What buildings decarbonisation means for the EU ETS

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Abstract

Efforts to decarbonise buildings are bound to be ratcheted-up to deliver on more ambitious goals as formulated in the EU's Green Deal. Until now, buildings decarbonisation policies have focused on reducing energy demand. Yet, next to energy demand, emission reductions crucially depend on decarbonising heat supply, i.e., phasing out fossil-based boilers and replacing them by heat pumps or district heating. Historical experience cast a shadow on the ability of policies to deliver energy demand reductions. The power sector will thus be at the crossroads of decarbonising buildings, which ultimately poses additional pressure on the EU ETS. The purpose of this paper is to assess the required investments to decarbonise buildings and their impact on the the EU ETS. We find that raising the renovation rate from 0.5% to 3% thereby reducing demand by up to 20% has only limited effect on carbon prices (+3%, from 250 €/tCO$_2$ to 259 €/tCO$_2$). Still, the required transformation of the power sector to cope with all buildings demand in the long-term is substantial, having to reduce emissions by 85 between 2015 and 2030 and largely deploying variable renewables to cover 90% of total supply by 2050. We also find that, in an optimised system, heat would rely almost entirely on decentralized heat pumps, while district heating share reaches 20% at the most. However, there are remarkable regional differences: district heating remains the major source of heating in Nordic, Baltic countries and Poland. Within the district heating energy-mix there is also a major transition as heat-only plants will progressively gain importance to the detriment of cogeneration plants. More specifically, district heating will depend on gas heat-only plants, large heat pumps and hydrogen cogeneration in the long-term.

Keywords

EU ETS, ESR targets, buildings decarbonisation, district heating, CHP, power sector

ACRONYMS

CHP: Combined heat and power plants

COP: Coefficient of performance (in heat pumps)

DH: District Heating

EGD: European Green Deal

ESR: Effort Sharing Regulation

EU ETS: EU Emission Trading System

HOP: Heat-only plants

NECPs: National Energy and Climate Plans

P2He: power to heat technologies

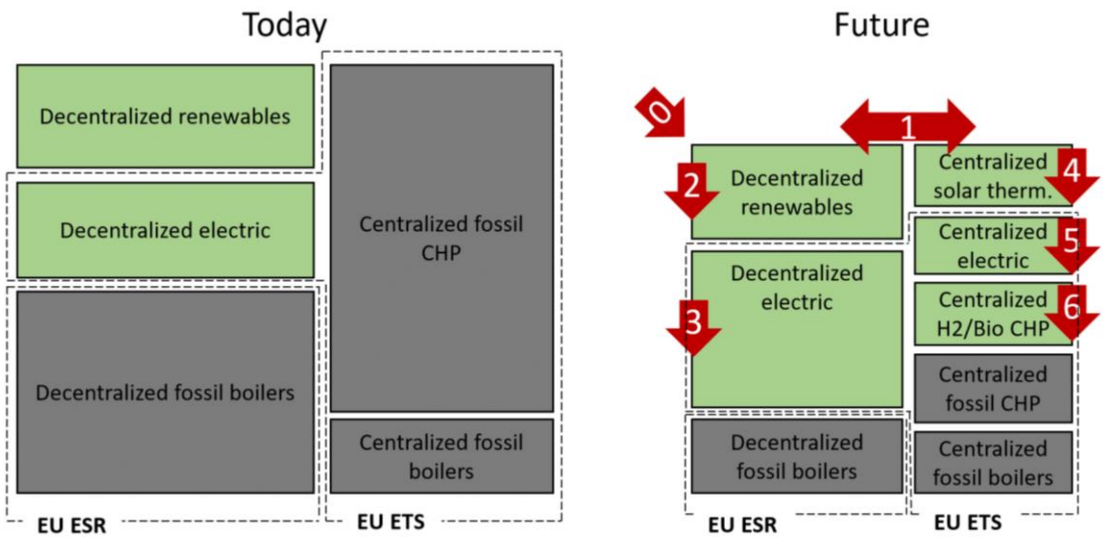
1. INTRODUCTION

With the EU Green Deal (EGD), the European Commission emphasises the need for urgent action to meet the long-term goal of climate neutrality by 2050. One of the key sectors that needs to undergo deep transformations is the buildings sector. Buildings are responsible for 40% of EU's total energy consumption and 36% of EU's total emissions, heating being their main end-use (European Commission, 2021a). Decarbonizing heating in buildings is thus of cardinal importance in order to meet medium- (2030) and long-term (2050) EU targets. With the Energy Efficiency First principle at the core of the transformation of the buildings sector, the EGD enforces the revised Energy Performance of Buildings Directive (EPBD) and aims at triggering a 'Renovation Wave' with the aim of renovating Europe's entire building stock by 2050 so that it becomes "nearly zero emissions". However, what if it failed or substantially fell short of what is required? Then the electrification of decentralized heating and/or expansion of district heating would be necessary all the more, which ultimately poses additional pressure on the EU Emission Trading System (EU ETS). In this paper we evaluate the required investments to decarbonise buildings and their impact on the EU ETS in light of more ambitious climate targets as proposed in the EGD.

The several options at hand to decarbonize buildings are displayed in Figure 1. The first option, as mentioned before, is energy demand reduction (measure 0). This has a large potential, considering that the lion's share of buildings in Europe is old (two thirds of the EU building stock was built before 1980 (Bean et al., 2019)) and very inefficient (according to the European Commission (2020a) Impact assessment 75% of buildings has poor energy performance). However, historic dynamics invite to be cautious about future reductions of energy demandas as they have stalled in the last years. Currently, 11% of EU buildings undergoes some level of energy renovation each year, but this translates in a weighted annual energy renovation rate of a mere 1% (European Commission, 2020b). However, the average energy rate of renovation should be increased to at least 3% per year to ensure the renovation of the full building stock by mid-century (Vitali Roscini et al., 2020).

Next to energy demand savings, buildings should undergo a massive penetration of carbon neutral technologies to reach climate neutrality (Levesque et al., 2021) with either centralized or decentralized options. One of the main alternatives is expanding centralized district heating (DH). This might be the best option for countries with already high shares of DH (e.g., Nordic and Baltic countries). However, DH is still dominated by fossil fuels (68% in 2020 at EU level (Eurostat, 2022)) and relying on DH requires simultaneously expanding the networks which cover only 10% of the demand nowadays and decarbonising the supply, i.e., switching to biomass, large-scale heat pumps, solar thermal, excess heat and potentially hydrogen (measures 4-6 in Figure 1). Because of its capital-intensive structure and of the high network losses, DH expansion is however constrained to areas densely populated.

The second alternative is expanding carbon-free decentralized technologies, i.e., biomass or electric heating (measures 2-3 in Figure 1). The former does not appear to be a realistic option as biomass resources remain limited and are therefore expected to be used rather in sectors difficult to decarbonise (e.g., long-haul transport). Furthermore, biomass boiler contributes to local air pollution and may therefore be restricted in some urban areas. The remaining decentralized technology, and eventually the only alternative for many households and businesses are heat pumps, and more generally electric heating.



	Decarbonization measure
0	**Renovation reduces emissions through reducing overall heating demand**
1	Share of district heating may shift decarbonization challenge to the EU ETS
2	Decentralized renewables can decarbonize decentralized heating
3	**Decentralized electric heating can shift decarbonization challenge to the EU ETS**
4	Centralized solar thermal can help to reduce decarbonization challenge in the EU ETS
5	**Centralized electric can help to solve centralized decarbonization challenge in the EU ETS**
6	**Centralized H2/Bio(CCUS) can help to solve centralized decarbonization challenge in the EU ETS**

Figure 1. Options to decarbonise the buildings sector and whether their inherent emissons are covered by the EU ETS or the ESR.

Whether heat demand is met with DH or whether it is covered with electricity consumption, both will impact the way emissions from the heating sector will be priced and regulated, owing to the idiosyncratic structure of European climate policy instruments. Currently, direct emissions from the heating sector, *i.e.* emissions stemming from decentralized fossil fuel boilers, are ruled under the Effort Sharing Regulation (ESR) that assigns each Member State an emission reduction target to meet. Each Member State is free to chose its policy instruments to reduce emissions in the ESR, e.g., oil boilers phase-out in new buildings in France and the proposed national German ETS for buildings and transport. By electrifying heat demand or supplying it with DH, direct emissions from the heating sector can be strongly decreased but lead to indirect emissions in the power and DH sectors governed by the EU ETS, and not the ESR (Figure 1). This constitutes a *de facto* inclusion of the building sector into the ETS. Given the expected limited role of biomass, buildings would be fully included in the ETS by 2050 under climate neutrality. The resulting pressure on the ETS, namely the higher demand for certificates, depends partially on the renovation executed. Decarbonisation of the building sector thus has an impact on the EU ETS, namely a substantial increase in demand for electrification (decentralized heat pumps and large-scale heat pumps in district heating) and a tighter link to the power sector through cogeneration of heat and power in district heating. As a result, the ETS and buildings' decarbonisation dynamics are deeply intertwined.

Beyond its influence on the EU ETS market, the heat decarbonisation will also impact the economics of the power market. First, it would increase electricity demand to a great extent. To illustrate this, if all current fossil-fuelled heat generation technologies were replaced by heat pumps overnight, heat pumps demand would be 26% of the total electricity demand adding 526 TWh to the final electricity consumption (2910 TWh). Second, and maybe more importantly for the power system, this demand would be mainly concentrated in winter, the increase in the winter peak demand expected to be 20% to 70% higher than today (Kavvadias et al., 2019). This poses additional constraints to the power sector. Third, electrifying heat contributes to sector-coupling and opens up the opportunity space for flexibility and storage options in the power sector. Thereby, it could contribute to the integration of renewable energy (Bloess et al., 2018; Ruhnau et al., 2020). In aggregate, while the power sector is considered to be relatively easy to decarbonize (R. C. Pietzcker et al., 2021), it is not clear how easily the power sector could keep the decarbonisation pace if it needs to cope with substantial increase of demand resulting from heating.

Both the energy demand reductions from efficiency improvements and the transformation of heat supply towards carbon-free sources will have massive implications for the EU ETS and the power system. A question thus arises: how will the decarbonisation of buildings impact the EU ETS market and more generally the sectors covered by the EU ETS, in view of the various energy demand reduction and electrification scenarios possible? In turn, we may ask what would happen in case energy efficiency policies do not deliver? Could the ETS and the power system cope with high heat demand? This even has an impact on how fast and costly decarbonisation of energy-intensive industry takes place.

So far there is extensive literature on the impact of larger electrification of heating on the power sector, but mainly at the national level (Bloess, 2019; Staffell and Pfenninger, 2018). Some of them focus on the interaction between heat pumps and variable renewables, assessing to what extent the former contribute to the later integration and reduction of costs for the whole system (Ashfaq and Ianakiev, 2018; Bernath et al., 2019; Ruhnau et al., 2020). Some papers indeed address the impact of buildings' decarbonisation on the power sector at the EU level. For instance, Thomaßen et al. (2021) describe the EU heat sector in detail and asses that most national power systems could cope with higher heat-electrification rates, but only few could afford full electrification scenarios. In a more similar approach to the one in this paper, Zeyen et al. (2021) optimise both supply and energy efficiency simultaneously including all European countries with hourly resolution. They find that renovation is strongly triggered by the resulting seasonal electricity peak, while annual demand has only limited impact. However, none of these approaches provide insights on the potential implications for the EU ETS. Furthermore, the explicit interaction of the EU ETS and buildings sector via non-ETS targets and the implications of more ambitious targets have not been studied.

In this paper we evaluate the impact of the buildings' decarbonisation requirements on the EU ETS in light of more ambitious climate targets as proposed in the EU Green Deal. More broadly, we contribute to the debate on how the construct of ESR and the EU ETS might enable or hamper the decarbonisation of EU energy system. More specifically, (i) we estimate the buildings' heat demand that would be included in the ETS in order to reach the non-ETS targets under more stringent EU climate objectives, and its associated investments in DH and decentralized heat pumps, and (ii) we assess the impact of such heat demand shift on the ETS, accounting for the interaction among the different sectors within the EU ETS. More particularly we address what this implies for carbon prices, and their effect on the power sector generation-mix and electricity prices. Besides these rather-policy contributions, we also we provide a methodological contribution. We derive heat profiles and we implement a stylised buildings model in a highly detailed ETS model that allow us to provide insights on the interaction of both the ETS and non-ETS sectors.

To this aim we use the model LIMES-EU, which explicitly captures the interactions between the power sector and the industry sector via allowances banking within the EU ETS following the spirit of Rubin (1996). The detailed modelling of heat and electricity supply and demand (hourly) patterns allows us to capture the interaction between the both sectors and the potential complementarity of heat demand with variable renewable energies (vRES). We thus contribute to two broad strands of the current literature: (i) interaction of sectors within the ETS scheme and (ii) power-to-heat and sector coupling alternatives, and their impact on the power sector.

2. METHODS

In this paper we expand the model LIMES-EU to analyse the decarbonisation of the buildings sector and its impact on the EU ETS. We extend the system operation and investment model of the European power sector to correctly represent additional demand from decarbonising the buildings sector. This demand comes in the form of DH expansion, which is dominated by fossil fuels and thus compete for EUA certificates, and from additional electricity demand required by heat pumps. The level to which DH needs to be expanded or heat electrified depends on the interaction between the ETS and the ESR through the National Energy and Climate Plans (NECPs) targets for the building sector, and on the inherent features of demand and supply of both electricity and heat, which are captured in detail in the model. This allows our analysis to partially internalize the advantages of full energy system models regarding the sector inter-relation and broader scenario analyses aspects, without giving up the detailed analysis present in detailed power sector models.

2.1. Modelling framework

LIMES-EU is a linear model which optimises investments and dispatch in the European power sector. It computes optimal transmission and generation capacities under emission constraints for the time period 2010–2070. The model contains a detailed representation of the power sector, comprising 61 technologies, 32 of which are electricity-only technologies, including different vintages for lignite, hard coal and gas plants. We also include 9 combined heat and power (CHP) and 11 heat-only plants (HOP) technologies, providing the heat to DH. Three electricity storage technologies are considered: pumped storage power plants (PSP), batteries and hydrogen electrolysis. The first two only provide intra-day storage, while the latter could provide seasonal storage. One heat storage technology is considered (tank), which only provides intra-day storage. Finally, five decentralized power to heat (P2He) technologies are considered. These include heat pumps for space and water heating, which despite using the same technology, might vary in costs and efficiency.

In order to capture both variation and correlation between demand, wind and solar power while keeping the computational cost manageable, each 5-year time step is modelled through a set of representative days, which are computed using a clustering algorithm (Nahmmacher et al., 2016). In this paper, we use 8 representative days with 3-hour bins for a total of 64 time slices. Capturing such intra-day and seasonal variation is essential to assess the economics of investments into generation plants, transmission and storage. The model includes all EU countries except for Malta and Cyprus, but additionally contains Switzerland, UK, Norway and an aggregated region covering the Balkan countries. Each country is represented as a single node, i.e., cross-border transmission is considered using the net transfer capacities (NTCs), but not the internal network.

To allow analysing the impact of ETS emission caps on the power sector and the interaction among sectors, the model also includes a stylised representation of the energy-intensive industry. Emissions from energy intensive industries are added to those from the power sector through a marginal abatement cost curve derived on the basis of (Gerbert et al., 2018) and (Enerdata, 2020).

We assume that the EU implements the still to be negotiated ‘Fit for 55’ package, setting a target of 55% total emission reduction by 2030 in comparison to 1990. This target implies a 62% reduction for the EU ETS by 2030 with respect to 2005, i.e., a linear reduction factor (LRF) of 4.2% for the emissions cap. Assuming that this LRF is continued after 2030, the last EU allowances (EUA) would be allocated and auctioned already by 2041. We assume that 5.1 $GtCO_2$ EUA will be cancelled by the market stability reserve (MSR) until the end of the EU ETS (Osorio et al., 2021b), and constant emissions (covered by the EU ETS) of 60 MtCO2/yr for the aviation sector. This results in an emission budget for the stationary sector of 19 $GtCO_2$ during the 2018–2057 period. For the ESR, the required reduction is 40% with respect to 1990 levels. This target determines the emission reductions in the buildings sector, and ultimately the decarbonisation of heat supply. We (endogenously) compute the heat demand that needs to be shifted from decentralized boilers (covered by the ESR targets) to DH and decentralized heat pumps, so the countries can reach their targets for the non-ETS sectors. These targets are based on the NECPs.

Since the electricity sector and the MACC used to model energy industry emissions has been already described in previous papers using LIMES-EU (Osorio et al., 2021b; R. C. Pietzcker et al., 2021) and are explained in detail in the most recent model documentation (Osorio et al., 2021a), in this paper we only elaborate on how the buildings sector and its heat supply are modelled.

We first revise the different NECPs and derive heat-related emission caps for the buildings sector. This cap will ultimately determine the volume of heat demand that needs to be shifted from the ESR to the ETS. We later explain in detail how LIMES-EU is extended to cover the buildings sector and how we model DH, in particular CHP operation. We additionally present the methodology to estimate hourly heat profiles, so we can capture the additional pressure posed by further electricity demand from heat pumps as well as the impact of heating consumption patterns on DH.

2.2. NECPs

Current EU regulation sets a 40% emission reduction of EU-wide emissions by 2030 (with respect to 1990), which translates in 43% in the EU ETS and 30% reduction in the non-ETS. To achieve the non-ETS targets, which concern the building sector, countries lay out a strategy and targets for 2030 comprised in the NECPs. In order to quantify to which extent the decarbonization of the building sector would weight on the EU ETS we rely on the NECPs. Since these fell short of the more ambitious targets set within the 'Fit for 55' package, we estimate new targets for every country and, based on these, for the building sector in each of them. We synthesize in Table 1 the non-ETS and –when available- the buildings targets outlined in these reports. The detailed methodology is explained in Appendix A.

Table 1. Review of NECPs, detailing the pledged emission reduction in non-ETS sectors as well as the specific target for the buildings sector in terms of maximum emissions.

Country	**Non-ETS reduction target (%)**	**Buildings target (MtCO2)**
Austria	36	5
Belgium	35	
Bulgaria	0	
Croatia	7	
Cyprus	24	
Czechia	30	
Denmark	39	
Estonia	13	
Finland	39	2.9

Country	Non-ETS reduction target (%)	Buildings target (MtCO2)
France	37	45
Germany	50	67
Greece	36	2.9
Hungary	7	
Ireland	30	4.3
Italy	33	53
Latvia	6	1.7
Lithuania	9	
Luxembourg	55	0.59
Malta	19	
Netherlands	36	17.7
Poland	7	
Portugal	17	3.1
Romania	2	
Slovakia	12	
Slovenia	20	-
Spain	39	18.4
Sweden	59	
United Kingdom	37	

2.3. Buildings module

In this section we focus on the heat demand side. First, we derive the heat-related emission caps for each country based on the (adjusted) NECPs targets. We later focus on heat and cooling demand, which are included as exogenous parameters in LIMES-EU. Finally, we discuss our assumptions regarding electricity demand. Since part of the electricity will be endogenous as a result of heat electrification, we make some assumptions for non-thermal use of electricity consumption (exogenous).

2.3.1. Emission targets for heating

In this study we only consider the impact of (buildings) emissions from heating purposes. Therefore, we need to derive emission targets for heating covered by the ESR. Energy consumed in buildings have five end-uses: lighting/electrical appliances, cooling, space and water heating, and cooking. Only the last three might produce on-site emissions, and thus be covered by the ESR targets. First, we scale cooking (on-site) emissions ($emi^{ESR}_{t,r,sec,cook}$) based on the forecasted useful area ($area_{t,r,sec}$) taken from EUCALC (2021).

$$e^{ESR}_{t,r,sec,cook} = e^{ESR}_{2015,r,sec,cook} \frac{area_{t,r,sec}}{area_{2015,r,sec}} \tag{1}$$

We then subtract such emissions from the adjusted buildings target to derive the heating (on-site) emissions cap ($cap^{ESR}_{t,r,heating}$) (see Figure 2).

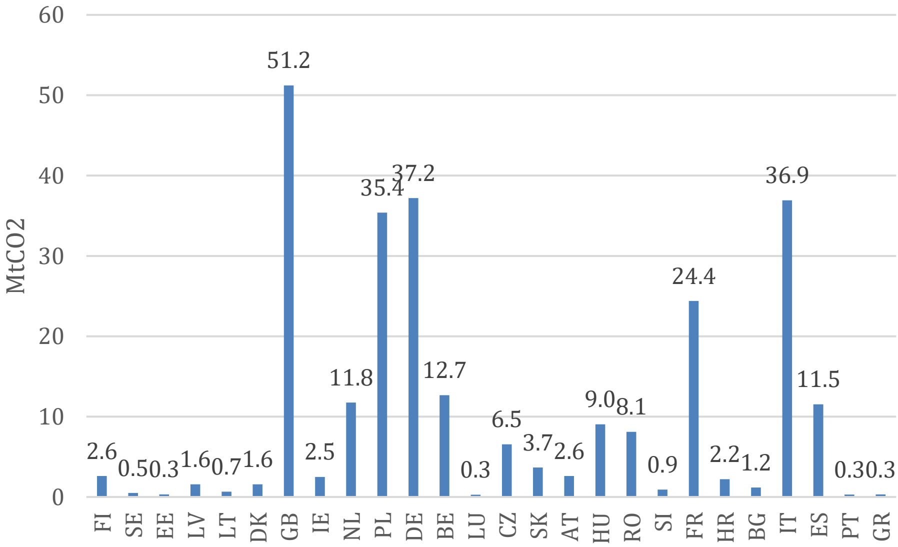


Figure 2. Estimated heat-related cap for emissions from buildings (non-ETS) in 2030.

We thus use the NECPs to generate pathways for heating and ultimately understand how they interact with the ETS. We assume the countries reach ESR targets, but we are agnostic on how they reach them. In other words, we assume the shift from ERS to ETS will occur, but the policies and incentives necessary for this are beyond the scope of this paper.

2.3.2. *Heat demand*

We derive annual heat demand from the HotMaps project[1] data (Müller and Fallahnejad, 2021). They provide this in terms of final energy for different sources. We then convert this data into

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[1] https://www.hotmaps-project.eu/

useful energy by using ratios from 2015, which are estimated from the JRC-IDEES database (Mantzos et al., 2018). Data is provided for different levels of renovation (0.5%, 1%, 2% and 3%), which are used for our different scenarios. Figure 3 shows the resulting useful energy at EU27+UK level for residential and non-residential space and water heating.

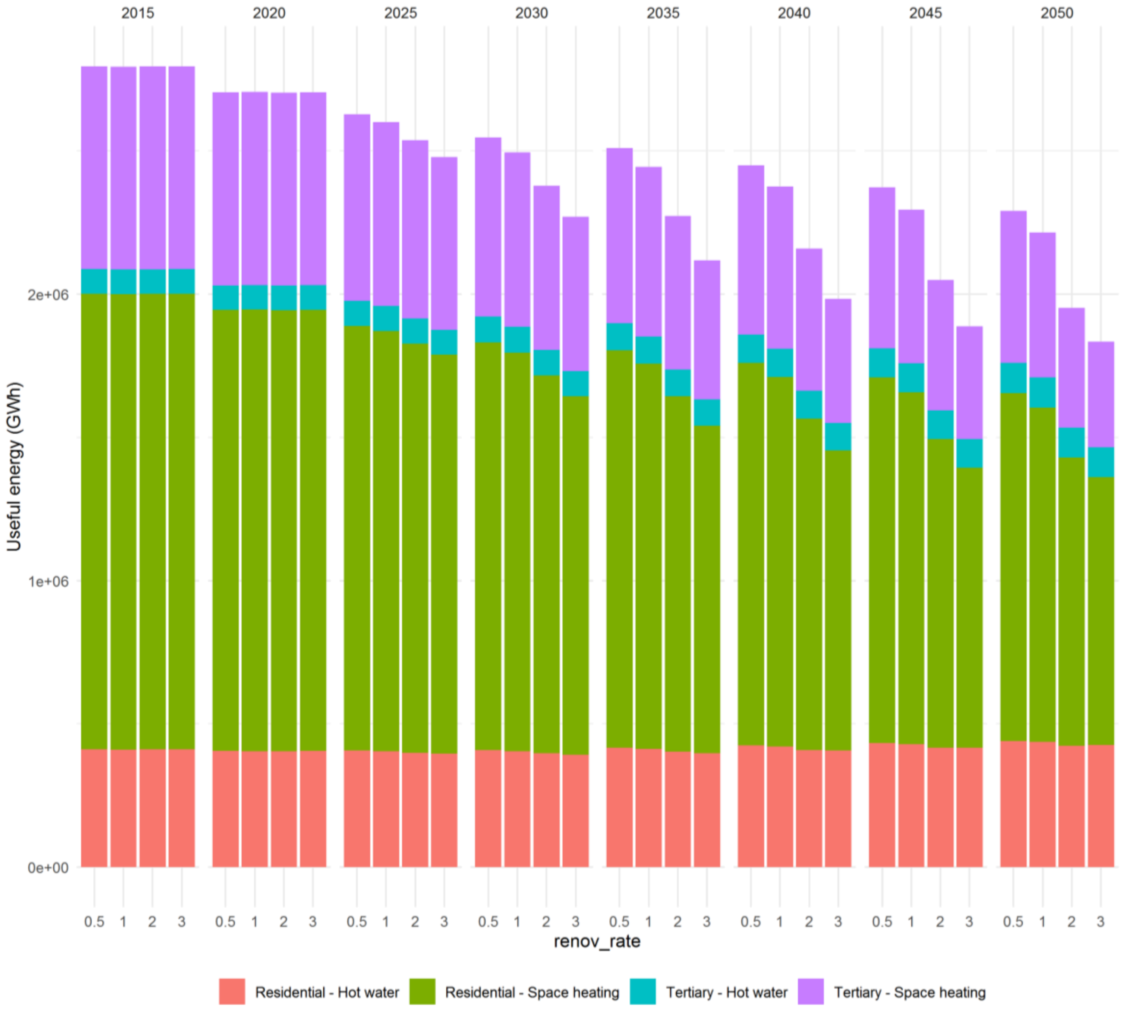

Figure 3. Computed heat demand at EU28 level in terms of useful energy for renovation rates ranging between 0.5% and 3%.

Demand reduction by 2050 oscillates between 18% and 34% with respect to 2015 level, the maximum difference between scenarios (0.5% and 3%) being 450 TWh in 2050. Renovation mainly impacts space heating consumption. This drops from 1595 TWh in 2015 to 943-1222 TWh, i.e., 24-41%, by 2050 in the residential sector and from 708 TWh to 373-534 TWh, i.e., 25-47%, in the same period in the tertiary sector. How water consumption barely decreases from 412 TWh to 431-446 TWh in the residential sector and even increases from 86 TWh to 105-106 TWh in the tertiary sector.

2.3.3. Electricity demand

Electricity demand (final energy) is partially endogenous in the model because the electricity consumption from P2He is a decision variable. We therefore decompose electricity demand depending on its end-uses an make several assumptions on its long-term evolution. We assume that non-thermal uses consumption in buildings (e.g., lighting and electric appliances) increases progressively by 20% between 2015 and 2050. Other components, also exogenous, are electricity demand from cooling, from transportation and from electrolysers.

In order to derive the space cooling demand over the 2015-2050 period at a national level, we rely on the empirical strategy developed by Andreou et al. (2020) for the residential sector of the 28 European countries. For the non-residential, we use potential saturation levels from Jakubcionis and Carlsson (2017) to compute the diffusion rate of space cooling assuming a standard S-shaped diffusion dynamic. More details about the empirical strategy are provided in Appendix B.

We assume electricity demand from the transportation sector to grow from 1 TWh in 2015 to 2000 TWh in 2050. We additionally assume a hydrogen demand from other sectors (e.g., industry) rising from 50 TWh in 2025 to 900 TWh in 2050 (European Commission, 2018) and assume this is entirely produced by electrolysers. The resulting electricity demand from electrolysers is thus endogenous in the model.

2.4. Heat profiles

The When2Heat dataset provides hourly heat demand for 15 European countries (Ruhnau, 2019; Ruhnau et al., 2019). These profiles are based on the German standard load profile methodology for the gas demand as a proxy for the heat demand in buildings and is thus applied only to countries with insulation characteristics similar to Germany. We expand this database to all countries in the model except for the aggregated Balkan by adapting the methodology to local building insulation characteristics. This is explained in detail in Appendix C.

These profiles are then incorporated into the clustering algorithm implemented to derive vRES and demand profiles for a certain number of representative days (Nahmmacher et al., 2016). We thus derive heat profiles for the residential and non-residential sectors for space and water heating ($\zeta_{\tau,r,sec,eu}^{Heat}$). For heat demand from other sectors, namely industry and agriculture, we assume average heat profiles from the non-residential sector. Based on the allocation of 'real' days to each representative day, we also derive 'representative' profiles for HP coefficient of performance (COP).

2.5. Heat supply

We consider a wide range of technologies supplying heat in the model. We constrain them to those whose direct or indirect emissions would be covered by the EU ETS. The former comprises two main subgroups: CHP and HOP which are connected to a district heating network. The latter comprise decentral P2He technologies, whose emissions are indeed produced by electricity plants.

Modelling the operation of these technologies implies several challenges, resulting mainly from the very limited data. For instance, HOP and decentralized P2He capacities are not available to our knowledge and need to be estimated. Although electricity capacity from CHP is available from the JRC-IDEES database (Mantzos et al., 2018), maximum heat output is not and depends on the CHP parametrization. We discuss in detail how we model DH in Appendix E.

For decentralized P2He technologies we fix the historic useful energy for 2015 and let the model compute the capacities. Afterwards only investments in heat pumps are allowed.

2.6. De-facto inclusion of buildings within the EU ETS

Total heat demand ($demyear^{H}_{t,r,sec,eu}$) is split between that supplied by plants whose emissions are covered by the ETS ($Demyear^{H_{ETS}}_{t,r,sec,eu}$), i.e., DH and decentralized P2He, and that supplied by plants whose emissions are covered by the ESR ($Demyear^{H_{ESR}}_{t,r,sec,eu}$), i.e., decentralized boilers.

$$Demyear^{H_{ESR}}_{t,r,sec,eu} + Demyear^{H_{ETS}}_{t,r,sec,eu} \leq demyear^{H}_{t,r,sec,eu} \qquad \forall s \in B_s, eu \in \{space, water\} \tag{2}$$

As mentioned before, we do not model explicitly the entire building sector, i.e., decisions on investing in decentralized non-electric heating boilers are not considered in the model. The sole focus is on shifting heating consumption from polluting (on-site) boilers to DH and P2He technologies. To this aim we constrain the heat produced by individual boilers to the derived emission caps for heating ($cap^{ESR}_{t,r,heating}$, see Section 2.3.1). These emissions are calculated assuming that the emission factor for individual boilers remain unchanged over time. In other words we assume that the shares of energy carriers remain constant. The remaining heat demand would inevitably have to be produced by DH or decentralized P2He technologies. This formulation also allows enough flexibility for sectoral decarbonisation, e.g., in the residential rather than in the non-residential, depending on the current emission factors ($\lambda^{Heat}_{r,sec,eu}$).

$$\sum_{sec\in B_{sec},eu\in\{space,water\}} \lambda^{Heat}_{r,sec,eu} Demyear^{H_{ESR}}_{t,r,sec,eu} \leq cap^{ESR}_{t,r,heating} \tag{3}$$

For 2050 we assume climate neutrality, which translates into zero emissions from the building sector. That is, all heat demand is to be supplied by DH and decentralized P2He. As the model does not see any costs from investing or operating decentralized boilers, we need to assume intermediary targets for the ESR. To this aim we interpolate the cap between actual emissions in 2015 and the estimated cap in 2030, and between the caps in 2030 and 2050. This is necessary to ensure that the model sees some heat demand (to be covered by the EU ETS) and does not only supply heat in those years with a specified target.

From this, we assume that heaters current sources generating emission on-site (e.g., gas boilers) will remain operating up to a level where their emissions reach such cap. Our implicit assumption is that these heaters will remain cheaper than shifting to ETS-covered technologies (heat pumps and DH), i.e., we disregard any option of overachieving the buildings emission cap. This is supported by the idea that many of these devices are already installed. Even if they had to be installed, current policies are not enough to bring ETS-covered technologies to parity.

Total heat demand covered by ETS is thus aggregated and allocated across the different time slices using the heating profiles estimated in Section 2.4. Recall that heat demand from industry and agriculture to be covered from is considered exogenous and is fixed to 2015 levels. This only includes supply from DH as there is no data regarding how space water heating are supplied, and only derived heat (i.e., heat from DH) is reported.

$$D_{t,\tau,r}^{H} = \sum_{sec\in B_{sec}, eu\in\{space,water\}} \zeta_{\tau,r,sec,eu}^{Heat} Demyear_{t,r,sec,eu}^{H_{ETS}} + \sum_{sec\in\{industry,agric\}} \zeta_{\tau,r,sec}^{Heat} demyear_{t,r,sec}^{H} \tag{4}$$

Such demand is thus covered by DH and individual P2He technologies. Output from decentralized P2He technologies has a specified (thermal) end-use, namely space or water heating. Hence, constraints are imposed on space and water heating supply.

$$\sum_{\tau,te\in TE^{P2He_{water}}} l_\tau G_{t,\tau,r,te}^{H} \leq \sum_{sec\in B_{sec}} Demyear_{t,r,sec,water}^{H_{ETS}} \tag{5}$$

$$\sum_{\tau,te\in TE^{P2He_{space}}} l_\tau G_{t,\tau,r,te}^{H} \leq \sum_{sec\in B_{sec}} Demyear_{t,r,sec,space}^{ETS}$$

As DH requires certain population density to be economically feasible, we also assume maximum potential for DH for the building sector ($maxDH_r$) based on EU CALC estimations (Codina Gironès et al., 2018):

$$maxDH_r \sum_{sec\in B_{sec}, eu\in\{space,water\}} Demyear_{t,r,sec,eu}^{ETS} \geq \sum_{\tau,te\in TE^{DH}} l_\tau G_{t,\tau,r,te}^{H} \tag{6}$$

We assume that all heating storage is centralized, i.e., connected to DH. Accordingly, heat storage input is constrained by DH output.

$$S_{t,\tau,r,heat\_sto}^{IN} \leq \sum_{e\in TE^{DH}} G_{t,\tau,r,te}^{H} \tag{7}$$

Finally, the electricity sector is also affected by the heat demand covered by P2He. The resulting electricity consumption (final energy) is thus aggregated to the non-heat-related component of electricity demand ($dem_{t,\tau,r}^{E}$), which is considered exogenous in the model.

$$D_{t,\tau,r}^{E} = dem_{t,\tau,r}^{E} + \sum_{tec\in TE^{P2He}} G_{t,\tau,r,te}^{H} \big/ \eta_{\tau,te} \tag{8}$$

A complete list of sets, indices, parameters and variables is provided in Appendix D.

3. RESULTS

In this section we first analyse the impact of renovation rates on decarbonising the buildings sector and ultimately on the EU ETS. We later focus on detailing the effects on the power sector, namely how the electricity and heat supply change and in which technologies investments should be addressed.

3.1. Impact of buildings decarbonisation on the EU ETS

As Figure 4 compared heat demand and resulting ETS prices for the scenarios of 0.5% and 3% renovation rates. The heat demand supplied by DH and decentralised heat pumps progressively increases to the point where all buildings heat demand is covered by the EU ETS in 2050. When renovation rate is 0.5%, up to 480 TWh (in 2045) would need to be supplied additionally either by DH or heat pumps with respect to the scenario with 3% renovation rate. By 2050 the difference between both scenarios is 450 TWh of useful energy. This implies an increase of 110 TWh of electricity consumption, i.e., 2% increase. The resulting higher pressure on the EU ETS translates into a carbon price increase of 3%. Although this appears to be a minor impact, the transformation required in the power sector is substantial.

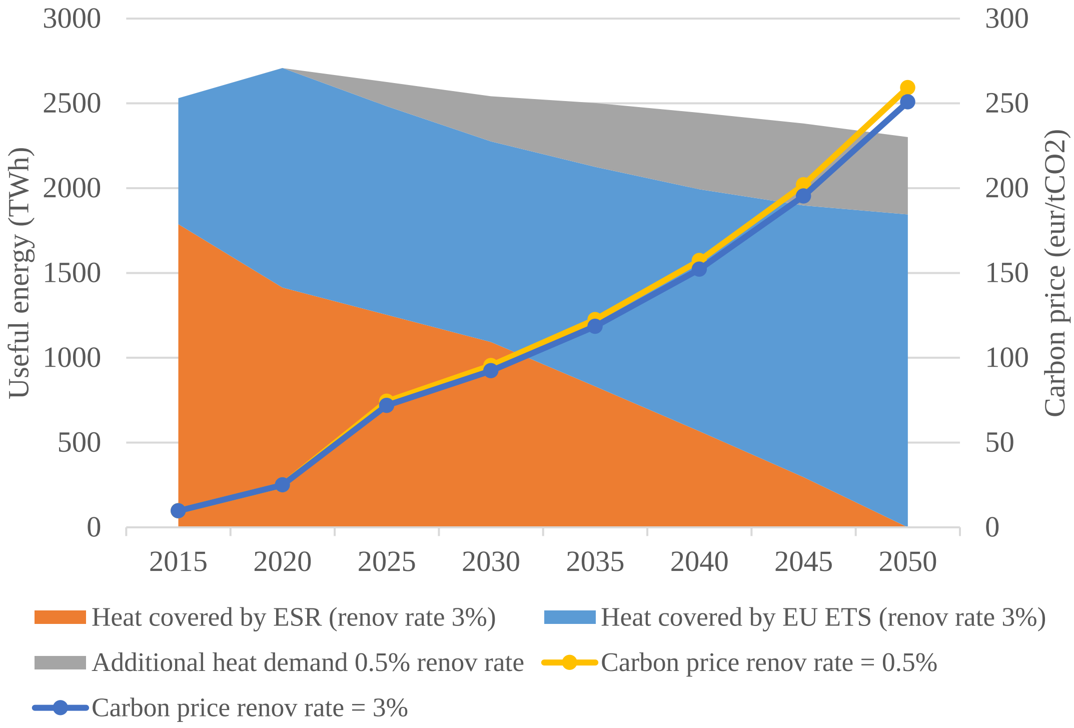

Figure 4. Shift of heat supply for the scenario with 3% renovation rate, additional demand (to be covered by the EU ETS) when renovation stagnates and remains at 0.5% and the impact of these renovation rates on EUA prices.

To illustrate the magnitude of the endeavour, Figure 5 shows the emissions per sector within the EU ETS when the renovation rate equals 1%. We choose this scenario and stick to it for the rest of the paper unless otherwise mentioned, as this is close to the current renovation rate. Electricity-related emissions would need to drop already to 190 $MtCO_2$ by 2025, i.e., 81% below the 2015 level. Compared to those lined to electricity production, heat-related emissions drop from 215 $MtCO_2$ to 147 $MtCO_2$ in the same period. The lion share of emissions (57%) would thus come from energy-intensive industry already by 2025. However, industry emissions decrease rapidly under the very stringent cap, according to which the last certificates would be issued by 2040. It is noticeable that emissions remain positive after 2050, when there should be zero emissions (climate neutrality assumed). This is explained by the certificates intertemporal trading.

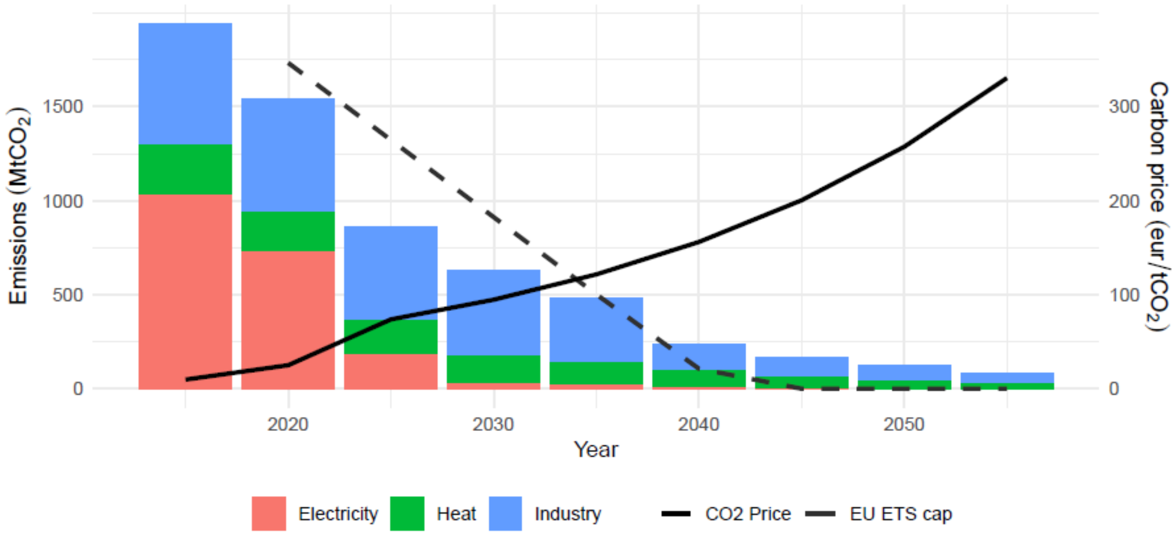

Figure 5. Evolution of emissions per sector within the EU ETS.

A question arises: how does the power sector need to transform to achieve deep decarbonisation? In the next section we present the evolution of both the electricity and heat-mix.

3.2. Power sector transformation

As expected from the sharp decrease in emissions, Figure 6 shows the transition to low-carbon technologies takes place in the medium-term: coal phase out is almost completed by 2025 as only 100 TWh are produced at EU ETS level. By 2030 gas phase-out takes place (< 100 TWh), yielding the electricity sector almost fossil-free. The gap left by fossils is mainly filled by variable renewables, these supplying respectively 61% and 90% of all electricity production by 2030 and 2050. To balance their variable output, there are large investments in batteries, whose output capacity increases from 14 GW in 2030 to 450 GW in 2050 and the energy capacity from 22 to 2000 GWh in the same period. It is noticeable the reliance of the electricity sector on vRES as biomass plays only a small role until 2030, and nuclear, in the absence of new investments, becomes marginal by 2040.

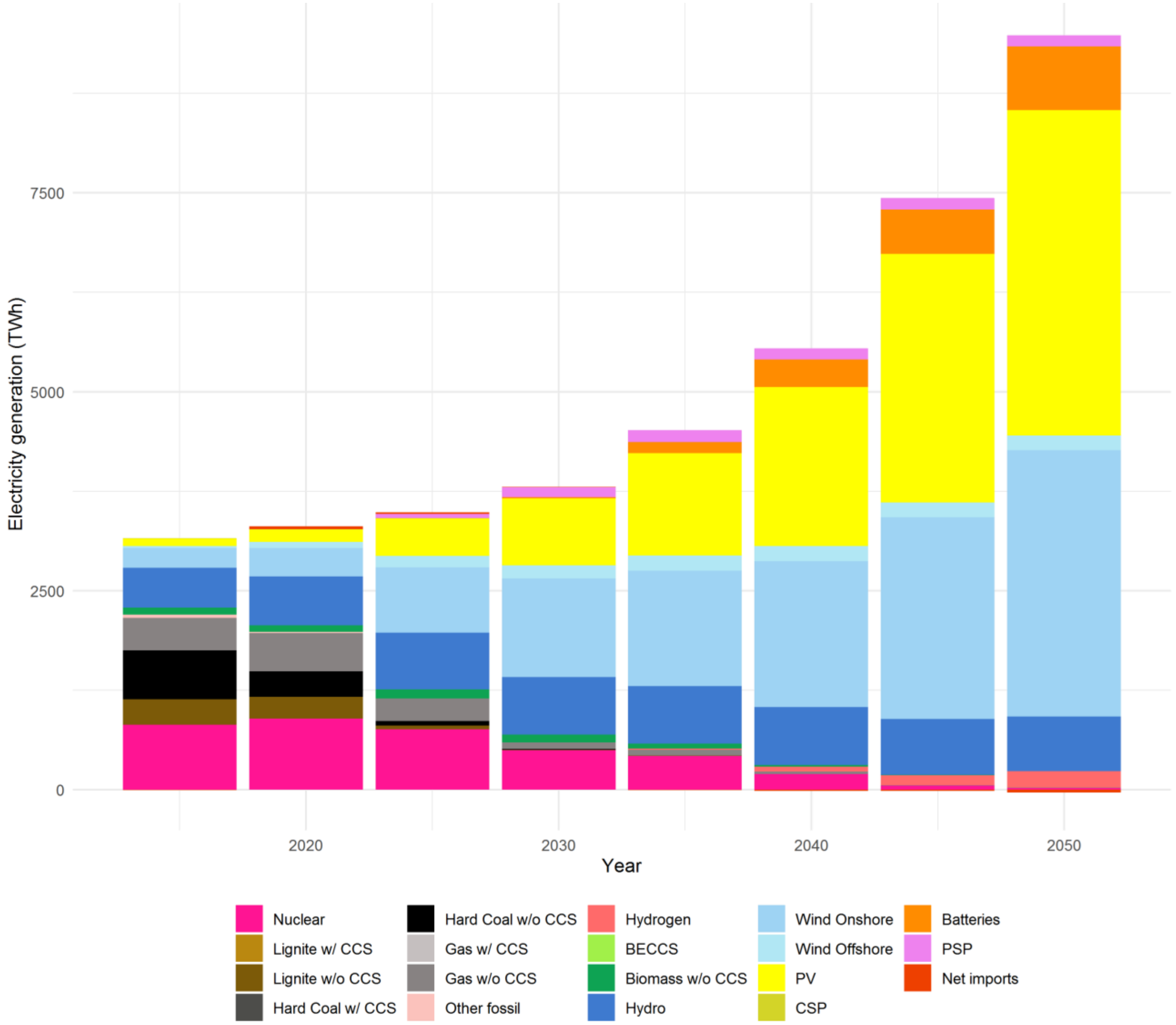

Figure 6. Electricity generation-mix over time at EU ETS level.

From Figure 5, it is clear that heat supply is more difficult and expensive to decarbonise than the electricity supply. Heat-related emissions, i.e., those produced by heat only plants and CHP (proportional to their heat to electricity ratio), decrease slower than those related to electricity generation. Figure 7 shows that there is a shift from CHP to HOP supply in DH networks. Remarkably, CHP plays only a marginal role in the long-term. Indeed, its share in DH gross heat decreases from 72% in 2015 to 14% in 2030 and 36% in 2050. This can be explained by the fact that biomass and gas do not play an important role in long-term decarbonisation of the electricity sector. However, investments in hydrogen CHP start in 2030 and becomes a major player in DH.

Overall, given the lack of need to expand CHP to supply electricity, there is less incentive for CHP compared to HOP, whose heat efficiency is higher.

More specifically, output from both biomass and gas HOP increase substantially in 2025. Unlike biomass, gas-based heat remains roughly stable over time. At the same time, DH is also electrified as large heat pumps are deployed and its share continuously from less than 1% in 2015 to 23% in 2050. By 2030 biomass CHP (125 TWh) still play an important role, accounting for 11% of gross heat generation, but disappears from the heat-mix after 2040. Likewise, lignite CHP also becomes marginal after 2040 and the only CHP technology that plays an important role in the long-term is hydrogen, which accounts for 36% of the gross heat in 2050. As a result, DH relies almost entirely on heat only gas, large heat pumps and hydrogen CHP.

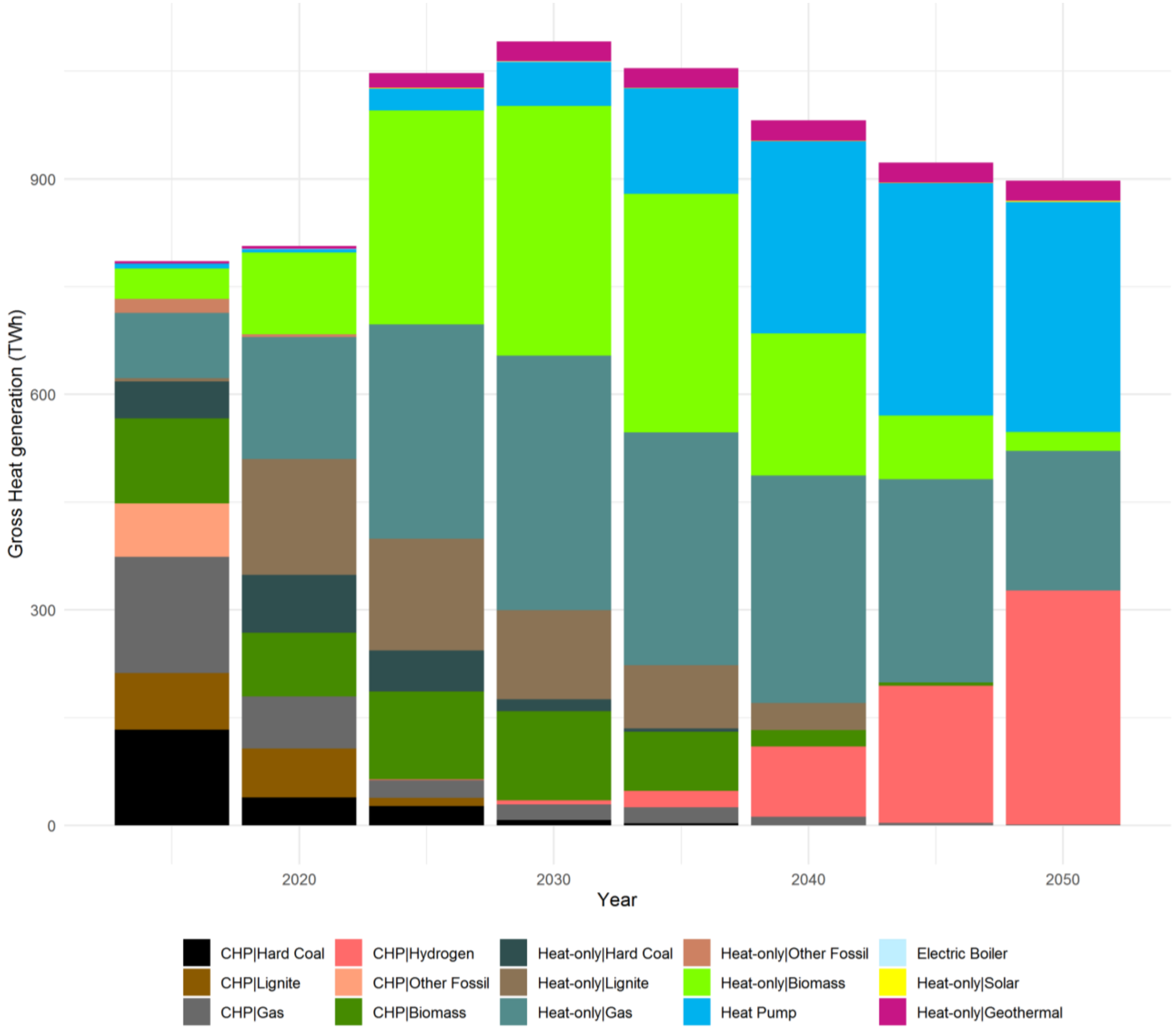

Figure 7. Heat generation-mix over time at EU ETS level.

Although DH share in total heating consumption remains low (between 10 and 20% over time), there are noticeable regional differences in how countries decarbonise buildings. Figure 8 shows DH is and remains dominant in Nordic, Baltic countries and Poland. In other countries it has rather a marginal participation, but it appears to play a bridge role in the medium-term as DH share increases in all countries by 2030 with respect to 2015 levels. The rest of countries mainly replace their decentralized boilers by heat pumps. Whether it is DH expansion or heat pumps large deployment, the buildings sector transformation is substantial considering that decentralised boilers were the dominant heat source in 2015 in all EU countries except for Estonia, Finland and Sweden.

Figure 8. Heat consumption in buildings per source in 2015, 2030 and 2050.

4. CONCLUSSION

With the proposed targets within the ‘Fit for 55’ package and climate neutrality in the long-term, the building sector is facing strong pressure to decarbonise. To this aim the EU is relying on the deep renovations triggered by the ‘renovation wave’. However, the current renovation rates remain low and, even if large efficiency gains are achieved, the remaining fossil-fuel boilers would need to be phased out. Two alternatives arise: expanding district heating and deploying largely heat pumps. This puts the power sector at the crossroads of decarbonising the building sector, and ultimately affects the whole EU ETS. In this paper, we investigated the impact that the heat demand reductions and the electrification of heat would have on the EU ETS and the power system.

Our results show that renovation rates have limited impact on the EU ETS, namely on carbon prices. As a result, one might question the extent to which renovations and energy demand reductions are worth pursuing. On the one hand, this highlights the need to evaluate carefully how EU funding is spent as efforts put into renovation might not actually pay off. This is more relevant now that improving energy efficiency in buildings is a key target of the 723 billion EUR allocated to recovery funds (European Commission, 2021b). On the other hand, we cannot assess in detail the cost-benefits of renovation given the model limitations. Renovations might be necessary (or at least cheaper) when substituting the heat source, e.g., installing a new heat pump. There are also certain cases in which renovation is absolutely necessary in order to improve air quality and health, and help alleviating energy poverty (European Commission, 2021a, 2020c).

Independently of the renovation rate, the pressure faced by the power sector is significant, emissions having to decrease by 85% with respect to 2015 already in 2030. This implies that electricity becomes almost fossil-free by 2030, the share of variable renewables increasing from 18% to 90% between 2020 and 2050. With increasing renewables and storage, there is little incentive for CHP, which ultimately yields a reconfiguration of the DH supply. This becomes more reliant on gas HOP as well as large heat pumps, while only hydrogen CHP plays a major role. Still, DH share remains below 20% and buildings decarbonisation is mostly dependent on decentralized heat pumps.

Although our paper does not elaborate on which kind of policy might trigger such a heat pumps deployment, one of the first measures should focus on setting a level playing field for low-carbon heat technologies. Currently, the cost ratio between electricity-sourced and gas-sourced technologies is unfavourable in most European countries, part of the reason being higher taxes and levies on electricity (Rosenow, 2021). Rebalancing levies and taxes might complement national/EU plans and provide the right incentives to decarbonise the buildings sector.

To sum up, independently of the level of renovation, buildings decarbonisation will lead to an automatic full integration of the building sector into the EU ETS. This might have unanticipated consequences: if the ETS cap is too tight relative to the ESR targets (or potentially an ETS2 for buildings and transport), prices may rise considerably – and might actually become higher than in the ETS2, contrary to what is currently expected (R. Pietzcker et al., 2021). This in turn can reduce incentives to further decarbonize buildings. A way out would be to adjust the cap contingent on renovation progress, or better to implement gradual linking between ETS and ETS2 (Edenhofer et al., 2021). In that way, high price differentials could be automatically balanced out, and the way would be paved for full integration from 2030 on.

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APPENDIX

A. Estimation of 2030 cap for heat-related emissions in buildings

Due by the end of the year 2019, the NECPs provide the most recent data when it comes to energy and climate commitments at the national level within the European Union. As of September 2020 every country had submitted their national plans, except the United Kingdom, for which we rely on the draft version that has been submitted during the previous stage of the process.

Targets for the emission reductions in non-ETS sectors are reported by all MS and range from 0% for Bulgaria to 59% for Sweden. The pledged reductions amount to 980 Mt. This is more than the 30% (861 Mt) determined in the previous EU target (40%), but likely lower than the requirement under the current more ambitious target (55%), which implies a reduction of 62% for the EU ETS and 39% for the non-ETS sectors (Under the ESR scope) with respect to 2005. Additional reductions within the non-ETS sector will thus amount to 343 Mt. Since NECPs pledges already consider 119 Mt additional reductions, the ESR target needs to be adjusted in 224 Mt. Accordingly, we adjust the national targets based on the current ESR contributions, i.e., we allocate the remaining 224 Mt among countries based on the share of their contribution. To illustrate this, Germany's target of 50% equals 238 Mt reductions, i.e., 24% of total pledged reductions. We thus assume that Germany would need to contribute additionally by 54 Mt.

Some countries specify sectoral targets (e.g., Austria), which also need to be adjusted. We assume that additional reductions in buildings are proportional to the current share of the sector's contribution. For instance, in Germany the 67 Mt emission limit for buildings implies a reduction of 85 Mt with respect to 2005, i.e., 35% of the entire non-ETS reductions. Therefore, from the 54 Mt additional requirements, the building sector would need to contribute by further reducing 19 Mt, i.e., the new target for the building sector would be 48 Mt. Where sectoral targets are not available, we estimate emissions cap for the building sector in 2030 assuming that the share of buildings in non-ETS emissions in 2030 will be the same as in 2015. This approach has undeniably the disadvantage of potential imbalances across sectoral efforts.

B. Cooling demand

In order to derive the space cooling demand over the 2015-2050 period at a national level, we rely on the empirical strategy developed by Andreou et al. (2020) for the residential sector of the 28 European countries. For each year y and country c, Andreou et al. (2020) compute the national diffusion rate of air conditioning ($Diff$) – that is to say the percentage of households having air conditioning at home – as a function of annual personal income (INC) and temperature levels in the summer months (June, July and August) of the current and past year (TMP^{JJA}) as well as saturation levels of air conditioning (Sat) and a time trend (t). The following equation hence characterizes their empirical strategy:

$$\ln\left(\frac{Sat_c}{Diff_{c,y}}-1\right) = ln(\alpha_c) + \beta_1 t + \beta_2 INC_{c,y} + \beta_{3y} TMP_{c,y}^{JJA} + \beta_{3y-1} TMP_{c,y-1}^{JJA} + \varepsilon_{c,y} \tag{9}$$

More particularly, they split countries into two saturation level groups – a “cold” group and a “warm” group – depending on the countries’ position with respect to the long-term average cooling degree days over the 1995-2015 period. Different saturation level values for each group are then evaluated so as to maximise the model’s performance.

In order to get estimates for the non-residential sector over the 2015-2050 period, we design a different empirical strategy since extending Andreou’s regression by replacing individual annual income by the Gross Domestic Product (GDP) does not provide any significant coefficients, neither for the GDP nor for temperatures. This might be due partly to omitted explanatory variables. Indeed, as underlined by Jakubcionis and Carlsson (2017), outside temperatures may impact less the cooling demand at the extensive margin in the service sector than in the residential sector. In their paper, they use the United States as a proxy in order to provide estimates of the space cooling potential penetration in the service sector for the 28 European Union members. We hence rely on these data in order to compute the diffusion rate of space cooling in the tertiary sector assuming a standard S-shaped diffusion dynamic. More precisely, we estimate the coefficients of S-shape curve relying on JRC-IDEES diffusion rates and potential saturation levels as outlined by Jakubcionis and Carlsson (2017) in order to derive diffusion rates at the national level over the 2015-2050 period.

We then assume a constant unit consumption per sqm (equal to that from 2015) to estimate the thermal energy consumption from cooling ($thuse_{t,r,sec,cooling}$).

$$thuse_{t,r,sec,cooling} = area_{t,r,sec} Diff_{t,r,sec} uc_{t,r,sec,cool} \qquad \forall sec \in B_{sec} \tag{10}$$

Final electricity demand from AC being:

$$demyear_{t,r,sec,cool}^{E} = {}^{thuse_{t,r,sec,cooling}}/_{\eta_{AC}} \qquad \forall sec \in B_{sec} \tag{11}$$

Where η_{AC} is the AC efficiency, which is estimated to remain constant at 2015 level.

C. Extension of When2Heat database

The When2Heat dataset provides heat demand time series in an hourly resolution for several European countries (Ruhnau, 2019; Ruhnau et al., 2019). These profiles are based on the German standard load profile methodology for the gas demand as a proxy for the heat demand in buildings. Because the parameters included in this methodology are specific to the German buildings stock, only 15 countries with building insulation characteristics similar to Germany have been included in the dataset. To extend the dataset to all European countries, we adapt the methodology to local building insulation characteristics by considering the heating threshold temperatures.

The main idea is that the heat demand in countries with better insulation features similar profiles at lower temperatures, and the heat demand in countries with weaker insulation features similar profiles at higher temperatures. This is captured in the heating threshold: the better the insulation, the lower the heating threshold (Figure 9).

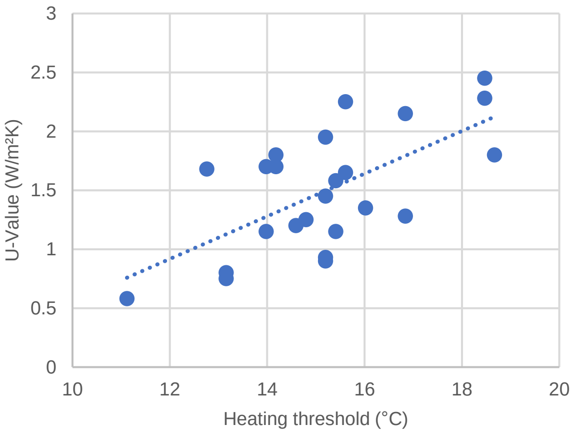

Figure 9: Building insulation (in terms of U-values) and heating thresholds in different European countries. Own illustration based on the EU Building Database and Kozarcanin et al. (2019).

Based on this rationale, we use national heating threshold temperatures as estimated by Kozarcanin et al. (2019) to shift the profile function of the German gas standard load profile methodology (BDEW, 2015). For every day, d, and every location, l, the profile function defines the daily demand factor, $f_{d,l}$, as a function of the local reference temperature, $T_{d,l}^{ref}$, which is shifted here by the difference of the national heating threshold as compared to Germany, ΔT_l^{th}:

$$
\begin{aligned}
f_{d,l} = {} & \frac{A}{1+\left(\dfrac{B\cdot{}^{\circ}C}{T_{d,l}^{ref}-\Delta T_{l}^{th}-T_0}\right)^{C}}+D \\
& + max\begin{Bmatrix} m_{space}\cdot\left(T_{d,l}^{ref}-\Delta T_{l}^{th}\right)/{}^{\circ}C+b_{space} \\ m_{water}\cdot\left(T_{d,l}^{ref}-\Delta T_{l}^{th}\right)/{}^{\circ}C+b_{water} \end{Bmatrix},
\end{aligned} \tag{12}
$$

Where:

$$\Delta T_{l}^{th} = T_{l}^{th} - T_{Germany}^{th} \tag{13}$$

With $T_0 = 40\,{}^{\circ}C$. The parameters $A, B, C, D, m_{space}, b_{space}, m_{water}, b_{water}$ differ depending on building types, namely single-family houses, multi-family houses, and commercial buildings. Figure 10 illustrates the shift of the profile function for the example of single-family houses in Germany, Italy, and Norway.

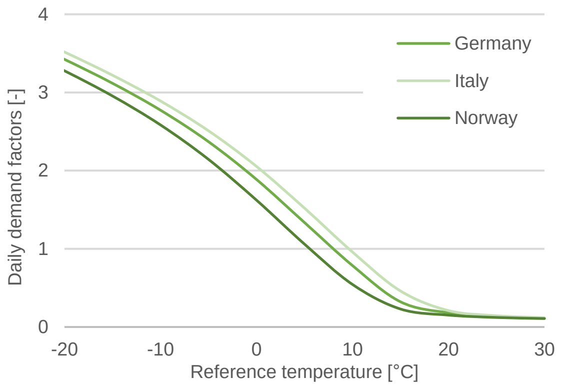

Figure 10: Daily heat demand factors as a function of the reference temperature. Exemplary profile functions for single-family houses for Italy and Norway are shifted by the difference of the national heating thresholds as compared to Germany.

The impact of adjusting the profile function to the national heating threshold is illustrated in Figure 11 for the case of Italy. As compared to Germany, Italy has fewer cold days, which will lead to the heat demand being more concentrated in fewer days of the year. This effect is captured by the applying the unadjusted German profile function to Italy ("IT not adjusted"). However, this concentrating effect is alleviated by the fact that buildings in Italy are less insulated than in Germany. This effect alleviating effect is captured by adjusting the German profile function to the Italian heating threshold ("IT adjusted"). Still, the adjusted heat profile in Italy is more concentrated than the German profile.

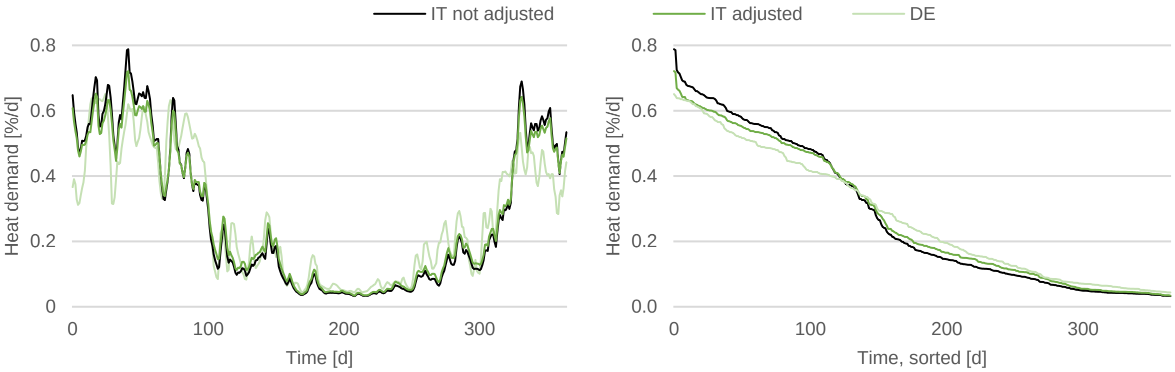

Figure 11: Modelled heat demand for space and water heating in 2013 for Italy and Germany, with and without adjusting the Italian profile function to the national heating threshold.

D. Sets, indices, parameters and variables

Table A1. Sets

Symbol	Description
t, tt	years
τ	time slices
r	regions
te	electricity generation technologies
st	storage technologies
sec	sector (e.g., residential)
eu	end use
mo	CHP operation mode

Table A2. Indices.

Symbol	Description
R	all regions
TE	all electricity generation technologies

Symbol	Description
B_{sec}	Sectors in building (i.e., residential and non-residential)
ESR_{sec}	Sectors in covered by the ESR
$TE^{P2He_{eu}}$, TE^{P2He}	P2He technologies
TE^{DH}	District heating technologies
$TE^{CHP_{ec}}$, $TE^{CHP_{bp}}$	Extraction and backpressure CHP
TE^{HOP}	Heat-only plants

Table A3. Parameters.

Symbol	Description
l_τ	length of time slice τ
$\zeta^{Heat}_{\tau,r,sec,eu}$, $\zeta^{Heat}_{\tau,r,sec}$	Time slice factor for heat demand
$\lambda^{Heat}_{r,sec,eu}$	Average emission factor decentralized heat in buildings
η_{te}, η_{st}, $\eta^{E_{mo}}_{r,te}$, $\eta^{H_{mo}}_{r,te}$, $\eta_{r,te}$	conversion efficiency
γ^H_r	DH losses
$e^{ESR}_{t,r,sec,cook}$	cooking (on-site) emissions
$cap^{ESR}_{t,r,heating}$	heating (on-site) emissions cap
$demDH^{Heat}_{t,\tau,r}$	DH demand from buildings
$thuse_{t,r,sec,cool}$	Thermal use from cooling
$demyear^{E}_{t,r,sec,cool}$	Final electricity demand from cooling
$demyear^{H}_{t,r,sec,eu}$, $demyear^{H}_{t,r,sec}$	Useful heat demand covered by the EU ETS
$dem^{E}_{t,\tau,r}$	(non-thermal use) electricity demand
$maxDH_r$	Max share of DH in total heat supply to buildings
a_{te}	auto-consumption rate

Table A4. Variables

Symbol	Description
$G^{E}_{t,\tau,r,te}$, $G^{H}_{t,\tau,r,te}$	Net electricity and useful energy (heat) generation
$Q^{H}_{t,\tau,r,te}$	Heat output produced in backpressure mode
$K_{t,r,te}$	Electricity/heat capacities. For CHP, this represents the electric capacity
$PE_{t,r,te}$	Primary energy (fuel consumption)
$S^{IN}_{t,\tau,r,st}$, $S^{OUT}_{t,\tau,r,st}$	storage input/output
$Demyear^{H_{ETS}}_{t,r,sec,eu}$	Annual heat demand covered by the ETS
$D^{E}_{t,\tau,r}$, $D^{H}_{t,\tau,r}$	Electricity/Heat demand per time slice

E. Modelling DH

Here we provide details how model and calibrate DH in LIMES-EU. First, we describe how CHP operation is modelled, as this affects the heat to power ratios and ultimately determines CHP heat capacity. We later elaborate on how we estimate heat-only capacities as these are not publicly available. Finally we provide details how the model is calibrated and how the model results compare to historic gross heat.

CHP

CHP can produce both heat and power. Before going deeper into the modelling of CHP, it is important to provide some background on the CHP functioning and technical features. A common assumption, e.g, in the Joint Market Model (Meibom et al., 2006) and the Balmorel model (Ravn et al., 2001), is to group CHP into plants with one or two degrees of freedom, i.e., backpressure or extraction units, respectively. The former produce heat and power simultaneously (at a certain heat to power rate given by the coefficient Cb[2]), while the latter are capable of operating both in backpressure and condensing mode as well as every combination in between. This enables a large degree of freedom in varying the electricity and heat generation. From the point of full production in condensing mode (maximum electricity production) to full production in backpressure mode,

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[2] The Cb-coefficient (backpressure coefficient) is defined as the maximum power generation capacity in backpressure mode divided by the maximum heat production capacity.

the loss of electricity generation per unit of heat generated is given by the coefficient Cv[3] (see Figure 12).

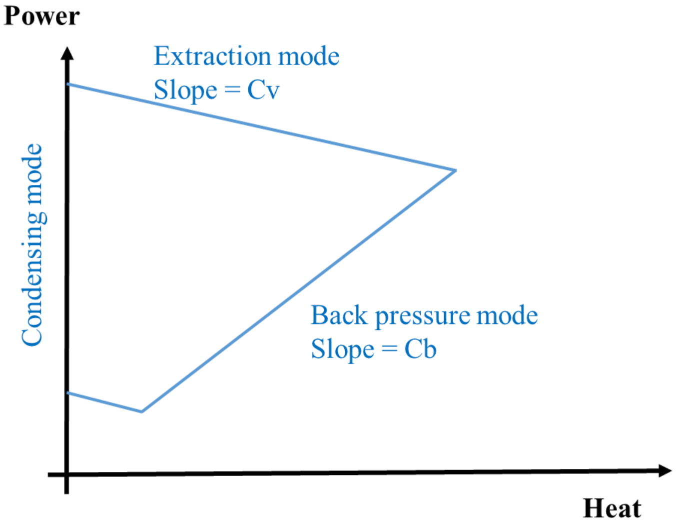

Figure 12. PQ-diagram describing CHP operation.

There are small variations on the formulation of backpressure units ($TE^{CHP_{bp}}$) and extraction units ($TE^{CHP_{ec}}$). In the former, the ratio between electricity ($G^{E}_{t,\tau,r,te}$) and heat ($G^{H}_{t,\tau,r,te}$) production is constant and equal to $cb^{net}_{r,te}$ (see Eq. (14)). In the latter, electricity needs to be split into electricity produced in back pressure and full condensing mode. For simplicity, we only distinguish the electricity produced in backpressure mode ($Q^{E}_{t,\tau,r,te}$), which determines the amount of heat produced ($G^{H}_{t,\tau,r,te}$). The electricity produced ($G^{E}_{t,\tau,r,te}$) can thus be larger than that produced in back pressure mode ($Q^{E}_{t,\tau,r,te}$), i.e., when operating in extraction-condensing mode (see Eq. (15)). Additional constraints on CHP operation ensure that heat and power output remain within the area limited by the PQ-diagram (Figure 12).

$$G^{E}_{t,\tau,r,te} = cb^{net}_{r,te} G^{H}_{t,\tau,r,te} \qquad \forall te \in TE^{CHP_{bp}} \qquad (14)$$

$$G^{Q}_{t,\tau,r,te} = Q^{H}_{t,\tau,r,te}$$

$$Q^{E}_{t,\tau,r,te} = cb^{net}_{r,te} G^{H}_{t,\tau,r,te} \qquad \forall te \in TE^{CHP_{ec}} \qquad (15)$$

$$G^{E}_{t,\tau,r,te} \geq Q^{E}_{t,\tau,r,te}$$

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[3] The Cv-value for an extraction steam turbine is defined as the loss of electricity production, when the heat production is increased one unit at constant fuel input.

In the model, generation quantities are expressed in terms of net output, i.e., net electricity and useful energy (for heat). We thus scale the coefficients $cb_{r,te}$ and $cv_{r,te}$ to account for electricity autoconsumption a_{te}, heat losses (γ_r^H) and the ratio thermal energy to energy consumption (ϖ_r)[4] (see Eq. (16)).

$$cb_{r,te}^{net} = cb_{r,te} \times \frac{1 - a_{te}}{\varpi_r (1 - \gamma_r^H)} \tag{16}$$

$$cv_{r,te}^{net} = cv_{r,te} \times \frac{1 - a_{te}}{\varpi_r (1 - \gamma_r^H)}$$

Unlike electricity-only and HOP plants, efficiency in CHP might vary depending on the heat/power ratio. The relationship between the efficiency in the different modes is described by Eq. (17), where $\eta_{r,te}^{E_{back}}$ is the electric efficiency in backpressure mode and $\eta_{r,te}^{E_{cond}}$ the electric efficiency in full condensing mode:

$$\eta_{r,te}^{E_{back}} = \eta_{r,te}^{E_{cond}} \frac{cb_{r,te}}{cb_{r,te} + cv_{r,te}} \tag{17}$$

Fuel consumption ($PE_{t,r,te}$) depends on the output in each mode, but can be simplified as follows:

$$PE_{t,r,te} = \sum_\tau l_\tau \sum_{te \in TE^{CHP}} \frac{G_{t,\tau,r,te}^E + cv_{r,te}^{net} G_{t,\tau,r,te}^H}{\eta_{r,te}^{E_{cond}}} \qquad \forall te \in TE^{CHP_{ec}} \tag{18}$$

HOP and decentralized P2He are modelled like electricity-only plants, accounting for typical operational constraints (e.g., ramping, minimum load and FLOH), and assuming constant efficiency.

Heat-only

While CHP capacities are provided by (Mantzos et al., 2018), we are not aware of any source in literature reporting capacities for HOP (TE^{HOP}). Based on 2015 data, we estimate the required capacities to meet historic annual gross heat production ($gross\ heat_{2015,r,te}$):

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[4] heat losses (γ_r^H) and the ratio thermal energy to energy consumption (ϖ_r) are estimated at country-level from 2015 data (Mantzos et al., 2018) and assumed constant during the entire modelling horizon. The former is estimated from the difference between gross heat (also referred as transformation output) and final energy, while the latter is the ratio between useful energy and final energy.

$$k_{2015,r,te} = \frac{gross\ heat_{2015,r,te}}{8760 \times nu2_{te}} \qquad \forall te \in TE^{HOP} \tag{19}$$

Where $nu2$ is the annual availability.

We then formulate an optimization problem, where the factor ($f_{2015,r}^{HOPcap}$) used to scale HOP capacities is minimised. This is subject to usual heat balance constraint as well as hourly and annual capacity constraints. The resulting factor ($f_{2015,r}^{HOPcap}$) is thus used to adjust HOP capacities:

$$K_{t,r,te} = f_{2015,r}^{HOPcap} k_{2015,r,te} \qquad \forall te \in TE^{HOP} \tag{20}$$

Calibration

Unlike the electricity sector, there significantly less data available for the DH sector. Several parameters thus need to be calibrated. We use 2015 as reference year to compare our results to historic data.

Although the European Commission and Joint Research Centre (2017) provides techno-economic parameters for most CHP technologies in the different modes, historic efficiencies and heat-to-power ratios vary widely across countries. We therefore calibrate the model by adjusting the efficiencies as well as the coefficients $cb_{r,te}$ and $cv_{r,te}$. More especifically we assume that $cb_{r,te} = cb_{r,te}^{*} \times f^{calib_{cb}}$, where $cb_{r,te}^{*}$ is the historic power to heat ratio and $f^{calib_{cb}}$ a factor to be calibrated. Such factor should be lower than 1 so the historic power to heat ratio, which is endogenous in the model, remains feasible. The parameter $cv_{r,te}$ is taken from European Commission and Joint Research Centre (2017).

We also adjust efficiencies using historical data as follows:

$$\eta_{r,te}^{E_{mo}} = f^{calib_{eff}} \eta_{r,te}^{*} \frac{1}{\eta_{r,te}^{E_{back}} \left(1 + {}^{1}\!/_{cb_{r,te}}\right)} \tag{21}$$

Where $\eta_{r,te}^{*}$ is the historic total gross efficiency and $f^{calib_{eff}}$a factor to be calibrated, assuming values in the range of [1, 1.1]. We additionally assume that total gross efficiency remains between 50% and 95%.

Given the lack of information regarding heat capacity margins, we also calibrate a factor $f^{calib_{demDH}}$. This is used in the formulation used to estimate heat-only capacities. We assume $1 \leq f^{calib_{demDH}} \leq 1.2$.

Finally, the fourth parameter to calibrate is the feed-in tariff paid to biomass plants (both CHP and electricity-only) in Germany. This is estimated to be between 20 and 60 eur/MWh.

To calibrate the model we minimize the sum of square errors between modelled and historic heat and electricity supply. Although the model has been calibrated for the electricity sector in previous versions, we also include electricity in this minimisation as the CHP configuration can also affect electricity dispatch.

The following figures show that LIMES represents fairly well the power sector and DH. The main problem seems to be the overestimation of hard coal heat (see Figure 13) and electricity (see Figure 14) generation.

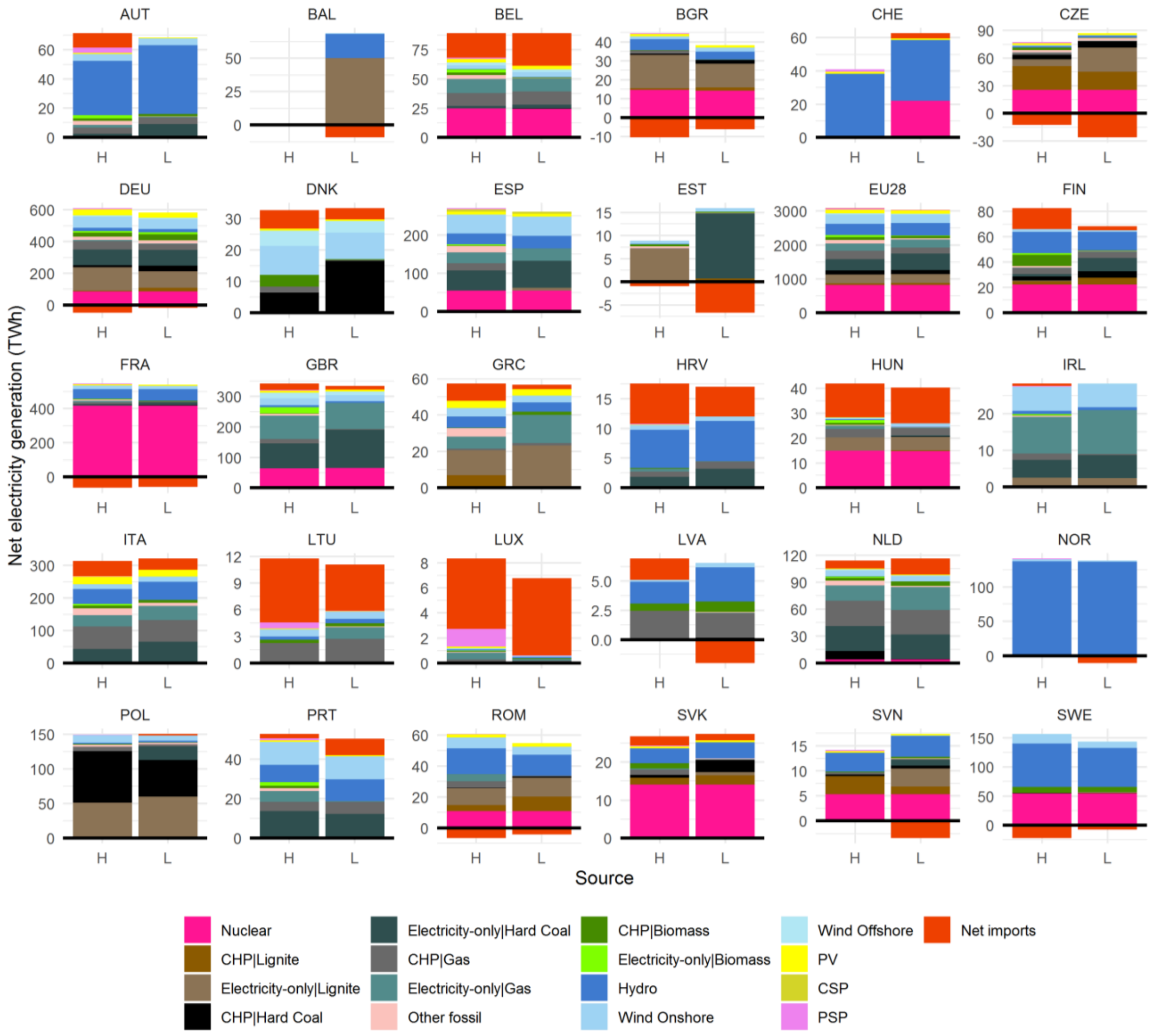

Figure 13. Comparison between historic (H, left bars) and modelled (L, right bars) electricity dispatch in 2015.

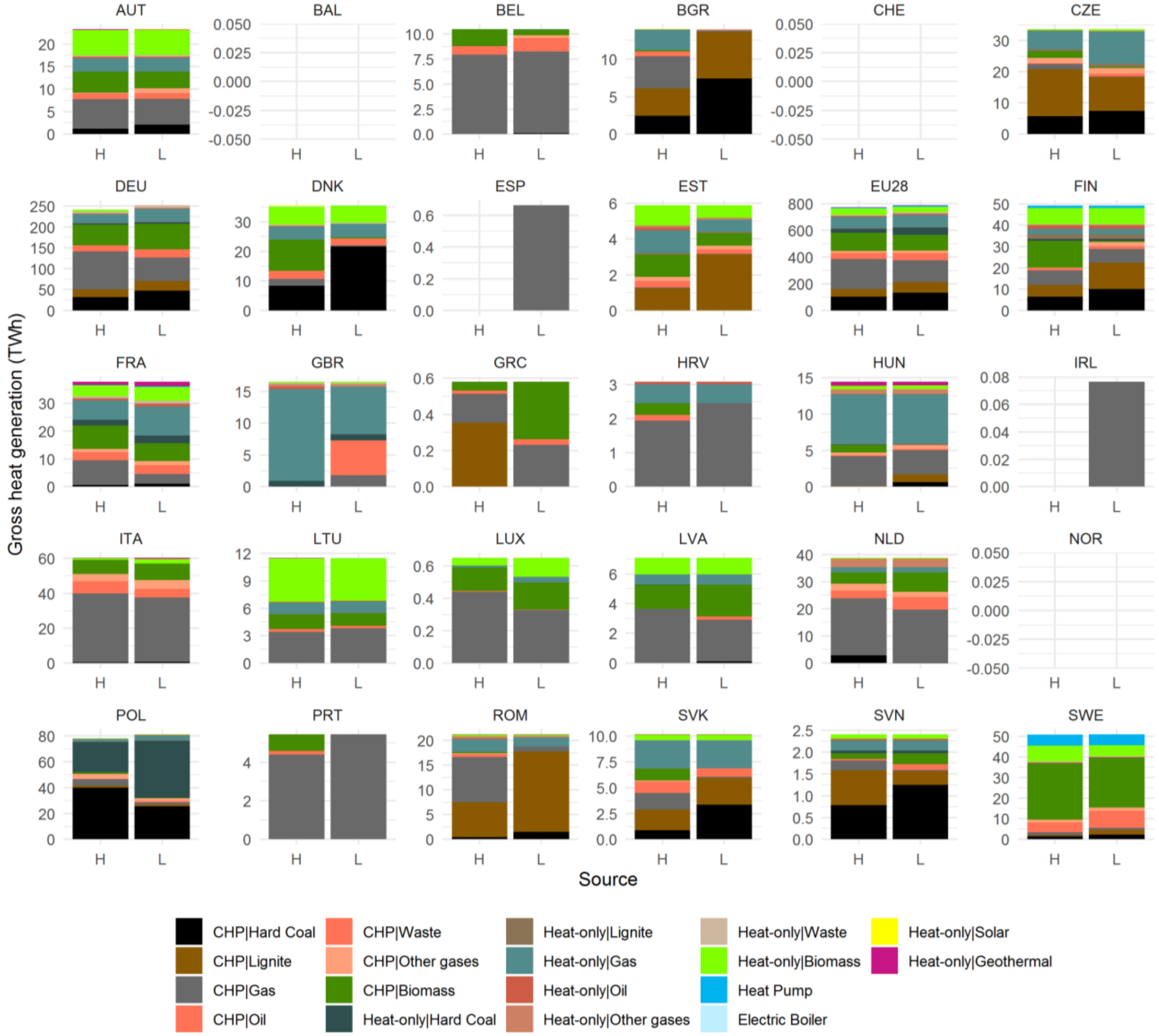

Figure 14. Comparison between historic (H, left bars) and modelled (L, right bars) DH heat output in 2015.

The resulting emissions (see Figure 15) are also within an acceptable range, which indicates that efficiencies, which in the case of CHP are endogenous, are reasonably calibrated.

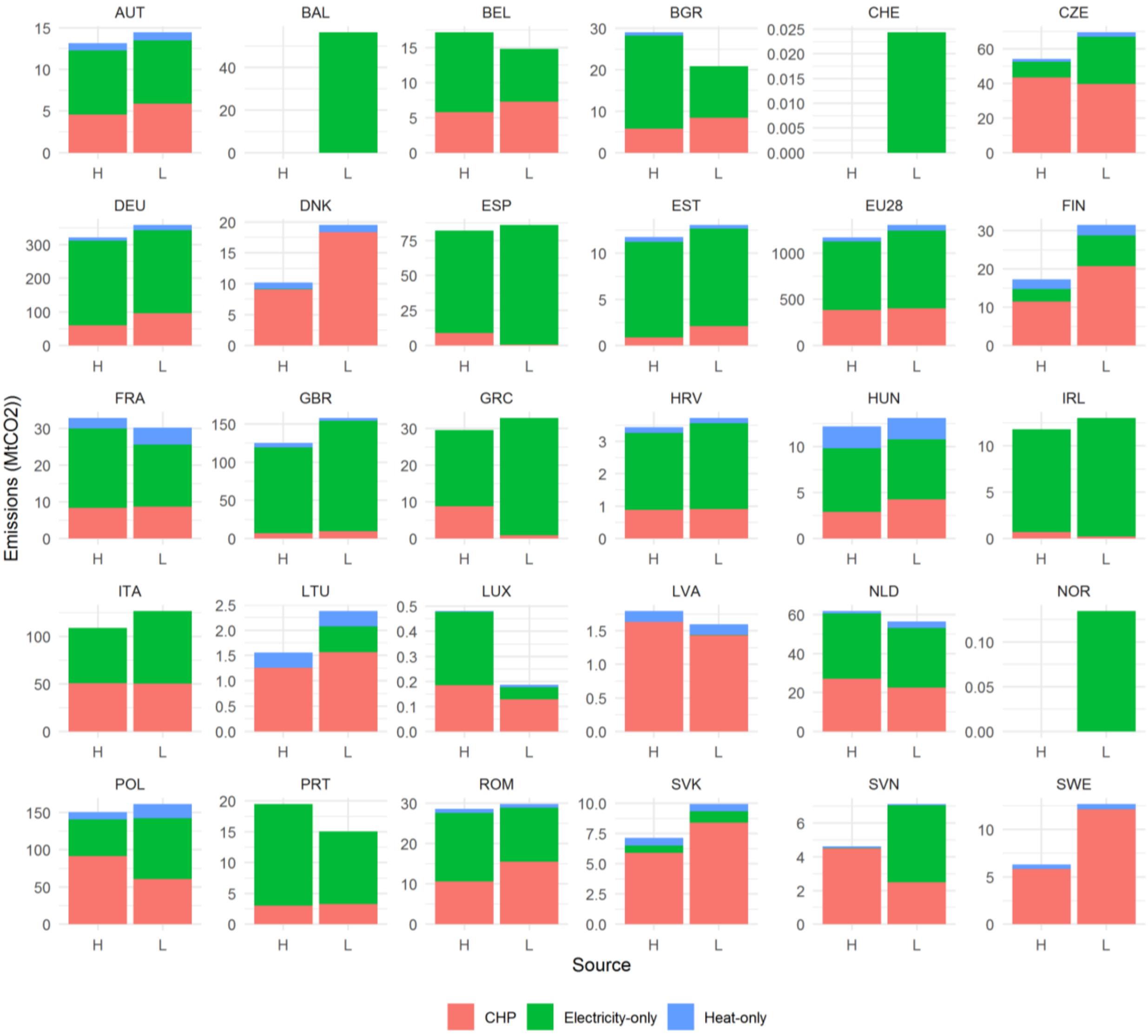

Figure 15. Comparison between historic (H, left bars) and modelled (L, right bars) emissions in 2015.