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The role of district heating in decarbonising the EU energy system and a comparison with existing strategies

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ABSTRACT

Many strategies have already been proposed for the decarbonisation of the EU energy system by the year 2050. These typically focus on the expansion of renewable energy in the electricity sector and subsequently, electrifying both the heat and transport sectors as much as possible. In these strategies, the role of district heating has never been fully explored system, nor have the benefits of district heating been quantified at the EU level. This study combines the mapping of local heat demands and local heat supplies across the EU27. Using this local knowledge, new district heating potentials are identified and then, the EU27 energy system is modelled to investigate the impact of district heating. The results indicate that a combination of heat savings, district heating in urban areas, and individual heat pumps in rural areas will enable the EU27 to reach its greenhouse gas emission targets by 2050, but at a cheaper price than a scenario which focuses primarily on the implementation of heat savings.

KEYWORDS

Europe, district heating, renewable energy, mapping, modelling, energy systems analysis

INTRODUCTION

In 2010, approximately 73% of all 502 million EU27 residents lived in urban areas, according to the United Nations World Urbanization Prospects [1], indicating that a major part of the EU's buildings are in high heat density areas. This condition is in itself a strong argument for utilising district heating in Europe, but as outlined in Figure 1, the market share for district heating in buildings is only 13%. Currently, the heat market for buildings is dominated by fossil fuels, which account for two-thirds of the heat supply. There are many suggestions that could be proposed to explain this low market share for district heating across Europe such as climate, the availability of natural gas, local governance, economic stability, institutional structures, and the historical development of the different national energy systems. However, from a technical viewpoint, previous research suggests that there is a sufficient heat demand in many cities in Europe for district heating [2]. This presents an opportunity for the expansion of district heating in Europe, by substituting individual fossil fuel boilers with district heating in these urban areas with a high heat density.

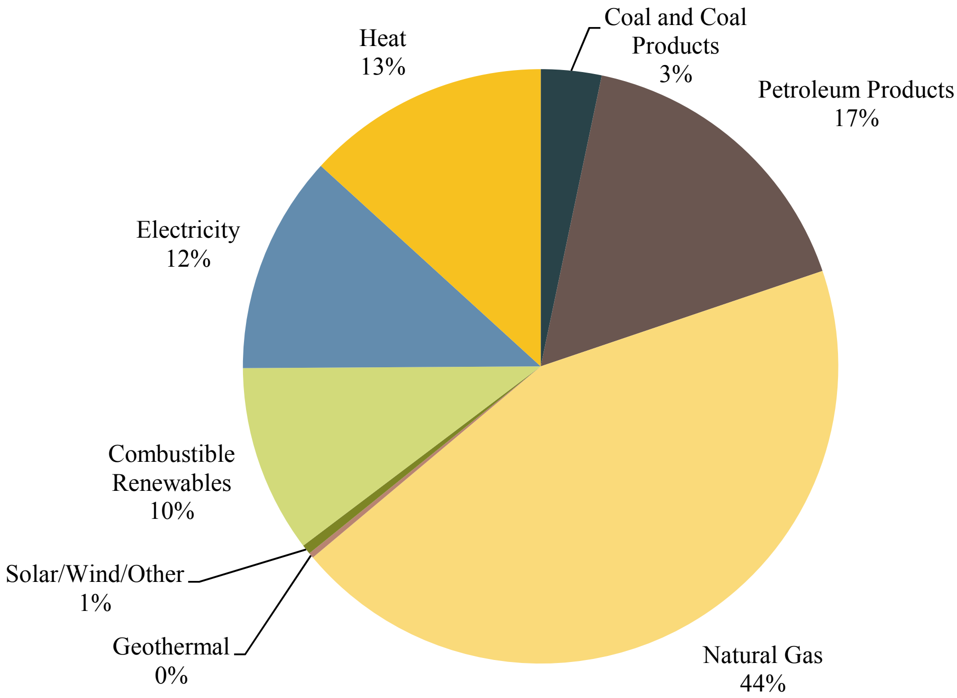

Figure 1. Composition of the origin for heat supply to residential and service sector buildings in EU27 during 2010. Total heat supply was 11.8 EJ (3300 TWh), not including indirect heat supply from all indoor electricity use. Labels refer to the standard commodity groups used in the IEA energy balances. Heat denotes mainly heat from district heating systems. Data sources: IEA energy balances for 2010 complemented with some external estimations.

METHODOLOGY

The methodology utilised in this study is based on a combination of geographical information systems (GIS) and energy system modelling. The GIS mapping of local conditions reflects the potential to expand district heating in the future. It is used in this study to develop a heat atlas for the EU27, which is the basis for establishing the potential for district heating in the future. The GIS mapping is also utilised to identify the quantities of heat that could be recycled into district heating networks in the EU27 from thermal power plants, waste-to-energy facilities, and industrial processes. Furthermore, the mapping of local renewable energy resources, which include geothermal heat and large-scale solar thermal, indicate the quantities of renewable heat available for district heating networks also. As outlined in Figure 2, these potential quantities for district heating demands and supply act as inputs for the energy systems analysis also completed in this study.

The purpose of the modelling is to provide a quantitative comparison between various energy scenarios for the EU energy system. In other words, the energy systems analysis quantifies the impact that district heating could have on the EU energy system, based on the inputs from the GIS mapping (see Figure 2). This approach is not completely new: the same methodology was used in the *Heat Plan Denmark* (*Varmeplan Danmark*) project [3]. In the following paper, the reference scenario used in this study is described and afterwards, the mapping and modelling methodologies intermingled to enable the design of a new heat strategy for the EU27 are presented.

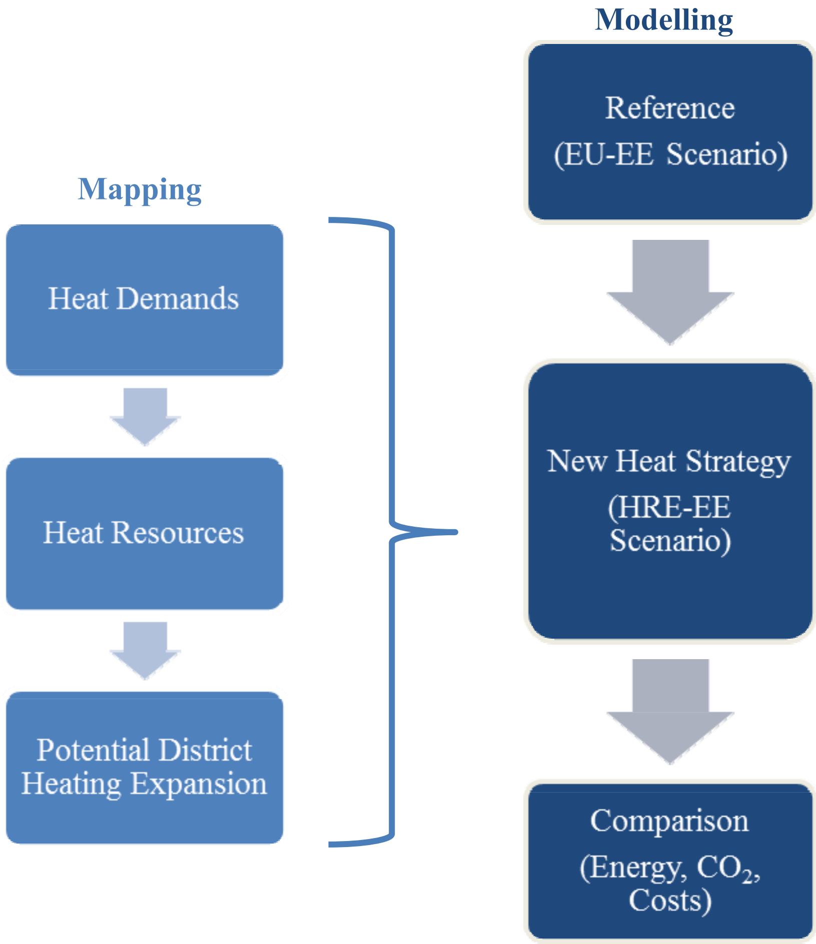

Figure 2. Linkage between the mapping and modelling in this study

REFERENCE SCENARIO

To begin, a starting point or reference model must be defined: this will act as a benchmark for the new heating strategy proposed here. In 2011, the European Commission published the *Energy Roadmap 2050* report [4]. It contains six different scenarios for the future of the EU energy system, including two business-as-usual scenarios as well as an energy efficiency, a high renewable energy, a nuclear and a carbon capture and storage (CCS) scenario. The PRIMES model, which is discussed in [5-7], was used to develop the projections in *Energy Roadmap 2050*. Since the EU energy system is the focus in this paper, it was deemed appropriate to use one of these official energy scenarios from the European Commission as a reference. In line with this, the EU Energy Efficiency (EU-EE) scenario from the *Energy Roadmap 2050* report was chosen. “This scenario is driven by a political commitment of very high primary energy savings by 2050 and includes a very stringent implementation of the Energy Efficiency plan” [8]. Some of the key policies in the EU-EE scenario include [9]:

- Strong minimum requirements for appliances

- High renovation rates for existing buildings due to better/more financing and planned obligations for public buildings (more than 2% refurbishment per year)
- Passive houses standards after 2020
- Obligation of utilities to achieve energy savings in their customers' energy use over 1.5% per year (up to 2020)

The EU-EE scenario was chosen as district heating can be considered as an energy efficiency measure, since it enables the recycling of surplus heat in the energy system. Furthermore, the construction of district heating is often questioned based on the premise that heat demands will be dramatically reduced in the future. Hence, by using the EU-EE scenario as a benchmark, it is possible to determine if there is justification for such concerns.

The EU-EE scenario was then modelled in a tool called EnergyPLAN. EnergyPLAN is an energy system analysis tool specifically designed to assist the design of national or regional energy planning strategies under the "Choice Awareness" theory [10]. It has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark [11]. As a result, it is now a complex tool which considers a wide variety of technologies, costs, and regulation strategies for an energy system. Previously, EnergyPLAN has been used in a variety of studies to analyse the role of district heating at national and local level [3, 12-22]. A detailed description of the model is available in Connolly *et al.* [5]. Validation of the model is discussed in detail in Lund and Mathiesen [23], while the algorithms used to create the tool are described in the user manual [24].

By modelling the EU-EE scenario in EnergyPLAN, it is possible to replicate the original projections created by the PRIMES model (see Figure 3). This is important as it ensures that EU-EE scenario is the same in both the original EU Energy Roadmap report and in this study. As outlined in Figure 3, the PES is almost exactly the same in 2010, 2030, and 2050 in both the original EU-EE projection and the copy created in EnergyPLAN. The minor differences (<2.5%) occur for two reasons: firstly, the CHP plants cannot operate as much as the original projection suggest and secondly, there is a larger electricity export in the EnergyPLAN model than in the original EU-EE projections. It is likely that these differences occur since EnergyPLAN considers the hourly balance between demand and supply for electricity, heat, and gas, which may be overlooked by the PRIMES tool since it primarily focuses on the annual energy balance. The overall difference for both 2030 and 2050 is small enough to conclude that the EU-EE scenario has been successfully replicated in the EnergyPLAN tool.

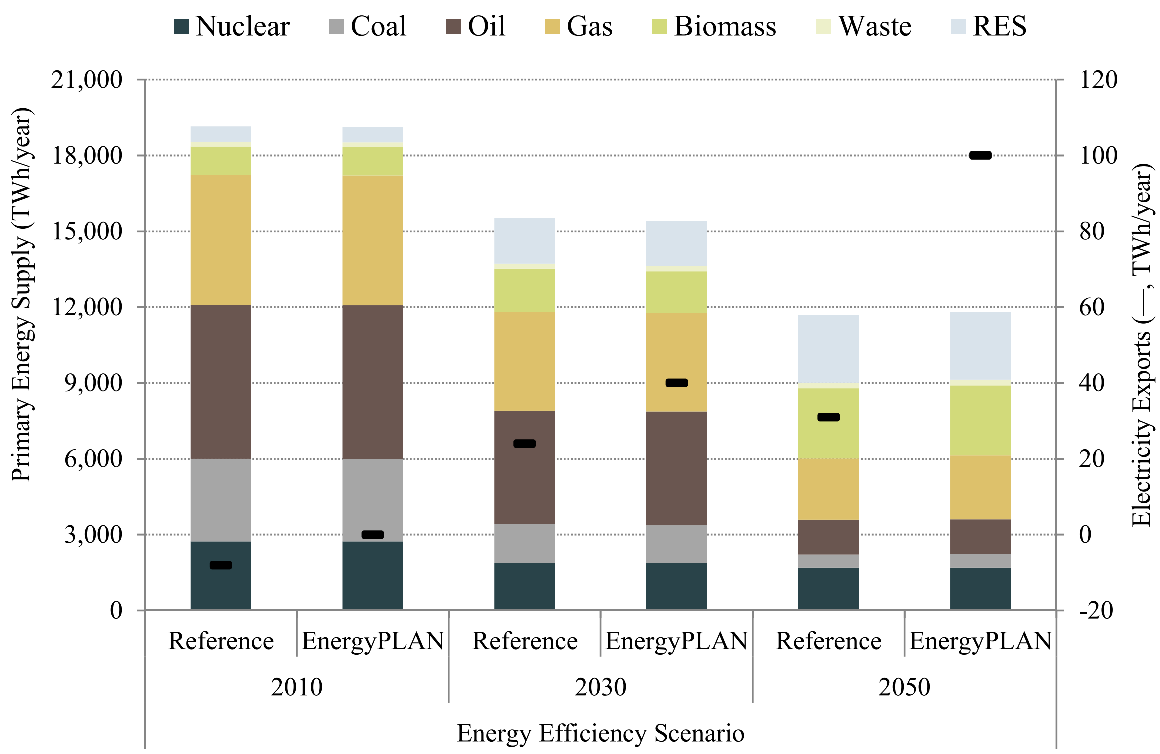

Figure 3. Primary energy supply by fuel and the net electricity exports for the EU-EE scenario from the original 'reference' projection and the EnergyPLAN model

HEAT ROADMAP EUROPE SCENARIO

After creating a model of the original EU-EE scenario in EnergyPLAN, the new Heat Roadmap Europe (HRE-EE) scenario could be created. The HRE-EE scenario contains a number of specific alterations for the heating of buildings in the EU27 for the years 2030 and 2050. This section summarises those key changes. Overall, based on numerous observations and consultations with industrial experts, the following key changes are applied to the original EU-EE scenario to create the HRE-EE scenario:

1. Fewer heat savings are implemented.
2. Individual boilers in high heat-density areas are replaced with district heating.
3. Design a new district heating supply by constructing and replacing different plants in the energy system.
4. Recycled and renewable heat is utilised in the district heating networks.

The key assumptions behind each of these alterations are outlined in the following section.

Reducing the level of heat savings

Firstly, it was concluded that the heat savings implemented in the EU-EE scenario will be very difficult to implement and they will be very expensive. Overall, there is a reduction of 55% in hot water demand and 62% in space heating demand between 2010 and 2050 in the EU-EE scenario. However, for hot water it is unlikely that there will be a reduction between now and 2050 for the following reasons:

1. The population is expected to grow by 3.2% between 2010 and 2050.
2. According to a number of interviews with industry experts, people tend to wash more today than they did in the past, which is likely to continue into the future. In other

words, individuals are likely to take more showers and baths in the future than they do today.

3. People are not expected to live with one another as much in the future. Hence, there will be a larger number of people living in their own houses rather than living together. This is also expected to increase the demand for hot water per individual.
4. At present, there are regions in Europe where the use of hot water is limited due to technical and financial limitations. As these regions become wealthier, the demand for hot water is expected to rise in these regions.
5. The building area for residential and non-residential buildings is expected to grow by 32% and 42% respectively between 2015 and 2050.

Based on these observations, it is assumed in the HRE-EE scenario that the hot water demand will increase rather than decrease. It is unlikely that the hot water demand will increase as fast as the building area, since people will live in larger houses and use the hot water more efficiently. However, it is unlikely that the hot water demand will increase at a lower rate than the population, for the reasons outlined in 1-4 above. Therefore, it is assumed here that the hot water demand will grow at a rate between the residential floor area and the population. The new hot water demand grows by 16% between now and 2050 in the HRE-EE scenario, instead of the 55% reduction proposed in the EU-EE scenario.

Like the savings for hot water, the reduction in space heating demands will also be very costly and difficult to implement in the EU-EE scenario. The European Commission recognises this challenge when stating that the EU-EE scenario *"...pushes the limits of what the chosen measures can achieve"* [8]. To be more specific, the EU-EE scenario proposes a total space heating reduction of 62% between now and 2050. To put this in context, the most ambitious scenario proposed for heat savings in buildings by EURIMA (the European Insulation Manufacturers Association) in a recent report [25], proposes that with the most ambitious deep renovations in the EU27, a space heating reduction of 47% is possible between now and 2050. Therefore, in the HRE-EE scenario, the space heating demand is reduced by 47% between now and 2050, instead of by the original 62%.

Overall, the total heat demand for the new HRE-EE is reduced by 34% between now and 2050, instead of by 61% as originally proposed in the EU-EE scenario. Since energy efficiency measures in buildings typically become more expensive as larger savings are achieved, the additional measures in the EU-EE scenario are likely to be extremely expensive. Hence, the key motivation for reducing the level of heat savings in the HRE-EE scenario is to avoid these very expensive heat saving measures. The aim in the HRE-EE scenario in this report is to identify if the same objectives in the EU-EE scenario, in terms of energy and emission reductions, can be achieved in a way that is both cheaper and easier to implement. To achieve such an objective, the strategy is to replace some of the heat savings in buildings, which are either very expensive and/or difficult to implement, with a heat supply from units such as district heating or individual boilers.

The cost of energy efficiency measures in the HRE-EE scenario is now reduced since there are fewer heat savings. To estimate these savings a new cost curve was developed based on cost data from the Danish Research Building Institute [26] and a Danish Heat Atlas [27, 28]. The costs in Figure 4 reflect the additional cost of implementing energy efficiency measures along with other building refurbishments.

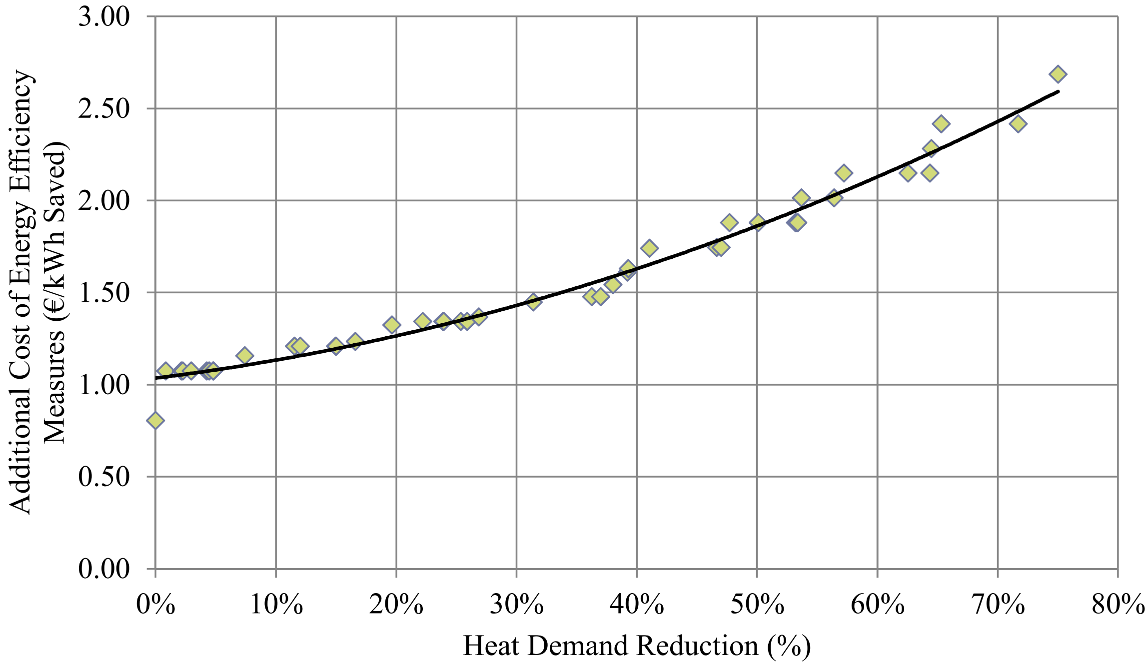

Figure 4. Additional costs per unit of heat saved for energy efficiency measures that reduce the heat demand by different percentages based on Danish buildings (scenario C) [26]. 'Additional' means it is assumed that these are the extra costs of completing the energy efficiency measures at the same time as implementing other building refurbishments.

There is a total reduction of approximately 70% in the specific heat demand (i.e. kWh/m^2) in the EU-EE scenario, equating to total savings of 2,460 TWh. Assuming a cost of €2.4/kWh based on the data in Figure 4, a 3% interest rate, and an average lifetime of 30 years for the energy efficiency measures, the annual costs of implementing the heat savings in the EU-EE scenario are approximately B€300/year. This is very similar to the costs suggested in the EU Energy Roadmap report of B€295/year, although this is still only a rough estimate since adequate data is not yet available to make a detailed calculation for all member states in the EU.

Using the same assumptions, the costs for the heat savings in the HRE-EE scenario are estimated. Overall, there is a 50% reduction in the specific heat demand between now and 2050, equating to a total energy saving of 1,215 TWh. Assuming a cost of €1.9/kWh, this means that the total annual costs for energy efficiency measures in this scenario are approximately B€130/year. Comparing this to the EURIMA report [25] suggests that this is a 17% underestimation of the total costs, since the average annual investments required in the Deep Renovation scenario (for a 47% reduction in space heating) are approximately B€160/year. This difference warrants further investigation in the future, but based on these comparisons, the indicative costs provided in Figure 4 are deemed an adequate representation of the variation in costs as more heat savings are implemented.

Overall, the EU-EE scenario is extremely ambitious in terms of heat savings, since they will be extremely difficult and expensive to achieve. Hence, a new heat demand has been created here for the HRE-EE scenario: this scenario is still extremely ambitious in terms of heat savings, since it follows the space heating recommendations of the Deep Renovation scenario created for EURIMA [25].

Replacing individual boilers with district heating

After creating a new heat demand for the HRE-EE scenario, individual boilers could then be replaced with district heating. In the EU-EE scenario, district heating provides approximately 13% of the heat demand for residential and services buildings in 2030 and 2050 [9]. To establish how much additional district heating could be implemented, the GIS mapping tools were utilised.

To begin, the mapping of heat demands is done in a top-down manner, where national level energy statistics allow for the calculation of Member State average per-capita heat demands, which are subsequently associated to total population counts within each NUTS3 region in respective country. Afterwards, the general climate of each Member State is represented by use of the European Heating Index (EHI), a concept presented by Werner in [2], to map sub-national deviations from national and European heat demand averages.

The greatest challenge is to map heat demands with sufficiently high geographical resolution. Eurostat statistics on NUTS3 region level are the smallest scale of public statistics available for all EU27 countries and contain, among other parameters, data on population and service sector activities. To achieve the highest possible resolution for mapping, the GEOSTAT European population grid by GISCO, the European Forum for Geostatistics, containing the 2006 population in one square kilometre grid cells was used [29]. Comprising of almost two million cells, this data set is assumed to be by far the best possible input to map high resolution demography in all EU27 Member States. Using the EHI-adjusted heat demands per NUTS3 region, as described above, this population grid was converted to a highly detailed heat atlas for Europe (see Figure 5). On the basis of a classification by Werner, four zones of heat demand density were modelled: below 15 TJ/km^2, 15-50 TJ/km^2, 50-150 TJ/km^2, and above 150 TJ/km^2, which represent different levels of technological development for district heating, as well as a general classification of areas by feasibility. The one square kilometre grid that contains heat demand in TJ/km^2 comprises of a heat demand density map. To our knowledge, this kind of heat atlas has never been published for the EU27 before. Using the new EU heat atlas, the heat demand in the EU27 could be classified by its heat density. Based on this mapping of local heat demands, the share of district heating is increased to 30% in 2030 and 50% in 2050 in the HRE-EE scenario.

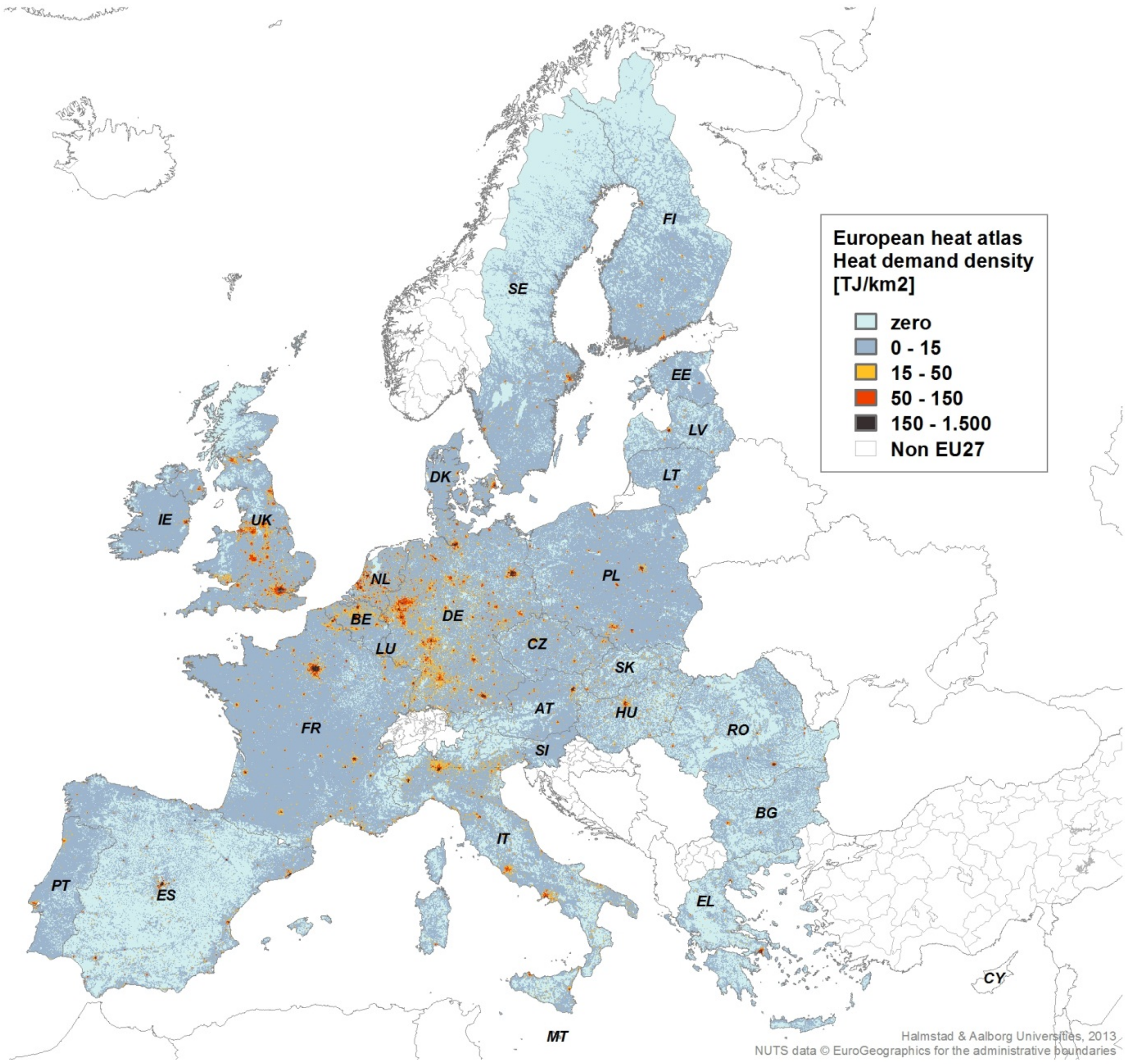

Figure 5. European Heat Atlas by heat demand density classes based on the GEOSTAT 2006 1 km^2 population grid

When replacing individual heating units with district heating, it is assumed here that individual heat pumps are not replaced since these are also considered a key decarbonisation technology for the EU27 energy system. Therefore, there is the same amount of individual heat pumps in the EU-EE scenario as in the HRE-EE scenario. There is an underlying assumption here that individual heat pumps are also placed outside the urban areas where district heating is implemented. Inside the urban areas, it is assumed that coal, oil, gas, biomass, and electric boilers are replaced by district heating. The volume of each type of boiler that is replaced by district heating is currently unclear, so in the HRE-EE scenario the different boilers have been replaced by district heating proportional to the heat demand they satisfy. The cost of transforming individual boilers into district heating is estimated here based on the number of boilers replaced, the size of these boilers, and the heat demand replaced. Details of these assumptions are provided in [30].

Designing a new district heating supply

Now the total district heating demand has been defined for the HRE-EE scenarios, the next step is to define the capacities for the production units in the HRE-EE scenarios. It is assumed that half of the district heating expansion in the HRE-EE scenarios will be decentralised and so, this will require the construction of new relatively small CHP plants. These plants are necessary since the power plants must be located near the heat demands if district heating is implemented, so their surplus heat can be utilised. These are assumed to be 10-100 MW gas power plants with an average electrical efficiency of 50% and an average thermal efficiency of 40% [31]. The remaining district heating is provided by centralised CHP plants that either already exist or are created by converting existing electricity-only power plants. The final capacities assumed are displayed in Table 1. It is assumed that the fuel mix for these power plants in the HRE-EE scenarios is the same as the fuel mix already defined for CHP plants in the EU-EE scenarios for 2030 and 2050.

Table 1. District heating production unit capacities assumed in the EU-EE and HRE-EE scenarios for the residential and services sectors for the years 2030 and 2050

	Assumed Efficiencies [31]	2030		2050	
		EU-EE	HRE-EE	EU-EE	HRE-EE
District Heating Production for Boiler Only Systems (TWh)	n/a	55	70	11	19
Boilers for Boiler Only Systems (MW_{th})	2030: $\eta_{thermal}$ = 80% 2050: $\eta_{thermal}$ = 81.5%	17,089	21,750	3,190	5,364
Other District Heating Production (TWh)	n/a	282	1268	169	1,571
CHP (MW_e)	Centralised: 2030 η_{elec}=40% & $\eta_{thermal}$=45% 2050 η_{elec}=45% and $\eta_{thermal}$=45% Decentralised: η_{elec}=50% and $\eta_{thermal}$=45%	33,570	103,570	25,916	205,916
Backup Boilers* (MW_{th})	$\eta_{thermal}$=90%	105,150	472,850	57,250	532,230
Heat Pumps (MW_e)	COP = 3	0	26,000	0	40,000
Thermal Storage† (GWh)	n/a	130	600	80	750

*Assuming a boiler capacity that is 20% greater than the maximum heat demand.
†Assuming a thermal storage capacity that is 17% of the average daily heat supply into the network [32].

Utilising local surplus heat and renewables

By adding district heating networks to the energy system, it is possible to utilise a number of additional resources that could otherwise not be utilised. These include surplus heat from power plants, waste incineration, and industry as well as from renewable heat resources such as geothermal and large-scale solar thermal. To analyse the potential of utilising these resources, local conditions must be considered using the GIS mapping tools once again. The main reason for this is simply that only local conditions disclose obtainable synergies between local heat assets and prevailing heat demands. Only at the local level can the excess heat from these various activities and sources be utilised by the recovery and distribution in district heating systems.

To identify the potential heat from thermal power generation activities, waste-to-energy facilities, and energy intensive industrial sub-sector activities, emission data from the E-PRTR dataset from the EEA has been utilised, along with assumptions about carbon dioxide emission factors and excess heat recovery efficiencies. For two local renewable heat resources, geothermal and large-scale solar thermal, qualitative maps of current availabilities have been complemented with hands-on projection estimates for future potentials based on e.g. currently best practice examples. These potentials have been assessed to provide indications of the potential volumes of geothermal and large scale solar thermal heat that can be utilised in future district heating systems.

The assessed and projected annual heat supply contributions from each of these sources are presented in terms of annual volumes in Table 2. The table specifies annual volume shares from each heat supply, given current and expected total district heating shares of total heat EU27 heat demands (in parenthesis). As outlined in Table 2, there is more surplus heat available in the EU27 than utilised in the 2050 HRE-EE scenario proposed here, thus indicating that there is no shortage of heat available for future district heating systems. Furthermore, this should be considered a conservative estimate, since it does not consider the surplus heat that is likely to be available from a number of new technologies in future energy systems such as bioethanol plants, biomass gasification facilities, and large-scale electrolysers.

Table 2. Annually delivered district heating volumes to residential and service sectors in EU27 for the current situation (2010), 2030, and 2050, by strategic heat supply sources, as modelled in the energy system analysis, and the resource potential assessed in the GIS mapping.

Main strategic heat sources (PJ/year)	Potential	2010 (13% DH)	2030 (30% DH)	2050 (50% DH)
Fossil fuel power generation excess heat and heat from boilers	7075	1120	2410	1540
Waste-to-Energy incineration excess heat	500	50*	330	585
Industrial excess heat	2710	25	205	385
Biomass heat	n/a†	250	325	810
Geothermal heat	430	7	190	370
Solar thermal heat	1260	0	180	355
Large-scale heat pumps	n/a	0	1290	1875
Total district heating in the modelling	**11975**	**1460**	**4930**	**5920**

*Total heat delivered from waste in 2010 was 170 PJ. However, only 50 PJ/year is assumed to go to the residential and services sectors due to the assumptions used to remove industry from the *Energy Roadmap 2050* projections.
†The biomass potential is not established in this context, but modelled levels correspond to volumes used in the reference scenario.

RESULTS

Using the EnergyPLAN tool, the primary energy supply (PES) and the CO_2 emissions have been estimated for both the EU-EE and HRE-EE scenarios in the years 2030 and 2050. As displayed in Figure 6, the PES is slightly larger in the HRE-EE scenario (~2%), but the fossil fuel and biomass consumption in both scenarios is the same (<1% difference). As a result, the carbon dioxide emissions in both scenarios are also the same. The slightly larger PES in the HRE-EE scenario is primarily due to the higher heat demands being met in the HRE-EE scenario, but it is a relatively small increase due to the additional resources utilised in the district heating network such as waste incineration, geothermal, and large-scale solar thermal. The HRE-EE scenario can also utilise approximately 5% more wind power than the EU-EE scenario due to the additional flexibility introduced into the system by integrating the electricity and heat sectors.

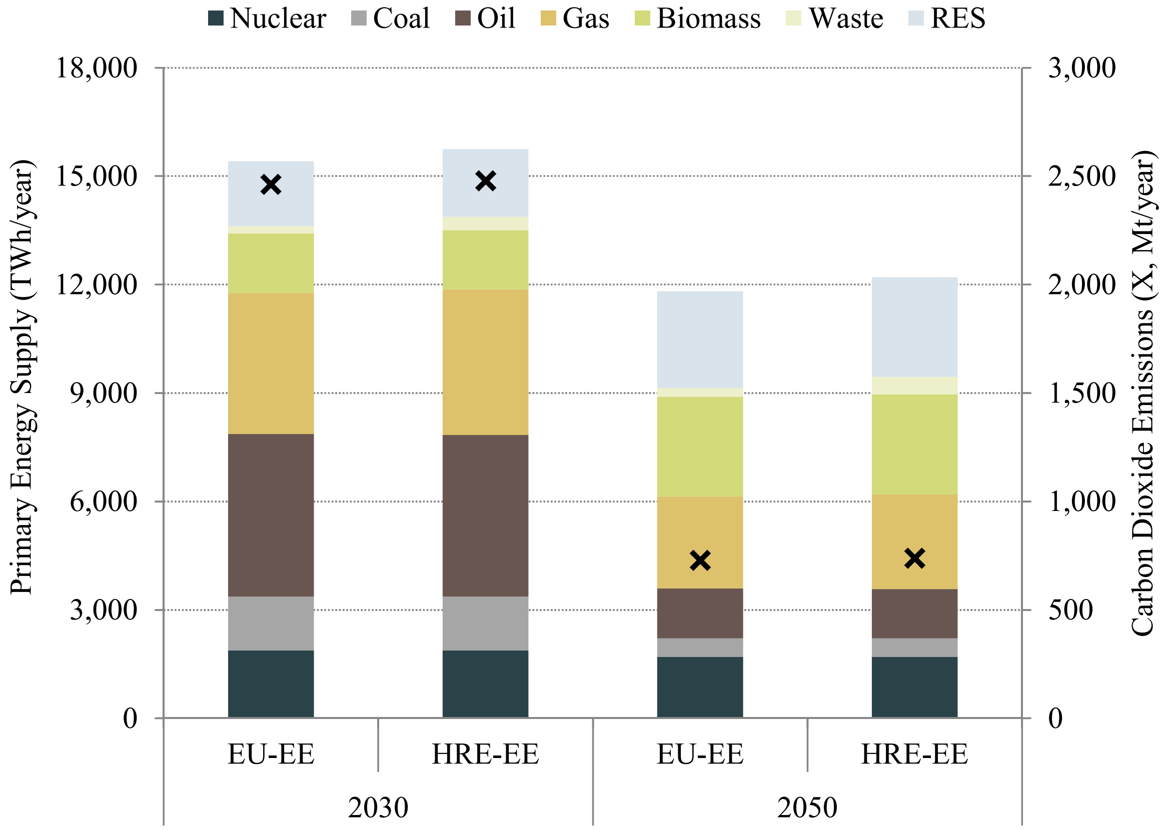

Figure 6. Primary energy supply and carbon dioxide emissions for the EU-EE and HRE-EE scenarios in the years 2030 and 2050

Figure 7 indicates that the HRE-EE scenario has lower annual costs than the EU-EE scenario, while achieving the same level of PES and CO_2 emissions. Both scenarios have very similar fuel, O&M, and CO_2 emission costs, but the HRE-EE scenario reduces the investment costs by approximately 10%.

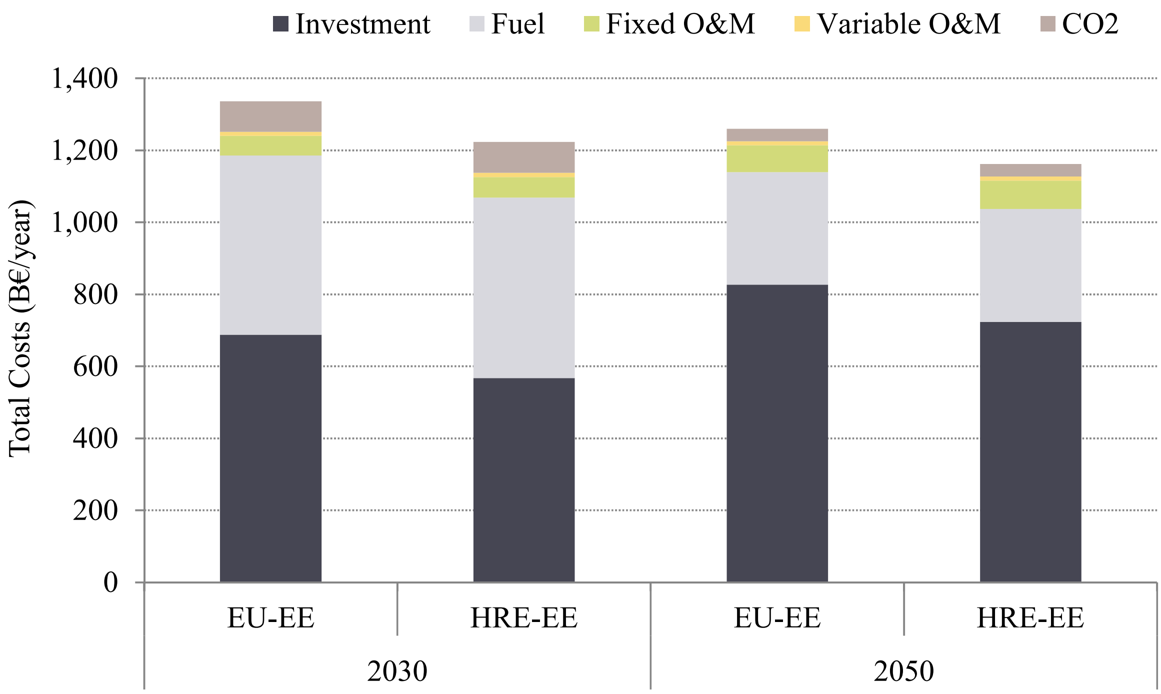

Figure 7. Total annual energy system costs for the EU-EE and HRE-EE scenarios in the years 2030 and 2050.

The source of these investment savings is more evident when the costs for heating and cooling buildings are separated from the whole energy system costs (see Figure 8). The HRE-EE scenario saves a lot of money on energy efficiency investments, which result in higher heat demands. However, to overcome these savings the HRE-EE scenario has higher shares of district heating and cooling, larger individual boilers, and it produces more heat. Therefore, the heating system, cooling system, and fuels are more expensive in the HRE-EE scenario than the EU-EE scenario. However, Figure 8 indicates that these additional costs are offset by the reduced energy efficiency investments, so the total cost of heating and cooling for buildings in the HRE-EE is ~15% cheaper than in the EU-EE scenario. In summary, the key message from this analysis is that, a combination of heat savings, district heating in urban areas, and individual heat pumps in rural areas, can result in an EU energy system which reaches its GHG emission targets for 2050, but at a lower cost than the EU-EE scenario currently being proposed.

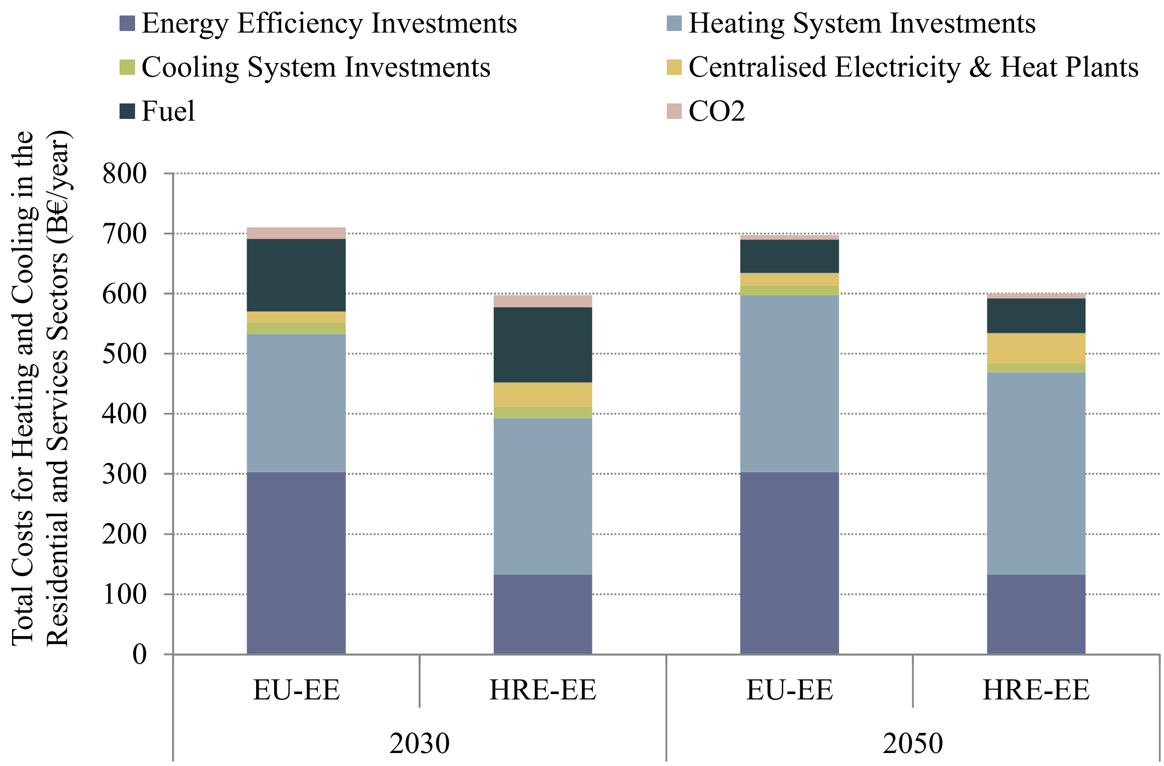

Figure 8. Total annual costs for heating and cooling in the residential and services sectors for the EU-EE and HRE-EE scenarios in the years 2030 and 2050.

CONCLUSION

This study has combined GIS mapping and energy systems modelling to develop a new heating strategy (HRE-EE) for the EU energy system which includes the expansion of district heating. The key conclusions from this study can be summarised as follows:

1. By adding district heating to an EU energy system with very low heat demands, it is possible to use the same amount of fossil fuels and biomass as the EU Energy Efficiency (EU-EE) scenario in the *Energy Roadmap 2050* report, but the total costs for heating and cooling buildings will be approximately 15% lower.
2. Energy efficiency measures will provide essential heat demand reductions in buildings in the future EU energy system, but at a certain point, these will become very difficult to implement and very costly. Ambitious energy efficiency targets should be pursued in the EU, but not to the extent that the EU-EE scenario suggests.
3. The HRE-EE scenario uses energy efficiency on both the demand and supply side of the energy system. By adding district heating for buildings, it is possible to utilise surplus heat from power plants, industry, and waste incineration, while also using more renewable energy such as wind power, large-scale solar thermal, and geothermal.
4. The EU-EE scenario relies heavily on heat savings in buildings to reach its CO_2 reduction targets. By introducing more district heating as an alternative energy efficiency measure, the HRE-EE scenario is a safer and more realistic alternative: there are more technologies to choose from, more renewable energy resources to utilise, and the heat demand does not need to be reduced as much.

This means that district heating should be considered as an essential technology for the cost-effective decarbonisation of the EU energy system. In future research, more information will need to be obtained about the specific energy efficiency measures that are necessary in the EU, the energy efficiency costs, the cooling demand, and cooling system costs.

ACKNOWLEDGEMENT

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