A model-based analysis of the opportunities and constraints of enhanced energy sector integration

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This work addresses the role of an enhanced integration of the power, heat and transport sectors in future energy supply systems with high shares of intermittent renewable power generation. Such integration is realized by technological linkages between the sectors, e.g. through combined heat and power (CHP) generation, electric heat pumps and electric vehicles (Figure 1). The analysis is focused on their application in Germany, and relies on a comprehensive and multi-step modelling approach.[1]

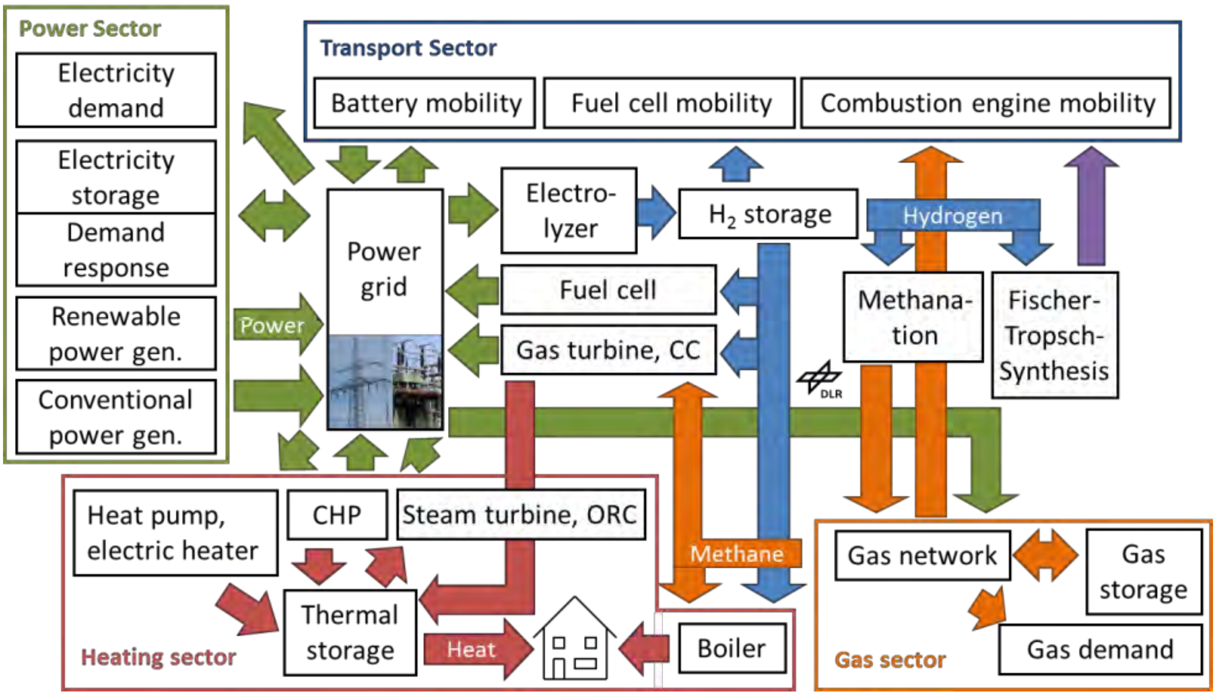

Figure 1: Overview of possible linkages between energy sectors.

Introduction

Wind and solar irradiation are not available to the same extent at any time. Figure 2 shows the power generation in photovoltaic (PV) panels and wind turbines, as it might occur in Germany in the year 2050, when around 65% of the demand is supplied by these technologies. Not only is the power generation highly fluctuating, it also exceeds the demand during some periods. Subtracting the intermittent power generation from the demand, the residual load is obtained. As we see, there are periods of a supply surplus and other with a supply deficit. Load balancing is required to fill the gaps on the one hand, and use the surplus on the other. This includes both the provision of power and energy. Deficits can be filled by dispatchable power plants, electricity storage, an import of electricity, or demand reduction. On the other hand, surpluses can be used for storage charging, electricity export or a demand increase. The latter includes the usage of electricity in other demand sectors. Today, intermittent renewable power generation is mostly balanced by conventional power stations, power transmission, and pumped storage hydro. Given that conventional power generation is

[1] This manuscript partial relies on a previous publication of the author [Gils 2015]

planned to be reduced in order to cut CO_2 emissions, and that potentials for additional hydro storage are limited, new balancing technologies will be required in the future.

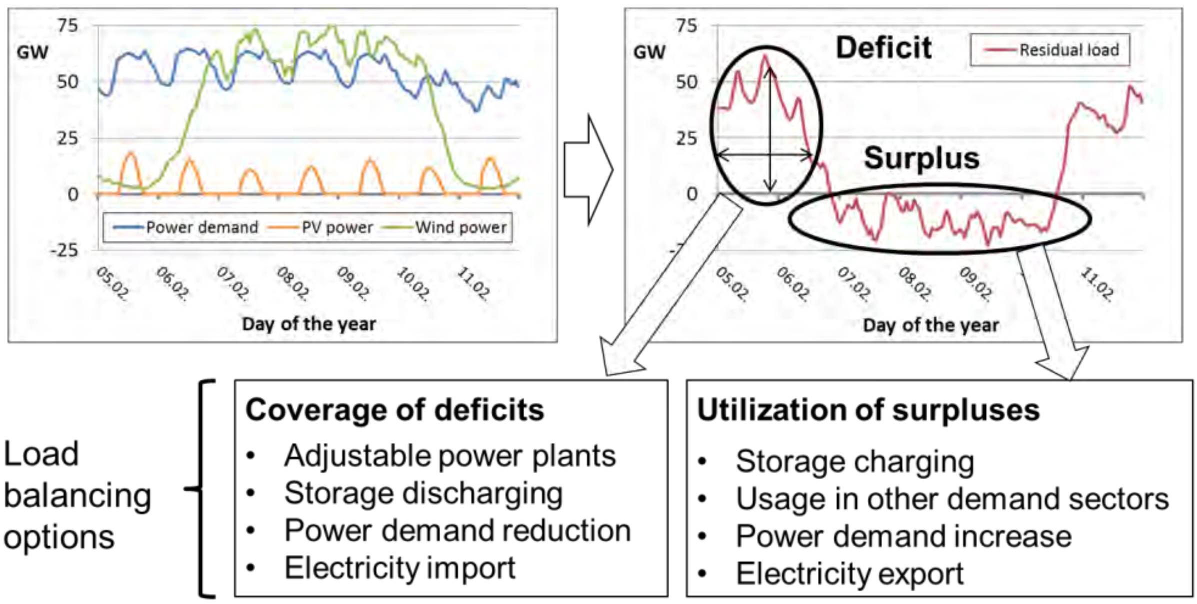

Figure 2: Fluctuations in demand, variable renewable energy (VRE) generation (left) and residual load (right)

This work assesses whether an enhanced integration of power and heating sector through thermal energy storage (TES) and electric heat production can help in solving this problem. More specifically, it addresses the question to what extent a power-controlled operation of CHP and heat pump (HP) supply systems can contribute to a mostly renewable power supply in Europe. The principle of a power-controlled operation of CHP compared to a heat-controlled operation is shown exemplarily in Figure 3. Its core element is the adjustment of CHP and HP operation to the residual load. Furthermore, this work analyses, whether the deployment of TES and electric boilers in district heating (DH) systems is competitive with other balancing options and how a more flexible heating interacts with other balancing options such as controlled charging of vehicle batteries or flexible operation of hydrogen electrolysers.

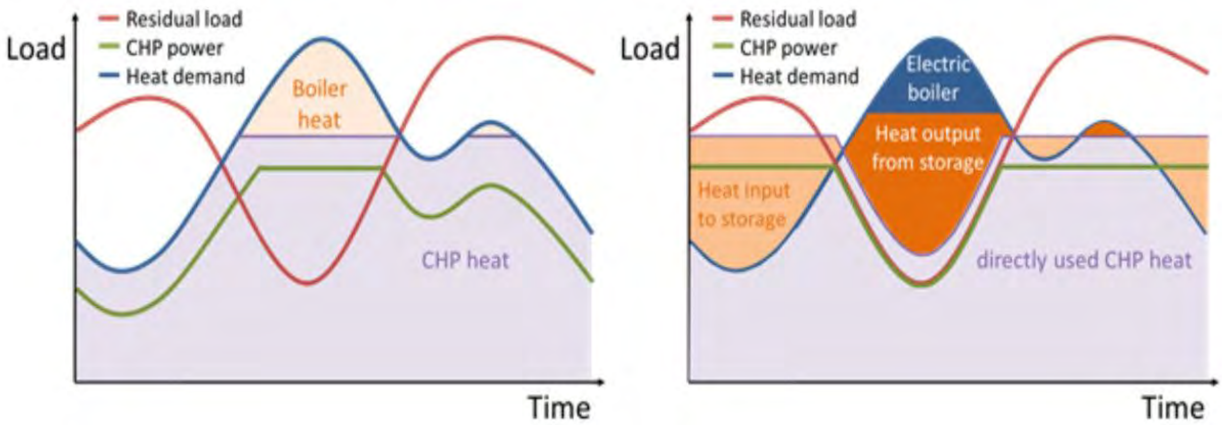

Figure 3: Heat-controlled (left) and power-controlled (right) operation of a CHP system. In the heat-controlled case, only a conventional peak boiler is available, in the power-controlled case also a TES and electric boiler.

Methodology

The analysis relies on the application of the DLR energy system model REMix (Figure 4) [Scholz 2012, Gils et al. 2017]. REMix was developed for the evaluation of energy supply scenarios in high spatial and temporal resolution. It provides a simplified representation of the power system, including demand, renewable as well as conventional generation, electricity-to-electricity storage, demand response, and power transmission. The model is not limited to the power sector, but also contains demand and supply of heat as well as hydrogen, and electric mobility. The model input comprises techno-economic parameters, scenario parameters (e.g. installed power plant capacities), and spatially resolved climate and weather data for each hour of the year. The latter input data are used in the energy data analysis tool REMix-EnDAT for the calculation of hourly wind and solar power production profiles in each model region [Scholz 2012, Stetter 2014]. Relying on these input data and using linear optimization, REMix-OptiMo assesses the least-cost composition and operation of the energy system during one year. The minimized costs comprise all expenditures arising from the installation of new assets and the operation of all assets, thus capital costs, fuel costs as well as other variable operational costs. Model results comprise the installation of new assets, the hourly operation of all assets, supply costs, and CO_2 emissions. Previous model applications range from optimized short-term integration of renewable energies into existing electricity systems or cost-minimum green-field capacity expansion analysis [Scholz 2012, Gils et al. 2017] to development and validation of long-term supply scenarios [Gils and Simon 2017, Stetter 2014] and impact assessment of different storage and balancing options on renewable energy integration [Luca de Tena 2014].

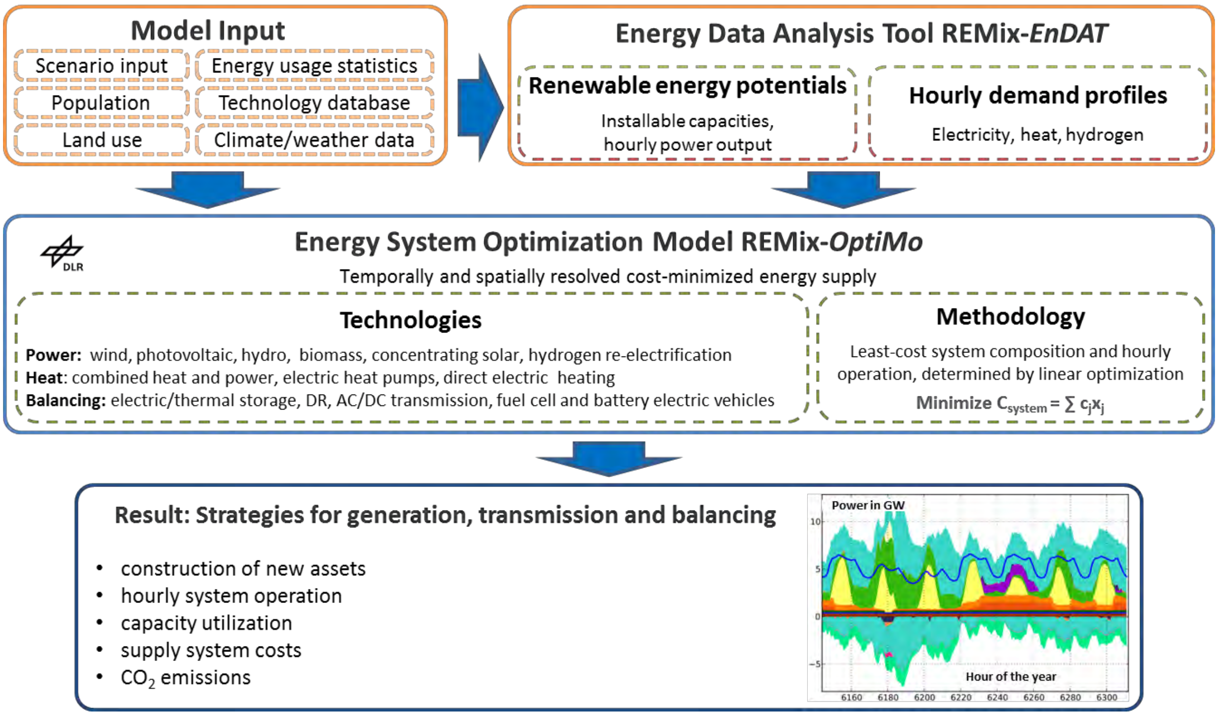

Figure 4: REMix model overview.

The regional focus of the case study presented here is on Germany. However, it also includes its neighbouring countries, as well as Northern Europe (see Figure 5). This assures that international power exchange is considered to some extent. A broad range of technologies is considered in the case study, including renewable and conventional power generation, CHP in industry and DH, pumped hydro storage, and high-voltage power transmission. In selected scenarios, a flexible production of hydrogen fuel and a controlled charging of battery electric vehicles (BEV) are considered as well. The case study is designed as scenario analysis. This means that the power plant park is mostly predefined in the model. With this approach, the case study does not aim at the determination of least-cost supply systems, but on evaluation of the least-cost utilization of balancing technologies. This said it is particularly focused on the usage of thermal energy storage and electric heating in DH-CHP systems. In the presentation of results, model runs without and with the enhancement of these systems are compared. In the second case, the model can endogenously invest in thermal energy storage and electric boilers. By undertaking these investments, the model can reduce the overall supply costs. Such reduction can for example result from a decrease in the additionally required gas turbine capacity, a more efficient utilization of the power plant park, fuel savings, or lower curtailment.

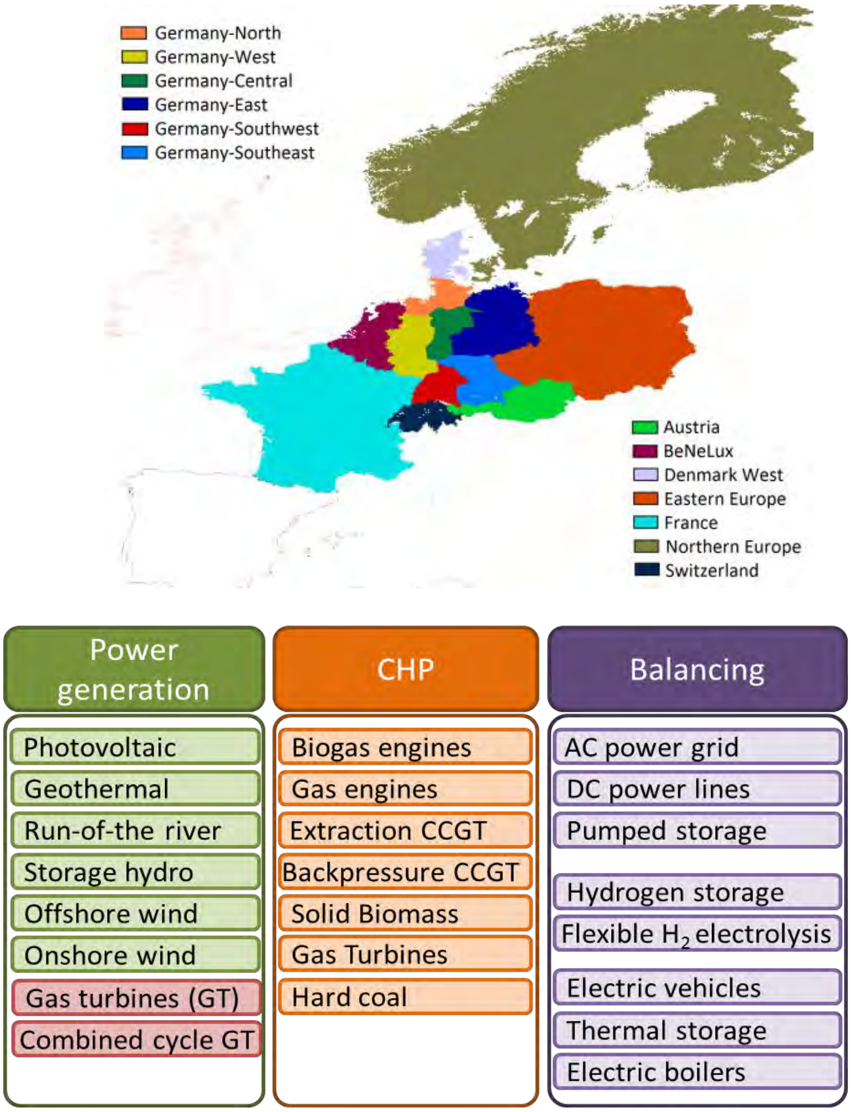

Figure 5: Study area (top) and considered technologies (bottom)

The installed capacities of power as well as CHP plants are assumed according to [Nitsch et al. 2012] for Germany and [Scholz et al 2014] for the other European countries. To focus on high shares of intermittent wind and solar power generation, only the scenario year 2050 is analysed here. Overall capacities reach 76 GW in Germany and 229 GW in the overall study area for PV, 55 GW and 219 GW for onshore wind, and 35 GW and 115 GW for offshore wind, respectively. In order to avoid supply shortfalls, the model can endogenously add gas turbine and combined cycle gas turbine (CCGT) capacity to the predefined power plant park.

The resulting power supply structure accounts for an 85% share of renewable power generation, three quarters of which is of intermittent nature (wind, PV, run-of-the-river hydro). CHP contributes around 20% of the power supply, with similar shares of biomass and natural gas-fuelled units. The remaining approximately 10% of the supply have to be provided by gas power plants without heat extraction. For details on regional renewable power generation and CHP capacities, see [Gils 2015]. Note that the gas condensing power generation capacities used there are not considered in this case study. The heat supply share is not only predefined for CHP, but also for heat pump (HP) technologies. The heat supply shares in the building sector are assumed with 30% for DH, 5% for building CHP, 21% for electric HP and 44% for others that are not related to the power sector. The industrial heat supply at temperatures below 500°C relies to 62% on CHP, 4% on electric HP, 34% on other heat sources. The Base Scenario is furthermore characterized by a 100% share of electric vehicles in passenger transport. The transmission capacities in the high-voltage power grid are assumed to correspond to today's state plus the expansion planned in the German and European grid development plans [Feix et al. 2013, ENTSOE 2012]. In order to reduce the model's complexity, the dimensioning of TES capacities and electric boilers is endogenously optimized only for DH-CHP. For industrial CHP and HP, fixed storage sizes are considered. Relying on previous REMix results presented in [Gils 2015], a dimensioning of four hours of peak demand for industrial CHP and two hours for HP is applied. The usage of electric boilers is not considered in industrial CHP systems.

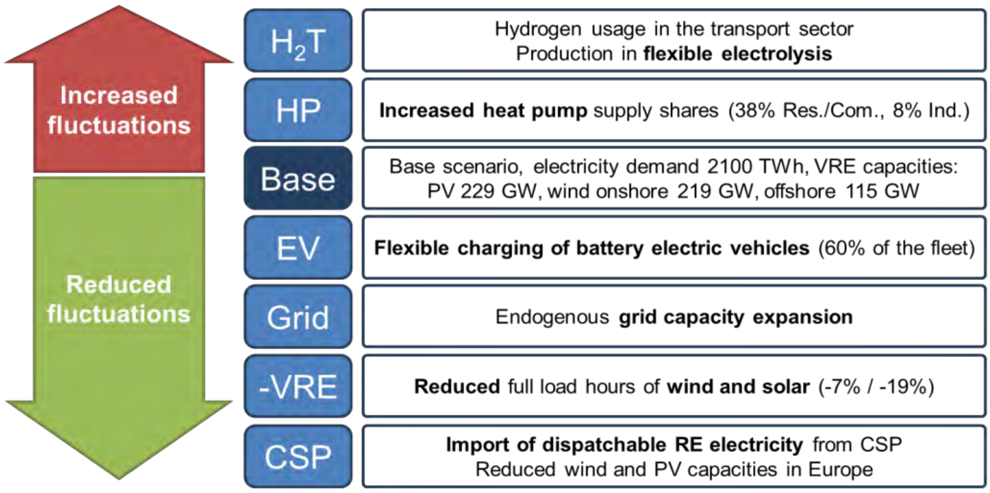

Figure 6: Scenario overview

To assess the interaction of power-controlled heat supply with alternative balancing technologies as well as the composition of variable renewable energy (VRE) supply, a number of scenarios are taken into account (Figure 6). An increasing balancing demand compared to the Base scenario described above is present in two alternative scenarios. In both scenarios it arises from an additional power demand in other sectors. In scenario HP, higher shares of electric HP are considered, whereas scenario H_2T assumes that the passenger transport partly relies on hydrogen-fueled vehicles, whose fuel supply is provided by flexibly operated electrolysers. Due to the lower efficiency compared to BEV, the overall power demand, and thus also the intermittent generation capacities are higher in this scenario. All assumptions on the hydrogen infrastructure can be found in [Gils 2015]. A reduced balancing demand is analysed in four additional scenarios. In scenario EV, balancing can also be provided by controlled charging of BEV. Scenario Grid considers a model endogenous grid expansion, -VRE a lower availability of wind and solar generation during the year. This is realized by considering a different historical weather year (2010 instead of 2006) as data input to REMix. Finally, in scenario CSP, the impact of an import of dispatchable renewable energy from Concentrated Solar Power (CSP), which reduces domestic wind and PV capacity and thus the fluctuations, is analysed. The major difference between the scenarios lies in the availability of balancing options on the one hand, and the shape of VRE fluctuations on the other. It can be assumed that these two characteristics have a significant impact on the economic potential of enhanced energy sector integration.

Results

The REMix results show that the enhancement of DH-CHP by TES and electric boilers is competitive across all scenarios. In the overall study area, a storage capacity between 0.5 and 0.61 TWh is added to the considered DH systems (Figure 7, left). This is almost twice as high as the 0.38 TWh of pumped hydro storage capacity currently available in Germany. The exogenously defined TES in industrial CHP and HP systems accounts for additional 0.21 and 0.14 TWh (0.26 TWh in scenario HP), respectively. DH-TES capacities are located mostly in Germany (0.17-0.19 TWh), the Eastern Europe region composed of Poland, Czech Republic and Slovakia (0.13-0.17 TWh) and France (0.09-0.13 TWh). The annual energy input to the TES is found to be much more dependent on the scenario assumptions than the capacity (Figure 7, right). It ranges between 48 TWh in scenario H_2T and 97 TWh in HP, equivalent to between 6% and 10% of the corresponding annual heat demand. If only TES in DH systems are considered, the annual input ranges between 26 TWh (8%) and 41 TWh (13%). The comparison of scenarios reveals that the flexible operation of hydrogen electrolysers significantly reduces TES operation, whereas controlled charging of BEV, additional grid extension, lower wind and solar generation, and import of dispatchable renewable power have far less impact. The consideration of additional HP with TES does not negatively affect the TES in DH systems.

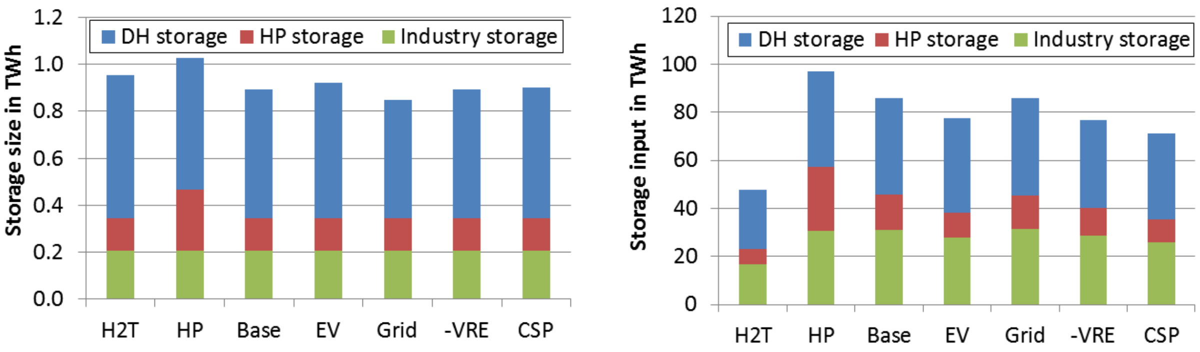

Figure 7: REMix results on thermal energy storage installation (left) and annual energy input (right)

The average dimensioning of the DH-TES shows significant differences between the considered model regions (Figure 8). Related to the annual peak demand, capacities range between four hours in Northern Europe and eleven hours in France. Further analysis reveals that TES capacities tend to be highest in regions that are mostly supplied by wind power, and lowest where the generation mix is dominated by hydro power. The relatively high values also in the German regions Central, East, and West arise from the significant wind power imports from Northern Germany. The technology-specific TES dimensioning is influenced by fuel, electricity-to-heat ratio and operational degrees of freedom of the corresponding CHP units. TES tend to be greater in combination with technologies relying on fossil fuels, having a high electricity-to-heat-ratio and flexible heat extraction, and smaller for renewable CHP, low electricity-to-heat ratios and strict backpressure turbine operation.

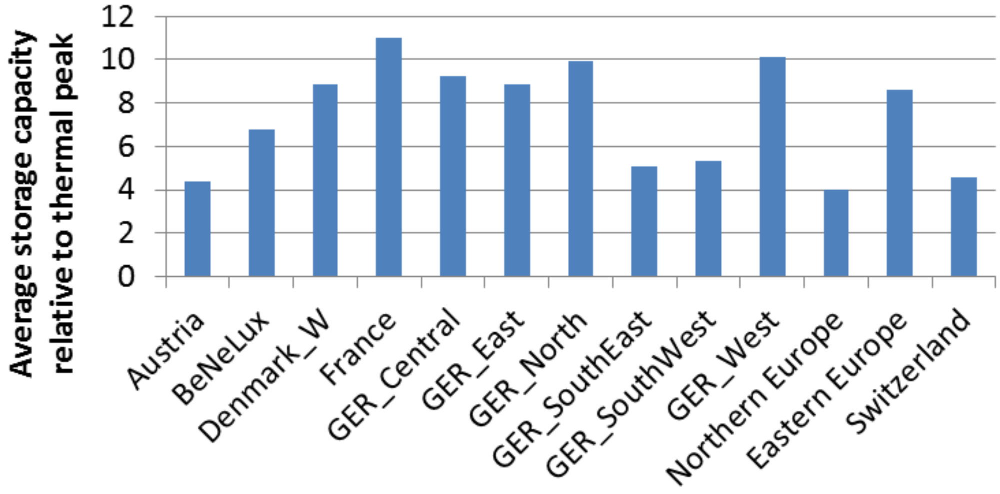

Figure 8: Dimensioning of TES in DH systems

The installation of electric boilers in CHP supply reaches between 30 and 42 GW (Figure 9, left). Compared to TES, it is to a slightly higher degree influenced by the availability of VRE generation and alternative balancing options. It is particularly reduced by a lower availability of wind and solar power, and by dispatchable CSP power import. Additional grid expansion, flexible hydrogen electrolysis, controlled BEV charging, and additional heat pumps also reduce the electric boiler capacity, but to a much lower extent. As for TES, highest capacities are found in Germany, France and Eastern Europe. The scenario comparison of the heat produced in the electric boilers exhibits a different pattern (Figure 9, right). A lower wind and solar power availability reduce the heat output of the electric boilers almost by half, grid expansion and CSP import by around 20%, all compared to the Base scenario. The electric boiler capacity expansion and utilization are also correlated to the wind power supply share, and are particularly high in the wind power regions.

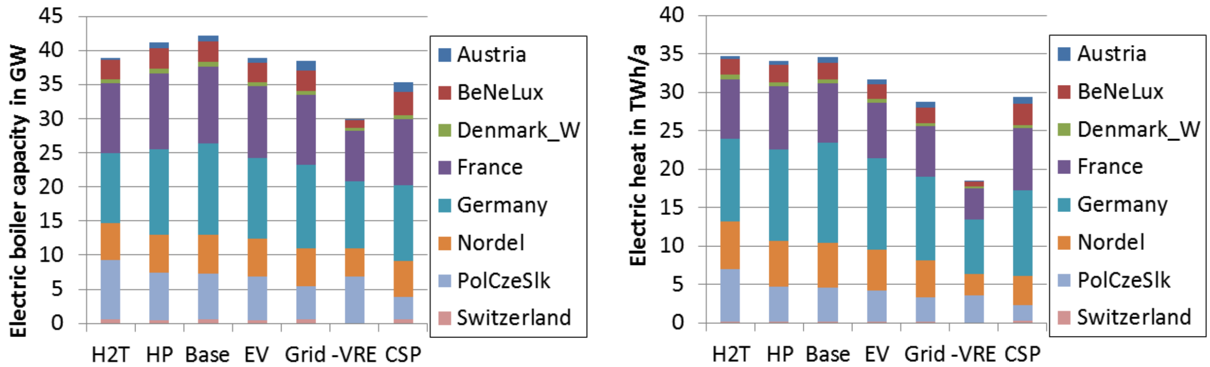

Figure 9: REMix results on electric boiler installation (left) and annual heat production (right)

The availability of supplementary TES and electric boilers significantly increases the flexibility in the operation of DH supply systems and allows for an adjustment of operation to power demand and VRE generation. Increased heat production flexibility proves to be a very effective measure for both the reduction of VRE curtailment and increase in CHP operation times. A down-regulation of the CHP unit in times of favourable weather conditions increases the usage of wind and solar power. In the opposite situation of low wind and solar generation, CHP can step in without heat being wasted, as it can be stored. Additional reductions in VRE curtailment can be achieved by the usage of electric heating in DH supply systems. The amount of wasted electricity is cut by up to 17 TWh or 71% (Figure 10). Furthermore, power-controlled operation of CHP and HP reduces the demand for additional power generation capacity by up to 29 GW (18%). This reduction mostly arises from the availability of TES in HP systems, which allows for lowering the power demand, as far as heat can be supplied from the storage. Increased CHP flexibility not only contributes to a better VRE integration, but also to an optimized power plant operation. In the considered scenarios, this mostly applies to biomass CHP, for which annual full load hours can significantly increase and ramping cycles and shutdowns reduce. The REMix results indicate that the availability of TES notably increases the CHP and HP supply share at the expense of the corresponding peak boilers. Optimized power plant operation, reduced capacity demand and higher VRE integration achieved by power-controlled heat supply enable a reduction in system costs by up to 4.1 billion euro (4.3%). This is equivalent to specific values of 0.03 to 0.05 €/kWh of stored heat or 0.07 to 0.14 €/kWh of electric boiler heat. An additional benefit arises from the reduction of CO_2 emissions by up to 2%. In the systems without TES and electric boilers, VRE curtailments range from 11 to 23 TWh, back-up capacity demands from 96 to 163 GW, and system cost from 86 to 107 billion euro. Both in absolute and relative numbers, highest impacts are found on costs and VRE curtailments in scenario Grid, and on back-up demand in scenario HP. The former indicates that an enhanced grid expansion is favorable for a flexibilisation of DH operation, whereas the latter can be easily explained by the temporal shifting of HP operation reducing backup capacity demand.

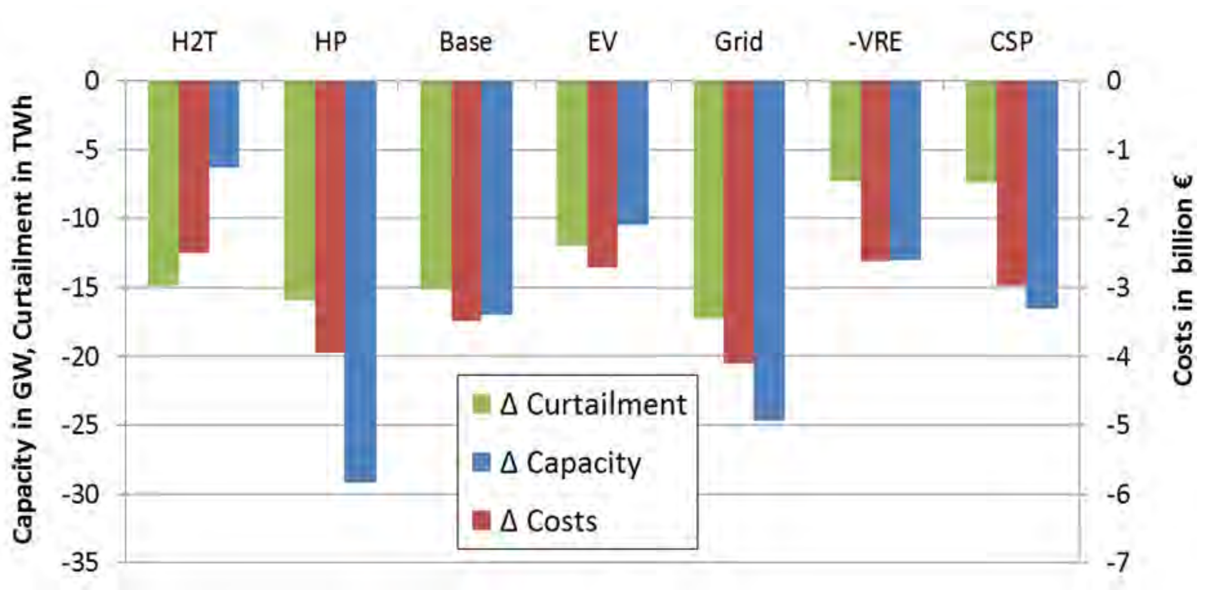

Figure 10: Impact of TES and electric boilers on VRE curtailment, required back-up capacity and costs.

The consideration of a broad range of load balancing options in REMix allows for a comprehensive comparison of their impact on the residual load. Figure 11 shows how the positive and negative peaks in residual load are reduced by the different technologies. The analysis indicates that the power grid is highly important for the absorption of midday PV generation peaks as well as evening deficits. Flexible CHP can move its generation to the morning and evening hours, further reducing the deficits. Electric boilers in CHP use some of the surpluses, but by far not all of them. TES are mostly used in spring and autumn, which are characterized by particularly high fluctuations in wind power generation on the one hand, and a heat demand close to the applied CHP and HP dimensioning on the other.

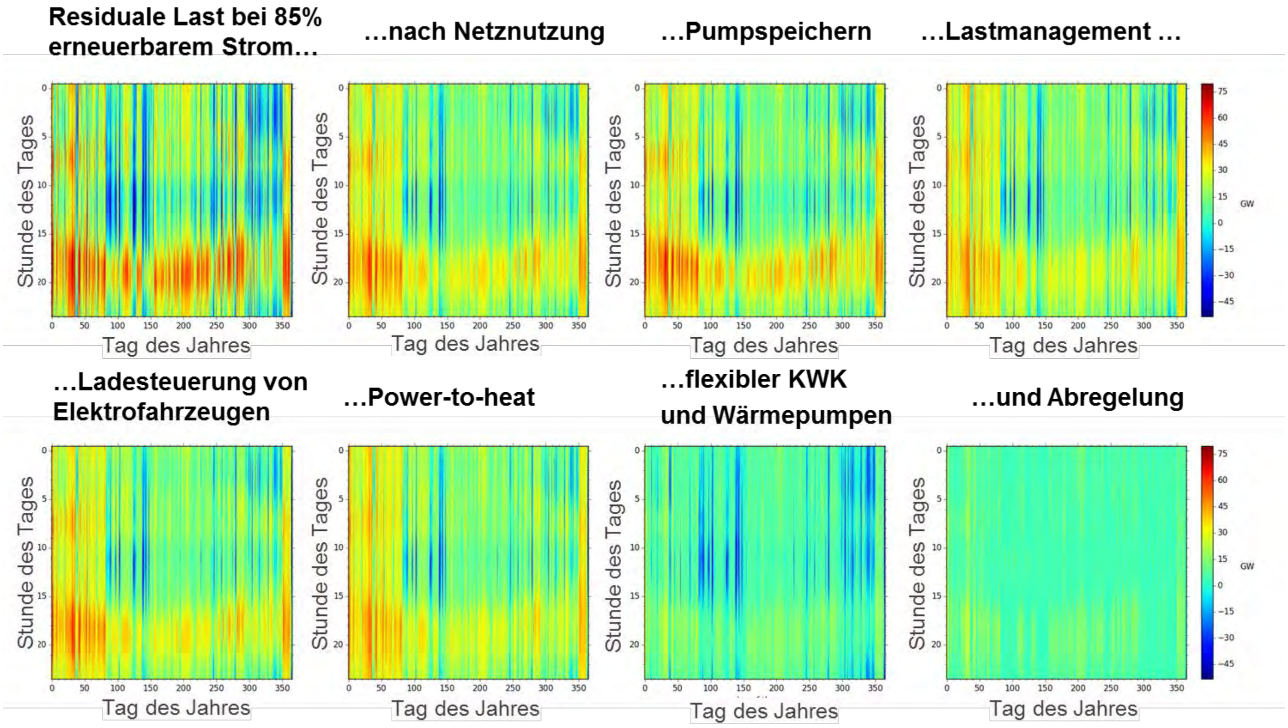

Figure 11: Impact of different balancing options on the residual load in Germany, based on results of [Gils 2015].Values range from a supply deficit of +75 GW (dark red) to a supply surplus of 45 GW (dark blue).

Discussion and conclusions

The scenarios considered in this work reflect a European energy system transformation, in which nuclear power is phased-out, fossil fuel power generation is drastically reduced and VRE become the major pillar of electricity supply. The corresponding heat supply scenario envisions an increased market penetration of public and industrial CHP as well as electric HP. In order to reflect a broad range of interactions between balancing technologies, seven scenarios have been taken into account in this study. They are all consistent with the political goal of a mostly renewable supply for power, heat and transport. The scenario input concerning power and heat demand and supply structure, as well as grid and electricity-to-electricity storage capacities significantly affects the capacity and utilization of the balancing technologies analysed in this REMix application. This limits the significance of the results to the scenario space assessed in this work.

The spatial and temporal resolution of REMix limits this assessment to the contribution of TES and electric boilers to hourly and interregional load balancing. Possible benefits on smaller temporal and spatial scales cannot be evaluated with the model in its current configuration. Major model approximations concerning power balancing include the representation of conventional and CHP power plants on the one hand, and alternating current power grids on the other. Both the conventional and CHP power plant model take into account neither restrictions in the ramping velocity nor a minimum load. Consequently, the flexibility of power generation is overestimated, which reduces the demand for other balancing technologies.

The case study presented here is based on numerous assumptions and premises concerning the structural development of the energy system, as well as technical and economic technology characteristics. Nonetheless, the results of the scenario assessment allow for a number of first conclusions concerning the potential load balancing by power-controlled heat supply.

The REMix results clearly indicate that TES and electric boilers in DH systems are a cost-effective measure to increase VRE integration. From this follows that the deployment of these technologies should go hand-in-hand with additional VRE power generation. We find a geographical concentration of the installation and operation of enhanced DH systems to regions with a high share of wind power. TES in both CHP and HP supply are mostly used for short-term and medium-term balancing in the range of some hours to a few days. This implies that they are particularly competing with peak load power plants and electricity-to-electricity storage technologies. The operation of pumped hydro storage is increasingly restricted to peak shaving of residual load, thus the provision of power, not energy. Due to its particular focus on flexible HP and CHP, the consideration of electricity-to-electricity storage is comparatively limited in this work. Future studies will have to gain insight into the potential application of other storage technologies as well as their interaction with competing balancing options. In this work, the assessment of electric heating and TES utilization has been focused on low-temperature heat demands. Given the available potentials, an extension to high temperature process heat appears attractive.

As a consequence of higher VRE integration, power-controlled heat supply can contribute to the reduction of CO_2 emissions in Germany. Furthermore, the additional balancing options can lead to energy supply cost reductions arising from the substitution of back-up power plant capacity on the one hand, and a more cost-efficient power and heat supply on the other. The latter includes a higher VRE integration into the power and heat sector, as well as a switch to power generation units with lower variable generation costs.

The availability of alternative balancing options such as controlled charging of electric vehicles, further grid expansion and dispatchable CSP import has only a very limited impact on the dimensioning of TES and electric boilers. This implies that these options cannot substitute the enhancement of DH systems. Thus, the combination of different sector integration technologies can be beneficial in achieving high VRE shares in power supply. The annual operation times of TES decrease notably if flexible hydrogen electrolysis is available. The highest impact on electric heat production is found for reduced wind and solar availability. Concerning the achievable cost reductions, we find that grid expansion has a particularly positive impact. The least-cost dimensioning of enhanced DH is furthermore influenced by technology, fuel and size of the corresponding CHP unit.

The scenario study presented in this work provides a first approximate economic assessment of the potential balancing of VRE power generation by power-controlled DH operation in Germany as well as its interaction with the balancing and sector integration technologies addressed in our analysis. It must be complemented by further and more detailed studies. This includes the development and evaluation of business cases for adjusted DH operation on the one hand, and potential incentive mechanisms on the other.

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