Spatial Variation of Greenhouse Gas Abatement Potential and Cost in Domestic Hot Water

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Abstract

Urban water systems have complex sources of greenhouse gas (GHG) emissions. Due to its high energy consumption and intensity, domestic hot water contributes significantly to GHG emissions in the residential sector. A transition towards cleaner water heating, such as heat pumps, could dramatically reduce carbon footprint. This study investigates the spatial variation of GHG abatement potential and cost in domestic hot water across the European Union (EU). The abatement potential and cost of the same abatement scenario vary from country to country due to different economic and social contexts. Therefore, the optimal scenario for domestic hot water in each country is determined in consideration of national circumstances. Results show that climate and electricity grid mix are essential factors contributing to spatial variation. Findings suggest that the EU could phase out subsidies for traditional water heaters and replace them with incentives for heat pumps and solar water heaters.

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1. Introduction

Water end use is the most significant contributor to energy consumption and greenhouse gas (GHG) emissions in the water sector (Rothausen & Conway, 2011; Kenway et al., 2015; Kenway et al., 2019). In the US, water end use contributes to 70.7% of carbon emissions from energy use in the US water sector (Griffiths-Sattenspiel & Wilson, 2009; Porse et al., 2020). Water end use includes residential, commercial, and industrial processes. Energy consumption and GHG emissions associated with domestic hot water are significantly higher than other processes in the water sector (Rothausen & Conway, 2011). For example, residential water heating comprises 58% of national water-related carbon emissions in the US (Griffiths-Sattenspiel & Wilson, 2009). In the European Union (EU), water heating accounted for 14% of household energy consumption by end use in 2019 (Enerdata, 2021). In the UK, household water use accounts for 6% of total CO_2 emissions (Ro, 2020). Globally, heating water is the second largest source of energy consumption in the home, next to space heating (Energy Saving Trust, 2013; Kenway et al., 2019).

Daily activities requiring a higher water temperature, such as bathing, showering, and cooking, lead to considerable energy consumption (He et al., 2019). Driven by behavior and population, energy consumption in hot water depends on demand. Hot water demands account for approximately 10% of the thermal energy demand in Europe (Paardekooper et al., 2018). It is feasible to reduce energy consumption demand in hot water by switching to renewable energy sources, adopting energy-efficient technologies, etc. Significant energy and carbon savings could be achieved by raising awareness of water-related energy saving and improving the way residents use hot water in the home (CIWEM, 2013; Copeland & Carter, 2017).

Since the early 21st century, researchers have recognized the potential for household water-related energy savings. For example, studies in Australia found that installing water-efficient showerheads can reduce energy use and GHG emissions by 7.7 million GJ/annum and 1.3 million tons CO_2/annum by 2015, which indicates that upgrading current appliances benefits households and the environment by reducing utility bills and carbon emissions. (Day and White, 2003; Willies et al., 2010). Previous studies have adopted various methods to quantify the energy use in residential water-related processes and appliances, including the Life Cycle Assessment (LCA) (Lee & Tansel, 2012), the Water Heater Analysis Model (WHAM) (Porse et al., 2020), the Monte Carlo analysis (Wong et al., 2016), and the Long-range Energy Alternative Planning (LEAP) (Subramanyam et al., 2017). In addition, Pezzuatto et al. (2019) quantified the energy consumption of space and water heating equipment in EU28 based on a bottom-up approach. Their results suggested that reducing water and hot water use during the end use phase can lessen the overall energy load associated with water use and increase sustainability.

Several studies have an emphasis on GHG abatement in water end use. For example, researchers quantified the carbon footprints of housing as well as GHG abatement cost curves for household-related opportunities in the US (Jones & Kammen, 2011). They concluded energy for domestic hot water (i.e., electricity and natural gas) is a massive contributor to the carbon footprint in the housing sector. Kesicki and Ekins (2012) developed marginal abatement cost curves (MACC) to assess the economic performance of GHG abatement measures. MACC has been used for assessing water-related energy and GHG saving potentials in residential energy and water efficiency opportunities (Chini et al., 2016), city-scale cost-effective water-related energy management options (Lam, Kenway and Lant, 2017), city-scale GHG emissions abatement potentials in the water sector (Lam & van der Hoek, 2020), and physical and behavioral opportunities in community and utility (Bors et al., 2021). These studies identified the significant GHG mitigation potential of hot-water-related opportunities. However, they have not dealt with spatial variation in these opportunities. GHG reduction potential and costs for the same opportunity vary across countries. Most studies have been carried out in a community or city and rarely at a regional or national level, resulting in findings from one area that cannot be generalized or be directly available to another area with a different context.

Cost is an essential determinant of the low-carbon transition in domestic hot water from two perspectives. First, it is essential to consider household affordability when replacing existing water heaters. Switching to high-tech devices or renewable energy may reduce household energy bills, but the installation and operation costs for low-carbon heating appliances are relatively high (Kerr & Winskel, 2021). There is a tradeoff between improving energy efficiency and cost control. The cost of an energy-efficient water heater cannot exceed the affordability of households. Therefore, it is necessary to identify the most cost-effective opportunity in domestic hot water. Second, government financial support should be based on the cost of the hot water system. Governments provide economic promotion schemes for domestic heating systems, in the form of loans, subsidies, and tax reductions. For example, EU 27 (except Estonia) provide subsidies to support the installation of renewable energy for heating in the form of heat pump and solar thermal heaters (European Environmental Bureau, 2021). The EU is aiming to install 50,000,000 heat pumps by 2030 (Farrel, 2022). Stable policy support, including financial support, structural incentives, and the regulatory backstop, is essential for achieving this ambitious goal (IEA, 2021; Lowes et al., 2022). Thus, examining the GHG abatement potential and cost is crucial to improve current subsidy policies and develop carefully targeted financial incentives (Environment Agency, 2009).

The costs of adopting new technologies and switching to another primary energy source vary in regions or countries due to demographic, geographical, social, and economic conditions (IEA, 2021). For example, an air-source heat pump investment is nearly ten times as expensive as a gas boiler in Belgium. In Italy, it is cheaper to invest in an air-source heat pump than a gas boiler (European Environmental Bureau, 2021). Even though shifting from the current energy source to natural gas or solar heating system in the US will lead to general reductions in energy use and carbon emissions, there is excellent spatial variation in its potential and cost across states. Due to a lack of financial support from local governments, states that might most benefit from technology transition are less likely to transfer to the new technology (Sanders & Webber, 2015).

However, there is a lack of research on spatial variation of GHG abatement potential and cost across countries and its policy implication. This study aims to quantify the potential and cost of GHG abatement opportunities in the household hot water system in the EU 27. The EU is a political and economic union of 27 member states located primarily in Europe. The EU was established in the aftermath of World War II to promote peace and economic cooperation among European countries. It has since grown to become one of the largest economic and political entities in the world. The 27 member states of the EU are: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden. Their country code is shown in the Appendix (Table A1).

This study collects data from the European Commission open-source database, e.g., Eurostat, Enerdata, Odyssee-Mure, Heat Roadmap Europe 4, etc. As the energy crisis intensifies, the need for a low-carbon transition in Europe becomes urgent and uncompromising. This is the first study to do a cross-country comparison of GHG abatement potential and cost in household water heating. It provides new insights into energy transition pathways in domestic hot water. Moreover, it gives solid statistical support for European governments to formulate subsidy policies for hot water appliances.

There are three major steps to answer the research question. First, GHG inventories on energy consumption in domestic hot water are conducted to develop a baseline scenario. The baseline represents current GHG emissions in domestic hot water. Second, six GHG abatement scenarios are developed for simulating GHG emission changes, e.g., replacing gas instantaneous water heaters with heat pumps, installing solar water heaters, etc. Third, the mitigation potential and costs of these scenarios are quantified and compared with the baseline. The performance of the same scenario in different countries is recorded separately to investigate spatial variation.

The remaining part of the paper has been organized in four sections. The following section describes the research design and data. The third section presents the findings of the research, focusing on the three key themes including (a) baseline GHG emissions from domestic hot water, (b) abatement potential of scenarios, and (c) mitigation cost and energy bill saving. A discussion section analyzed the spatial variation and policy implication based on the results, followed by a conclusion.

2. **Methodology**

2.1 Research design

To quantify the GHG emissions from energy consumption in domestic hot water, this paper adopted the IPCC methodology for GHG inventories (IPCC, 2019). The GHG emissions of energy consumption in domestic hot water for each country can be calculated as follows:

$$E_i = \sum_k AD_{k,i} \times EF_{k,i}$$

where i refers to each country in the EU 27 and k captures the type of energy consumption. $AD_{k,i}$ is the activity data applicable to energy k (i.e., final energy consumption quantity by type of fuel) in country i. $EF_{k,i}$ stands for energy k specific emission factor in country i.

The 2020 inventory results are the baseline of subsequent simulations. Then, GHG abatement scenarios are defined based on literature and policy reports. Scenarios are related to the shift from traditional water heating appliances to energy-efficient water heaters. Traditional water heating appliances include electric instantaneous water heaters, electric storage water heaters, gas-fired instantaneous water heaters, gas- or oil-fired storage water heaters, instantaneous COMBI, etc. Energy-efficient or eco-friendly water heaters are air-source heat pumps, ground-source heat pumps, solar-assisted electric storage water heaters, etc.

Scenarios include:

(1) switching from gas storage/instantaneous water heaters to solar water heaters.

(2) switching from gas storage/instantaneous water heaters to electricity storage/instantaneous water heaters.

(3) switching from gas storage/instantaneous water heaters to heat pumps.

(4) switching from electricity storage/instantaneous water heaters to solar water heaters.

(5) switching from electricity storage/instantaneous water heaters to heat pumps.

(6) switching from oil heating equipment to electricity storage/instantaneous water heaters.

The replacement ratio in these scenarios is 30%, which means switching 30% of existing water heaters to another in each country.

Based on the final energy consumption and water heater stock data, I quantify the GHG emissions of each unit of water heater by matching the energy sources in two datasets. In the study, the energy types of water heaters were classified into five categories: (1) electricity, (2) gas, (3) solar, (4) ambient heat (i.e., heat pump), and (5) oil. The scenario settings are consistent with these categories.

The GHG abatement potential and cost of each scenario will be measured in each country. In terms of potential, I simulate the GHG emissions in each country under each scenario and compare them with baseline emissions. The gap between the simulation and the baseline is the GHG mitigation potential. The same type of water heater may perform differently in every country. For example, climate influences the coefficient of performance of heat pumps, so the energy consumption for heating 1-gallon water using the same heat pump in Spain and Germany varies.

Regional differences are more pronounced regarding costs. In the cost calculation, this paper considers the market price of hot water appliances, installation cost, maintenance cost, fuel price, etc. Cost analysis includes (a) upfront investment and (b) energy bill saving per dwelling. Due to the unavailability of costs related to oil boilers, the country-specific analysis covers five scenarios except for the sixth one.

2.2 Data

The EU 27 final energy consumption data from 2010 to 2021 is from the Eurostat (Code: NRG_D_HHQ) (Eurostat, 2023a). Energy consumption is divided into six major categories according to the energy source, including (1) solid fossil fuels, peat, peat products, oil shale and oil sands, (2) natural gas, (3) oil and petroleum products, (4) renewables and biofuels, (5) electricity, and (6) heat. In the current inventory, GHG emissions from heat are not covered. There is no clear definition of heat in the Eurostat dataset, resulting in the emission factor of heat not being determined.

The emission factor is from the Covenant of Mayors, the JRC, and the IEA (Koffi et al., 2017; Lo Vullo, et al., 2020; IEA, 2022). The grid electricity emission factor is country specific. The emission factor of solid fossil fuels, natural gas, oil and petroleum products, and renewables and biofuels are the same for all EU countries. Based on the EU unified emission factor, the emission factors are refined according to the energy mix of each country. For example, to specify the emission factors of natural gas for each country, investigation on the sources of natural gas in each country, such as the proportion of renewable and non-renewable gas, are conducted. For countries lacking data, the default emission factors of the EU are used.

Water heater stock dataset is from final reports of the Review Study of Ecodesign and Energy Labelling for Water Heaters and Tanks by the European Commission and the Heat Pumps Barometer by the EurObserv'ER. The former report includes 7 tasks. The water heater stock data is from Task 2 in the review study (Kemna et al., 2019). The original data is modeled by the BRG Building Solutions. Water heater park 2016 per EU member state is used as the baseline stock data. The types of water heating are as follows: district heating, collective heating, and individual sanitary hot water heating. Individual water heaters include (1) electric instantaneous water heaters (EIWH), (2) electric storage water heaters (ESWH), (3) gas-fired instantaneous water heaters (GIWH), (4) gas-fired storage water heaters (GSWH), (5) solar thermosiphon systems (SOL), and (6) heat pump water heaters (HPWH). This paper adopts the water heater stock data of the EIWH, ESWH, GIWH, GSWH, and SOL. The heat pump stock data in 2020 is from the Heat Pumps Barometer (EurObserv'ER, 2021).

The Review Study by the European Commission also provides data for energy efficiency, average product life, product price, installation costs, and maintenance costs (Kemna et al., 2019). The energy efficiency data is divided according to water heater type, size, energy label, and climate. The biannual energy price data is from the Eurostat (Code: NRG_PC), including electricity and natural gas prices by country in 2020 (Eurostat, 2023b; Eurostat, 2023c). The annual energy price is calculated by taking the average of biannual values.

Instead of hot water consumption, water consumption by end use is used in this study. The data source is Task 3 of Ecodesign Review Water Heaters (Kemna & van Elburg, 2019). The use of hot water is rarely specifically surveyed, although there are sources for the average residential use of water, and occasionally consumer surveys (diaries, interviews) that go into further detail on the prevalence of showers, baths, bathroom sinks, and other factors. Nearly all of these studies and figures on water consumption originate from associations of water utilities, either directly or indirectly (national statistics bureau, Eurostat, NGOs, environmental organizations, etc.). Particularly, the information provided by indirect sources is frequently stale, lacking, or incorrect. Not every nation has an efficient national water utility organization that collects information from its members. As a result, even the EU association cannot include all nations. For example, the EurEau, an organization of European water utilities, is unable to provide data on water use in Bulgaria, Estonia, Croatia, Ireland, and Luxemburg (Greene, 2022). It should be noted that water companies sometimes only take water from the grid into account, which is good for using hot water. Although the influence of bottled water on overall water consumption is minimal, data on total consumption may be distorted when sources include non-grid water, such as surface water.

3. Results

3.1 GHG emissions from domestic hot water

The GHG emissions from energy consumption in household water heating in the EU 27 peaked in 2017 (99,350,118 metric tons CO_2 equivalent) (Figure 1). Three countries are excluded due to missing data for some years. Germany is the most significant contributor to hot-water-related GHG emissions, with annual emissions of approximately 30,000,000 tons CO_2e, followed by Italy, Spain, and France. They are also countries with the highest population in the EU 27. Total emissions have decreased year by year from 2017 to 2020. It is probably attributed to improvements in energy efficiency. In addition, it is closely associated with the decrease/increase of hot water. The slight decline in 2020 compared to 2019 is noteworthy because the change in the domestic hot water use pattern brought about by COVID-19 remains unclear. People may use hot water at a higher frequency because the prevention policy has increased the time of working from home. They may also cut down shower times due to reduced exercise activities. Therefore, it is hard to draw conclusions on the impact of COVID-19 on hot-water-using habits without solid survey results.

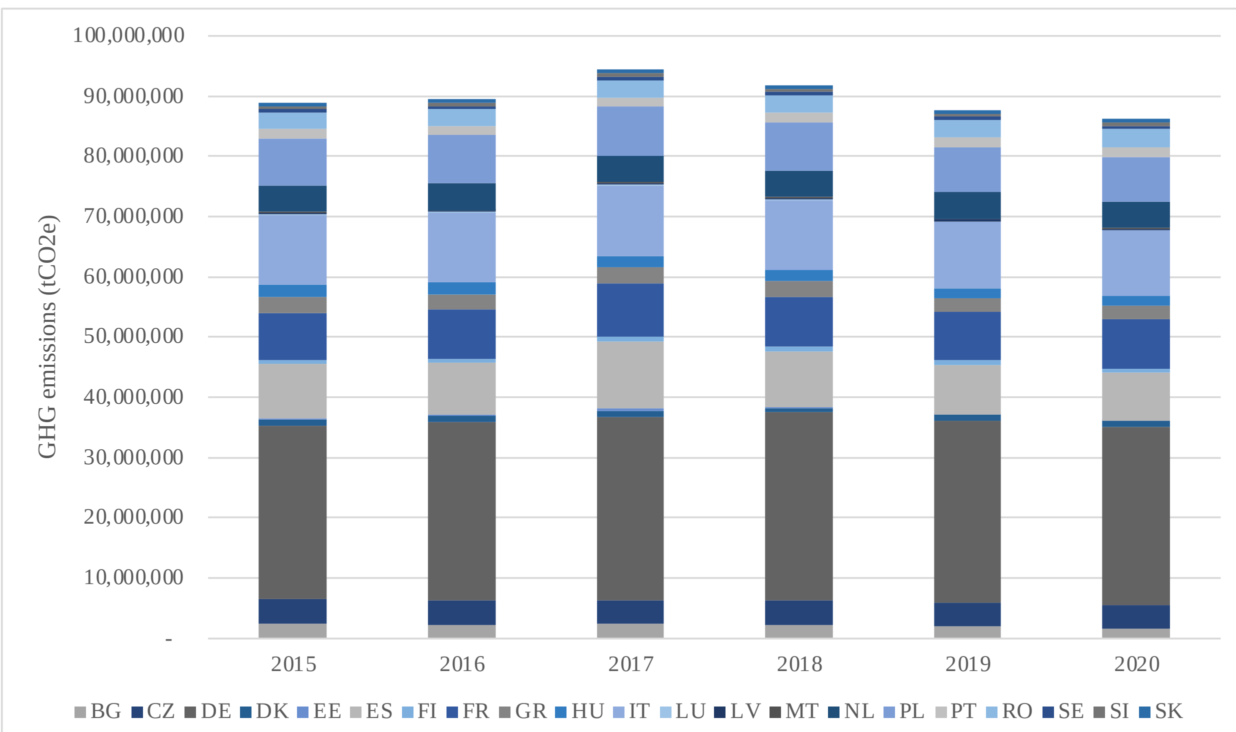


Figure 1 EU 27 GHG emissions from energy consumption in household water heating from 2015 to 2020

Note: Belgium, Republic of Cyprus, Lithuania is excluded due to data limit.

The EU 27 emitted 94,013,326 metric tons of CO_2e in 2020. It accounts for approximately 10% of GHG emissions in the building sector. Though bias may occur due to the outbreak of COVID-19, there is little influence on the composition of GHG emissions by country because the pandemic has a similar impact on each country. Germany accounts for 32% of the EU 27 hot-water-related GHG emissions (Figure 2). Italy, France, Spain, and Poland contribute 12%, 9%, 8%, and 8% of GHG emissions, respectively. These five countries are responsible for approximately 70% of GHG emissions from energy consumption in domestic hot water. Netherlands, Czech Republic, Romania, and Belgium account for 5%, 4%, 3%, and 3% of the GHG emissions, respectively. France is the second largest country in the EU 27 in terms of population, but it ranks after Italy regarding GHG emissions in household water heating. It is mainly because the energy structure in France is cleaner than in other countries.

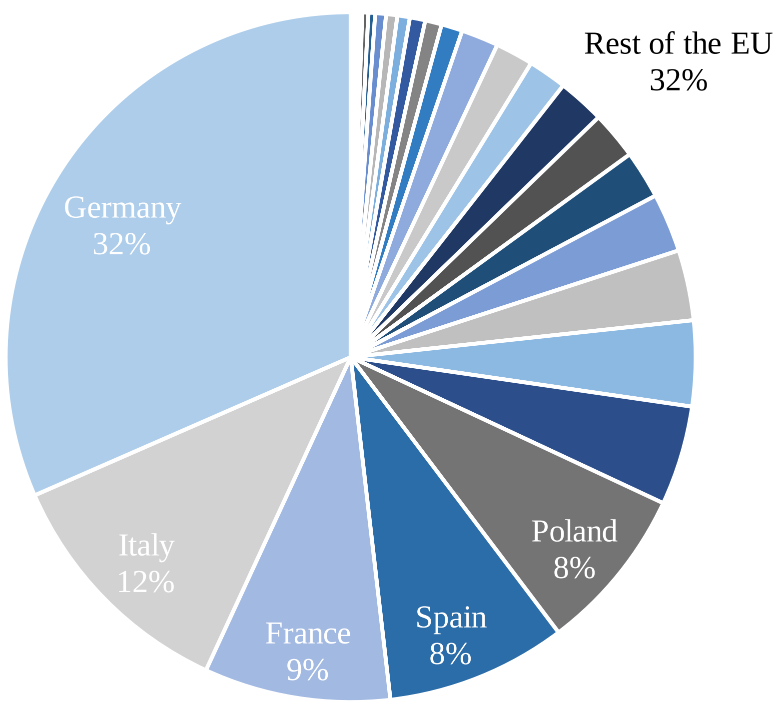


Figure 2 EU 27 GHG emissions from energy consumption in domestic hot water in 2020 (by country)

Large emitters are facing greater pressure to reduce emissions in domestic hot water. Figure 3 demonstrates the GHG emissions by energy source for the top four emitters. In general, natural gas has a large proportion of the total GHG emissions, followed by electricity and oil and petroleum products. Emissions from solid fossil fuels are less than 0.01%, which is negligible. Despite the commonalities, there are significant differences in trends and composition from country to country.

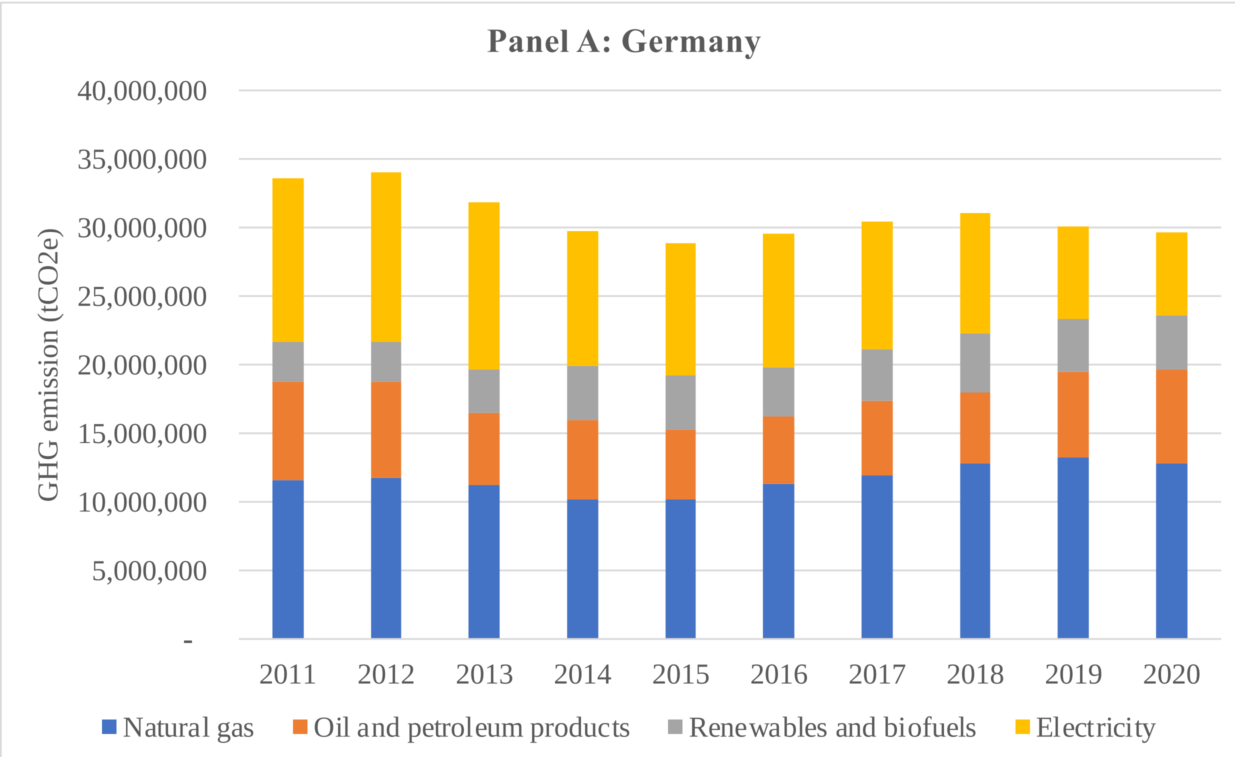
In Germany, emissions from natural gas increased over time. The gas instantaneous water heaters increased because of government incentives in past years. Oil and petroleum products, replacing electricity, became the second largest source of emissions. The GHG emissions from electricity decreased from 38% to 20% of the total GHG emissions in domestic hot water because the emission factor decreased (Figure 3 Panel A). As energy consumption increases, the GHG emissions from renewables and biofuels also increased from 8% to 13%.

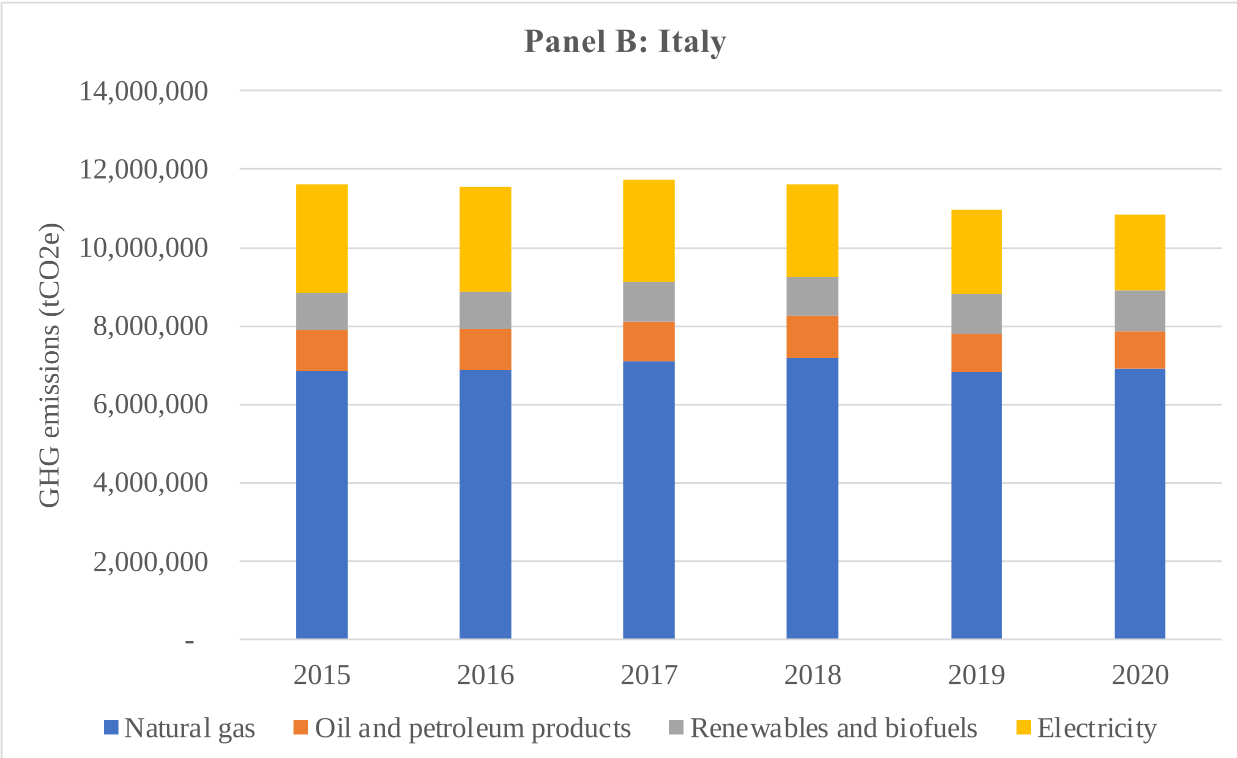
In Italy, the emission trend is relatively stable. Since Italy has no relevant statistical data before 2015, the inventory results are from 2015 to 2020. Natural gas is the main source of energy for water heating in Italy (Figure 3 Panel B). It accounts for 60% of GHG emissions, higher than in other countries. Electricity is the second largest contributor to GHG emissions, but while the final consumption of electricity was reducing, the share of emissions from electricity decreased. The low-carbon transition challenge facing Italy is how to reduce the huge reliance on natural gas for domestic hot water systems.

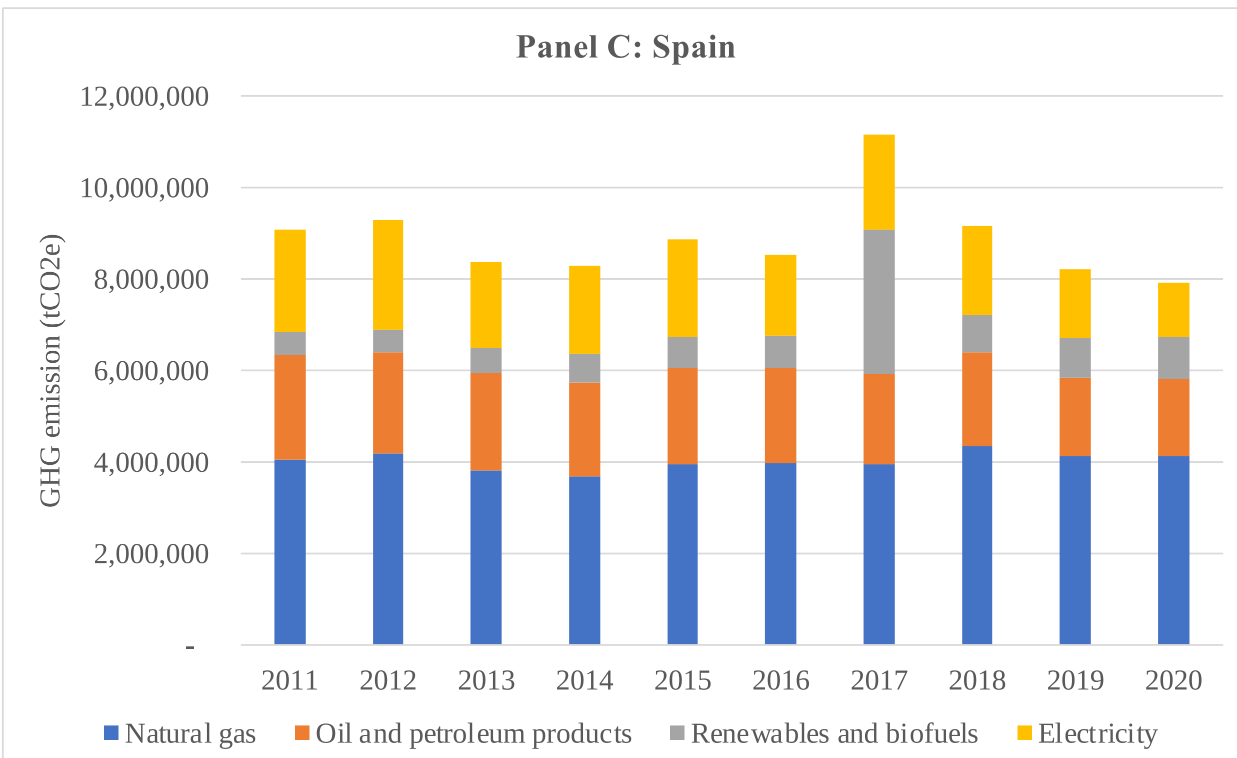
In Spain, emissions from natural gas contributes to over half of the total emissions in 2019 and 2020. There is an abrupt increase in GHG emissions from renewables and biofuels in 2017. The sudden increase is also present in the raw energy consumption data for unknown reasons. Along with the rising proportion of natural gas emissions, emissions from electricity and oil and petroleum products are gradually decreasing (Figure 3 Panel C).

In France, nuclear power accounts for 69% of total electricity generation in 2021 (Alves, 2022). Hydropower plants ranked second with 10.7% percent. With the highest proportion of nuclear electricity in the world and a strong reliance on renewable energy sources, the grid electricity in

France has low carbon intensity. For example, the final consumption of electricity in France is two-fold in Germany in 2019. However, the GHG emissions from electricity in France is one-third of that in Germany. Emissions from natural gas account for 45% of the total emissions (Figure 3 Panel D). Switching from natural gas to green electricity or renewable energy is a feasible path for France.




Panel B: Italy
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
-
GHG emissions (tCO2e)
2015
2016
2017
2018
2019
2020
Natural gas
Oil and petroleum products
Renewables and biofuels
Electricity


Panel C: Spain
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
-
GHG emission (tCO2e)
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Natural gas
Oil and petroleum products
Renewables and biofuels
Electricity

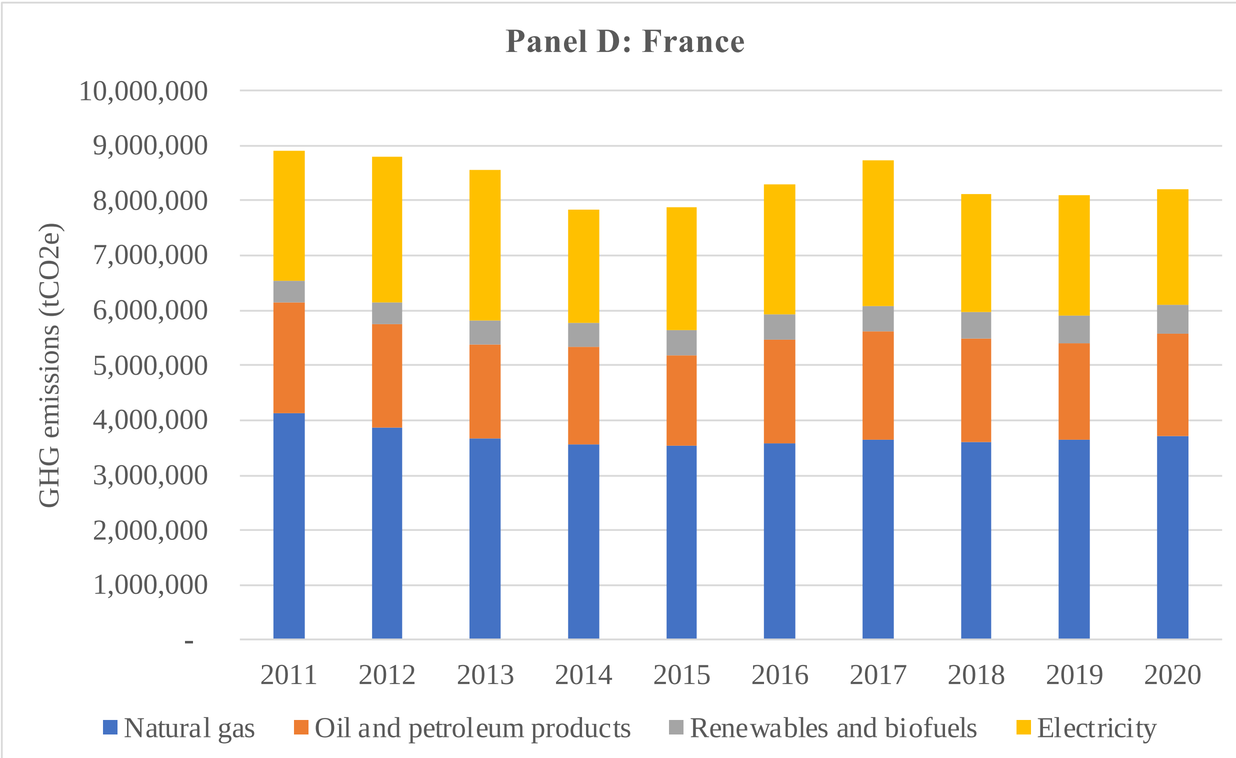


Figure 3 GHG emissions from energy consumption in household water heating in Germany, Italy, Spain and France from 2011 to 2020 (by energy source)

3.2 GHG mitigation potential in domestic hot water

Simulating the GHG mitigation potential requires a base year and baseline emissions set for 2020. Since each country has a different energy structure and varies in the distribution of water heaters, the contribution of each energy source to GHG emissions varies (Figure 4). In general, gas boilers account for the most significant proportion in many countries (e.g., Netherlands, Italy, Luxemburg, Spain, Slovakia, Romania, etc.). For these countries, replacing existing gas boilers with cleaner water heaters is supposed to be the most efficient way to reduce GHG emissions from domestic hot water in terms of the reduction potential. However, the cost varies because the stock in each country differs.

In some countries, electricity has the largest share of GHG emissions (Figure 4). The high grid emission factor and the large stock of electric water heaters in operations can explain the high proportion of electricity. For example, the emission factor of electricity in Czechia is the highest among the EU countries, so electricity water heaters account for over 55% of GHG emissions from domestic hot water.

One thing to note is missing data for some countries in the original dataset. For instance, the final energy consumption from gas in Malta and Cyprus is unavailable.

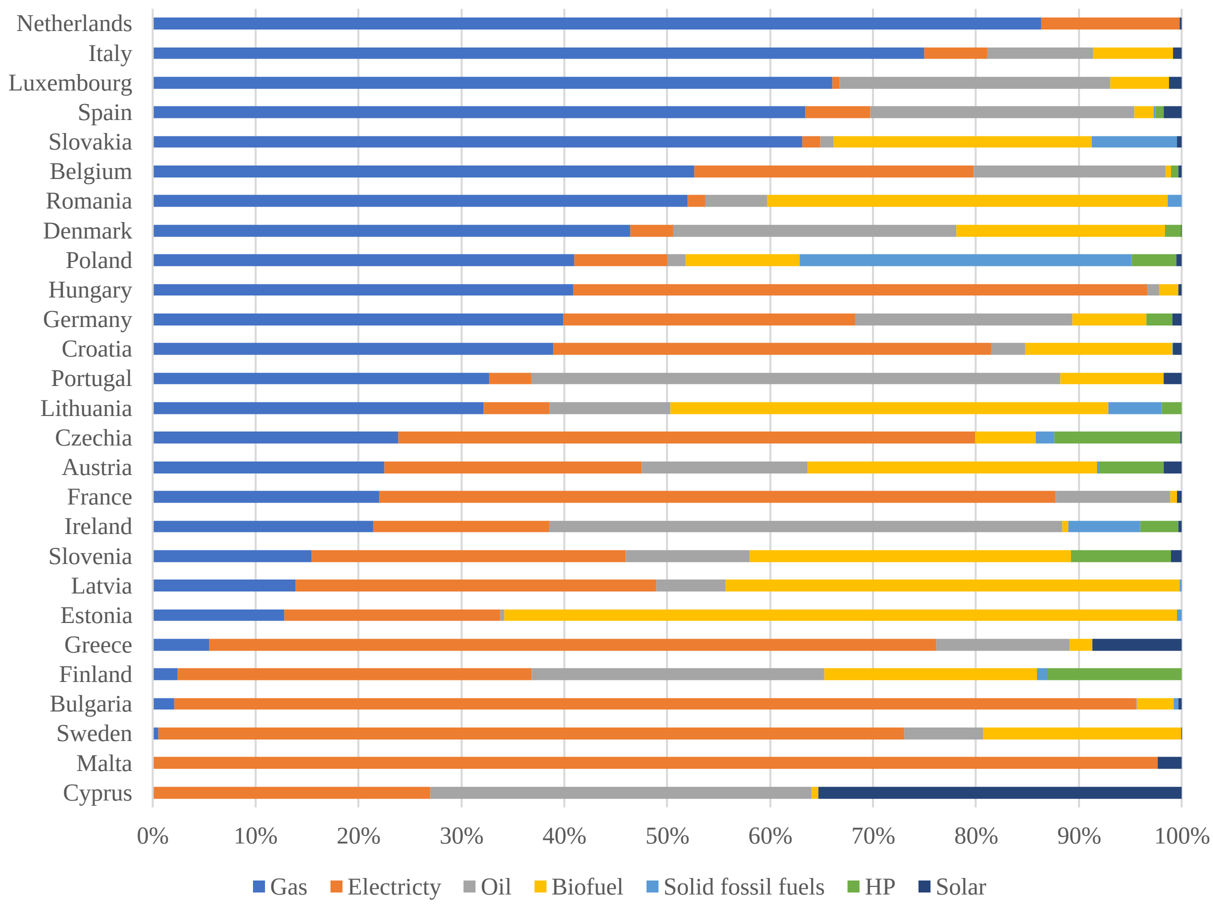


Figure 4 Fraction of GHG emissions from domestic hot water in 2020 (by country and energy source)

In 2020, the majority of GHG emissions came from the use of natural gas (41%) and electricity (32%), specifically due to the use of the EIWH, ESWH, GIWH, and GSWH (Figure 5). The third largest source of GHG from domestic hot water is oil heating, accounting for 15%. Therefore, these three major energy sources of heating are the ones that are switched the most times in the scenarios. It is worth noting that although the energy source of the heat pump is also electricity, it is separated from the EIWH and ESWH due to its higher energy efficiency.

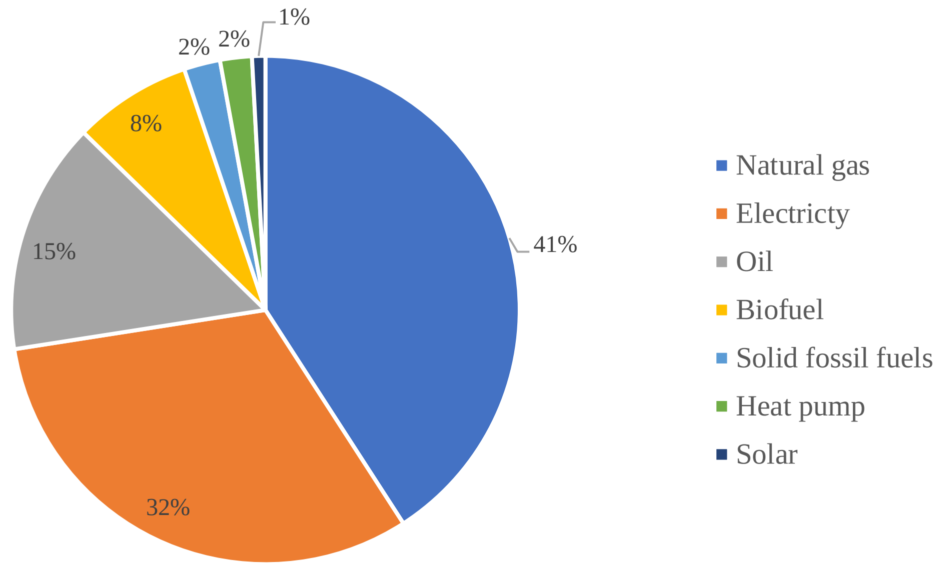


Figure 5 Contribution of energy sources to EU GHG emissions from domestic hot water in 2020

By quantifying the increase or decrease in GHG for each country in each scenario, this study found the most preferred scenario in terms of GHG reduction potential differs in each country and climate zone (

Table 1 and Figure 6). In general, switching to solar water heating has the strongest potential for decarbonization in domestic hot water. There are 13 EU member states where solar water heating is the best option (i.e., having the largest abatement potential among six scenarios).

Table 1 Scenarios with the greatest potential for GHG mitigation in each EU member state

Scenario	Countries with the highest GHG mitigation potential
1	Spain, Croatia, Italy, Netherlands, Poland, Slovakia
2	Estonia, France, Latvia, Romania
3	Denmark, Belgium, Germany
4	Austria, Bulgaria, Czechia, Greece, Hungary, Ireland, Slovenia
5	Sweden
6	Finland, Portugal

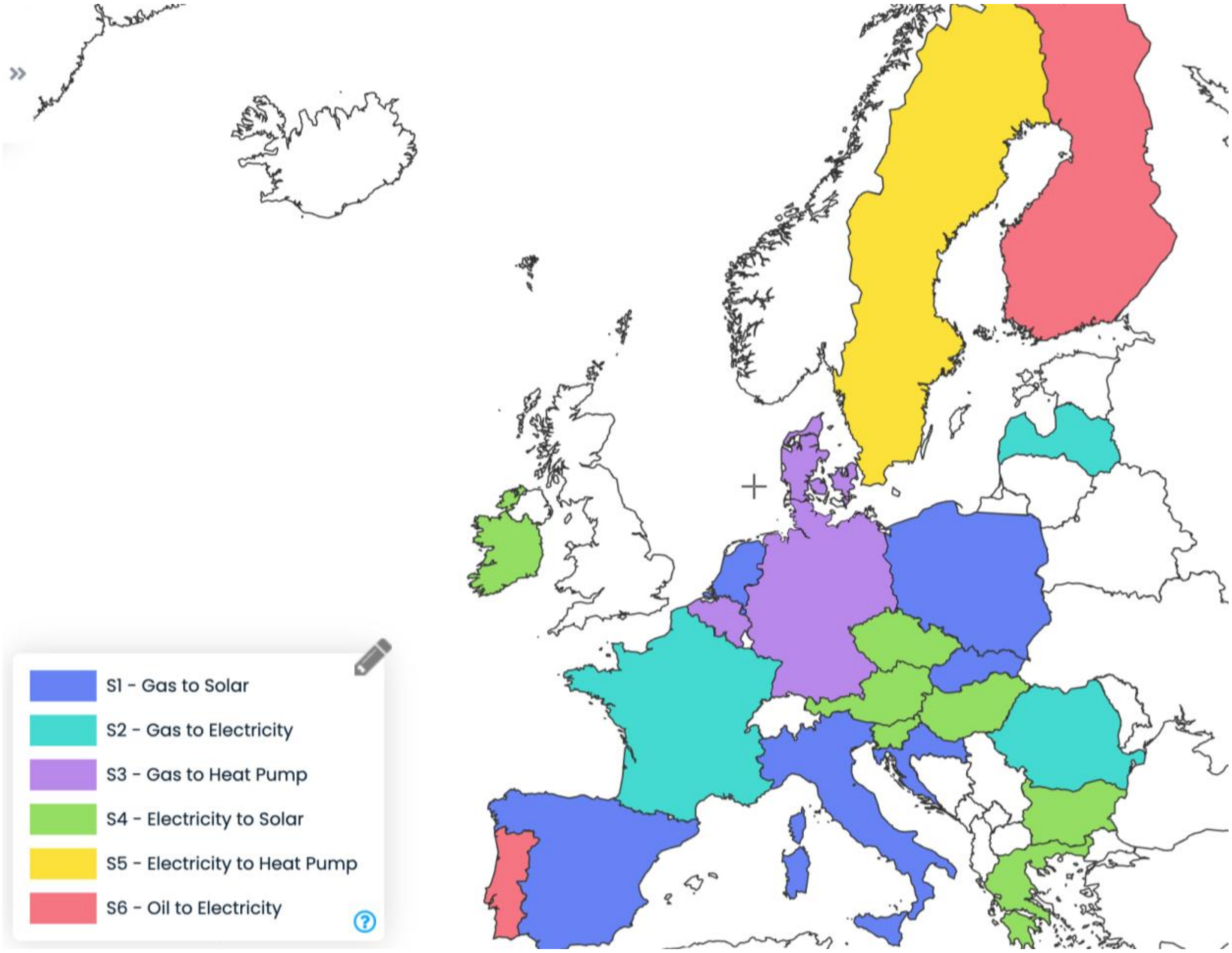


Figure 6 Scenario with highest GHG abatement potential by country

(Created by https://www.scribblemaps.com/)

Portugal and Spain, both in the Mediterranean climate, are suitable for different scenarios. For Spain, replacing the existing 2,115,000 dwellings of natural gas water heaters with solar water heaters would have the best carbon mitigation effect. Spain has good sunshine conditions and high average temperatures, so solar water heaters can fulfill the residents' hot water demand. Portugal, which has the same excellent conditions, is suitable for another scenario, which is the replacement of 34,200 oil heating units. The reason is that the per-unit energy consumption of oil heating equipment in Portugal is extremely higher than other heaters, and the urgency of being replaced is greater than that of electric water heaters. In addition, electric water heaters have the highest energy efficiency in Portugal, partly because they are newer installations. Replacing the heating equipment with the highest GHG emissions per unit with the heaters that emits the least is the most promising scenario for decarbonization. However, in terms of the magnitude of simulated GHG reductions, the best scenario in Spain will reduce more GHG because of the conversions of greater amount of water heaters.

Many countries in the western and northern regions of Europe have a temperate oceanic climate, such as Ireland, France, the Netherlands, and the northern regions of Germany. The climate in these areas is mild and humid, with abundant rainfall, relatively warm winters, and cool summers. Temperate oceanic climate can have an impact on water heater efficiency, as it affects the temperature of the incoming water supply. In areas with a temperate oceanic climate, the incoming water supply temperature is usually cooler compared to areas with a warmer climate. This means that water heaters in temperate oceanic climates may need to work harder to heat up the water to the desired temperature, resulting in higher energy consumption and lower efficiency. To compensate for this, water heaters in temperate oceanic climates may need to have a higher energy efficiency rating to ensure they are operating at their maximum efficiency. This can be achieved by installing a water heater that is specifically designed for use in cooler climates, such as a heat pump water heater or a tankless water heater. These types of water heaters are designed to provide more efficient heating in colder temperatures, which can help reduce energy usage and lower energy bills.

Though the countries are in the same climate zone, they have different GHG mitigation potentials for the same scenario. France and the Netherlands are both in a temperate oceanic climate zone, but the per-unit GHG emissions of gas-fired water heaters in the Netherlands (6.57 metric tons of CO_2e) are six times higher than that in France (1.07 metric tons of CO_2e).

3.3 GHG mitigation cost in domestic hot water

Spatial variation of GHG mitigation cost is investigated by comparing upfront cost and energy bill saving per dwelling in each member state. Upfront cost includes water heater purchase cost, installation fee, and maintenance fee. Electric water heaters are less expensive than other water heaters, so Scenario 2, assuming a switch from gas to electric water heaters, has the lowest upfront investment in all countries. In terms of clean energy scenarios, the investment in solar water heaters is higher than that in heat pumps (Table 2). Results for Cyprus, Estonia, Luxembourg, Malta, and

Slovenia are unavailable due to data limitations. The difference in the price level of home appliances between countries leads to the difference in upfront investment.

Table 2 Upfront cost per dwelling under scenarios (in euro)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
AT	5,262	820	2,965	4,804	2,965
BE	2,769	432	1,560	2,528	1,560
BG	1,662	259	936	1,517	936
CZ	2,077	324	1,170	1,896	1,170
DE	4,431	691	2,497	4,046	2,497
DK	5,816	907	3,277	5,310	3,277
ES	2,077	324	1,170	1,896	1,170
FI	-	-	-	3,793	2,341
FR	3,600	561	2,028	3,287	2,028
GR	2,077	324	1,170	1,896	1,170
HR	1,662	259	936	1,517	936
HU	2,077	324	1,170	1,896	1,170
IE	2,769	432	1,560	2,528	1,560
IT	2,077	324	1,170	1,896	1,170
LT	2,077	324	1,170	1,896	1,170
LV	2,077	324	1,170	1,896	1,170
NL	2,769	432	1,560	2,528	1,560
PL	2,077	324	1,170	1,896	1,170
PT	2,077	324	1,170	1,896	1,170
RO	1,662	259	936	1,517	936
SE	6,923	1,079	3,901	6,321	3,901
SK	2,077	324	1,170	1,896	1,170

The spatial difference in scenarios is more apparent regarding annual energy bill saving, mainly attributed to the difference in energy price and energy consumption intensity of water heaters in each country. Switching to heat pumps and solar water heaters can save homeowners large energy bills. However, the saving potential of heat pumps in domestic hot water is below the expectation

(Table 3). One possible explanation is that heat pumps are used for water heating and space heating. The energy-saving potential for space heating is beyond the scope of this paper, but it is expected to have a larger energy bill saving if combining space heating and water heating for heat pumps.

Table 3 Energy bill saving per dwelling under scenarios (in euro)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
AT	1,150	681	554	469	127
BE	1,378	714	1,332	664	618
BG	965	784	965	182	182
CZ	1,677	851	885	825	33
DE	2,119	1,634	1,827	485	193
DK	1,931	1,719	1,844	212	125
EE	968	918	968	50	50
ES	556	367	518	190	152
FI	-	174	97	174	77
FR	887	632	887	255	255
GR	1,770	1,601	1,770	169	169
HR	615	434	615	180	180
HU	369	84	369	453	453
IE	702	-183	158	885	25
IT	1,548	1,353	1,548	195	195
LT	934	866	813	68	53
LV	3,118	2,855	3,118	262	262
NL	3,817	3,518	3,817	300	300
PL	929	762	180	167	942
PT	106	50	106	55	55
RO	2,293	2,278	2,293	14	14
SE	338	1,410	122	1,748	1,532
SI	233	7	81	226	74
SK	5,944	5,882	5,944	62	62

4. Discussion

4.1 Spatial variation within the EU

The spatial variation of GHG abatement potential and cost from domestic hot water across the EU is complex and depends on several factors, including the energy mix, climate conditions, and building stock.

The energy mix used to generate electricity and heat varies across EU member states. Countries that rely heavily on fossil fuels for electricity generation and heating will have a higher GHG emissions intensity associated with water heating. In contrast, countries that have a higher proportion of renewable energy sources in their energy mix will have lower GHG emissions from water heating. For example, in 2019, coal and other solid fuels accounted for over 40% of electricity generation in Poland, resulting in a high GHG emissions intensity associated with water heating in Polish households. In contrast, countries like Sweden, which has abundant hydroelectric and nuclear power, rely less on fossil fuels for electricity generation and heating. As a result, Swedish households have a lower GHG emissions intensity associated with water heating.

The climate conditions in different EU member states also play a significant role in determining the GHG abatement potential and cost from domestic hot water. Countries with colder climates will require more energy to heat water, resulting in higher GHG emissions from water heating. However, these same countries may have considerable potential for using renewable energy sources, such as solar thermal systems or heat pumps, which could significantly reduce GHG emissions. For example, Finland has a cold climate and a high demand for domestic hot water. However, Finland also has abundant forest resources, making it an ideal location for generating biomass-based heat and electricity. By utilizing biomass-based heating technologies, Finnish households can significantly reduce GHG emissions from domestic hot water, despite their high demand for hot water.

The building stock in different EU member states can also affect the GHG abatement potential and cost from domestic hot water. Buildings that are well insulated and use efficient heating technologies will require less energy to heat water, resulting in lower GHG emissions. Additionally, buildings that have been retrofitted with renewable heating technologies, such as solar thermal panels or heat pumps, can significantly reduce GHG emissions from water heating. For instance, Germany has been retrofitting its building stock with energy-efficient technologies and renewable heating sources under its Energiewende program. This initiative aims to transition Germany to a low-carbon economy by 2050. The installation of solar thermal systems and heat pumps in German households can help to reduce GHG emissions from domestic hot water while also reducing overall energy consumption.

Spatial differences exist not only between countries, but also within the same country, especially in countries with a large geographical span. Germany has a cold climate and a significant proportion of its energy mix comes from coal and natural gas. However, the country has ambitious policies aimed at reducing GHG emissions, and it has made significant progress in increasing the share of renewable energy sources in its energy mix. The potential for using renewable energy sources to heat water varies across Germany, depending on the availability of sunlight and wind. The southern regions of Germany have a higher potential for solar thermal systems, while the northern regions have better wind resources, which could be used for generating electricity to power heat pumps. In terms of building stock, Germany has a large number of older buildings that require significant energy improvements. Retrofitting these buildings with efficient heating technologies, such as heat pumps or solar thermal systems, could significantly reduce GHG emissions from water heating.

The results have limitations due to insufficient data. First, this study only considers GHG emissions from direct energy consumption. Fugitive emissions, including methane and nitrous oxide from natural gas leaks, are not accounted for in the GHG inventory. Other indirect emissions from upstream and downstream of water heater production, energy delivery, and energy recovery are out of the research scope. Increasing spatial characteristics may appear by considering the data mentioned above. Second, district heating is excluded in the design of the abatement scenario. Due to the data limit, GHG emissions from district heating cannot be calculated by unit (i.e., per dwelling) in the same way as a dedicated water heater. Third, due to the unpredictability of energy costs, this study only considers short-term installation and energy bills instead of long-term payback of investments. The change in energy structure and future energy prices of EU member states vary.

4.2 Influencing factors of GHG emissions from domestic hot water

GHG emissions from hot water can be decomposed into several sources, including the type of fuel used, the efficiency of the water heater, and the amount of hot water used, etc. (Figure 7). By decomposing GHG emissions from water heating into these sources, it is possible to identify areas where improvements can be made to reduce emissions, such as switching to a more efficient water heater or reducing hot water usage.

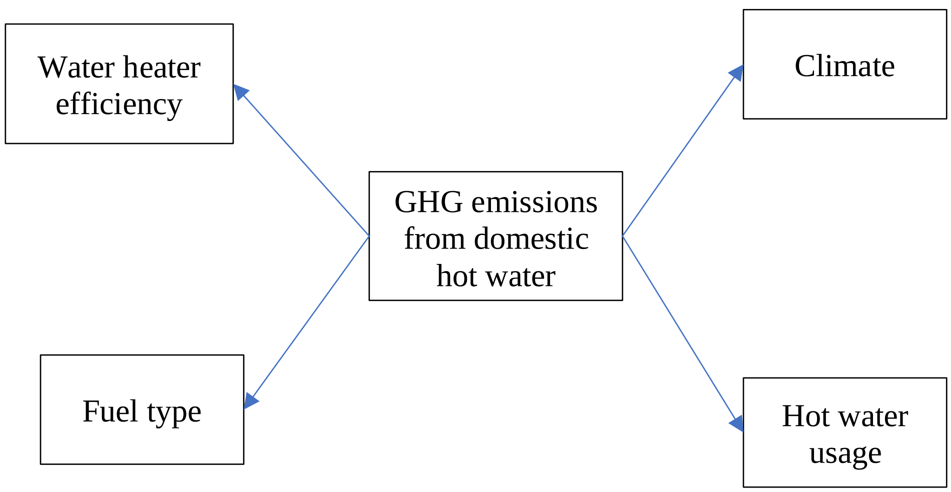


Figure 7 Factors associated with GHG emissions from domestic hot water

The type of fuel used for water heating has a significant impact on GHG emissions. For example, natural gas produces fewer GHG emissions than fossil fuels. Renewable energy sources such as solar thermal or geothermal systems can also significantly reduce GHG emissions from water heating. In the case of electricity, the fuel sources for electricity generation in the EU vary by country, the composition of which also affects the GHG emissions from hot water. Most EU countries have a diverse mix of fuel sources for its electricity grid. Main sources include fossil fuels, nuclear power, and renewable energy (e.g., hydropower, wind power, solar power, etc.). The fuel mix and the efficiency of the power generation technology have a significant impact on the emission factor.

Water heater efficiency is another important factor in GHG emissions. Older, less efficient water heaters consume more energy and emit more GHG emissions than newer, more efficient models. Choosing a high-efficiency water heater, such as a tankless or heat pump water heater, can significantly reduce GHG emissions. In addition, the type and size of water heater affect the efficiency. For example, tankless water heaters are generally more efficient than traditional storage tank water heaters because they heat water on demand and do not store hot water. A water heater that is too small for a household's needs may have to work harder to keep up with demand, which can reduce its efficiency. On the other hand, a water heater that is too large may waste energy by constantly heating excess water. Water temperature also influences efficiency. Higher water temperatures require more energy to heat, so setting the water heater temperature lower can improve efficiency.

Hot water usage also contributes to GHG emissions from water heating. Reducing hot water usage through behavioral changes, such as taking shorter showers or washing laundry in cold water, can help reduce GHG emissions.

Other factors that can affect GHG emissions from water heating include the size of the home, the number of occupants, and the climate zone. The climate zone where a home is located can affect the efficiency and performance of a water heater. Homes located in colder climates require more energy to heat water because the incoming water is colder. This can result in higher energy consumption, higher GHG emissions, and higher energy bills for homeowners. In colder climates, thicker insulation is required around the water heater tank to prevent heat loss and maintain the water temperature. Water heaters may need additional insulation or heating elements to prevent freezing. In warmer climates, solar water heaters can be an efficient and cost-effective option for heating water. These systems work best in areas with abundant sunshine, so they may not be as effective in colder, cloudier climates. Government should take into account their climate zone when promoting a water heater and consider factors such as insulation, energy consumption, and freeze protection.

4.3 Policy analysis

4.3.1 EU Policy review

In July 2021, the EU proposed a Fit for 55 packages to reduce the EU GHG emissions by 55% by 2030 (European Council, 2021). The EU has implemented energy efficiency regulations for water heaters in order to achieve the GHG abatement target. The current EU policy on water heaters is established by the EU directive on ecodesign (Directive 2009/125/EC) and energy labelling (Regulation 2017/1369). The Ecodesign Directive sets minimum energy efficiency requirements for water heaters, which are designed to improve the performance of these products while reducing their environmental impact. The directive covers a range of water heaters, including electric storage water heaters, gas-fired storage water heaters, and instant water heaters. The Energy Labelling Directive requires manufacturers to label their products with an energy efficiency rating, which ranges from A+++ (most efficient) to G (least efficient). This label provides consumers with information about the energy efficiency of different water heaters, allowing them to make informed purchasing decisions. These regulations aim to reduce the energy consumption of appliances and promote the use of more efficient technologies. By limiting the energy used in heating water, these regulations indirectly contribute to GHG abatement by reducing the amount of CO_2 released during the combustion of fossil fuels.

In addition to minimum energy performance standards and labeling requirements, the EU has also introduced several initiatives to promote the use of renewable energy sources in water heating. The Renewable Energy Directive (RED II) (Directive 2018/2001/EU) requires member states to increase the share of renewable energy sources in heating and cooling by at least 1.3 percentage points each year from 2021 to 2030. This initiative will stimulate the production and use of solar thermal panels and heat pumps, which can provide hot water using renewable energy sources. Furthermore, the EU is currently developing renewable hydrogen production strategies, which could have applications in water heating systems.

In order to accomplish the urgent GHG emission reductions needed to meet the EU's higher climate aspirations, the directive's goals and measures have undergone several revisions. The Commission put out a new amendment in July 2021 in an effort to hasten the adoption of renewable energy sources in the EU and support the achievement of the 2030 energy and climate goals. The regulation establishes a uniform goal for the share of renewable energy in the EU's energy consumption by 2030, which is now 32%. The REPowerEU plan (COM/2022/230 final), which was presented in May 2022, designed to reduce dependence on Russian fossil fuels, and the proposed amendment both imply further development of the goal to 45% by 2030 to hasten the adoption of renewable energy in the EU, notably by accelerating the permission procedures for the deployment of renewable energy. Some policies are associated with domestic hot water, e.g., the objective of doubling the heat pump deployment rate.

Regarding renewable energy use, the RED II Initiative is an ambitious plan to increase the use of renewable energy sources in heating and cooling. If implemented effectively, this initiative could significantly contribute to GHG abatement by reducing the reliance on fossil fuel-based heating systems. However, it remains to be seen how effectively individual nations will implement this directive and what incentives will be provided to encourage the uptake of renewable heating technologies.

Additionally, the EU's Ecodesign Working Plan 2016-2019 (COM/2016/0773 final) included measures to improve the energy efficiency of water heaters and promote the use of renewable energy sources. Under this plan, the EU introduced new minimum energy efficiency requirements for water heaters, including stricter requirements for energy efficiency, insulation, and control systems. The plan also addressed the issue of standby losses, which occur when heat is lost from the water heater tank even when no hot water is being used.

The implementation of these policies has been effective in improving the energy efficiency of water heaters, thereby reducing the amount of GHG emissions generated from heating water. According to the European Commission, energy efficiency measures implemented under the Eco-design Directive have helped to reduce GHG emissions by 840 million tonnes of CO_2e between 2005 and 2018. However, the reduction in GHG emissions from water heaters is only one part of the overall emissions reductions required to achieve the EU's climate targets.

Many EU countries provide subsidies or incentives to encourage consumers to improve the efficiency of their water heaters. These incentives vary by country and can include rebates, tax credits, and grants for the purchase of energy-efficient water heaters or for upgrading existing ones. For example, in Germany, the Federal Office for Economic Affairs and Export Control (BAFA) offers grants for the installation of renewable heating systems, including solar thermal water heaters (BAFA, n.d.). The grant amounts vary depending on the type of system and the size of the home. The Energy Efficiency Fund provides subsidies for the installation of energy-efficient heating systems, including efficient water heaters. The subsidies are available to homeowners, landlords, and companies. In France, the government's Energy Transition Tax Credit (CITE) provides tax incentives for the purchase and installation of energy-efficient water heaters (Schneller & Hennig, 2018). In addition, some EU countries have implemented energy efficiency standards for buildings, which include requirements for efficient water heaters. These standards may require the installation of high-efficiency water heaters in new buildings or as part of major renovations.

However, the implementation and effectiveness of these policies and regulations can vary significantly between EU member states. Some countries may have more stringent regulations, while others may not enforce them effectively. Despite evidence that subsidies for new gas boilers in households are hindering the adoption of renewable heating and contradicting Europe's 2030 climate goals, most EU governments still provide millions of euros in subsidies for traditional water heaters (European Environmental Bureau, 2021). As part of their budgetary or climate policies, only 7 EU nations (i.e., Croatia, Estonia, Ireland, Lithuania, Luxembourg, Malta, and the Netherlands) have so far halted the torrent of public funds from being used to subsidize the construction of fossil fuel heating systems. At least 16 of the 27 EU members still provide tax breaks, loans, or grants (between €200 and €2,500) to encourage individuals to purchase or install new gas boilers (European Environmental Bureau, 2021). According to the EU's water heater energy policy, these incentives were intended to encourage residents to use more energy-efficient and sustainable water heaters (Directive 2018/2001/EU), but the governments are promoting the installation and use of water heaters that are not environmentally friendly for reasons other than sustainability, e.g., creating jobs. Additionally, 8 countries still offer subsidies for oil boilers, and in Belgium and Hungary, there are still support schemes for coal heating. Finally, 14 governments are promoting hybrid solutions that combine both fossil and renewable heating.

Due to the differences in existing policies on incentivizing water heaters and GHG abatement potential and cost results across countries, it is important to develop national policies for GHG mitigation in domestic hot water in addition to union-level policies.

4.3.2 Policy implication

Improving energy efficiency and reducing hot water usage are two of the most fundamental carbon reduction measures in domestic hot water. However, in developing and improving policies related to domestic hot water, we need to be aware of the spatial variation across the EU. Policies should be tailored to specific climatic conditions, energy mix, socio-economic factors, and infrastructure. It is fundamental to ensure that policies are effective, feasible, and do not disproportionately affect certain regions or countries.

The EU could establish stricter minimum energy efficiency standards for water heaters, encouraging the adoption of more efficient models that consume less energy and emit fewer GHG emissions. The country-and type-specific per-unit energy consumption result implies gas-fired water heaters are energy inefficient but the degree of inefficiency varies across countries. Therefore, instead of increasing minimum energy efficiency standards to a uniform EU specification, each member state could set its own national minimum standards based on the average energy consumption of water heater models. This could be done through the recast of Eco-design Directive, which sets energy efficiency requirements for products sold in the EU.

The EU could promote renewable energy sources through incentivizing the use of renewable energy sources, such as solar thermal or heat pumps, for water heating. This is in progress through subsidies, tax credits, or other financial mechanisms that make these technologies more affordable and accessible to consumers.

First, subsidies for fossil fuel heating are one that needs to be reduced or eliminated. Belgium, Hungary, and Poland have subsidies or tax reduction incentives for all three types of fossil energy water heaters (Table 4). For these three countries, it is most urgent to remove their dependence on solid fossil fuels (i.e., coal boilers), which have the highest emission factor and pose other environmental hazards, such as the harmful gases that accompany combustion. At current stage, these three countries do not need to immediately remove subsidies for gas heaters because of their relatively high energy efficiency compared to coal and oil. It is worth noting that all three countries have incentives for all types of heat pump, biomass, and solar thermal heating. Even with subsidies, Hungary has the lowest number of heat pump installations per capita among EU member states. The long recovery period is the main reason. A one-earner-couple with two children could take 4 years to recover the installation costs in Belgium, however, a same size family in Hungary and Poland still take roughly 8 years to recover it.

Table 4 Incentives for fossil heating by country

Incentive	Country
Incentives for coal boilers	Belgium, Hungary, Poland
Incentives for oil boilers	Belgium, France, Greece, Hungary, Italy, Latvia, Poland, Sweden
Incentives for gas boilers	Belgium, Bulgaria, Cyprus, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden

Second, the majority of member states encourage the use of heat pumps and solar heating as sources of renewable energy for water heating in one way or another. These subsidies can make the transition to sustainable energy more affordable for residents, but to varied degrees in every country. Both in terms of support levels and accessibility, the support programs for renewable heating are highly variable. Some programs have very small budgets and are only available for a short period of time. The variety of programs now in place results in significant variations from nation to nation for the average home wishing to transition to renewable heating. For example, the governments only provide loans as an incentive for air source heat pumps, so residents of Bulgaria, Croatia, and Latvia need more than 15 years to pay back their investment. In contrast to heat pumps, gas boilers only take approximately 5 years to repaid in these countries.

The EU could raise awareness among consumers about the benefits of energy-efficient water heaters and the impact of their choices on GHG emissions. This could be done through public education campaigns, labeling requirements, and energy performance certificates that provide information about the energy efficiency of appliances. For countries in different climatic zones, governments can raise awareness of the residents through different means. For example, homeowners can take steps to improve water heater efficiency in temperate oceanic climates. This can include insulating the hot water pipes, installing a timer or smart thermostat to control water heater usage, and reducing hot water usage by taking shorter showers or using a low-flow showerhead. By implementing these measures, homeowners can help improve water heater efficiency and reduce their energy consumption in temperate oceanic climates.

The EU could strengthen monitoring and enforcement of existing policies related to water heaters. This could be done through more rigorous testing and certification procedures, as well as penalties for manufacturers and retailers that do not comply with energy efficiency standards or other regulations.

Overall, improving existing policy on water heaters in the EU requires a combination of regulatory, financial, and educational measures that encourage the adoption of more energy-efficient, low-carbon, and sustainable technologies.

5. Conclusion

As energy efficiency increases in the building sector, GHG emissions from domestic hot water have decreased in the EU since 2017. However, following the current trend of reducing emissions, fulfilling the 2030 climate goals would be challenging. Natural gas, a significant source of GHG emissions from domestic hot water, needs to be replaced by cleaner and more efficient water heaters. The results indicate that solar water heaters have the most tremendous GHG abatement potential in a dozen EU member states, most of which are in a warm climate. Solar water heaters require a substantial upfront investment in each country, but annual savings in energy bills can pay them off after a few years. Heat pumps perform the best in the Scandinavian countries. The payback period could be shortened if energy savings in space heating are also considered.

Policies related to water heaters and GHG reduction in the EU need to consider various factors, including spatial variation among member states. Developing policies tailored to the specific climatic conditions, energy mix, socio-economic factors, and infrastructure of each member state is crucial to ensure that policies are practical, feasible, and do not disproportionately affect certain regions or groups. To encourage the adoption of more energy-efficient and sustainable water heaters, EU member states offer financial incentives, subsidies, regulations and standards, and green public procurement policies. However, it is essential to note that the types and effectiveness of incentives may vary widely among EU member states.

Despite the efforts to promote sustainable heating, there is still evidence that some EU governments continue to incentivize the installation of new gas boilers, undermining Europe's 2030 climate goals. It highlights the need for more robust policies that prioritize the adoption of renewable heating systems, such as solar thermal or heat pumps, and phase out the use of fossil fuel heating. In addition, the EU needs to be developed in a way that considers spatial variation among member states and prioritizes the adoption of sustainable heating systems. By doing so, the EU can take a significant step towards achieving its climate goals and promoting a more sustainable future.

Further research may explore GHG abatement potential on behavioral change. In addition to converting water heaters, perceptions and behaviors of residents are also critical to GHG reduction in domestic hot water. For example, homeowners can reduce GHG emissions by shortening the showering time or lowering the water temperature. A future study could assess the impact of changes in daily water use habits on GHG emissions. There might also be some spatial variation in the results, thus improving existing energy policies in each country.

References

Alves, B. (2022, Feb 10). *Power production breakdown in France 2021, by source*. Statista. https://www.statista.com/statistics/1235410/france-distribution-of-electricity-production-by-source/

BAFA. (n.d.). Energy & Climate Protection. https://www.bafa.de/EN/Energy/energy_node.html

Bors, J., Kenway, S., Satur, S., Skinner, R., Smith, L., Lam, K.L. (2021). Phase 1 Draft Report: Drivers for energy reduction in the use of water in residential households - Opportunities. Melbourne, Australia: Monash Sustainable Development Institute (and The University of Queensland), Monash University, April 2021.

Chini, C. M., Schreiber, K. L., Barker, Z. A., & Stillwell, A. S. (2016). Quantifying energy and water savings in the US residential sector. *Environmental science & technology*, *50*(17), 9003-9012.

CIWEM. (2013). A blueprint for carbon emissions reduction in the UK water industry.

COM/2016/0773 final. *Ecodesign Working Plan 2016-2019*. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52016DC0773

COM/2022/230 final. *REPowerEU Plan*. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

Copeland, C., & Carter, N. T. (2017). Energy-water nexus: The water sector's energy use.

Day, D., & White, S. (2003). Minimum performance standards for showerheads in Australia: the benefits and the barriers. *Water Science and Technology: Water Supply*, *3*(3), 239-245.

Directive 2009/125/EC. *Establishing a framework for the setting of ecodesign requirements for energy-related products (recast)*. European Parliament and Council. http://data.europa.eu/eli/dir/2009/125/oj

Directive 2018/2001/EU. *On the promotion of the use of energy from renewable sources (recast)*. European Parliament and Council. http://data.europa.eu/eli/dir/2018/2001/oj

Enerdata. (2021). Evolution of households energy consumption patterns across the EU.

Energy Saving Trust. (2013). At home with water.

Environment Agency. (2009). A low carbon water industry in 2050.

EurObserv'ER. (2021). Heat pumps barometer 2021. https://www.eurobserv-er.org/heat-pumps-barometer-2021/

European Council. (2021). Fit for 55. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

European Environmental Bureau. (2021). Analysis of the existing incentives in Europe for heating powered by fossil fuels and renewable sources.

Eurostat. (2023). Disaggregated final energy consumption in households – quantities [Data set]. https://ec.europa.eu/eurostat/databrowser/view/NRG_D_HHQ$DEFAULTVIEW/default/table?lang=en

Eurostat. (2023). Electricity prices for household consumers - bi-annual data (from 2007 onwards) [Data set]. https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_204/default/table?lang=en&category=nrg.nrg_price.nrg_pc

Eurostat. (2023). Gas prices for household consumers - bi-annual data (from 2007 onwards) [Data set]. https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_202/default/table?lang=en&category=nrg.nrg_price.nrg_pc

Farrel, H. (2022, May 31). *EU Heat Pumps: warnings against "one size fits all" policies.* Energy Post. https://energypost.eu/eu-heat-pumps-warnings-against-one-size-fits-all-policies/

Greene, C. (2022). EurEau Annual Report 2021. EurEau. https://www.eureau.org/resources/publications/annual-reviews/6454-eureau-annual-report-2021-1/file

Griffiths-Sattenspiel, B., & Wilson, W. (2009). The carbon footprint of water. *River Network, Portland*.

He, G., Zhao, Y., Wang, J., Zhu, Y., Jiang, S., Li, H., & Wang, Q. (2019). The effects of urban water cycle on energy consumption in Beijing, China. *Journal of Geographical Sciences*, *29*(6), 959-970.

IEA. (2021). Renewables 2021: Analysis and forecast to 2026. https://www.iea.org/reports/renewables-2021/executive-summary

IEA. (2022). Emissions Factors 2022 [Data set]. https://www.iea.org/data-and-statistics/data-product/emissions-factors-2022

IPCC. (2019). 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories.

Jones, C. M., & Kammen, D. M. (2011). Quantifying carbon footprint reduction opportunities for US households and communities. *Environmental science & technology*, *45*(9), 4088-4095.

Kemna, R., & van Elburg, M. (2019). Review Study existing ecodesign & energy labelling Water Heaters & Tanks: Task 3. European Commission.

Kemna, R., van Elburg, M., Aarts, S., & Corso, A. (2019). Review Study existing ecodesign & energy labelling Water Heaters & Tanks: Task 2. European Commission.

Kenway, S. J., Binks, A., Lane, J., Lant, P. A., Lam, K. L., & Simms, A. (2015). A systemic framework and analysis of urban water energy. *Environmental Modelling & Software*, *73*, 272-285.

Kenway, S. J., Lam, K. L., Stokes-Draut, J., Sanders, K. T., Binks, A. N., Bors, J., ... & McMahon, J. E. (2019). Defining water-related energy for global comparison, clearer communication, and sharper policy. *Journal of Cleaner Production*, *236*, 117502.

Kerr, N., & Winskel, M. (2021). A review of heat decarbonisation policies in Europe.

Kesicki, F., & Ekins, P. (2012). Marginal abatement cost curves: a call for caution. *Climate Policy*, *12*(2), 219-236.

Koffi B., Cerutti A.K., Duerr M., Iancu A., Kona A., Janssens-Maenhout G. (2017). *Covenant of Mayors for Climate and Energy: Default emission factors for local emission inventories–Version 2017*, EUR 28718 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-71479-5, doi:10.2760/290197, JRC107518.

Lam, K. L., & van der Hoek, J. P. (2020). Low-carbon urban water systems: Opportunities beyond water and wastewater utilities?. *Environmental science & technology*, *54*(23), 14854-14861.

Lam, K. L., Kenway, S. J., & Lant, P. A. (2017). City-scale analysis of water-related energy identifies more cost-effective solutions. *Water research*, *109*, 287-298.

Lee, M., & Tansel, B. (2012). Life cycle based analysis of demands and emissions for residential water-using appliances. *Journal of Environmental Management, 101*, 75-81.

Lo Vullo, E., Muntean, M., Duerr, M., Kona, A. & Bertoldi, P. (2020). GHG Emission Factors for Electricity Consumption. European Commission, Joint Research Centre (JRC) [Data set]. PID: http://data.europa.eu/89h/919df040-0252-4e4e-ad82-c054896e1641.

Lowes, R. Rosenow, J., Scott, D., Sunderland, L., Thomas, S., Graf, A., Baton, M., Pantano, S., Graham, P. (2022). *The perfect fit: Shaping the Fit for 55 package to drive a climate-compatible heat pump market.* Regulatory Assistance Project, Agora Energiewende, CLASP, Global Buildings Performance Network.

Paardekooper, S., Lund, R. S., Mathiesen, B. V., Chang, M., Petersen, U. R., Grundahl, L., … & Persson, U. (2018). Heat Roadmap Europe 4: Quantifying the impact of low-carbon heating and cooling roadmaps.

Pezzutto, S., Croce, S., Zambotti, S., Kranzl, L., Novelli, A., & Zambelli, P. (2019). Assessment of the space heating and domestic hot water market in Europe—open data and results. *Energies*, *12*(9), 1760.

Porse, E., Mika, K. B., Escriva-Bou, A., Fournier, E. D., Sanders, K. T., Spang, E., ... & Pincetl, S. (2020). Energy use for urban water management by utilities and households in Los Angeles. *Environmental Research Communications, 2*(1), 015003.

Regulation 2017/1369. *Setting a framework for energy labelling and repealing Directive 2010/30/EU*. European Parliament and Council. http://data.europa.eu/eli/reg/2017/1369/oj

Ro, C. (2020, March 27). *The hidden impact of your daily water use.* BBC. https://www.bbc.com/future/article/20200326-the-hidden-impact-of-your-daily-water-use#:~:text=The%20energy%20needed%20to%20move,the%20nation's%20overall%20carbon%20emissions.

Rothausen, S. G., & Conway, D. (2011). Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, *1*(4), 210-219.

Sanders, K. T., & Webber, M. E. (2015). Evaluating the energy and CO2 emissions impacts of shifts in residential water heating in the United States. *Energy*, *81*, 317-327.

Schneller, A. & Hennig C. (2018). The Energy Transition Tax Credit (Cite) in France. BEACON. https://www.euki.de/wp-content/uploads/2019/09/20180827_FR_CITE_Study.pdf

Subramanyam, V., Kumar, A., Talaei, A., & Mondal, M. A. H. (2017). Energy efficiency improvement opportunities and associated greenhouse gas abatement costs for the residential sector. *Energy*, *118*, 795-807.

Willis, R. M., Stewart, R. A., Panuwatwanich, K., Jones, S., & Kyriakides, A. (2010). Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households. *Resources, Conservation and Recycling*, *54*(12), 1117-1127.

Wong, L. T., Mui, K. W., & Zhou, Y. (2016). Impact evaluation of low flow showerheads for Hong Kong residents. *Water*, *8*(7), 305.

Appendix

Table A1 EU 27 country code

Country	ISO 3166 alpha-2 code
Austria	AT
Belgium	BE
Bulgaria	BG
Croatia	HR
Republic of Cyprus	CY
Czech Republic	CZ
Denmark	DK
Estonia	EE
Finland	FI
France	FR
Germany	DE
Greece	GR
Hungary	HR
Ireland	IE
Italy	IT
Latvia	LV
Lithuania	LT
Luxembourg	LU
Malta	MT
Netherlands	NL
Poland	PL

Portugal	PT
Romania	RO
Slovakia	SK
Slovenia	SK
Spain	ES
Sweden	SE