Robust investment strategies for the Norwegian power system in the energy transition?

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Abstract— **The energy transition requires fundamental changes in society and all parts of the energy system. Understanding these changes can be possible by consistent analyses with various specialized modelling tools. This paper concerns the bidirectional linking of energy and power system models for analyses of renewable energy systems reliant on reservoir hydropower. The energy system model IFE-TIMES-Norway is soft-linked with the hydro-thermal power market model FanSi to analyse the Norwegian energy system towards 2050. The power market model is used to evaluate the operational robustness of the investment strategies from the energy system model. We use socio-technical pathways as a basis to do techno-economic analyses at different levels of the energy system. The main aim is to understand and discuss the income potential of power generation and storage technologies, and the valuation of the operational flexibility of hydropower and other flexible resources in the two models.**

Index Terms—**Energy transition, investment strategies, model linking, flexibility resources, hydropower**

I. INTRODUCTION

Transition scenarios towards decarbonized energy systems are often quantified using mathematical energy system models to support complex policy decisions. Such models provide quantitative insight into potential transition pathways for the decarbonization of the energy system by optimizing investments in different technologies and energy carriers to meet the energy demand over long planning horizons. A range of energy system models with various scopes, resolutions, level of technical details and objectives have been developed to tackle the many aspects and challenges of energy system modelling [1], [2]. Energy system models strive to account for details that are important for system operation, profitability of various assets and thus correct investment incentives, nevertheless, no single modelling tool can do it all [3]. Efforts should therefore be targeted towards linking different tools to each other to utilize the many capabilities that are already available [1].

Combining models with supplementary strengths and scope usually can provide complementary perspectives about the energy transition. A review of the status of model coupling in the energy system domain [4], shows that multi-model frameworks are becoming more frequently applied. However, it is in itself a demanding task to evaluate which models to use and how to combine different types of models. A structured approach to evaluate energy system modelling tools is suggested in [2]. The authors highlight, like others before them, e.g., Chang et al. [4], the need for a purpose-driven approach where the selection of modelling tools and linking procedures are designed to answer a target research question.

A soft-linking procedure allows the models to share information without integrating them within the same platform or code [2]. A survey of 54 tools conducted in [1] finds that soft-linking is the most applied linking approach considering energy system models. Soft-linking can be divided into uni- and bidirectional linking procedures depending on if the information only flows in one direction or if there also is included a feedback loop [2]. A bidirectional linking-approach may provide an improved optimal solution from the energy system model [5]. However, previous studies have shown that convergence in the results from energy and power system models in a bidirectional linking process can be challenging for systems with high shares of variable renewables [6].

To limit the problem size, certain modelling aspects are often simplified in energy system models, such as the temporal resolution, representation of uncertainty or technical details of components [7]. Consequently, energy system models can struggle to represent the uncertainty and short-term variation associated with high shares of variable renewable energy (VRE) [8]. This may again lead to a simplified representation of the requirements for flexibility and an undervaluation of technologies with these capabilities. Olivera et al. [2] observe that an increasing number of papers address the linking of energy system models and power system models to address the challenges imposed by increasing amounts of VRE. Soft-linking of energy system models with power system models can provide a deeper insight into the resulting power system infrastructure suggested by the energy system model [5]. Previous studies have, for example, shown that energy system models may overall provide a robust power system portfolio, but tend to underestimate curtailment and undervalue flexibility [9].

Our research investigates two techno-societal pathways towards a decarbonized European power system with the intention of answering the target research questions*:*

1) Are the investments from the energy system model economically robust, and what insights can be learned from the power system model?

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2) Is the value of flexible technologies captured in energy system models, and how does this impact investment decisions?

To answer these questions, we are applying a bidirectional soft-linking approach to combine the IFE-TIMES-Norway energy system model [10] and the FanSi power market model [11]. The models are selected for their tailored representation of the Norwegian energy system, including industry specific energy demands (IFE-TIMES-Norway) and detailed modelling of the complex hydropower systems (FanSi). We use the more detailed power market model to investigate the robustness of the investment strategies from the energy system model for two alternative pathways to a fully decarbonized energy system. Furthermore, a bidirectional linking procedure is applied, restricting the cross-border trade and hydropower generation in the energy system model based on the results from the power market model, to improve the investment decisions in the energy system model. The models and linking procedure are described further in Section II, while the scenario descriptions and results from the model runs are provided in Section III. The results are discussed in Section IV before the paper is concluded in Section V.

II. Method

The presented assessment is part of a larger work with the aim to establish potential development pathways for the energy transition, which are consistent over multiple research disciplines and provide the possibility to identify challenges by going from a general perspective into detailed analyses of selected sectors.

A. From qualitative pathways to quantitative techno-economic modelling

Large societal changes may be required to succeed with the ambitious European decarbonization targets. The transition can follow different pathways depending on transformative pressures at a wider societal level. According to [12], such pressures may be related to factors that change slowly (e.g., climate change), long-term trends or rapid external shocks such as war and economic crises. Qualitative descriptions of four pathways have been developed by an inter-disciplinary team in the research centre FME NTRANS based on a conceptual framework and a combination of aspects from existing socio-technical pathway typologies. Then, the qualitative descriptions have been quantified and implemented in the IFE-TIMES-Norway model. In the quantification process, assumptions are made on aspects ranging from how to represent technological developments of key energy supply and demand technologies and infrastructure across the different end-use sectors, to socio-institutional and behavioural changes impacting the projected demand for energy services. The qualitative scenarios and the quantifications are documented in [12]. To further investigate the robustness of the power system portfolio, the IFE-TIMES-Norway energy system model is soft-linked with the FanSi power market model. The models are described below, and a comparison of certain important characteristics are provided in Table 1.

B. Energy system model: IFE-TIMES-Norway

IFE-TIMES-Norway, hereafter referred to as TIMES, is a technology rich optimization model for investments in the Norwegian energy system [10], based on the TIMES modelling framework [13]. The model provides optimal investment decisions for 5-year periods from 2018 towards 2055, by minimizing the total discounted system cost of meeting the Norwegian demand for energy services. A 5-year investment period is considered a meaningful timeframe due to the uncertainty in technological development and political processes on a yearly basis, as well as being computational efficient. The demand for energy services is represented by numerous demand sectors such as industry, buildings and transport, and can be met by existing and new technologies. Furthermore, the model includes several energy carriers such as electricity, hydrogen, district heat and different fuels, allowing for the model to utilize sector coupling to unlock flexibility. The model is split in five regions, representing the price zones in the Norwegian power market (NO1-NO5). The operational variation within a year is captured by dividing each period into four seasons represented by 24 hours (96 sub-annual time steps). The representative seasonal periods are constructed based on historical hourly data for multiple decades.

C. Power market model: FanSi

The FanSi model is a stochastic power market model that maximizes expected socioeconomic welfare in a hydro-thermal power system by optimizing the dispatch of generation and transmission capacity [11]. The problem is formulated as a sequence of two-stage stochastic, linear problems embedded in a rolling horizon framework. Uncertainties in weather patterns are represented in the second stage by a scenario fan, while the first stage represents a weekly, deterministic scheduling problem. One strength of the model is the detailed modelling of complex, cascaded hydropower systems and other energy storage systems in the power system. In this study, the model is used to simulate operation of the North-European power system for a 3h time resolution with weekly stochastic stages over 30 historical weather scenarios. The Norwegian power system is strongly impacted by the power and energy situation in the other Nordic countries, the UK, and continental Europe, as several transmission cables links the countries together.

Table 1. Comparison of certain key model-characteristics

Characteristics	**TIMES**	**FanSi**
Uncertainty	Deterministic	Stochastic
Sectoral scope	Multiple sectors and energy carriers	Electricity system
Spatial scope	Norway	Northern-Europe++
Investments	Yes, 5-year periods	No
Planning horizon	From 2018-2055	One year
Temporal resolution	24h x 4 seasons (96 time-steps)	3hx52 weeks (2912 time-steps)
Representation of hydropower	Aggregated	Plants and reservoirs
Exogenous demand	Energy services per sector	Electricity demand

D. Linking procedure

The linking procedure consists of three main steps. The first step is to harmonize the model input and structure. Fuel prices for gas and carbon prices were harmonized between the models, as well as capacity factors for wind and solar power. This was done to avoid large deviations in the total energy balance between the models. Furthermore, spatial and temporal mapping methodologies were established to exchange data between the models. The second step is to run the models iteratively and transfer data in between, illustrated in Figure 1. The energy system model was run first and the resulting power generation capacities, transmission capacities, and electricity demand for each area in Norway were given as input to the power system model. Secondly, the power system model was run with the data from the energy system model. The resulting average yearly hydropower generation per area, average yearly import and export per cross-border cable, capacity factors for the transmission cables, and power prices for electricity trade were given to the TIMES model. To preserve the short-term variability, power prices from a normal weather year (year 2013) from FanSi were used rather than average power prices over all simulated year.

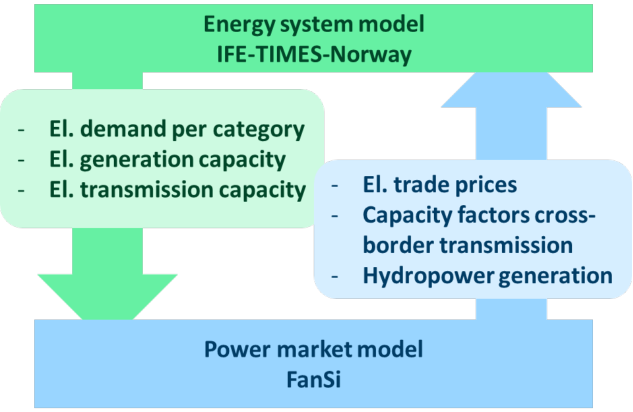

Figure 1. Illustration of the second step of the linking procedure.

The data from FanSi was used to represent the system borders in TIMES, i.e., the power prices and volumes for trade, and to limit the expected electricity generation from hydropower. TIMES was then re-run to see the implications of these changes for the investment decisions. The TIMES and FanSi models run iteratively until a stop-criterion is reached. The stop criterion can be a predefined convergence criterion or just a fixed number of iterations. We used a predefined number of two iterations in this study. Previous linking studies have demonstrated that a large share of the convergence gap often is closed within the first two iterations, at least when the models tend to converge [6].

III. SCENARIO ANALYSES

A. *Scenario description*

The analyses of the Norwegian energy system for 2050 are based on two low carbon energy transition pathways: the technological substitution pathway (TECH) and radical transformation pathway (RAD) [12], [14]. The TECH scenario is characterized by a pressure for technological change, leading to development and deployment of new core technologies, such as hydrogen and CCS, while there is low socio-institutional change. Moreover, this scenario is also characterized by high activity levels in industry and trade, moderate demand developments in the building and transport sectors, as well as high potential and cost reductions for energy supply options. On the other hand, the RAD scenario represents a major change in both the technological and the societal dimension. In this scenario, the growth in demand stabilizes (due to local consumption and behavioural changes) and there is more local energy production, as well as progress in the technological dimension. For both scenarios, biomass is limited to Norwegian resources, and relatively high biomass import prices. An overview of the assumptions for Norway used in the TIMES model is given in Figure 2, and additional detail of these assumptions and quantifications can be found in [12].

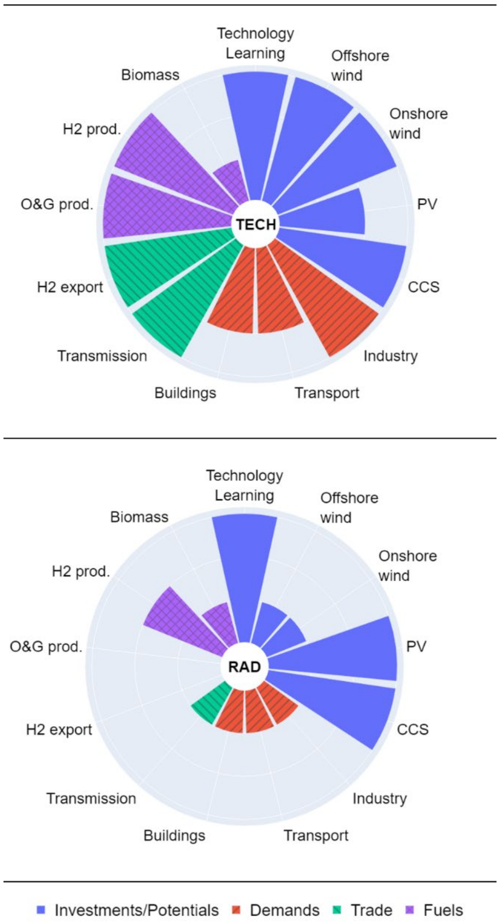

Figure 2. Radar plot overview of difference in assumptions and input quantifications for the RAD (top) and TECH (bottom) scenarios. Modified from [14], based on quantifications from [12].

Moreover, it is reasonable to assume that the development in Norway to some degree follows the developments in the European system, especially regarding technological advances. The results from TIMES are used to represent the Norwegian system in the FanSi model. The European power system is assumed to be fully decarbonized by 2050 and relies on large amounts of VRE, electrolysis and hydrogen plants, as well as flexibility from the end-use sector and batteries to balance supply and demand. We have kept the representation of Europe constant between the scenarios to isolate the implications of investments in the Norwegian system.

B. *Results*

The results from the model simulations demonstrate the large differences between the RAD and TECH scenarios. In Norway, there is considerably higher electricity consumption in the TECH scenario compared to the RAD scenario in 2050. The high electricity demand in the TECH scenario is met by a large increase in wind power production, both from onshore and offshore installations in Norway. The development in the electricity generation mix in Norway is shown in Figure 3. Both scenarios have an energy surplus in Norway for an average weather year in 2030 and 2050, and the surplus is larger in 2050 for both scenarios (ranging from around 25-20 TWh in 2030, to around 70-190 TWh in 2050, for RAD and TECH respectively). Investments in transmission capacities are quite conservative in the RAD scenario, both within Norway and for exchange with neighbouring countries. In the TECH scenario, on the other hand, there are large increases in transmission capacity within Norway and to other countries. The Norwegian system is therefore more strongly influenced by the power system in the neighbouring countries in the TECH scenario.

The results from the power system model allow us to investigate the situation in the power system in 2030 and 2050 more closely for the two scenarios. Figure 4 and Figure 5 shows the average power price and price variability for selected regions in Norway. The average price is considerably higher in the TECH scenario, indicating a higher price impact from neighbouring countries. The short-term price variability, on the other hand, is higher in 2050 than 2030 for both scenarios reflecting the large changes associated with decarbonizing the European power system in this period. The variability in TECH is a result of both increases in wind power generation in Norway and the close integration with the European power system. In the RAD scenario there is considerably lower wind power generation in Norway and less cross-border transmission capacity, but still a strong impact on the price variability in 2050 due to the changing European system. An

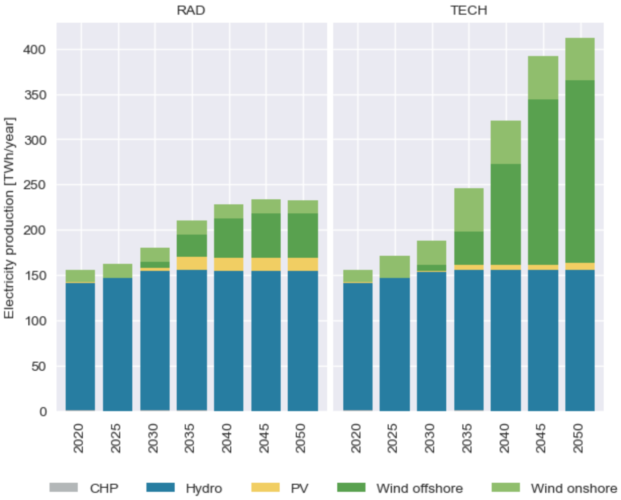

Figure 3. Electricity generation mix for TECH and RAD from the IFE-TIMES-Norway model.

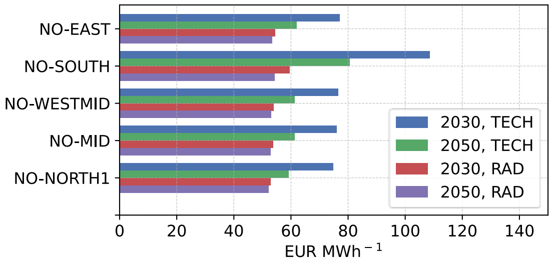

Figure 4. Average power prices in different regions of Norway for TECH and RAD in 2030 and 2050 from FanSi.

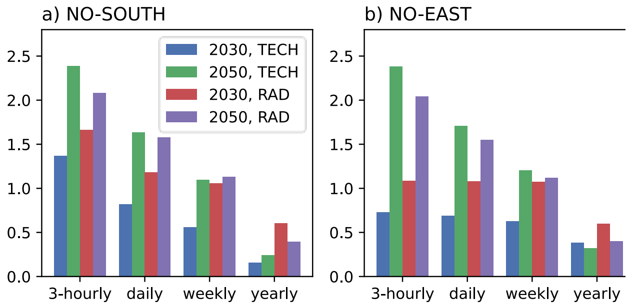

Figure 5. Variability in the power prices in two selected regions of Norway for TECH and RAD in 2030 and 2050 from FanSi.

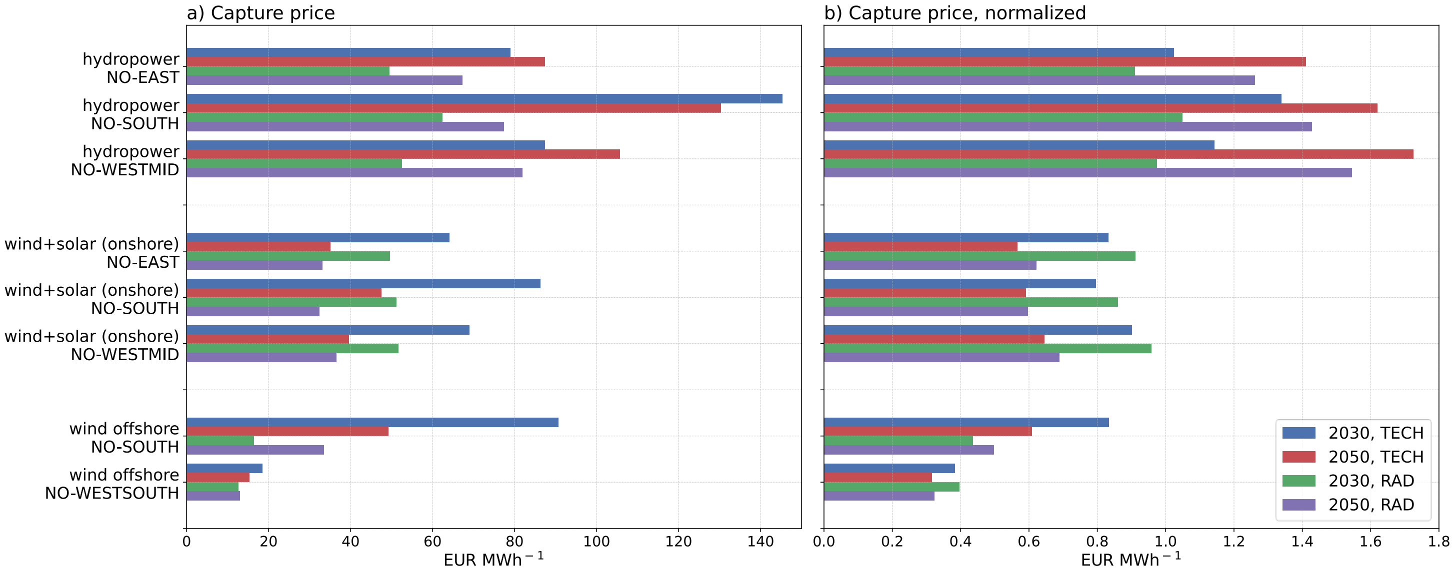

Figure 6. Capture price (left) and normalized capture price (right) for power generation technologies in selected regions of Norway for RAD and TECH in 2030 and 2050 from FanSi. Onshore wind and solar is combined to one category, but this is mainly wind as there is low investments in solar power.

interesting distinction can be found in the long-term price variability, where there are smaller differences between the scenarios. Especially, the higher yearly price variability in the RAD scenario for 2030 may indicate that the Norwegian system is more vulnerable to yearly inflow variations, and that investments in wind power and transmission capacity can reduce this dependency.

Finally, the capture price and normalized capture price of the main power generation technologies in selected areas of Norway are shown in Figure 6. Hydropower has a considerably higher capture price than wind power in most of the scenarios, while onshore VRE (this is mainly onshore wind) generally perform better than offshore wind. An exception is offshore wind in south of Norway in the TECH scenario, where the capacity is directly connected to several European countries. The normalized capture price indicates if a technology performs better or worse than the average power price in the region, this is also referred to as the value factor of a technology. A normalized capture price higher than one indicates that the technology is flexible to adapt generation to the expected power price, or that it complements the dominating generation pattern in the system (e.g., follows a different weather pattern than the rest of the system and is therefore shielded from cannibalization effects). Hydropower has generally a high normalized capture price and performs particularly well for both scenarios in 2050 when there is higher price variability, reflecting the operational flexibility of this technology. Onshore wind also performs well for both scenarios in 2030, with a normalized capture price in the range of 0.8-1. However, this is reduced to 0.5-0.7 in 2050. The reduction indicates that there is a stronger cannibalization effect in 2050 caused by the large investments in VRE in Europe. Again, offshore wind performs worse with a normalized capture price falling towards 0.3 in some regions.

IV. DISCUSSION: ROBUSTNESS OF INVESTMENTS AND LINKING PROCEDURE

The presented results are based on initial analyses after two iterations with model simulations and demonstrate several inconsistencies that should be addressed in further work. An important question is whether variability and the need for flexibility are captured and reflected in investment decisions from energy system models. The results from the power system model reveal considerable variation in the capture price of different technologies, and the cannibalization effect for wind power (especially offshore) seems to be stronger in the power system model. The capture price can be used to evaluate if technology investments are profitable. In general, there are higher investment costs associated with offshore wind than onshore wind. Consequently, the relatively low capture prices of offshore wind in some regions indicates an inconsistency between the energy and power system model that should be assessed further.

Furthermore, the price differences in the power market model between the scenarios are unexpectedly large and should be investigated. Considering that there is a decent surplus in Norway for all the scenarios, the average power price was expected to remain at a lower level. Remembering that the configuration of the European power system (except Norway) is constant between the scenarios, the large difference in average price, an especially for NO-South, is remarkable and could indicate an overestimated value of the long-term water values for the hydropower in the power market model.

The normalized capture price of hydropower indicates a high value of flexibility. This may be a signal that further investments in flexibility could be profitable. On the other hand, the electricity demand in Norway (from TIMES) is modelled as inflexible in the FanSi runs, which could cause an underrepresentation of the flexibility in the system. At the same time, some of this flexibility is already accounted for in the TIMES results, such as investments in energy efficiency and sector substitution. Still, TIMES often chose to invest in cheaper but less flexible technologies, for example non-flexible hydrogen production technologies. There are also limited investments in hydropower when the energy generation is restricted. In theory, capacity expansions could still be valuable to unlock flexibility to respond to price variations. Similarly, calculations indicate that battery investments could be profitable with the price characteristics seen in some of the scenarios. Consequently, it is reasonable to question if the value of flexibility is adequately captured.

The findings demonstrate how analyses with power market models can be useful to deepen the understanding of the results from the energy system model. Nevertheless, the challenge remains to evaluate how the power market model can be used to provide signals to the energy system model. One suggestion is to evaluate the effect of substituting or including flexible technologies in the power system model and then, if the results find it to be profitable, favour these technologies in the energy system model either by subtracting a flexibility premium from the costs or restricting the use of other technologies. Another suggestion is to assess the effect of using power prices from different simulated years, weeks and days as input to the energy system model, or to investigate ways of representing correlations between price patterns and wind power generation to better capture the cannibalization effect.

V. CONCLUSIONS

This paper investigates the robustness of investments from the IFE-TIMES-Norway energy system model in the FanSi power market model. Energy system models can provide quantitative scenarios for investments in power system infrastructure with a certain consistency over time and among energy vectors. However, the detailed analysis of the power system, given the scenarios provided, reveals some inconsistencies between power prices and infrastructure development. Especially, production variability and resulting price variation seem to have a higher impact om profitability in the power system simulations. The capture prices indicate that the cannibalization effect may be underestimated for wind power, especially offshore wind power. Furthermore, we find that the value of flexibility is undervalued, which may result in under-investments in flexible technologies. Further work should investigate how the value of flexibility can be represented in the energy system model. Furthermore, the power market model can be used to evaluate the profitability of flexible technologies such as flexible hydrogen production and batteries, as well as investigate how to properly represent end-use flexibility without overestimating this contribution in the power market model.

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