heat pump to enable flexible heat pump operation.
- Operating the energy system flexibly lowers the total energy system cost by 1% in a high heat pump scenario, an annual savings of €0,8 billion. This requires investments in energy efficiency improvements in buildings to enable flexible operation of heating. Some investments which will not pay back if the building is considered in isolation may in fact be cost-effective if impact on the wider energy system is considered.
- Smart and responsive heating can reduce the annual consumer cost of heating, saving consumers up to 9% on their total annualised heating costs in both multi-occupancy buildings and single family homes.

District heat networks

- Our analysis indicates that there is significant potential for cost-effective district heating in Spain.
- We have investigated two levels of district heat deployment in Spain. An expansion of district heat networks to reach 16% of total building stock from less than 1% today results in comparable costs for consumers relative to building-level technologies. Expanding heat networks even further, to an ambitious level of 32% of homes in 2040, increases the average cost of district heating only marginally.
- The consumer benefits of district heating are most notable when compared with hybrid heat pumps and hydrogen boilers. District heat can offer savings of around 15% of annual heating costs compared with these systems, and can be a suitable option for homes in areas with high density of heat demand.
- Local, regional, and national decisions on investing in district heating are likely to depend on the priorities of the area in question. District heat allows decarbonisation of buildings through more centralised infrastructure investments rather than action and expenditure at the individual household level. Depending on the local context, cities and towns with dense heat demand may find

decarbonising buildings through district heat to be more practically achievable than through other means.

- It is important that low carbon heating technologies are installed when heat networks are initially constructed. While this may increase the capital cost of district heating in the short term, costs will be avoided in the longer term by avoiding the need to replace thermal plant in future to comply with Spanish and EU carbon targets.
- This study analyses district heating potential at a high level. Costs for individual networks will depend on the local heat demand and the appropriate heat sources, which may include waste heat. More granular local analysis is required to estimate the costs of a heat network in a particular area.
- Appropriate consumer protections are required to mitigate the risks to end-users that can arise due to the inherent nature of heat networks as monopolies. These risks have been successfully mitigated in a number of countries using a range of methods including codes of practice, transparent cost methodologies, service standard, and innovative ownership structures.

Contents

Authors

For comments or queries please contact:

Sam.Foster@element-energy.co.uk

Fiona.Hughes@element-energy.co.uk

Joachim.Dias@element-energy.co.uk

+44 (1223) 852 499

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Acronyms

CZ	Czechia
DH	District heat
DSR	Demand side response
ES	Spain
HP	Heat pump
HHP	Hybrid heat pump
kWh	kilo Watt hours
ISDM	Element Energy's Integrated system dispatch model
IT	Italy
MFH	Multi family home
MWh	Mega Watt hours
PL	Poland
SFH	Single family home

1 Introduction

1.1 Context and objectives

Heat is recognised as one of the hardest sectors to decarbonise. Currently most consumers use fossil fuels to provide their heat, but to meet emissions targets they will have to swap to a cleaner technology. One possible solution is to electrify heating via heat pumps, however since the seasonality of heating is far greater than of electricity demand this may create a large winter peak in electricity demand causing issues for generators and the distribution network. Another possible option is to decarbonise the gas grid by injecting hydrogen rather than natural gas into it, this might reduce the impact of electrification on the electricity system, but creates challenges in producing zero carbon hydrogen, and converting the distribution network. Since there is significant uncertainty around the costs and risks of these two methods of decarbonising heat, this study aims to understand the impacts of different future scenarios and particularly focuses on the possible impacts on consumers.

In addition to the technologies used to heat dwellings in the future, the installation of energy efficiency upgrades is considered. Currently EU member states have an ambitious target for energy efficiency installation, this study aims to show both the benefits to the energy system of energy efficiency whilst also understanding the potential financial risks to consumers of these installations. We also consider the possible benefits of going beyond current energy efficiency installation targets for consumers.

This study considers the energy system in 2040, this is because it is sufficiently far in the future that significant steps towards the decarbonisation of heating will have been taken by then, we model that 80% of homes are using decarbonised heating by this date, but near enough to the present that accurate projections of the electricity generation mix can be found. The choice of this year will allow us to analyse with greater certainty the cost of different scenarios than we would be able to if choosing a year further into the future even though the system might be more decarbonised by then.

This study determines what the overall cost of heating will be to end users In Europe, under different heating delivery scenarios (primarily electric heat pumps, green hydrogen boilers and hybrid options, and including both individual building and district heating approaches). All costs are determined, including purchase, installation, and maintenance, and the fuel cost, which covers the commodity itself (gas or electricity) and the cost of the infrastructure required to deliver it to homes and to run a safe and secure energy system. The key aims of the study are to:

- Assess the costs of decarbonised heating options from a consumer perspective.
- Analyse the cost and benefit from building fabric energy efficiency measures to individual consumers and the energy system.
- Determine the impact of smart and responsive heating on the energy system and the financial benefits to heat consumers who provide flexibility.
- Compare the costs of decarbonised district heating systems with individual dwelling level approaches.

The study has produced reports on four European Member states (ES, IT, CZ, PL), as well as one overall report providing insights into EU-wide consumer impacts. This report summarises the key findings and conclusions about decarbonised heating in Spain, and makes recommendations around policies that should be implemented to protect consumers.

1.2 Technology scenarios

For this work three technology deployment scenarios for 2040 were created. These three scenarios were focused on the deployment of a single technology as the main low carbon heating option, these were air source heat pumps (ASHP), hybrid heat pumps (ASHP + hydrogen boiler), and hydrogen boilers. Additionally, this work considers two level of district heating penetration for each of these scenarios, with 16% of homes supplied by district heating in the central case, which is increased to 32% in the high district heating case. These two scenarios represent an ambitious and very ambitious rollout rate of district heating and aim to quantify if there are benefits from Spain pursuing a policy of faster district heating rollout. The technology mix for each scenario in Spain is shown in Figure 1. These scenarios are used to analyse the likely cost of different technology options in Spain under different possible futures and are not intended to be projections or predictions of the likely future technology mix.

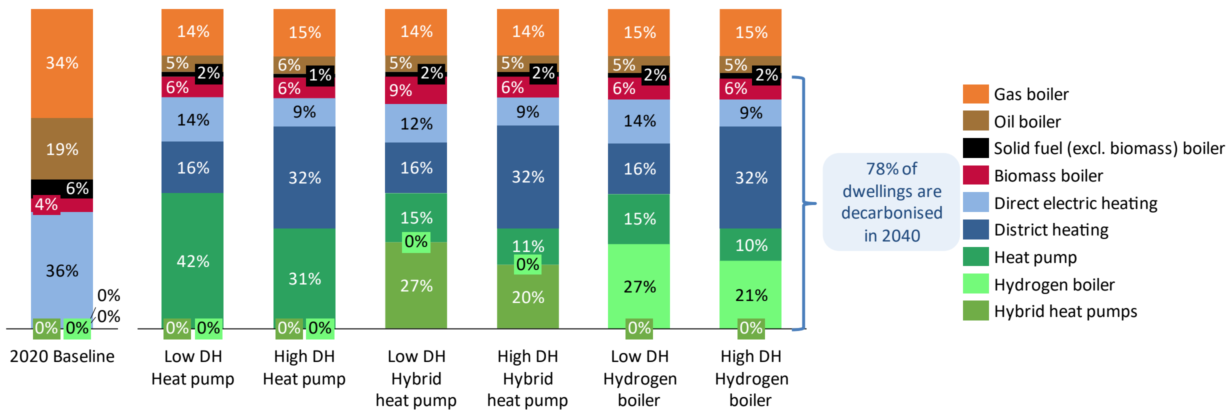

Figure 1 - Fraction of dwellings with each technology in 2040 in each scenario

In these scenarios the hydrogen boiler and hybrid scenarios are based on the gas network transitioning to hydrogen. This is likely to be a phased process which will not be completed by 2040; hence some remaining natural gas boilers are included in the scenarios above. In these scenarios hydrogen for heating is modelled as “green” hydrogen produced from electricity via electrolysis.

Each of the three technology deployment scenarios are analysed in two ways:

1. The **Baseline-Passive** scenario includes fabric energy efficiency deployment at a rate of 2% of buildings per year, and energy demands such as heating continuing to operate in a passive way.
2. In the **Efficient-Smart** or **Flexible** scenario a higher rate of fabric energy efficiency rollout of 2.6% of buildings per year is assumed, and heating systems behave in a flexible way, responding to the needs of the energy system as a whole.

In addition, in the Baseline-Passive scenario it is assumed that hydrogen is produced by grid-connected electrolysers, whereas in the Smart-Efficient scenario hydrogen is produced by dedicated renewables collocated with electrolysers and grid curtailment to produce cheaper hydrogen with less impact on the overall energy system.

1.3 Case study buildings

The housing stock in Spain is made up of a large range of different buildings. To present results in this report the key building level results for consumers are presented for two typical buildings. These typical buildings are a single-family home (SFH) built before 1970 and a multi-family home (apartment, MFH) built after 1970. These buildings are chosen to illustrate the trends that consumers are expected to see, however since all buildings are different there will be some variation from the trends presented for individual buildings. Table 1 shows the characteristics of the selected dwellings.

Table 1 Details of the two key archetypes that results are presented for in this report

Feature	Archetype 1[1]	Archetype 2[2]
Picture		
Type	SFH	MFH
Age	Pre-1970	Post-1970
Assumed climate	Madrid	Madrid
Floor area (m^2)	95	91
Annual heating demand (kWh)	6.047	4.612
Annual hot water demand (kWh)	1.989	1.904

1.4 Method

An overview of the method is shown in Figure 2 below. The key steps in the modelling are:

1. The archetype stock model calculates the heat demand and final energy consumption on an annual and hourly basis for domestic dwellings in Spain. The outputs are generated at the building level and at the country-level (i.e. including all buildings). Non-domestic buildings are included in the national demand although they are addressed with less detail than the residential stock.

[1] LBM1948, CC BY-SA, via Wikimedia commons

[2] Nicolas Vigier, CC-Zero via Wikimedia Commons

2. Each residential building archetype undergoes a flexibility assessment to determine whether and how much its heating demand can be shifted to accommodate the needs of the wider electricity system.

3. The energy demands and flexibility potential of the heating system is used by the ISDM in modelling the hourly behaviour of Spain's energy system throughout 2040. The ISDM predicts the retail costs of electricity and green hydrogen. A more detailed description of the ISDM model is given below.

4. The upfront and ongoing costs of heating are calculated by the consumer cost model for the selected Spanish building archetypes.

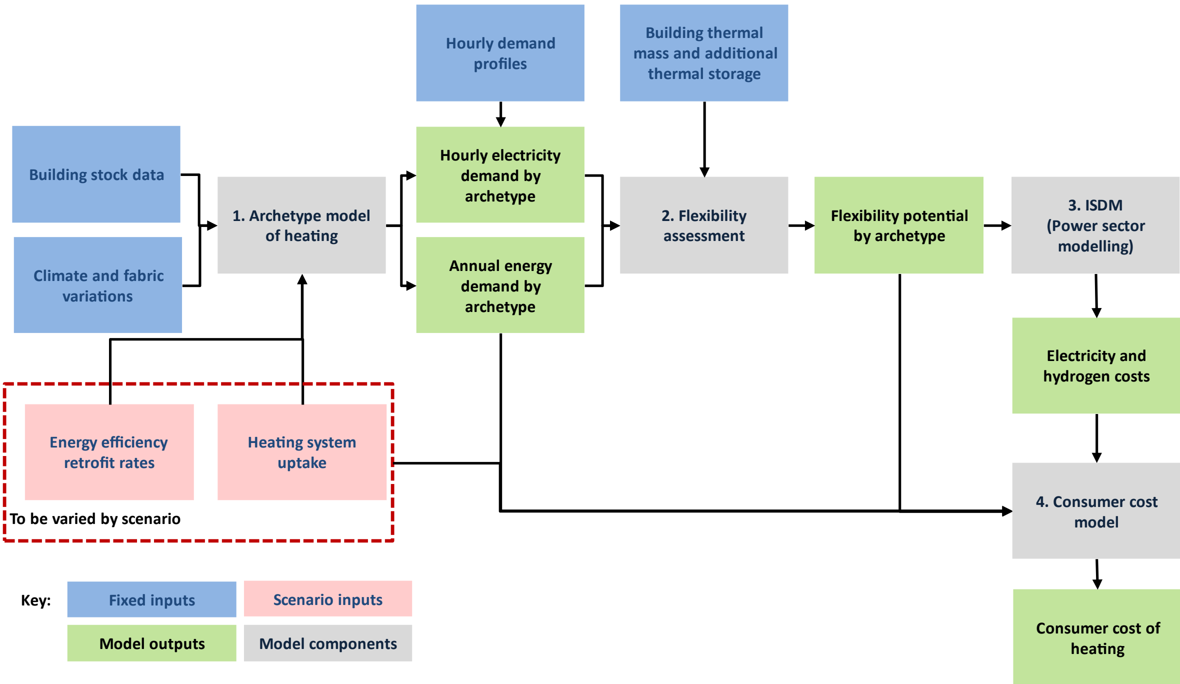

Figure 2 - Full heating system costing model flowchart

1.5 Energy system modelling

Element Energy's Integrated Supply and Demand Model (ISDM) was developed to overcome limitations of typical power system dispatch models when applied to zero carbon systems. Many such models continue to treat the power system as it currently is: highly dispatchable and reliant on thermal sources for flexibility on the supply side. Future low carbon systems, where variable renewable energy is dominant, will require flexibility on the demand side to support the integration of high levels of renewable energy, while minimising curtailment and reliance on backup thermal plant. ISDM utilises all available sources of power system flexibility in an integrated manner to determine the optimised operation of the power system.

The main principles of whole system operation are summarised here. The starting point for the modelling is a set of hourly energy demand profiles for each sector. Some demand profiles are fixed (no flexibility), while others are able to be shifted over defined periods. For heating, these demands are based on the building heat loss, heating technology and outside air temperatures. Transport demand is based on the stock of electric vehicles, their efficiency, the daily usage, and arrival/departure times from home and work to generate baseline electrified transport demand. Grid-responsive smart charging can schedule charging to times of most use to the grid, while still providing vehicles with sufficient charge for transport. Flexibility provided by thermal storage and thermal mass of buildings allows heat demand to move demand to times most useful to the grid, without reducing thermal comfort in homes and offices.

Hourly weather data is also used to generate hourly load factors for wind and solar production. Using the assumptions on the installed VRES generation capacity, the model calculates the hourly VRES generation. By subtracting this from the demand profiles, initial net load curves are generated. Demand shifting, as enabled through smart EV charging and smart heating is deployed to minimise the peak system demand and therefore the required network capacity. Further demand shifting is then applied to reduce curtailment of renewables and fossil fuel use, by moving demand from hours of high to hours of low net demand. By reducing the peak net demand, demand shifting leads to a decreased requirement for dispatchable generation capacity.

The dispatchable generation fleet is then deployed in merit order to fill in the supply gap. Once all hourly demand is met, annual system performance metrics are evaluated, among them fuel and carbon cost, variable OPEX, VRES curtailment, peak demand (for determining the required network capacity), and peak net demand (for determining the required dispatchable generation capacity).

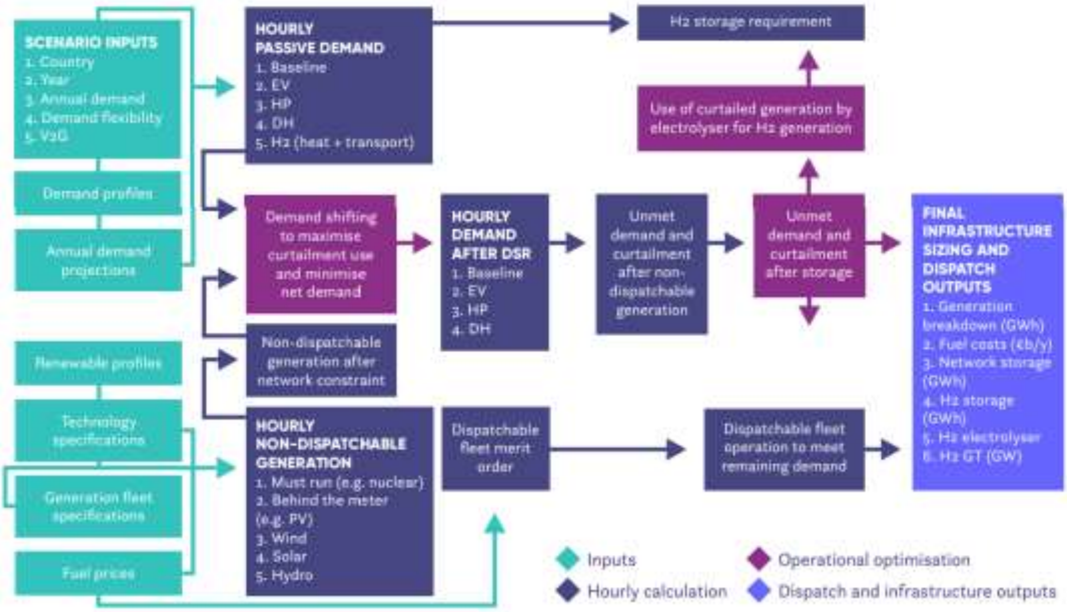

Figure 3 – Schematic of the calculation within the ISDM

1.6 Costing hydrogen for consumers

The cost of producing green hydrogen produced from electricity with electricity was modelled in this project. In the baseline case, it was assumed that the electrolysers were connected to the electricity grid, and pay a wholesale price (excluding grid fees) for their electricity. The cost of hydrogen distribution and storage was then calculated based on a parameterised model of the gas grid and costs of converting the low-pressure distribution grid to hydrogen. The costs of hydrogen production and transmission used were taken from the BEIS hydrogen supply chain evidence base[3]. In the flexible case it was assumed that hydrogen production would not be connected to the electricity grid. Hydrogen production electrolysers and renewable generation were assumed to be collocated and the production of hydrogen was found on an hourly basis to optimise the relative generation and electrolyser capacities for the cheapest hydrogen cost. Country specific renewable generation profiles were calculated from NASA MERRA-2 data, and the cost of renewable generation was found from the BEIS 2020 cost of generation report[4]. In addition to this the curtailed electricity produced from renewable generation for the rest of the electricity system was also used to produce hydrogen in the flexible case at 0 cost for the electricity. The costs of hydrogen in the Baseline and Flexible scenarios for the high hydrogen scenario are shown in Figure 4. Both wind and solar generation to produce hydrogen were considered, but in Spain solar was the cheapest way to produce hydrogen and this was used for the purpose of costing production in the flexible case. To find the cost per MWh the capex of generation and electrolysers was annualised over the expected lifetime of the technologies at a discount rate of 5% in the consumer cost case and a 3% discount rate in the system cost case.

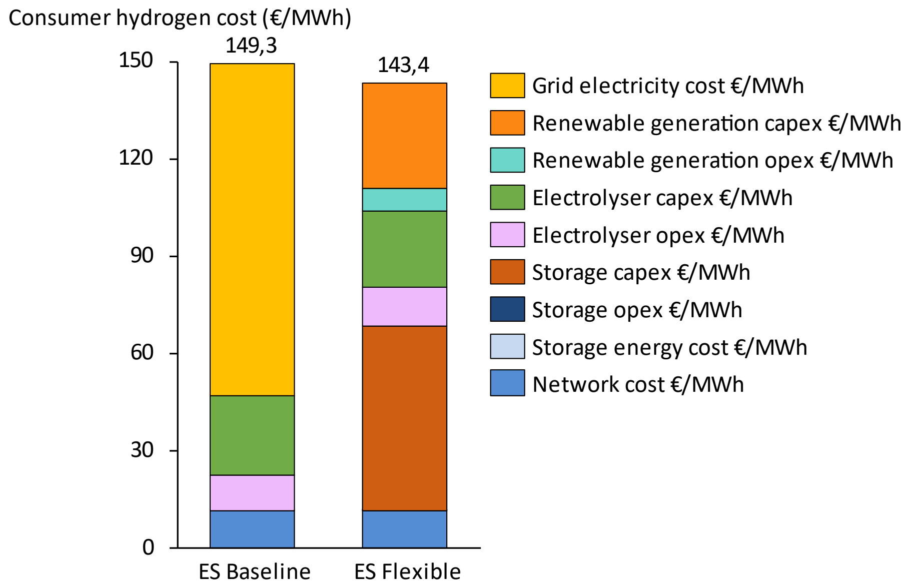

Figure 4 - Cost of hydrogen for consumers in the two cases.

3 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf
4 https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

2 Impact of ambitious energy efficiency deployment

2.1 Energy efficiency scenarios in Spain

In Spain, 2 energy efficiency rollout scenarios were analysed, one baseline scenario with rollout at the rate equivalent to existing targets and one very ambitious rollout rate combined with smart heating system operation. Energy efficiency rollout was analysed by using two packages, one shallow and one deep retrofit, these packages each contain a set of measures that reduce heating demand. The rollout rate of these packages in the different scenarios is shown in Table 2.

Table 2 - Energy efficiency rollout rates in different scenarios.

Scenario	Shallow retrofit rate per year		Deep retrofit rate per year		Total retrofit rate
	SFH	MFH	SFH	MFH	
Baseline	1.5%	1.5%	0.5%	0.5%	2%
Efficient	2.5%	1.5%	0. 5%	0.5%	2.6%

Figure 5 shows the breakdown of the 2040 housing stock in the two energy efficiency rollout scenarios in Spain. In the efficient scenario, 3% more of the stock has had an energy efficiency retrofit than in the baseline scenario.

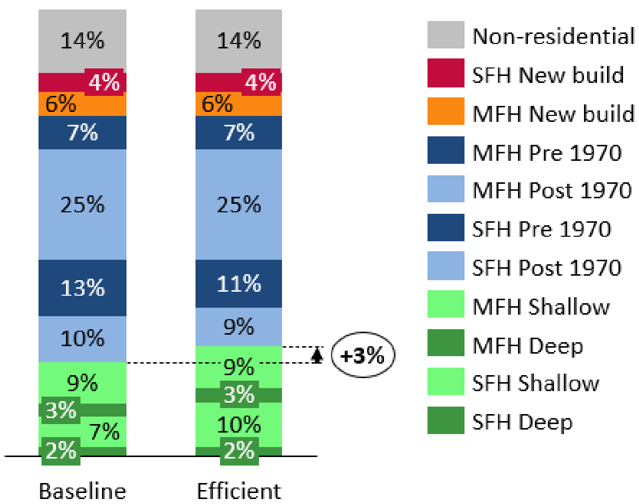

Figure 5 - 2040 housing stock in baseline and efficient scenarios.

Figure 6 shows the reduction in heating demand in typical buildings from a shallow and deep retrofit. Shallow packages reduce the heating demand by 14% in older single family homes and 13% in newer multi family homes. Deep packages give savings of 53% in the older single family homes and 52% in newer multi family homes.

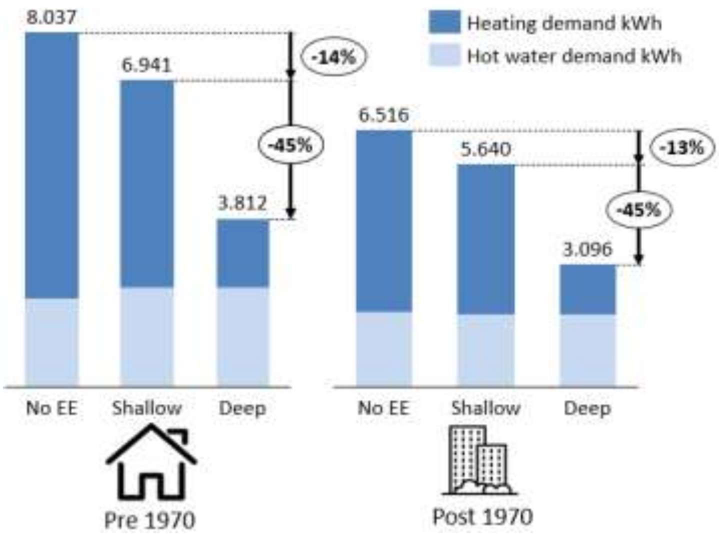

Figure 6 - Reductions in heating demand of typical buildings.

Figure 7 shows the heating demand changes between the baseline 2020 housing stock and the two 2040 scenarios. The baseline scenario has 4% less heating demand than 2020 and the efficient scenario has 1% lower heating demand than the baseline. Both of these reductions are despite the fact that 10% of the building stock in 2040 is made up of new buildings, new buildings are assumed to have heating demand similar to or lower than a building which has undergone a deep retrofit.

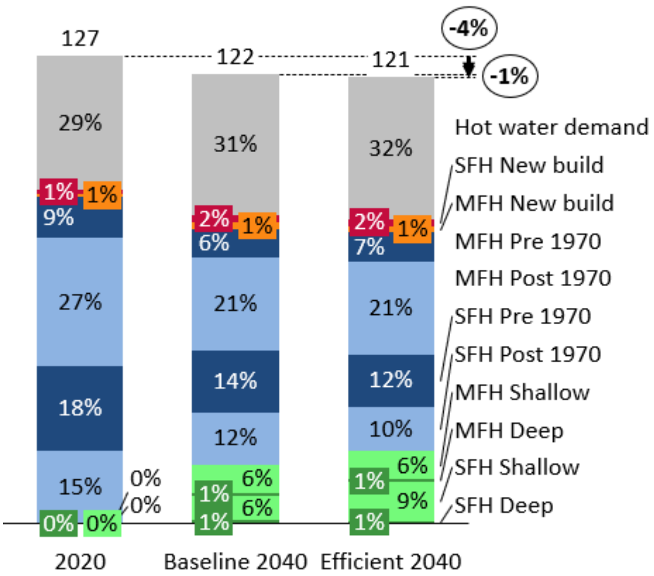

Figure 7 - Residential heating demand by scenario, in TWh.

Figure 8 shows the building level heating cost in € per year for the two key archetypes with different energy efficiency packages installed. This shows that despite the fuel cost savings from improved energy efficiency, the high additional annualised capex of energy efficiency installation in both large single family homes and smaller multi family homes result in a net increase in total heating system cost. However, consumers who do install energy efficiency measures despite their high capital cost will see lower fuel bills.

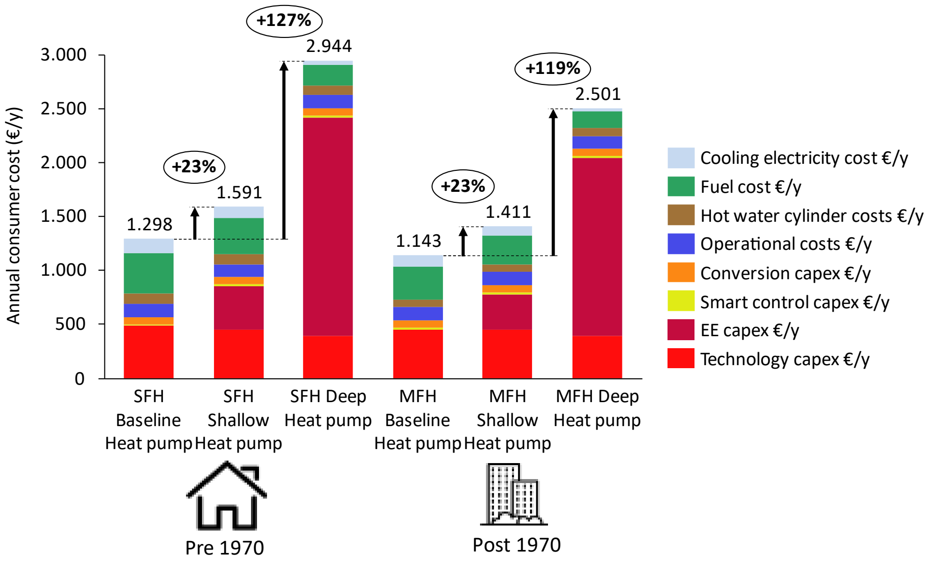

Figure 8 - Building level costs (€/y) and impact of energy efficiency in typical archetypes.

Figure 9 presents the same annual consumer cost of heat with the addition of a public subsidy for energy efficiency, in the form of a 50% grant or rebate to defray the initial capital costs. With this support, the annual cost impact of a shallow retrofit is reduced to less than 10% of the total annual cost. The annual cost impact of a deep retrofit is significantly reduced but is still close to 60% of the annual cost of heating before retrofit.

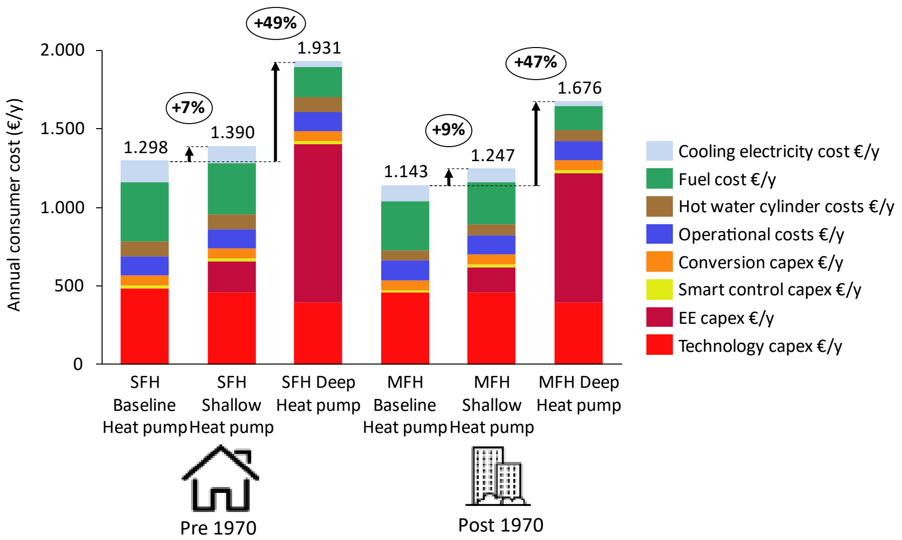

Figure 9 - Building level costs (€/y) and impact of energy efficiency in typical archetypes, with a 50% public subsidy supporting energy efficiency improvements.

Although energy efficiency measures may not be cost effective at an individual building level, the installation of these efficiency measures brings about cost savings to the entire energy system. These savings depend on the type of renewable heating system deployed but are likely to be at least €0.7 bn per year; the exact figures are shown in Figure 10. It is important to note that for the system to realise the full savings from energy efficiency rollout, policy support will be required to remove the significant upfront cost of energy efficiency from households such that they are incentivized to invest in reducing their dwelling's heating demand.

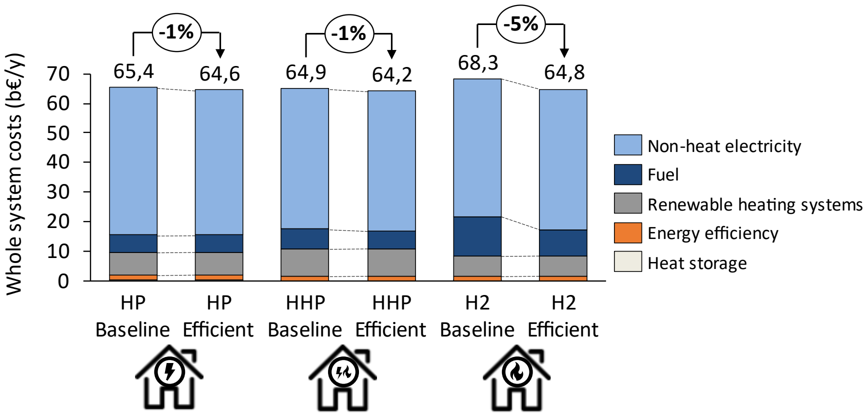

Figure 10 - The system cost saving from the efficient scenario.

Energy efficiency upgrades require significant capital outlay depending on the size and age of the home and the level of retrofit. Figure 11 shows the upfront cost of energy efficiency retrofit in the two typical archetypes. The total annual expenditure on energy efficiency measures would be €1.5bn in the baseline scenario, and €1.6bn in the efficient scenario.

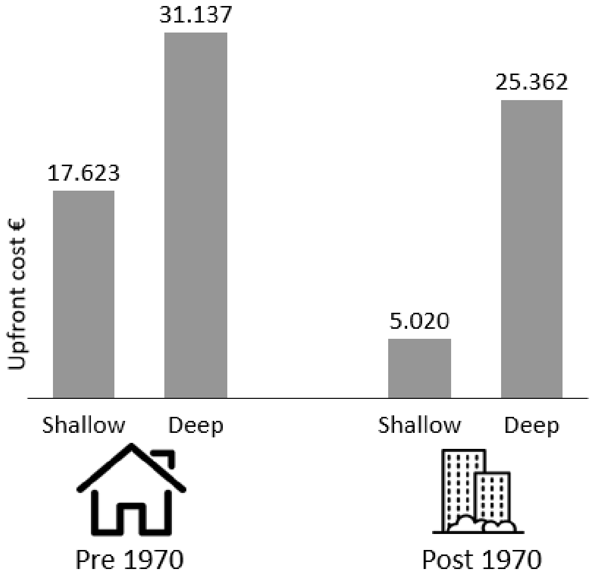

Figure 11 - Upfront cost of energy efficiency packages.

3 Consumer costs of low carbon heating options in 2040

The cost of heating systems to consumers has two parts. There is an upfront capital cost (capex) that is incurred when the heating system is replaced and there is an ongoing cost of fuel and maintenance. This section shows the total cost of heating made up of both of those components, and then looks at each component individually.

3.1 Total cost of heating for consumers

The total cost of heating for consumers is found by summing the annualised capital cost, at a 5% discount rate with a 15-year technology lifetime, with the annual operating cost. This represents the total cost for a consumer in each year of heating their dwelling with that technology. This comparison shows that heating dwellings with heat pumps is the cheapest option for consumers in both key archetypes. A high rollout of hydrogen boilers relative to a rollout of heat pumps could leave consumers paying 1.6x more for their heat.

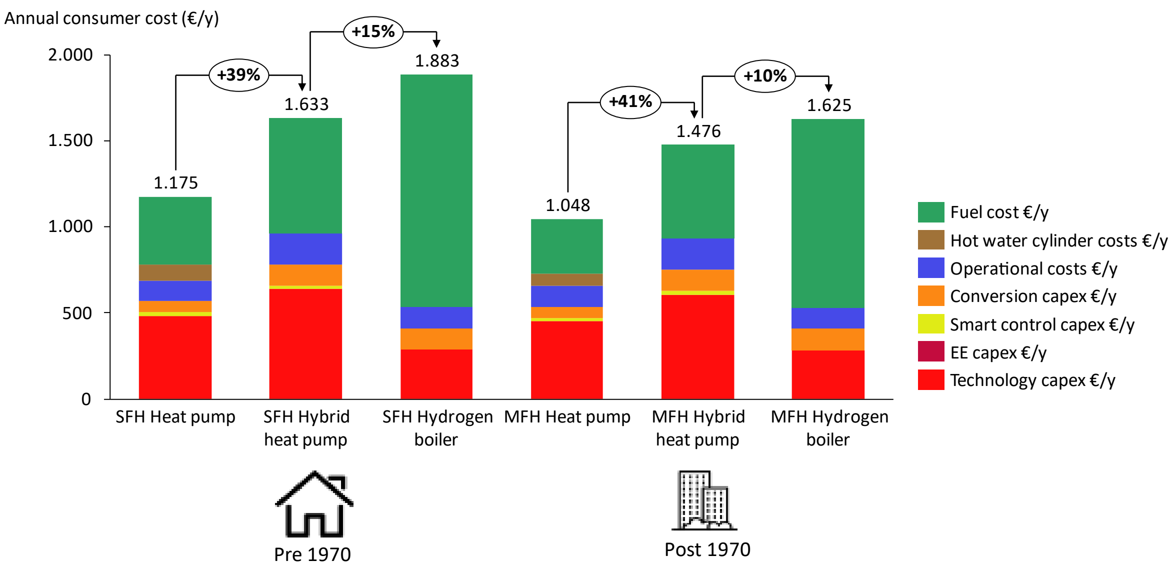

Figure 12 - Annual consumer cost of heat with the main technology in each scenario.

In buildings which adopt a shallow retrofit, heat pumps are significantly more cost-effective than hybrid heat pumps and hydrogen boilers. The cost difference between heat pumps and hydrogen boilers is lower in the deep retrofit scenario, but heat pumps remain the most cost-effective solution, as shown by Figure 13 and Figure 14. Since the cheapest overall option, heat pumps, come at a significant upfront cost premium to hydrogen boilers and counterfactual heating technologies, it is important that government provides adequate support to consumers to switch their heating through incentives and financial products that address these high upfront costs in order for consumers to achieve the possible savings.

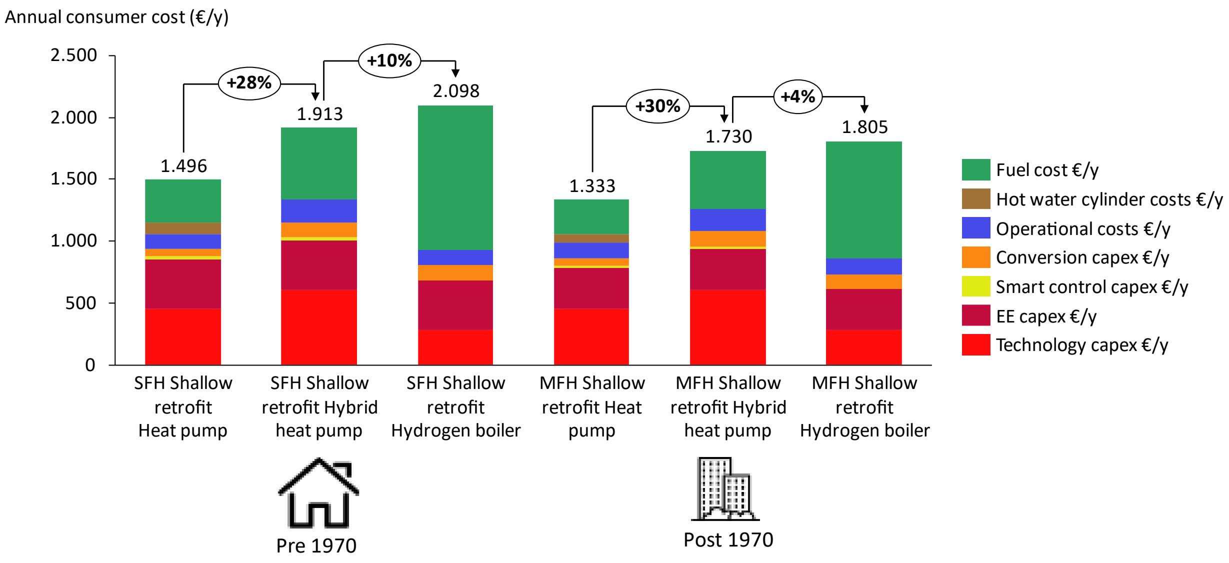

Figure 13 - Annual consumer cost of heat with the main technology in each scenario - Shallow Retrofit

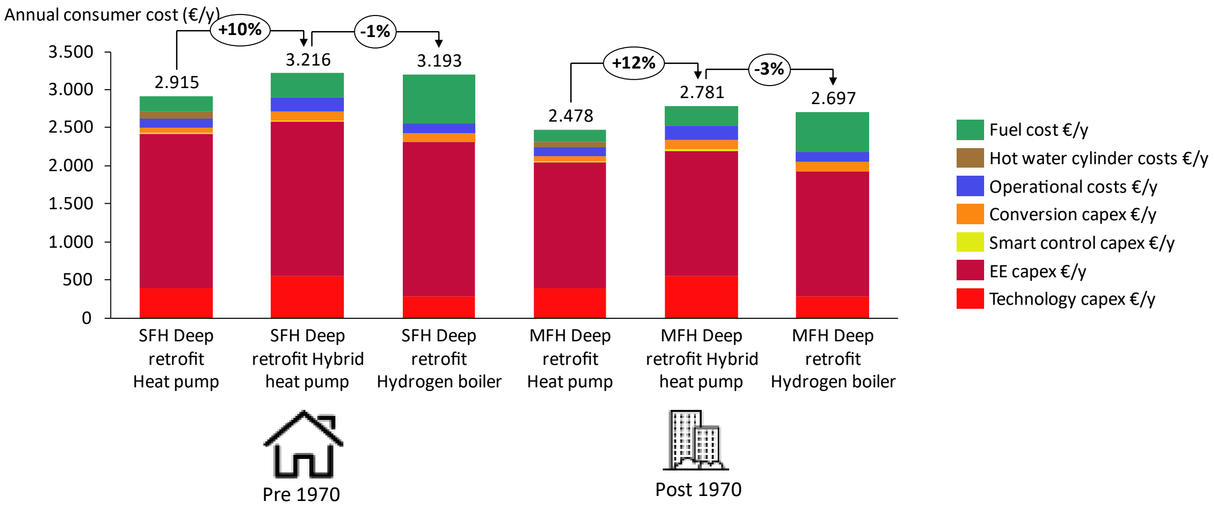

Figure 14 - Annual consumer cost of heat with the main technology in each scenario - Deep Retrofit

3.2 Ongoing costs of heating systems

Fuel costs are found from electricity system modelling based on the uptake of heating systems and energy efficiency for that scenario. The technologies considered here have different efficiencies of producing heat from their fuel, heat pumps can operate at 280% efficiency, whereas hydrogen boilers are 85% efficient. Since hydrogen is produced from electricity via electrolysis using hydrogen boilers to produce heat typically uses 4.5x as much primary electricity as producing the heat with a heat pump. Due to this the operational costs of hydrogen systems can be 3x as large as those of heat pump systems. This means although hydrogen can be cheaper than electricity per kWh the additional consumption outweighs this. Hydrogen is also likely to be significantly more expensive than gas is today for consumers. Figure 15 shows the annual running costs for the different heating systems in the two main archetypes.

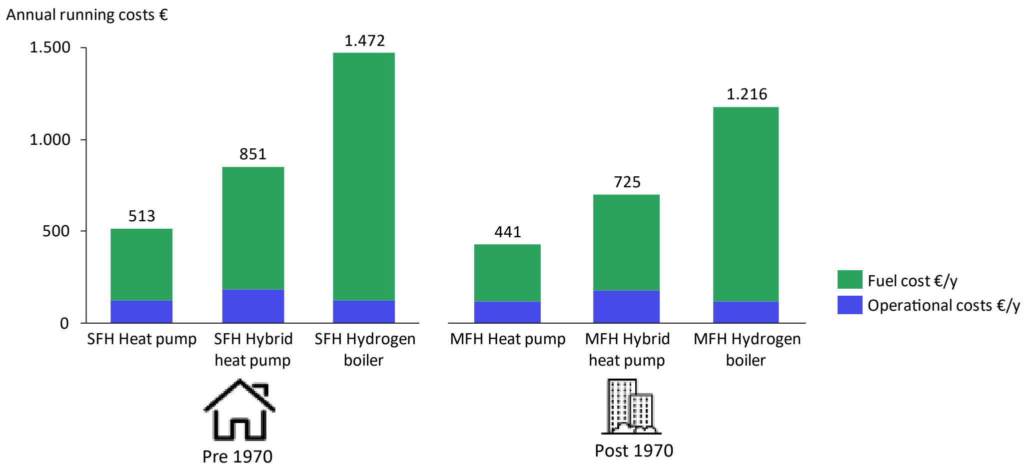

Figure 15 - Annual running costs of different heating systems.

3.3 Capital cost of heating systems

Capital costs are found from the element energy database of heating system costs and include the cost of the heating system as well as the cost of hot water cylinders and smart controllers where appropriate. Hydrogen boilers have the lowest capital cost of the heating systems considered; hybrid heat pumps have the highest capital cost.

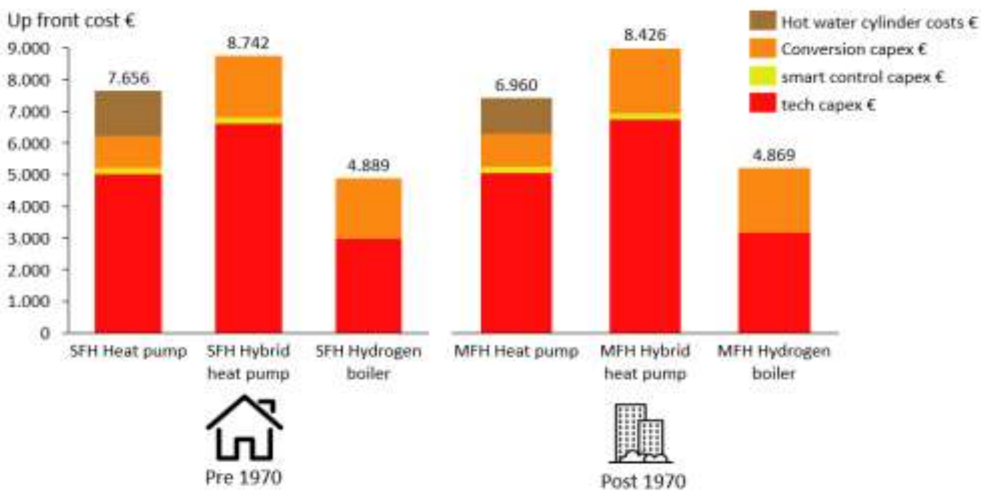

Figure 16 - Capital costs of different heating systems for typical archetypes.

4 Benefit from smart and responsive low carbon heating

Two system operation scenarios are presented in this study, the **Baseline-Passive** scenario involves passive operation of the energy system to meet demand, and the **Efficient-Smart** or **Flexible** scenario involves a higher rate of energy efficiency and operation of the energy system in a flexible way such that demand is changed to better match supply of power. Each of these two scenarios has been run with the three different technology deployment levels, so in each case the impact of smart system operation can be quantified. In all scenarios smart operation of electric vehicle charging is assumed.

4.1 Energy system benefit of smart operation

When heat pumps are operated in a smart way, they act to move demand away from the peak, this is achieved by pre heating houses with high thermal mass relative to their heat loss rate, or by storing thermal energy in a phase change heat battery. We assume that by 2040, 50% of buildings with heat pumps that cannot be flexible through their thermal mass purchase a thermal battery.

When heating is operated flexibly, the total demand for heating is unchanged, but the profile of electricity use is less "peaky". The lower peaks mean that the total required capacity of electricity generation can be lower and less upgrade to higher capacity electricity networks is required, reducing the cost of the electricity system. In addition to the peak reduction, flexibility also allows demand to be better matched to when there is high generation of renewable technologies, this means those technologies with zero marginal cost have higher load factors and less thermal generation is required decreasing the system cost. Figure 17 shows the nationwide electricity demand over a typical winter week in 2040 in the scenario with high uptake of heat pumps. Under smart operation, heat demand is removed away from the peak, increasing demand at other times of day. This decreases the peak system demand and means less network capacity is required. In addition, heat demand can be moved into times where variable renewable electricity is available, reducing both the cost of electricity production and its carbon content. The model first moves demand that is flexible based on thermal mass, and then moves the demand that is flexible based on installing additional thermal storage, Figure 17 shows the change in the demand profile after the thermal mass flexibility and thermal storage are applied, the majority of flexibility comes from additional thermal storage.

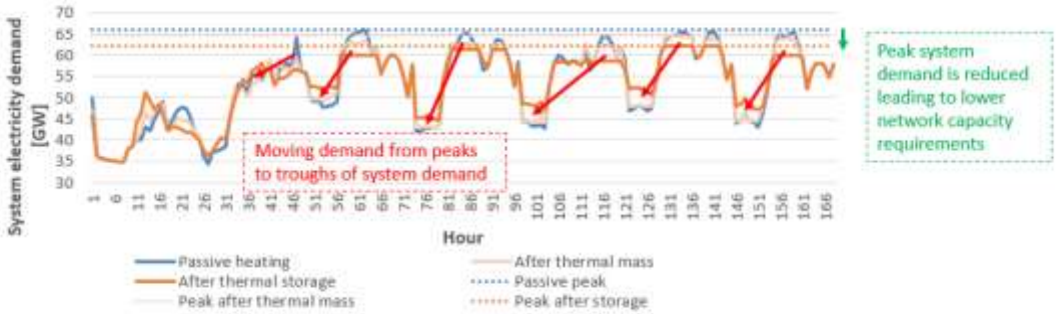

Figure 17 - Example of total electricity demand in Spain under the heat pump scenario with passive and smart heating system operation.

District heating also provides flexibility to the system through use of larger-scale thermal storage (typically in the form of stored hot water). This allows the peaks and troughs of heating demand from buildings on a district heat network to be mitigated locally so the loads on the wider energy system are minimised. In the flexible case hydrogen is considered to be produced by collocated renewables and curtailment so does not impact the wider electricity system relative to the baseline scenario where it is produced by grid connected electrolysers.

4.2 Costs and savings of flexibility for consumers

The total cost of the energy system, and therefore the energy costs faced by consumers, is reduced when heating systems are operated flexibly. The level of savings seen by different types of consumers will depend on the policies, tariff design, incentives for flexibility, taxation systems and market structures created to enable and incentivise smart operation of domestic heating. The cost savings may be passed on to the consumers that provide flexibility services, or they may be socialised across all electricity consumption. In practice, a mix of these two options is likely. While consumers may be incentivised to participate in DSR through Time-of-use electricity tariffs or through regular discounts on bills, these incentives may be less than the total system cost savings.

Older single family homes have several routes to providing system flexibility: they may install a shallow or deep retrofit to reduce heat losses and allow their heating system to be turned off at times of peak demand, or they may purchase a heat battery allowing flexible use of the heating system despite higher building heat losses. More modern flats have the same options, but have sufficient levels of energy efficiency in their current state to already allow flexible operation.

The range of different annual heating costs that could be seen by consumers in the smart and flexible heat pump scenario relative to the baseline passive scenario is shown in Figure 18. The dashed bars show the range of different fuel costs that consumers might pay in different circumstances. If the benefits of flexibility are fully socialised, both flats and larger homes make negligible savings, less than €10/y. If savings are directed towards the households providing flexibility, large flexible households may save a further €120/y, for total savings of €125/y over the baseline case. Similarly, flexible flats may save up to €100/y. If all savings are passed along to households providing flexibility, those unable to operate flexibly will have fuel bills unchanged from the passive case.

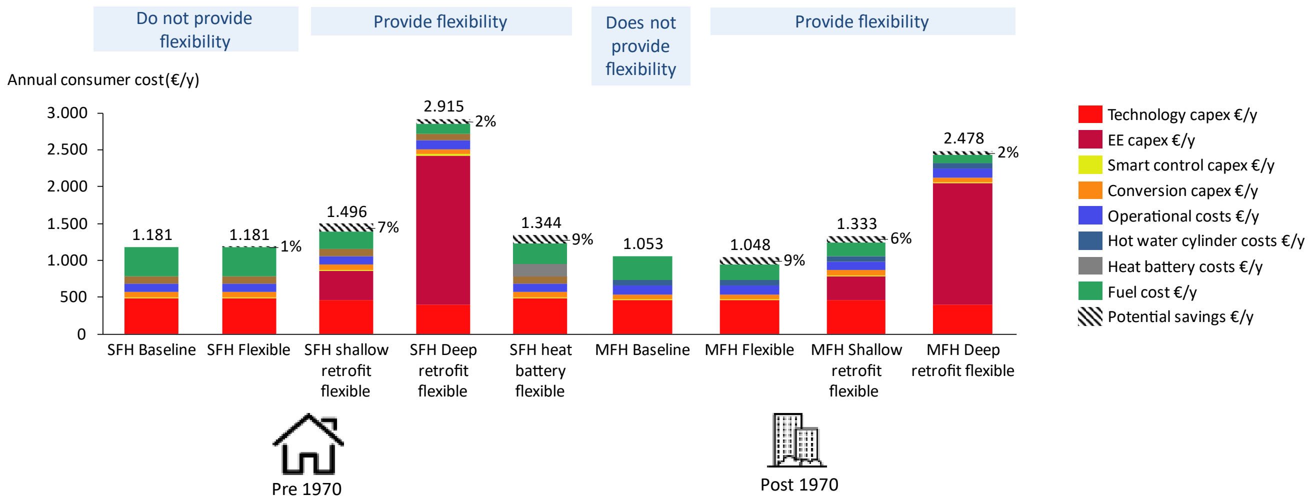

Figure 18 - The range of total consumer costs (€/y) possible in the flexible scenario.

As can be seen in Figure 18, the single family home has higher annual costs in the cases where it is enabled to operate heating flexibly, despite the potential savings mentioned above. Similarly, the multi family home has higher annual costs after investing in shallow or deep retrofit. It is therefore likely that policy support will be needed so consumers providing system flexibility do not pay higher costs overall. These supports may take the form of grants or other subsidies for energy efficiency measures, or enhanced payments for flexibility services.

4.3 System level savings from flexibility

This section considers savings at the system level from operating heating systems in a flexible way. This includes both the upfront cost of achieving flexibility and the final fuel savings resulting from the flexibility. Figure 10 above shows the full system costs for each technology deployment scenario in both the baseline and efficient flexible cases for the lower DH uptake case. Across all scenarios the system cost is less in the flexible scenario compared to the baseline scenario. In the heat pump scenario, smart system operation reduces the total system costs about €0.8 bn/y, despite the increased outlay on energy efficiency measures and heat batteries. The efficient and flexible hybrid heat pump scenario has the lowest whole system cost in Figure 10, and is €0.4 bn/y less than the efficient and flexible heat pump scenario. This is due to savings on non-heat electricity costs although the total cost of heating is higher with hybrid heat pumps than in the heat pump scenario.

Figure 19 presents the total fuel costs for the Spanish heating system in the low district heating case and for each technology scenario. The Efficient-Smart heat pump case has the lowest heating system fuel costs, followed by the Baseline-Passive heat pump and the Efficient-Smart hybrid heat pump scenarios. While the hydrogen scenario has the largest benefit from smart system operation, it nevertheless has the highest ongoing costs for heating fuel.

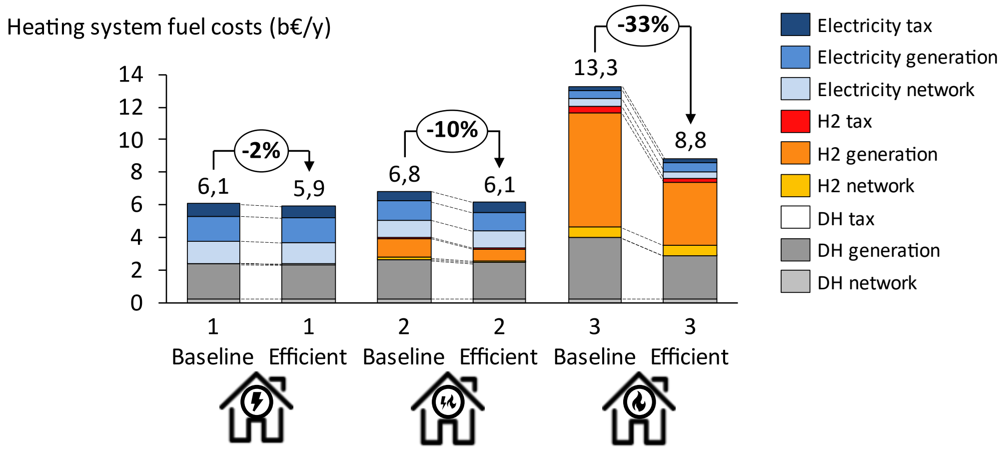

Figure 19 – Fuel cost savings from operating the electricity system in a flexible way (costs shown from system perspective).

When the energy system is operated flexibly consumers will see a difference in their fuel bill. Some of the benefits of flexibility are likely to be passed on to the consumers that provide the flexibility, but some of the benefit is also likely to be socialised across all consumers. Since there is high uncertainty around how these savings will be shared in 2040 we show a range of possible savings for each consumer based on the maximum and minimum possible savings that they could be given by the system. Figure 20 shows the range of different costs that might be given to consumers in the Efficient-Smart scenario, the first and second bars represent the range of costs that a dwelling that doesn't provide flexibility might have, and the second and third bars show the range of costs that a consumer that does provide flexibility may have. In the extreme case of the third bar, all savings from flexibility are passed on to consumers who provide flexibility, and so consumers not providing flexibility would see the baseline electricity cost shown in the left hand bar.

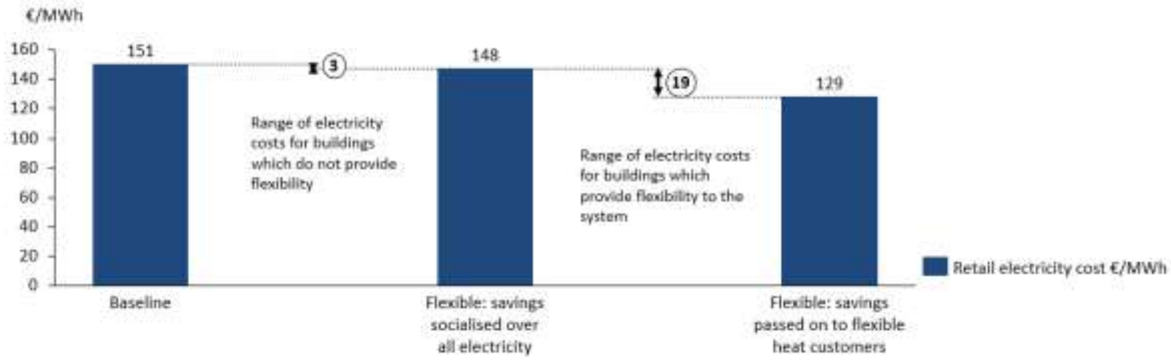

Figure 20 - The range of different fuel costs available to consumers in Spain.

5 Consumer costs of low carbon district heating

In Spain, district heating penetration is modelled as two distinct scenarios, for each heating technology scenario. This approach has been chosen because currently there is very little district heating in Spain and so we aim to assess to what extent district heating could be cost effective. In the lower penetration scenario, district heating systems reach 16% of the total stock by 2040, doubling to 32% in the higher penetration scenario by 2040, from less than 1% at present.

The heat sources used by district heating are varied with the technology scenarios (see Table 3), with the further assumption that district heating is fully decarbonised by 2040. As with individual building technologies, the deployment of hybrid heat pumps and hydrogen boilers is limited to areas with access to the gas network. Therefore there is a significant fraction of heat pumps used in district heat even when hybrid heat pumps and hydrogen are dominant.

In Spain, where the vast majority of district heating will be new construction, it is important that low carbon heating technologies are installed initially. While this may increase the capital cost of district heating in the short term, costs will be avoided in the longer term by avoiding the need to replace thermal plant in future to comply with Spanish and EU carbon targets. Although not modelled explicitly in this study, waste heat can be used as a cost-effective heat source for heat networks and should be considered where available.

Table 3 – Heat sources assumed for district heat in each technology scenario.

Scenario	Heat pump scenario		Hybrid heat pump scenario		Hydrogen scenario	
District heat penetration	Low	High	Low	High	Low	High
Heat pumps	87%	83%	27%	27%	33%	28%
Hybrid heat pumps	-	-	56%	56%	-	-
Hydrogen boilers	-	-	-	-	53%	53%
Other low carbon systems (biomass, waste heat)	13%	17%	17%	17%	14%	19%

While decarbonising district heating will bring benefits in terms of lower carbon emissions, it is important that adequate regulation is put in place to protect consumers on district heating networks. Because district heating is inherently a monopoly supply, consumers are at higher risk of high costs and poorly performing systems, and relatively less recourse to address these issues.

5.1 Cost of district heating networks for consumers

Figure 21 compares the consumer costs of district heating with the cost of heating using technologies installed in individual buildings. Technology capex in Figure 21 refers to the heat interface unit (HIU) and heat meter installed in individual dwellings. The district heating plant and network costs are included in the fuel cost seen by the consumer. In the high heat pump case, district heat is cost-competitive with building-level heating systems. In the hybrid heat pump and hydrogen scenarios, district heating systems offer consumers between 12%

and 16% savings relative to building-level heating. This is partly due to economies of scale when purchasing larger heating plant for use in many dwellings, and partly due to the mix of heating technologies used in district heat (see Table 3). Some heat pumps are included in heat networks which are not connected to the gas network. These have a lower operating costs which brings down the average cost of district heat.

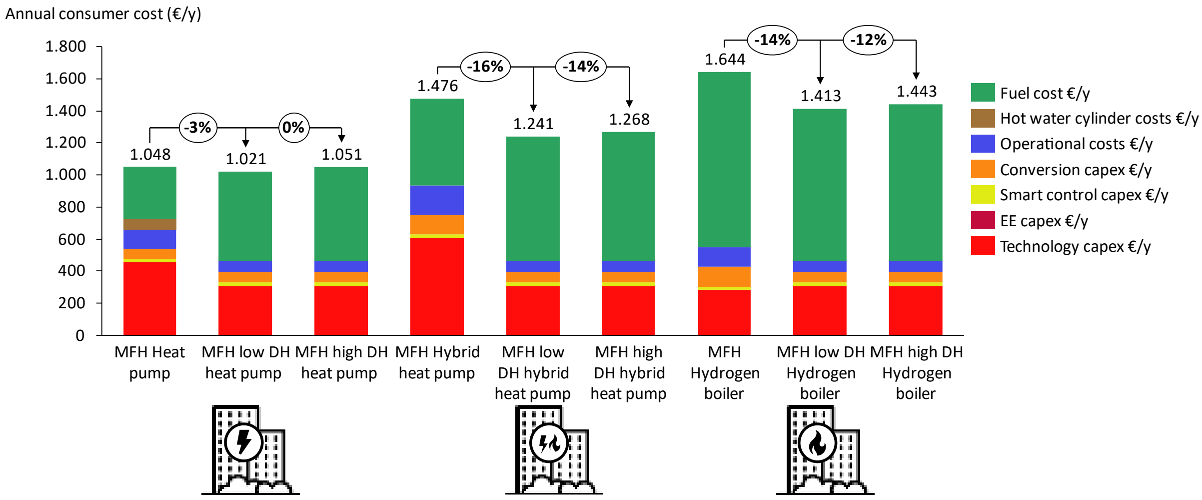

Figure 21 - District heating and building level technology cost for consumers, district heating plant and network costs are included in the fuel cost.

District heating networks are likely to have similar or lower costs for consumers compared to the building level technology in each scenario. This is true in both the high and low district heat scenarios, as shown above. However, the cost of any heat network is highly dependent on the local area in which it is installed and so drawing exact comparisons between district heating and building level technologies is difficult.

The costs of district heating heat for the average consumer are 2-3% higher in the higher penetration scenario than in the lower penetration scenario. This is because district heating is assumed to be installed first where it is most cost effective. These are areas where heat demand is the most dense and relatively less investment in network infrastructure is required to deliver a given volume of heat. The cost of heat network infrastructure is based on the Heat Roadmap Spain[5]. As district heat expands into areas with less dense heat demand, the additional district heating installations are somewhat more costly, and hence increase the average cost of district heating. However the increased cost of network infrastructure investment is less than the savings made from switching away from hybrid heat pumps and hydrogen boilers, as can be seen in Figure 21.

This analysis indicates that heat networks are likely to be a good option for consumers, particularly where they can be designed from the beginning with low carbon heating technologies. District heat networks can offer a cost-effective way for individual dwellings to adopt low carbon heating and can provide cost-effective system flexibility, notably for homes

[5] Heat Roadmap Spain, part of the Heat Roadmap Europe 2050 project, Aalborg University, 2018, https://vbn.aau.dk/ws/portalfiles/portal/287932746/Country_Roadmap_Spain_20181005.pdf.

where installing a shallow or deep retrofit to allow flexible operation does not lead to cost savings.

5.2 System cost for high and low district heating penetration

The total system costs are compared for the low and high district heat uptake cases in Figure 22. The change in costs with higher district heat uptake is very marginal, with a small savings seen in the heat pump and hydrogen cases and a small cost increase in hybrid heat pump case. The annual cost difference is between -€ 0.1bn/y and +€0.3bn/y in 2040.

These results stand in contrast to those in Figure 21 which indicate that consumers could save around 15% of their annual costs by switching from hybrid heat pumps and hydrogen boilers to district heating. This difference arises due to the mix of heating systems that are being converted to district heating in each scenario, shown in Figure 1 above. In the hybrid heat pump scenarios for example, a mix of hybrid heat pumps, heat pumps, and electric resistive heating systems are replaced with district heating. In this scenario, consumers using heat pumps have lower annualised heating costs than those on district heat. While the households switching from hybrid heat pumps see savings, these are approximately offset by the increased costs for consumers moving from heat pumps to district heat within the hybrid heat pump scenario. Hence the net effect is marginal as shown in Figure 22.

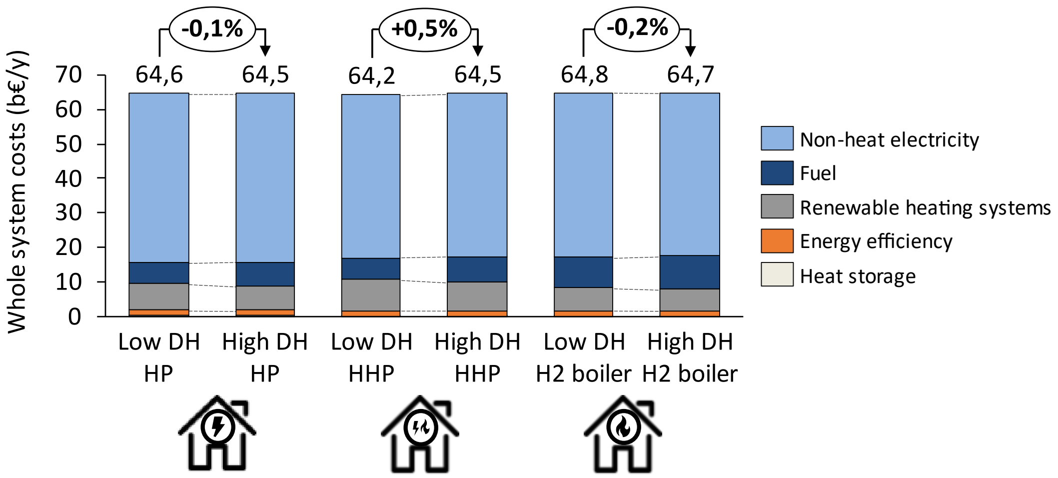

Figure 22 - Whole system costs comparison between low and high district heat uptake

The above results indicate that there is significant potential for cost-effective district heating deployment in Spain. As shown, average consumer costs can be competitive with other heating systems even at ambitious levels of deployment. Ultimately, decisions on whether and how much to invest in district heat networks are likely to depend on where national or regional priorities lie and the preferred strategy for decarbonisation. Implementing district heat requires large investments in the network infrastructure and central plant, but reduces the need for many hundreds or thousands of individual decisions by households to change their heating system. Depending on the local context, cities and towns with dense heat demand may find decarbonising buildings through district heat to be more practically achievable than through other means.

6 Conclusion

As in most European countries, fossil fuels play a significant role in domestic heating and in electricity generation in Spain today. Across the economy, electricity and heating contribute about 16% of Spain's carbon emissions[6]. Recent steps to reduce emissions include an increased target of 26% reduction in carbon emissions by 2030 compared to 2005, which will need to be supported by sector-specific policy supporting the energy transition. Roughly 60% of homes in Spain are heated with fossil fuels, including almost 20% heated with oil[7]. By 2040, a significant shift towards renewable heating sources will be required to fulfil Spain and EU's commitments towards net zero emissions in 2050.

Electric heating and green hydrogen are the primary options for widespread decarbonisation of domestic heating, while there are a range of other options likely to play smaller roles. The analysis presented above indicates that electrification of heat via heat pumps is likely to be the most affordable for consumers in the long run. Although heat pumps have a higher upfront cost than hydrogen boilers, the high running costs of hydrogen boilers result in a lifetime cost of heat approximately 60% higher than that offered by heat pumps. Policy support in the form of grants or low cost loans enabling consumers to cover the initial capital cost of heat pumps will result in significant savings across the energy system.

District heating can be cost competitive with other low carbon heating technologies, this study modelled a significant expansion in district heating supply in Spain. The results suggested that with ambitious and very ambitious rollout targets of 16% and 32% of total heating demand the costs of district heating networks would be similar to that of individual heating systems. This means that an expansion in district heating in Spain will have significant benefits for decarbonisation. Implementation of district heating can lead to lower in-home disruption and more rapid decarbonisation, although care will need to be taken to ensure consumers are protected and receive fair prices and reliable heat supply.

Building fabric efficiency is a key enabler of a smart, cost effective energy system in future. As shown above, energy efficiency retrofits in Spain could reduce demand for heating by 5% (6 TWh) by 2040 relative to today. Raising the ambition for energy efficiency deployment beyond 2% of dwellings per year could contributes to system-wide savings of €0.8bn despite the additional expenditure of €0.1bn on efficiency measures. This means that for every €1 spent on additional energy efficiency €8 are saved by the system; smart operation of heating and the electricity system are required to realise this savings. However, insufficient fuel bill savings from flexibility and energy efficiency will mean a net increase in expenditure for individual households, so financial incentives that support energy efficiency adoption are essential to realise the system-wide savings. Smart and responsive operation of heating systems could reduce electricity costs by €3 to €20 per MWh. Households providing flexibility services may see yearly savings of between €100/year and €125/year, depending on home size and energy demand, if appropriate rewards for flexible operation of heating systems are in place.

[6] EU Parliament Briefing, Climate Action in Spain, 2021, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/690579/EPRS_BRI(2021)690579_EN.pdf
[7] EntraNZE European Buildings database, https://www.entranze.eu/pub/pub-data

elementenergy

The Consumer Costs of Decarbonised Heat

Technical Annex

for

BEUC

February 2022

Element Energy Limited
Suite 1, Bishop Bateman Court
Thompson's Lane
Cambridge
CB5 8AQ

Tel: 01223 852499

Contents

Authors

For comments or queries please contact:
Sam.Foster@element-energy.co.uk
Fiona.Hughes@element-energy.co.uk
Joachim.Dias@element-energy.co.uk
+44 (1223) 852 499

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Acronyms

CZ	Czechia
DH	District heat
DSR	Demand side response
EE	Energy efficiency
ES	Spain
H2	Hydrogen
HP	Heat pump
HHP	Hybrid heat pump
kWh	kilo Watt hours
ISDM	Element Energy's Integrated system dispatch model
IT	Italy
MFH	Multi family home
MWh	Mega Watt hours
PL	Poland
SFH	Single family home

1 Introduction

This document is the technical annex to the following reports prepared by Element Energy for BEUC:

- The Consumer Costs of Decarbonised Heat in the EU Integrated report
- The Consumer Costs of Decarbonised Heat Executive summaries for Spain, Italy, Czechia, and Poland

While these reports present the findings from our modelling, this technical annex describes in more detail the methodology and the underlying assumptions used in our modelling.

2 Methodology

2.1 Creating a stock of building archetypes for each country

A building stock model for each of the countries (Spain, Italy, Czechia, and Poland) was created so that energy efficiency and heating system deployment could be analysed. This building stock model is based on the European building stock, with data collected from the Building Stock Observatory[1]. This includes data on fabric of buildings and their size and age.

As well as the existing building stock it was necessary to include rates of new building of commercial and domestic properties. These rates were assumed based on historic rates from the Eurostat database, and are given in

Table 1. These rates were applied each year between 2015 which was the base year for our building stock and 2040 which was the year in which the energy system analysis was carried out. The size and demand of new buildings was estimated from the building regulations and aligned with previous ECF studies[2].

Country	Construction rate (%)
ES	0.22%
IT	0.72%
CZ	0.69%
PL	1.03%

Table 1 – Construction rates (applied to dwellings for domestic and to buildings for non-domestic) in the four analysed countries.

Using the information about building age and fabric, and climate data gathered for the four countries it was possible to estimate the heating demand for each of the building archetypes

[1] EU Building Stock Observatory, European Commission, 2016
[2] Towards Fossil-Free Energy in 2050, Element Energy and Cambridge Econometrics for ECF

considered. This was calibrated to data on the overall fuel use of each country to ensure consistency between different data sources.

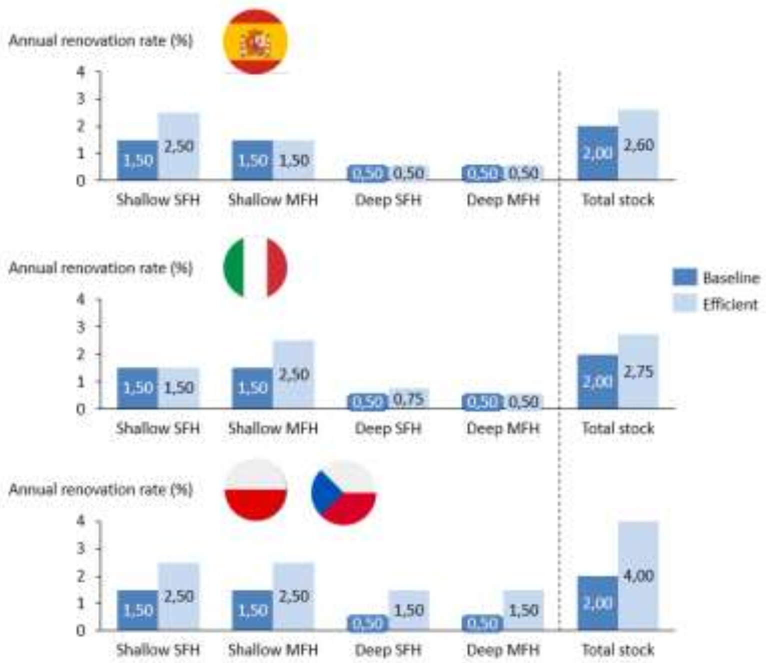
2.2 Creating energy efficiency deployment scenarios and savings

The energy savings possible in each building type in the building stock were estimated using data from the ZEBRA2020 cost assessment and performance report[3]. This report gave data on the costs per square meter and relative heating demand savings of different levels of retrofit on buildings in the EU. This data for four levels of retrofit was combined with our building stock database to create two levels of retrofit per country, where the costs depended on the initial state of the building given by its age, described in

Table 7. These energy efficiency retrofit levels were called shallow and deep.

In Italy the costs for deep retrofit in the ZEBRA2020 report were very high. Therefore, costs for "total upgrade" from the 2020 annual report on energy efficiency[4] were used instead for the deep retrofit cost, as these costs were more in line with the data from the other countries.

Two energy efficiency deployment scenarios were created for each country, one "Baseline-Passive" which represented the European commission's current goal of 2% retrofit per year, and a higher ambition, "Efficient-Smart" scenario. In the warmer countries analysed (ES and IT) it was found that higher levels of ambition were expensive relative to other components of the system and so in those countries additional retrofit was focused on buildings where this would enable them to provide system flexibility. The split between shallow and deep retrofits was assumed based on a review of relevant literature[5] [6] [7], these splits are shown in Figure 1.



[3] ZEBRA2020: nearly zero-energy building strategy 2020
[4] 2020 Annual report on energy efficiency from the ministry of economic development
[5] Energy Efficiency Directive, Article 7
[6] On the way to a climate-neutral Europe – Contributions from the building sector, BPIE, 2020
[7] Renovation Wave for Europe, European Commission, 2020

Figure 1 – Annual renovation rates in the four countries considered. SFH is Single family home, MFH is multi family home.

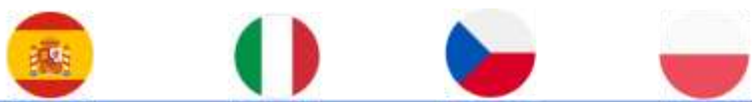
2.3 Creating heating system uptake scenarios

Each of the four countries analysed has a different distributions of existing heating systems and since not all of these systems will be replaced by low carbon alternatives by 2040 it was necessary to produce bespoke heating system uptake scenarios for each country.

There were three scenarios created in each country: a high heat pump, a high hydrogen, and a hybrid scenario. These scenarios are not designed to be projections of the heating system mix in 2040 but rather to represent plausible futures from which the relative costs of pursuing different technology mixes can be assessed. The rollout of technologies was adapted from the 2050 technology rollout scenarios used in the *Towards fossil-Free energy in 2050*[8] report, with some changes to account for the different year being used, but also the more recent EU wide net zero emissions target.

It was assumed that, in line with targets for net zero emissions by 2050, residential heating would be 80% decarbonised by 2040 and district heating fully decarbonised. Existing counterfactual heating systems which are renewable e.g. direct electric or biomass boilers were kept as the same fraction of the stock. The share of hydrogen deployment was dependent on the penetration of the gas network and an assumed transition to hydrogen. That transition was assumed not complete by 2040, hence why some buildings would still be on gas boilers in 2040. In Poland it was assumed that there would be an expansion in the gas network in the high hydrogen scenario, leading to a larger share of dwellings heated by gas in 2040 relative to the baseline since it is unlikely that the network would be fully decarbonised using hydrogen by the early 2040s.

As well as this, the share of district heating in the stock was kept as the same as 2020 in 2040 in all countries except Spain. In Spain, two different district heating scenarios were modelled since the existing percentage of district heating in Spain is very low and our aim was to understand the impact of different higher district heating rollout rates in the years between now and 2040. Figure 2 summarises the rationale described above.



Heating System	Development level in each heating system specific scenario, DH across all scenarios			
Heat Pump	• 2040 deployment based on building suitability, uptake rate, and national targets			
Hybrids	• As above			
Hydrogen	• 2040 deployment based on gas network extent, shown below; • And timeline for conversion of gas network to hydrogen			
	• 35% homes	• 40% homes	• 45% homes	• ~40% homes (network expansion)
DH	• Low (16% homes) • High (32% homes)	• Similar to today (20% homes)	• Similar to today (30% homes)	• Similar to today (40% homes)

8 Towards Fossil-Free Energy in 2050, Element Energy and Cambridge Econometrics for ECF

Figure 2 – Heating system scenario definition across the four countries analysed

2.4 Finding the level of flexibility in the building stock and including additional thermal storage

Flexible operation of heating systems and other parts of the energy system enables demand to be shifted away from times where the demand for electricity is at its highest and into hours where there is comparatively lower demand, usually associated with lower fuel costs and lower carbon emissions.

There are significant differences in how flexibility operates depending on the heating system scenario modelled. The operation of flexibility has been split below into three categories to highlight how flexibility can benefit the whole energy system the most for each of the three heating systems that dominate the future scenarios

1. Heat pumps: The description shown here applies to heat pumps operation across all scenarios. There are two mechanisms for buildings to provide flexibility in the current case:
    a. The first is via the thermal mass of dwellings. This allows for pre heating of a dwelling so that no electricity needs to be used at the peak time. In our modelling, a first principles heat loss calculation was carried out to understand which archetypes in the building stock could be operated flexibly. This involved making assumptions about the construction of different archetypes such that the thermal mass could be calculated. From the thermal mass and the heat loss parameter it was possible to estimate the number of hours it would take for the dwelling to cool by more than one degree centigrade on the peak heating demand day. If this cool down time of one degree was greater than four hours, then that building was assumed to be flexible.
    b. The second is via the installation of thermal storage for space heating, this is assumed to be a heat battery, and can be charged overnight due to the lower costs of electricity at night to provide heat at peak time. In the case of additional thermal storage, there were two sizes of additional thermal storage included in the modelling, one for SFH and another for MFH. This additional storage provides 24-hour flexibility when the heating system is used.
2. Hybrid heat pumps: The flexibility offered by hybrids is also based on two mechanisms:
    a. As is the case for heat pumps, the heat pump component of hybrids can be used for pre-heating via the thermal mass of the buildings. For it, all aspects described above also apply.
    b. The second mechanism is by using the boiler component of hybrids only during the peak demand hours. This allows the heat pump component to be sized at a smaller capacity, thus reducing its capex, as well as allowing the heat pump component not to run in hours of peak demand, which coincide with hours of peak electricity costs.
3. Hydrogen boilers: The aspect of flexibility for hydrogen boilers does not actually concern the use in buildings, but rather the generation and storage of hydrogen. Green hydrogen is generated through electrolysis of water using renewable energy sources. For example, it is expected that significant photovoltaic renewable output will be available in summer months, where heating demand is at its lowest, hence leading to available electricity for producing hydrogen for storage. For on-shore and off-shore wind, the availability of resource vary less significantly on a seasonal basis but is more dependent on weather patterns. In order to benefit from this low-cost electricity and to

avoid curtailment, hydrogen can be generated through electrolysis at times where more supply than demand is available, and stored in long-term interseasonal storage sites, to then be used in when heat demand is highest and hydrogen supply from renewable generation is too low to meet the demand. This smart operation of electrolysers allows a significant reduction in costs of hydrogen fuel, which is then reflected in the consumer bills.

2.5 Power sector modelling

This section describes how the electricity retail costs have been modelled in each scenario. Retail costs are modelled as consisting of wholesale generation cost, network costs, and taxes.

2.5.1 Integrated Supply and Demand Model (ISDM) overview

Traditionally balancing demand and supply in power systems was solely the responsibility of the supply side, with thermal power plants adjusting their output according to the rises and falls of demand. In lower and eventually zero carbon power systems with high penetration of variable renewable energy sources, flexibility will also to a large extent be required on the demand side in order to ensure this balance.

Element Energy's Integrated Supply and Demand Model (ISDM) was developed to adequately represent the potential of demand side flexibility to contribute to security of supply in future power systems. It models electricity supply and demand at the national level in hourly resolution. The key principles and methods of the model are described in the main report. The following sections specify the key assumptions used in the runs of the model used to calculate electricity prices for this study.

2.5.2 Scenarios

The study considered three principal technology deployment scenarios:

- Scenario HP: high deployment of heat pumps
- Scenario HHP: high deployment of hybrid heat pumps
- Scenario H2: high deployment of hydrogen gas boilers

Two versions of each technology scenario were modelled: a Baseline-Passive version and a Smart-Flexible version. In the Baseline version, heat pumps are operating in every hour of the day to meet the demand in that hour, without any flexibility. In the Flexible version, the flexibility of thermal mass of buildings and thermal storage are utilised to shift electricity for heating out of periods of high demand and thus reduce the impact of electrified heating on electricity networks and peaking generation capacity requirements. In addition, the deployment of energy efficiency is higher in the Flexible scenario than in the Baseline scenario, which also helps to reduce network and generation capacity requirements. In all scenarios it is assumed that electric vehicles are charged smartly, by charging at home at night, and at work during the midday demand trough.

2.5.3 Electricity demand

Total electricity demand has been modelled as consisting of the three main components:

- **Baseline:** lighting, household appliances, industrial electricity demand
- **EV:** electricity demand for electric vehicles

- **Heat:** electricity demand for heat pumps and direct electric heating (i.e. resistance heaters)

Baseline electricity demand in 2040 is taken from the 2018 ENTSO-E TYNDP Distributed Generation scenario. ENTSO-E only publishes the total national electricity hourly demand profile in the TYNDP and does not provide a breakdown into the above components. The contribution of EV and Heat electricity to the overall electricity demand profile has been estimated, and then subtracted from the total demand profile, resulting in a baseline electricity demand profile which corresponds to all non-EV and non-heat electricity demand.

The Heat electricity demand profile included in the TYNDP is approximated by using Element Energy's building electricity demand model, run with the number of heat pumps specified in the TYNDP. The EV electricity demand profile included in the TYNDP is approximated using the number of EVs as specified in the TYNDP and annual consumption per EV as projected by Element Energy's proprietary model of uptake of electrified road transport, which has been used across a wide range of projects for clients including National Grid ESO[9], Greenpeace[10], Greater London Authority[11] and is also used by the British Government for modelling purposes[12]. It is assumed that the EV electricity demand is included as a flat block – i.e. constant consumption at a fixed power capacity - in the TYNDP profile as no further information on the profile could be found in the ENTSO-E TYNDP documentation.

EV electricity demand is projected using the above mentioned in house model simulating the uptake of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) as well as the annual electricity consumption of the corresponding stock at the national level. The hourly demand profile of EVs is constructed using assumptions on the plug in times of EVs across different EV segments as well as on the breakdown of total EV demand among those segments. More information on modelling the hourly profile of EV electricity consumption is provided in a subsequent section below.

Heat electricity demand is modelled using Element Energy's building electricity demand model, explained in more detail in the main report, which represents the development of the thermal insulation of the building stock in each country. Based on historical weather data and assumptions on thermal insulation across the building stock, hourly heating demand of buildings is calculated. This is then converted to hourly electricity demand profiles based on efficiency assumptions for heat pumps and direct electric heating. The heating demand profiles used in this study are based on 2007 hourly temperature data. 2007 was chosen as it is one of three years for which ENTSO-E provide corresponding total demand profiles in the TYNDP and among those three it is the most representative for the 1982-2015 period, for which ENTSO-E have sourced weather data and subsequently modelled national electricity profiles. The baseline electricity profile is also approximated (as described above) using the total TYNDP profile based on 2007 weather data.

2.5.4 Electrified transport and its flexibility potential

Transport electrification

Electrification of transport will add significant new load to the electricity system and there is great potential to make this flexible. The main reason for this is that most vehicles are stationary for most of the time. Subsequently, electric vehicles (EVs) could be plugged in at

9 Element Energy 2019
10 Element Energy 2020
11 Element Energy 2018
12 Department for Transport, 2021

charging stations at home or work for a much longer time than required to charge them. Thus, their charging could be moved into hours when it is most beneficial to the system, e.g. to times of high solar generation or low overall electricity demand. Such smart EV charging could contribute significantly to integration of variable renewable energy sources such as wind and solar.

Element Energy's in house modelling tools on EV uptake were used to develop projections of EV (BEVs and PHEVs) stock in 2040 across the modelled countries. The modelling was informed by the recent proposal of the EU COM to ban the sale of fossil fuel cars by 2035. The projected EV stock and its electricity consumption in the four modelled countries is shown in Table 2.

Table 2 – Projection of EV stock and EV electricity consumption

	ES	IT	CZ	PL
EV stock 2040 (million)	26.4	43.2	6.4	26.4
EV electricity consumption (TWh/y)	50.6	68.0	12.3	51.1

Principles of smart EV charging

The flexibility of EV charging comes from the fact that EVs are plugged in for a longer period than required for their daily charge. A typical adjustment of an EV charging profile through smart charging is illustrated in Figure 3 below.

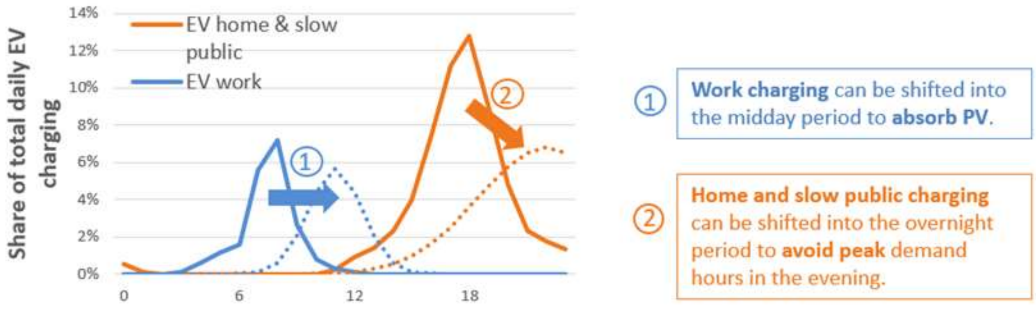


Figure 3 – Illustrative passive (solid line) vs smart (dotted line) charging of EVs at home and at work; source: Element Energy

Charging of EVs plugging-in in the morning at work can be shifted to the midday and early afternoon when PV output is high. EVs plugging-in in the evening when returning home will either charge at their own charger or slow public chargers close to their home if they do not have access to off street parking. The charging of these EVs plugging-in in the evening can be shifted to the night period to avoid increasing peak demand of the electricity system which in many countries appears in the early evening hours, and to move charging demand into the cheap hours overnight. Plug-in profiles and plug-in times set the boundaries of the flexibility of EV charging. They differ between different types of EV charging so we need to account for each. Assumptions on those are detailed further below.

Breakdown of EV charging

The type of charging is important as it determines the flexibility potential. While charging at home and work is expected to be flexible, rapid public charging will not offer flexibility. Trials have shown that slow public charging at destination, e.g. at super markets or theatres, (plug in window length 1-2h) is negligible. Slow on-street public charging in residential areas is equivalent for our modelling purposes to home charging (mostly overnight) and is modelled as flexible.

In line with EV consumer research[13], we assume that total EV electricity consumption in 2040 is broken down into 20% rapid public charging, 20% work charging, and 60% is home charging or slow public charging. We consider rapid public charging to be fast and inflexible. Rapid public charging is included in the model as an energy demand, but it is not flexible i.e. cannot be adjusted according to system need. Rapid/superchargers with buffer batteries could provide flexibility, but these are treated as grid-level storage and outside the scope of EV flexibility. Home, work and slow public chargers are assumed to have 7kW charging capacity, while rapid public chargers are assumed to have 150 kW charging capacity.

The breakdown of charging into home/work/slow and rapid public charging is the most important characteristic determining the potential and dynamics of EV DSR. It determines the energy flows into EVs which can be shifted to the midday period and the overnight period. Depending on the system characteristics (e.g. high solar penetration / low overnight demand), shifting demand to the midday or the overnight period can provide higher value.

Passive plug-in profiles and plug-in times

The starting point of the analysis are the unmanaged, or "passive" charging profiles that would be expected without smart charging. Plug-in profiles at home and work as well as at rapid public chargers are based on the recent evidence from an exhaustive literature review on EV usage profiles conducted for UKPN[14].

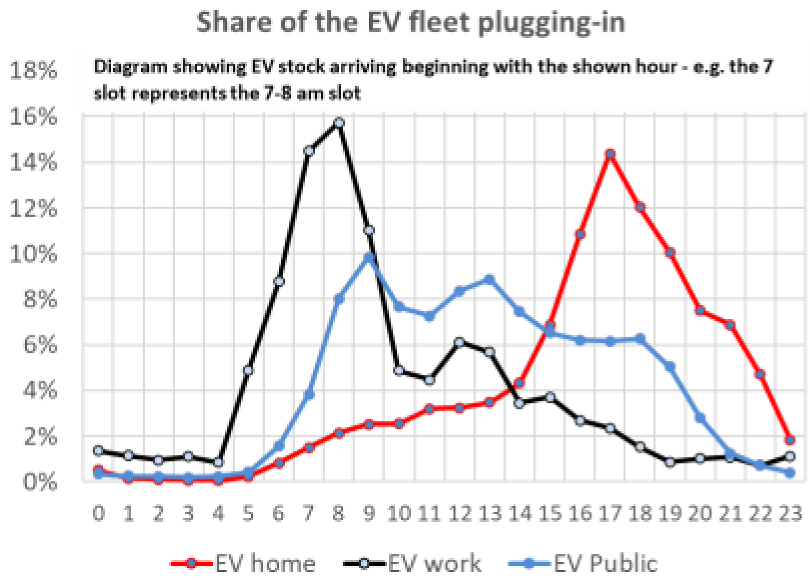


Figure 4 – EV plug in profiles at home, work and public chargers as reported in a recent literature review

While there is some seasonality to charging demand, daily electricity consumption of EVs is held constant throughout the year for the purpose of this modelling work. The passive EV

13 Electric vehicles in Europe: Gearing up for a new phase?
14 UKPN Charger Use Study

charging profile, including inflexible rapid charging, based on the assumed plug-in profiles and charger capacities is shown Figure 5 below.

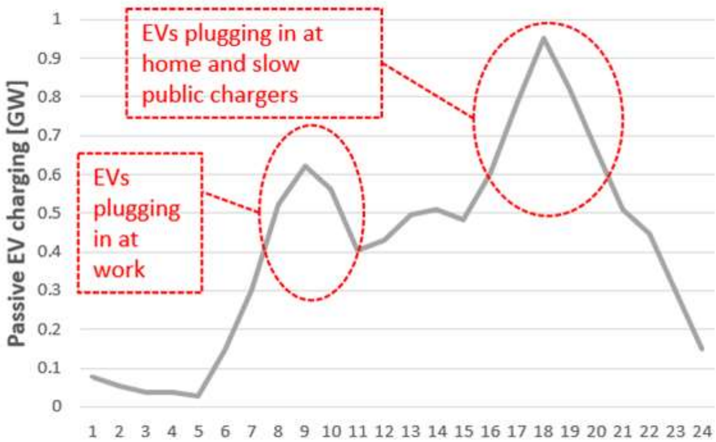


Figure 5 – Typical daily profile of passive EV charging, showing a morning and evening peak in demand.

Smart EV charging flexibility

We assume home, work and slow public charging are flexible and their passive charging can thus be adapted to a smart profile according to system needs. Home, work and slow public charging represent 80% of total EV charging. The degree of flexibility of EV charging is determined to a large extent by the time for which EVs stay plugged in at EV chargers. The following assumptions, aligned with EV consumer research[15], have been made on plug in windows of EVs:

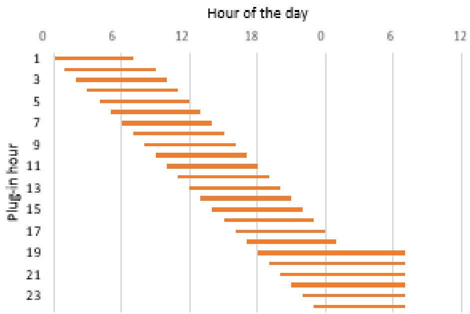
- EVs charging during the night, i.e. EVs charging at home and at slow public chargers, stay plugged in until 7:00 if plugged in between 18:00 and 00:00, otherwise for 8 hours.
- Work EVs stay plugged in until 17:00 if plugged in between 8:00 and 13:00, otherwise for 4 hours.
- The smart charging algorithm of the dispatch model ensures that all vehicles are fully charged at the end of their plug-in window.

These assumptions are illustrated in Figure 6.

[15] Les véhicules électriques en perspective

Home EV plug-in time

It is assumed that at home EVs stay plugged in until 7:00 if plugged in between 18:00 and 00:00, otherwise for 8 hours.



Work EV plug-in time

Our modelling assumes that at work EVs stay plugged in until 17:00 if plugged in between 8:00 and 13:00, otherwise for 4 hours.

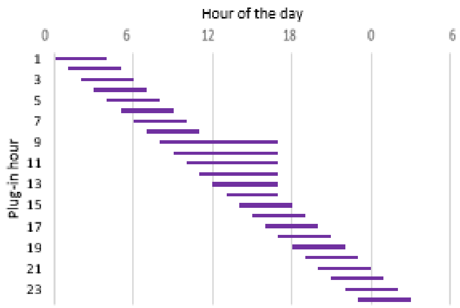


Figure 6 – Assumptions on plug-in windows of EVs plugging in at various times during the day determine EV charging flexibility

2.5.5 Generation capacities and profiles

Assumed installed capacity per electricity generation technology in each of the four modelled countries is based on the installed capacity in the 2040 Distributed Generation scenario of the 2018 ENTSO-E TYNDP. The capacities are adjusted according to the ratio of total electricity demand supplied via the grid (i.e. not including electricity demand of electrolysers collocated with dedicated renewable generation). The capacities in the Baseline version of the HP scenario are given in the table below.

Table 3 – Assumed installed generation capacities in the four modelled countries for the Baseline version of the HP scenario

	ES	IT	CZ	PL
Solar	82.76	158.14	21.43	96.46
Wind-onshore	42.90	23.97	1.79	19.28
Wind-offshore	-	2.36	-	7.49
Hydro flex	32.86	29.90	2.76	4.43
Hydro	4.60	7.60	0.49	1.58
Biomass	3.05	7.08	1.57	2.68
Nuclear	3.71	-	2.87	4.58
CCGT	29.37	109.82	1.34	9.13
OCGT	10.16	7.80	2.02	11.10
Coal	-	3.58	-	12.71
Lignite	-	-	5.18	2.95
Oil	-	-	-	6.10
Interconnector	16.74	4.96	5.24	2.43

Hourly renewable generation profiles were calculated based on NASA MERRA-2 weather data. In line with the consumption profiles (for non-heat and non-transport electricity demand and heat electricity demand), the profiles are based on the weather profile of the year 2007.

2.5.6 Generation cost assumptions

Table 4 lists the generation cost assumptions used along with the sources of the estimates used. All estimates are in 2018 €, the values from the original sources have been converted where necessary using UK ONS CPI, the EU HICP, and ECB exchange rates. Most generation cost data is based on estimates from a recent report by the British government. All considered types of generation represent mature and standardised technologies typically produced by a small number of producers for the global market. We therefore assume the same generation technology cost across European countries[16].

Table 4 – Generation cost assumptions

Technology	Lifetime (years)	CAPEX (€/kW)	Fixed OPEX (€/kW/y)	Variable OPEX (€/MWh)	Source
Solar	35	487	8	0	BEIS, 2020[17]
Wind-onshore	25	1,231	28	7	BEIS, 2020
Wind-offshore	30	1,780	106	3	BEIS, 2020
Hydro flex	41	3,685	54	7	BEIS, 2020
Hydro	41	3,685	54	7	BEIS, 2020
Biomass	25	3,551	93	10	BEIS, 2020
Nuclear	60	5,225	100	6	BEIS, 2016[18]
CCGT	25	705	17	5	BEIS, 2020
OCGT	25	532	8	5	BEIS, 2020
Coal	30	1,712	22	4	Fraunhofer, 2021[19]
Lignite	40	1,859	31	4	Fraunhofer, 2021
Oil	15	480	13	3	BEIS, 2020
Interconnector	25	694	13	62	CERRE 2017[20]

The peaking capacity saving in the flexible scenarios has been quantified by multiplying the peak net demand reduction compared to the respective baseline scenario with the assumed CAPEX of an OCGT. Typical efficiency ranges of national fleets of thermal plants (CCGT, OCGT, Coal, Lignite, Biomass, Nuclear) have been chosen based on data from ENTSO-E and IRENA[21]. The assumed prices and carbon intensities of fuels are listed in Table 5. All values are for a MWh of fuel in LHV terms. Fuel prices are taken from the Distributed Generation 2040 scenario of the 2018 ENTSO-E TYNDP, except biomass prices which are

[16] This refers to the cost of machinery - the levelized cost of generation differs between the countries depending on the load factor, i.e. utilisation of this machinery, which is determined by the dispatch modelling of the electricity system.
[17] BEIS Electricity Generation Costs (2020)
[18] BEIS Electricity Generation Costs (November 2016)
[19] Fraunhofer Institute for Solar Energy Systems ISE Levelised cost of electricity
[20] Cerre Brexit and its implications for British and EU energy and climate policy ; the variable OPEX of the interconnector has been adapted such that it appears after the most expensive national generation plant (typically an OCGT) in the merit order
[21] ENTSO-E: 2018 TYNDP, IRENA: Renewable Power Generation Costs

taken from a report on global biomass markets for the UK government[22]. Carbon intensities are based on UK and German government publications and guidelines.

Table 5 – Cost and carbon intensity of fuels

Fuel	Price (€/MWh or €/tCO2)	CO2 (t per MWh of fuel)
Nuclear	€ 1.69	0
Lignite	€ 3.96	0.381
Coal	€ 10.08	0.334
Gas	€ 35.28	0.204
Oil	€ 87.84	0.266
Biomass	€ 29.14	0
CO2	€ 187.94	

2.5.7 Network costs

Network fees have been modelled based on the “peakiness” of the aggregate national consumption profile, given by the ratio of peak demand (in MW) to annual demand (in MWh). As the network capacity needs to be sized according to peak demand, this ratio is a measure for the network capacity requirement per MWh of electricity demand.

In any of the modelled countries, the assumed network fees (in €/MWh) in a particular scenario is given by the current network fees multiplied by the ratio of the “peakiness” in that scenario to the 2019 “peakiness” (based on the 2019 national consumption profile[23]). Current network fees in each country are taken from the 2019 ACER Market Monitoring Report[24], compare Figure 7. The ACER residential electricity price data is closely aligned with the one reported by EUROSTAT for 2019[25].

[22] BEIS Global biomass markets
[23] ENTSO-E
[24] ACER-CEER Market Monitoring Report
[25] EUROSTAT Electricity prices for household consumers

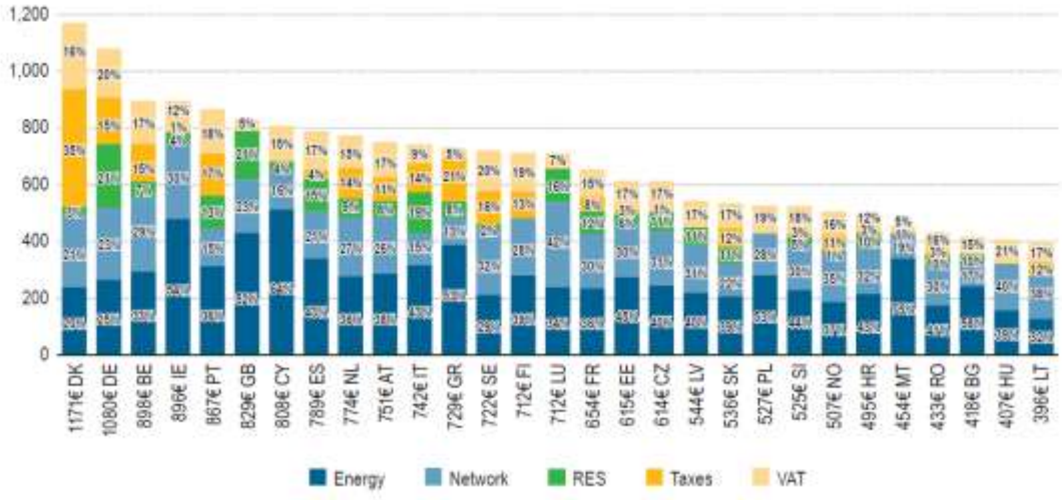


Figure 7: breakdown of residential electricity cost; figure shows cost of a residential electricity bill for 3,500kWh annual consumption; source: 2019 ACER Market Monitoring Report

2.5.8 Taxes

The taxes included in energy bills are VAT as well as energy specific taxes in some countries. Taxes have been modelled by assuming the same tax rate on non-taxed energy bills (consisting of wholesale electricity generation cost and network fees) as today. Current tax rates in the four modelled countries have been taken from the ACER Market Monitoring Report, cp. Figure 7 (tax rates used are based on the combination of categories “VAT” and “Taxes” in the ACER report).

2.6 Costing hydrogen for consumers

The cost of producing green hydrogen by electrolysis was modelled in this project. In the baseline case, it was assumed that the electrolysers were connected to the electricity grid, and pay a wholesale price excluding grid fees for their electricity. The cost of hydrogen distribution and storage was then calculated based on a parameterised model of the gas grid and costs of converting the low-pressure distribution grid to hydrogen. The costs of hydrogen production and transmission used were taken from the BEIS hydrogen supply chain evidence base[26]. The lifetimes of both the hydrogen network in all countries and the gas network expanding in Poland were assumed to be 40 years. This value was used when calculating the annualised network cost component of the hydrogen fuel cost.

In the Flexible scenario, it was assumed that hydrogen production would not be connected to the electricity grid. Instead, hydrogen production electrolysers and renewable generation would be co-located, and the production of hydrogen was modelled on an hourly basis to optimise the relative generation and electrolyser capacities for the cheapest hydrogen cost. Renewable generation profiles were calculated from NASA MERRA-2 data, and the cost of renewable generation was found from the BEIS 2020 cost of generation report[27]. In addition to this, curtailed electricity from renewable generation was also used to produce hydrogen in the flexible case at 0 cost for the electricity. The cost of storing hydrogen between the time when it is produced and used was also included. Storage in liquid organic hydrogen

[26] BEIS Hydrogen supply chain evidence base
[27] BEIS Electricity Generation Costs (2020)

carriers was the cheapest option for storage based on the costs from HYSTOC[28] and future costs from Reuß et al[29], cheaper than salt cavern storage or tank storage.

Both wind and solar generation to produce hydrogen were considered for the Flexible scenario. In Spain using solar generation to produce hydrogen was cheapest, in Czechia and Poland onshore wind was cheapest and in Italy offshore wind was cheapest. The costs shown in Figure 8 are based on hydrogen produced from the cheapest renewable source in each country. To find the cost per kWh, the capex of generation and electrolysers was annualised over the expected lifetime of the technologies at a discount rate of 5% in the consumer cost case and a 3% discount rate in the system cost case. The cost of hydrogen for consumers in €/kWh is shown in Figure 8.

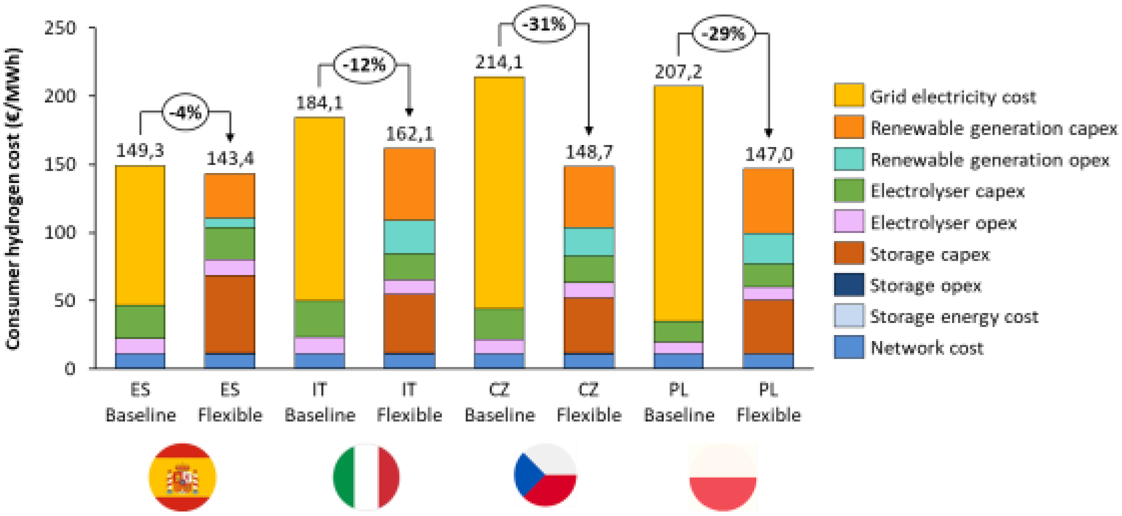


Figure 8 – Breakdown of hydrogen cost for consumers in all countries in the baseline and flexible scenarios.

2.7 Consumer cost modelling

The consumer cost of heating was modelled initially at an archetype level. The results from this initial modelling were then fed into a whole system model.

Additionally, when modelling consumer cost at archetype level, a discount rate of 5% was used to reflect a financial calculation of costs to consumers, based on standard loan rates consumers can be expected to obtain. The whole system modelling was performed using a lower discount rate, of 3%, which is more aligned with a whole system economic calculation which also reflects the change in available funding stream that can be obtained from large scale, long-term investments. The process, methodology, and data sources used for the archetype-level calculations will be described first.

[28] HYSTOC (Hydrogen Supply and Transportation using Liquid Organic Hydrogen Carriers) Deliverable 8.3 - Preliminary feasibility study (Rev 3, 2020)
[29] Reuß et al, Seasonal storage and alternative carriers: A flexible hydrogen supply chain model, Applied Energy, 2017

2.7.1 Archetype cost modelling

Energy efficiency

The underlying assumptions regarding energy efficiency costs and savings are described in detail in Section 2.2. For each archetype, the cost of a shallow or a deep retrofit per square meter was multiplied by the average floor area to find the total energy efficiency cost. The heat demand reduction from packages were defined as shown in Table 6, and costs in

Table 7. The energy savings from a shallow package is higher for older buildings to reflect the difference in initial building fabric condition. The cost for that level of retrofit was also higher for older buildings and is referred to as "medium" in the ZEBRA2020 report[30]. The energy demand in new buildings was assumed to be equivalent to that of buildings with a deep retrofit package, saving 75% of annual heat demand compared to the baseline. This is aligned with the new builds standard in each country analysed.

Table 6 – % Energy savings from retrofit based on archetype age

Age	Retrofit level	% Energy savings
Post 1970	shallow	15
Pre 1970	shallow	45
Post 1970	deep	75
Pre 1970	deep	75

Table 7 – Retrofit costs of packages based on building age and country

Country	Age	Energy efficiency	Cost (€/m2)
ES	Post 1970	Shallow	57
ES	Pre 1970	Shallow	163
ES	All	Deep	288
IT	Post 1970	Shallow	101
IT	Pre 1970	Shallow	231
IT	All	Deep	315
CZ	Post 1970	Shallow	96
CZ	Pre 1970	Shallow	153
CZ	All	Deep	219
PL	Post 1970	Shallow	60
PL	Pre 1970	Shallow	170
PL	All	Deep	220

Heating system

The heating system costs were calculated explicitly for each archetype assuming an uptake of air-source heat pumps, hybrid heat pumps, hydrogen boilers, or district heating. The capex and opex of heating systems, conversion costs, and heat storage costs are based on data from the CCC[31] and an ECF study looking at fossil-free heating in Europe in 2050[32]. The costs were compared and validated against country-specific costs provided by the consumer organisations in each country. The heating systems were costed per archetype based on the following process:

[30] ZEBRA2020: nearly zero-energy building strategy 2020
[31] Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget
[32] Towards fossil-free energy in 2050 - European Climate Foundation

1. The annual heat demand was calculated after the energy efficiency uptake, where relevant
2. The annual heat demand was divided by the number of heating degree days and the number of hours in a day to find the average building heat loss parameter in kW per degree.
3. The average heat loss parameter is multiplied by the maximum outdoors-indoors temperature difference in the peak demand hour of the year to find the expected peak heat demand.
4. This value is then rounded to the nearest higher integer value, and this is used to define the heating system kWth sizing.
5. For heat pumps, this is divided by the efficiency at the time of peak demand to find the equivalent kWe sizing.
6. The capex of heating system is then obtained based on the heat system sizing calculated. The capex includes only the heating system itself, or the heat interface unit in the case of district heating, and the costs of installation and smart meter where relevant.

As well as the capex, the following heating system costs were calculated:

- Conversion costs, which reflect the changes needed to go from a counterfactual to a renewable heating system
- Thermal storage and hot water costs, for heating system where required

To simplify the conversion costs, we have calculated them based on the two most common fossil fuel counterfactual heating systems in each country, as shown in Table 8.

Table 8 – Counterfactual heating systems for which conversion costs were calculated

Country	Counterfactual heating system
ES	gas boiler
ES	oil boiler
IT	gas boiler
IT	oil boiler
CZ	gas boiler
CZ	solid
PL	gas boiler
PL	solid

The conversion costs were estimated based on the needs of the counterfactual and renewable heating systems. The main costs calculated were the replacement of cooker hobs (where moving away from gas), the decommissioning of boilers, and the hydrogen in-building pipework. Based on feedback from the consumer organisations within each country, we assumed all buildings to have existing wet heating systems and therefore did not include this in the conversion costs.

Heat storage has been tracked in two ways:

1. Hot water tank requirement
2. Heat battery requirement

Hot water tanks were assumed to be required for heat pumps but for no other renewable heating systems. They were also assumed to be present in the building stock with solid counterfactual heating systems but not with oil or gas boilers, so their cost would only be incurred for the oil/gas boiler to heat pump transition.

It is also assumed that only heat pumps require heat batteries, and is the only heating system incurring these costs.

Lifetimes and depreciation

All heating system were assumed to have 15 years lifetimes, and energy efficiency packages 30 years lifetimes, also aligned with the ECF and CCC assumptions. Costs have all been annualised based on discount rate for consumer or whole system calculations as appropriate.

Fuel consumption

For calculating fuel costs, we assumed that hybrid heat pumps use the heat pump component to meet 80% of the demand, with the remaining 20% being met with the hydrogen boiler component. This ratio has been selected as it allows a minimisation of the overall hybrid annualised costs, though a reduction of the heat pump capex component while limiting the increase in fuel cost from the hydrogen boiler component.

For heat pumps and hybrid heat pumps, the yearly-average COP was used to calculate the fuel consumption based on the annual heating demand.

District heating - DH

The DH plant and network costs were calculated by modelling a typical energy centre size of 2 MW for each of the following heating systems: heat pump, hybrid heat pump, hydrogen, and biomass. In all cases, 0.015 m^3 of thermal storage per MWh of demand was assumed to be used, allowing to optimise the sizing of the heating system, and leading to a plant load factor of 31%. The generation plant lifetimes were assumed to be 30 years. Those assumptions are aligned with work from the CCC[33] and SEAI[34]. From this, the annualised plant generation costs, excluding fuel costs, were obtained for each of the heating systems.

The overall district heating generation costs were generated using the fraction of each heating system that is used to meet the overall demand, an example of which is shown in Figure 9 for Spain and Poland. Similar values were used for Italy and Czechia.

The levelised costs for DH were calculated by adding together the generation plant, network costs, and fuel costs. A further 5% tax cost was included for the generation plant and network costs, but not for fuel costs, which already include a tax.

The heat network costs were obtained from the Heat Roadmaps Europe database[35], for typical costs per kwh of DH schemes, in areas of high heat demand density. For Spain, two costs were defined depending on the DH final uptake. For the higher DH uptake scenario,

[33] Research on district heating and local approaches to heat decarbonisation
[34] Comprehensive Assessment of the Potential for Efficient Heating and Cooling in Ireland: Report to the European Commission
[35] Heat Roadmaps Europe

the average network costs per kwh were assumed to be higher than for the lower DH uptake scenario, representing uptake of DH in areas which have lower heat demand density.

When DH data is presented at an archetype-level, all the generation, network, and primary fuel costs are included in the final DH fuel cost shown.

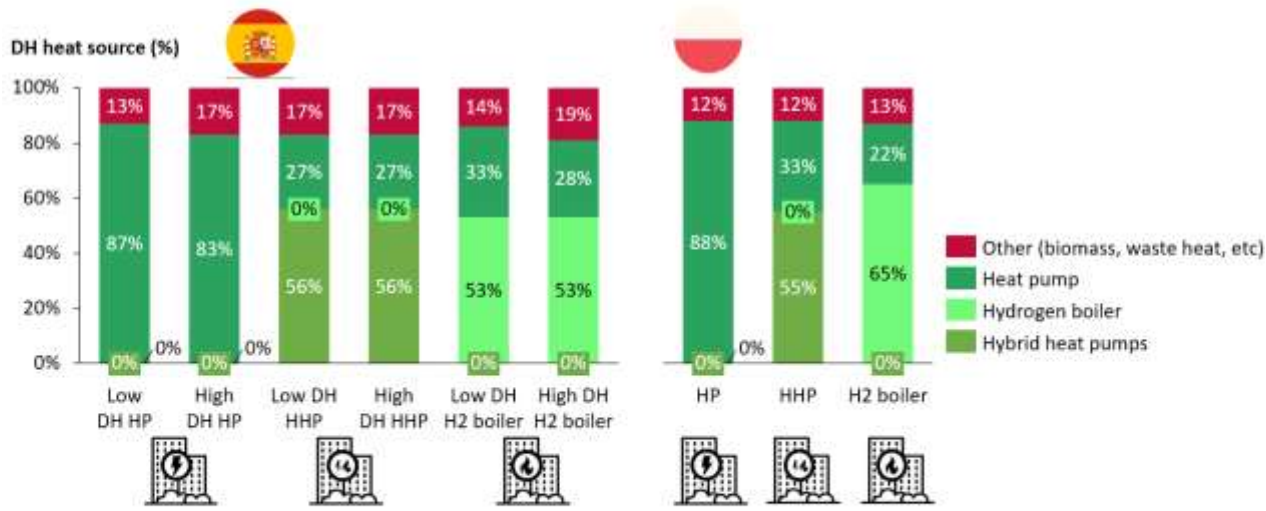


Figure 9 – District heating heat source % in Spain and Poland across the three technology scenarios

2.7.2 Whole system cost modelling

The previous section described how the costs of individual archetypes were calculated. The whole system costs were calculated by changing the discount rate from 5% to 3% and by summing the costs of decarbonisation for the archetypes in the housing stock of each country. The cooling costs were ignored in this analysis as they represent a very minor component of the overall system costs, and are not relevant for all countries investigated. The following steps were performed in the model:

1. First, the number of building archetypes in 2040 were calculated based on the assumed new build construction rate, and the energy efficiency retrofit rate scenarios assumptions.
2. A defined fraction of heating systems to be taken up in each archetype was applied to find the final number of buildings in 2040 with one of the 4 heating systems investigated: heat pumps, hybrid heat pumps, hydrogen boilers, and district heating.
3. The heating system, network, and fuel costs for the whole stock taking up the 4 main heating systems (ASHP, HHP, H2 and DH) was summed together and calibrated so the same number of buildings are taken into account across all scenarios. Using Spain's Heat pump scenario shown in Figure 10 as an example, we can see that not calibrating this number would lead to more buildings being costed in the high DH scenario (63% or 31%+32% of the total stock) than the low DH scenario (58% or 42%+16% of the total stock).
4. The electricity consumption from non-heating use was added to the overall whole system costs. This is done because the benefits brought by the flexible use of heating systems can lead to electricity cost reduction for all consumers.

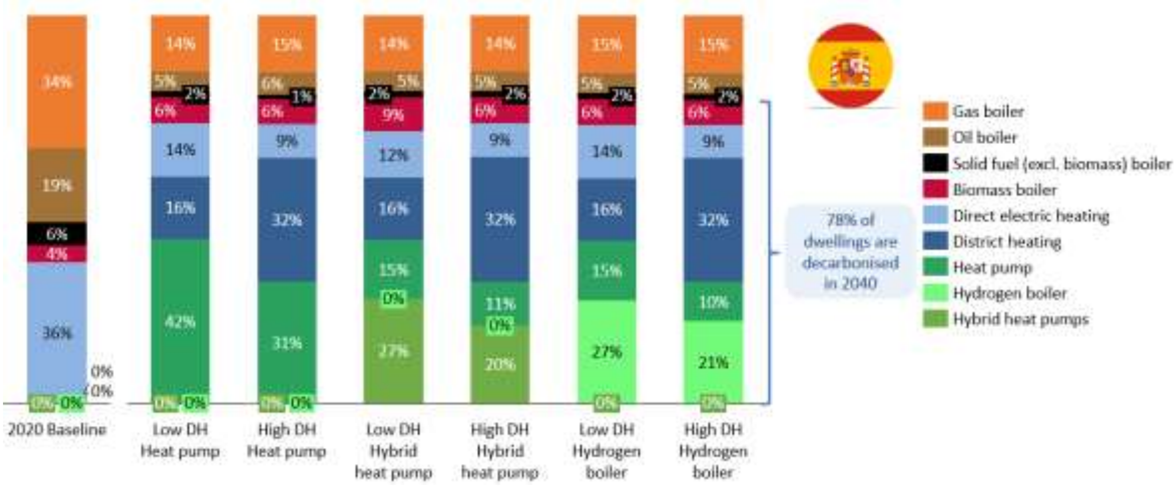


Figure 10 – Heating system uptake scenarios in Spain