Deliverable 6.2 Policy implications of case studies on different aspects of energy system integration

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Lead contractor KTH

Author:
Manuel Marin KTH
Maren Ihlemann KUL
Arne van Stiphout KUL
Kris Poncelet KUL
Topi Rasku VTT
Juha Kiviluoma VTT
D6.2 Policy implications of case studies on different aspects of energy system integration

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Author(s) Manuel Marin KTH, Maren Ihlemann KUL, Arne van Stiphout KUL, Kris Poncelet KUL, Topi Rasku VTT, Juha Kiviluoma VTT

Reviewer(s) Erik Delarue KUL, Iasonas Kouveliotis-Lysikatos KTH

Description of the related task and the deliverable. Extract from DoA

This work package will carry out case studies that help to expand and verify the generalized energy system model and the Spine Toolbox. The case studies represent a wide variety of energy conversion and transfer pathways. Each of them will help to identify needed developments and help to expand the model formulation. As a result, Spine Model will be able to cope with many kinds of problems. Many case studies will also contribute to the expected impacts of the call topic – these contributions are highlighted in the case study descriptions.

The case studies are divided into three tasks that serve only to group the case studies (no resource allocation and no task leader – the WP leader is directly co-ordinating all the case studies). The case studies will start with individual technological systems where the objective is to expand and verify proper behaviour in each case. Further case studies will expand the temporal and geographical capabilities of the model. Final case studies will demonstrate the capability of the toolbox to perform credible analysis for integrated energy systems and produce results that contribute to the expected impacts of the call.

The level of detail in each case study will reflect its end goal. Consequently, each case study will select a suitable level of representation in the following categories:

- energy grids (e.g. a gas grid with simple transfer constraints or a gas grid with flow-based constraints)
- geographical scope (e.g. a single country or whole Europe)
- modelling time frame and method (e.g. a stochastic operational simulation with rolling planning or a deterministic planning with a several year time horizon)

D6.2 Policy implications of Spine project case studies on different aspects of energy system integration. Success criteria: At least 20 policy implications.

(T6.1, T6.2, T6.3, T6.4) Report that discusses the policy implications of the case studies performed within the Spine project.

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1. INTRODUCTION

The purpose of this document is to discuss policy implications related to energy system integration, resulting from the execution of the thirteen case studies in the Spine project. The document has one subsection per policy implication. The policy topics are based on the EU Horizon 2020 call for proposals from which the Spine project was funded.

More detail concerning each case study can be found in the Spine Deliverable 6.1 “Summary of the case studies”. The case studies are also available as Spine Toolbox projects on the public repository of the project\(^1\) that can be accessed, modified and used for further analysis.

The primary purpose of Spine case studies was to advance the capabilities of the modelling tools developed in the Spine project and consequently, they mainly consist of smaller data sets well suited for testing but less suited towards drawing elaborate conclusions. Therefore, the main audience for the report is other modellers who should consider including some of the capabilities of SpineOpt in their modelling activities if not yet implemented. That said, many of the case studies generate insights on different technologies or policies corroborating existing evidence, which can be valuable also to decision makers and people supporting decision making.

2. SECTOR COUPLING AND ELECTRIFICATION

2.1 Emission reductions through increased use of green hydrogen in non-electric energy sectors

With the European Green Deal, the EU has the aim to strongly reduce emissions in all energy sectors, aiming to be carbon neutral by 2050. While significant progress has been made towards the decarbonisation of the electricity sector, other sectors rely more heavily on fossil fuels and the decarbonisation has so far been rather challenging. Next to increased levels of electrification, the adoption of hydrogen as an energy carrier could facilitate the decarbonisation of the other sectors, including industry and specific transport means. Production of “green hydrogen” [WC06] within the electricity grid also facilitates increased shares of variable renewable generation through flexible operation of the electrolysers. That could also provide valuable grid services and lead to large reductions in load and renewable generation curtailment. Case study C3, which considers investments with high operational detail, explores the benefits of hydrogen deployment within the grid. C3 demonstrates how investments in hydrogen technologies can support increased investments in variable renewable generation, leading to significant emission reductions. However, the hydrogen pathway is not found to be cost effective for most scenarios by 2030 - the exceptions being a “High Fuel Price” scenario (which also considers higher carbon prices) and a “Hydrogen Network” scenario, which assumes large increases in hydrogen demand. By 2040 however, large investments in electrolysers and underground hydrogen storage occur across all considered scenarios, driven by the reduced technology costs and improved efficiencies. Significantly large increases in hydrogen demand are also assumed, based on the TYNDP Global Ambition scenario [EE19]. The large investment costs required for the infrastructure to support this demand is not considered as part of this case study. Furthermore, potential electrification of other energy sectors is only partially examined which could have a considerable impact on the results.

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1. [https://github.com/Spine-project](https://github.com/Spine-project)
2.2 Increased use of renewable electricity in the other energy sectors through green hydrogen

Case study C3 explores, through a range of scenarios, the potential of “green hydrogen” to decarbonise other energy sectors. Since, in general, we can argue that fuel is less expensive and more efficient to store than electricity, hydrogen could offer an effective means of seasonal energy storage. This becomes increasingly important in the coming decades as the pace of decarbonisation increases along with the need to balance electricity demand with variable renewable energy. To this end, case study C3 considers different levels of hydrogen adoption external to the electricity grid (as well as various power-to-X options within the grid). Hydrogen demand is modelled for industry, transport and also heating, which introduces significant seasonal variations. These changes in the demand profile impact optimal investments in hydrogen technologies, in particular long-term storage. Large investments in hydrogen storage occur by 2040, particularly when hydrogen is used to meet heating demand in the “Hydrogen Network” scenario. Future work will explicitly compare alternative decarbonisation pathways to the hydrogen pathway demonstrated in case study C3.

2.3 Increase the potential of conversions and exchanges between energy networks

Case study C3 explores the potential benefits of hydrogen as an energy carrier, with the ability to make significant progress in the decarbonisation of multiple sectors, and the advantage of cost effective seasonal storage. While the base scenario in this case study is based on the TYNDP 2020 Global Ambition scenario [EE19] (compliant with 1.5°C target of the Paris Agreement), alternative scenarios explore the importance of different enablers for the wide-scale adoption of hydrogen as an energy carrier, both within the electricity grid and in other sectors. Alternative fuel and carbon prices are considered, as well as alternative costs and efficiency levels for the electrolyser technologies, and varying adoption levels of hydrogen in the industrial, transport and heating sectors. Limited investments take place in most of the 2030 scenarios, although investments in electrolyser are demonstrated when fuel and carbon prices are high (“High Fuel Price scenario”) and when increases in hydrogen demand occur as in the “Hydrogen Network” scenario, as hydrogen is used to meet heating demand. While “green hydrogen” has significant potential in the long term, in the short to medium term, significant support would be required until the technologies scale up and costs reduce sufficiently. “Blue hydrogen” (where hydrogen is produced by a reforming process combined with CCS) is likely to be required at least during the transition phase to a large-scale hydrogen economy. Case study C3 allows the import of “blue hydrogen” to meet base hydrogen demands in 2030, which “green hydrogen” struggles to compete with in this time frame. For the 2040 scenarios, limited “blue hydrogen” imports are still allowed, but based on the model assumptions, the “blue hydrogen” is largely displaced in the C3 scenarios. Combined with the large investments in underground hydrogen storage, significant decarbonisation of industry, transport and heating takes place via large-scale wind and solar energy deployment. Obviously, these results are to be interpreted under all assumptions and boundary conditions taken, and serve to gain insight, rather than to present firm quantitative statements.

2.4 Create business cases through the interconnection of energy networks

In case study B5, the potential electrification of the industrial sector was explored through an example from the paper and pulp industry. The drying of pulp is predominantly done using fuels to heat the pulp sludge. However, electricity is an alternative heat source that could
avoid GHG emissions, if the power system is mostly decarbonized. An electrified drying process could also offer some flexibility for the power system, since the dried pulp can be stored before use. In this case study, a 2-day storage with an oversized electric dryer was compared to a natural gas based dryer under varying CO2 and fuel price assumptions. The results demonstrate cost-effectiveness of electric dryers at high shares of variable electricity generation, while also showing that at low shares of variable electricity generation (as is currently the case in most power systems) natural gas was the more cost effective option also when CO2 price was raised to 40 €/CO2 ton.

Spine Toolbox and SpineOpt allowed the modelling of complicated industrial and space heating processes within a larger energy system. Thus they can be used in the future to evaluate the business potential of specific investments that span energy sectors, like the example from the paper and pulp industry.

### 2.5 Avoid curtailment by exploiting new flexible electricity consumption from other energy networks

Case study C3 demonstrated the potential of “green hydrogen” production and storage within the grid to significantly reduce curtailment levels and reduce overall emissions. While power-to-power is also considered, the ability to meet the hydrogen demand of external sectors significantly improves the efficiency of the energy system as a whole, reducing the curtailment of the electricity consumed by the electrolysers. Furthermore it enhances the operational flexibility of the system, and the provision of ancillary services.

### 2.6 Enable new flexibility services to the grid from different energy sectors

In general, energy sector integration allows utilising potential flexibility sources across the sectors’ boundaries. This is perhaps most important for the power grid and electricity markets, as flexibility from other sectors like heating and cooling, gas networks, or transport, can often be exploited without noticeably affecting the service provided to the end-user. The flexibility offered by SpineOpt can be used to seamlessly model multiple energy sectors operating at their native timescales, and thus permits studying different business models for intersectoral flexibility services.

For example, case study A4 demonstrated the capability of SpineOpt to co-optimise the heating and cooling of a large number of electrically heated detached houses in Finland along with the operation of the overarching power and district heating systems. While the case study is made from the system’s point of view, similar methodologies could be used to optimise electricity market bids of a demand response aggregator in control of widespread flexible electric heating systems in residential buildings.

### 2.7 Maximize the capacity of the grid to host variable renewables through electrification of end-use sectors

The hosting capacity of the grid for variable renewable generation is limited by prevailing electricity demand. Excessive curtailment of variable renewables challenges the economic viability of future investments. Case study C3 explored the expansion of the hosting capacity of the grid, considering different end-user demand levels for e.g. heat pumps. The hosting capacity can be further expanded by running electrolysers with excess electricity and meeting the demand of other sectors with “green hydrogen”. While C3 demonstrated a limited role for hydrogen by 2030, by 2040 based on the assumed boundary conditions, technology costs and efficiencies, wide-scale investments occured, assuming strong demand for hydrogen. Case
studies A4, B3 and B5 modelled space heating, electric vehicles and an example industrial heat demand, respectively. They also gave some indication of how the increased electrification of the energy end-use sectors can impact the hosting capacity of the grid. If those new demands are flexible, they enable a more cost effective expansion of the grid to accommodate both generation from variable renewables and increased demand. On the other hand, if those loads are inflexible, it was found that there will be more difficulties to balance the power system in the future.

2.8 Take advantage of consumption devices and variable renewables for stability and security of the European grid

In several Spine case studies, electricity consuming devices were allowed to participate in the provision of different power system ancillary services. While the main focus of these case studies was not to analyse the impact of these devices on stability and security, they provided corroborating evidence about the importance of including those devices in the provision of power system services. Case study A4 demonstrated space heating in individual buildings. Electric heating in combination with heat storages allowed the buildings to participate in the balancing of the power system. The modelling results showed a cost-effective source of balancing once it has been implemented. However, cost-effective control systems for individual buildings are not easy to achieve and this is an important barrier for wide-scale adoption. Case study B3 analysed smart charging electric vehicles. These had a similar impact on the balancing of the power system as electric heating of individual buildings. If the cost and behavioral barriers related to adoption of smart charging can be overcome, they could be an important source of balancing and reserves for the power system. Case study B5 added to the evidence, by showcasing the balancing services provided by flexible electric drying of pulp in the paper and pulp industry.

3. PLANNING AND INTER-ANNUAL ASPECTS

3.1 Optimize grid planning and design by modelling the whole energy system with sufficient detail

Grid planning requires modelling the energy system over the long term and for different scenarios of the future while capturing as much detail as possible of the short-term operation, in order to optimize investment decisions. There is a tension between extending the horizon and/or number of scenarios, and at the same time increasing the time resolution of the model. This tension needs to be managed by the computational tool in order to produce meaningful results in a tractable way. Spine Toolbox and SpineOpt provide outstanding features that can help achieve this objective. On the one hand, Spine Toolbox automatically parallelizes scenario runs by relying on a Python's multiprocessing library, managing whatever computing resources are available. On the other hand, SpineOpt uses Benders decomposition to accelerate the solution of an optimization problem that includes both investment and operational decisions, where, instead of having a separate data structure for each subproblem, a unique data structure is used that is updated “in-place” leading to considerable speed-ups. These features have been tested in Case Study C2 which determined grid investment decisions for a model of the Nordic synchronous power system (including Norway, Sweden, Finland, and Denmark) with about 490 nodes, over a time horizon of ten years. Results of measurements showed that one Benders iteration can be completed in about three hours on a standard laptop, with three scenarios running in parallel, rendering the calculation time quite favourable.
In addition, Case Study C3 included a detailed model of the power system in Ireland, including interconnectors between Ireland, Great Britain, and France. System services such as the operating reserve are included and an inertial floor is also assumed, ensuring stable operation. Crucial cross-sectoral interactions are also considered, with grid investments in hydrogen technologies and long-term storage playing an important role in decarbonising other sectors, including the industrial, transport and heating sectors. These synergies will be essential in meeting ambitious decarbonisation targets in an efficient manner for the energy system as a whole. Case study C3 identified strong investments in hydrogen electrolysers with underground storage technologies by the year 2040 (under the assumptions taken).

## 3.2 Storable energy in combination with seasonal and inter-annual variations in the resource availability

Case study B4 examines biomass as a flexible resource for future power systems. While biomass can be stored, it decomposes over time and its available energy content is affected by moisture that can vary with weather. Analysing the model’s results, it was found preferable to store larger amounts of biomass only during the spring-summer time and avoiding long-term storage in the fall and winter. While this result needs to be further scrutinized in larger and more representative energy systems, it does indicate that solid biomass can have limitations as a seasonal and inter-annual energy storage and this likely improves the comparative value of biomass-derived liquid or gaseous fuels over solid biomass.

Case study C3 demonstrates optimal investments in generation and storage technologies, while also including high levels of operational detail, allowing the full value of storage technologies to be valued. Trajectories for seasonal storage are also optimised, allowing inter-annual variations to be balanced, both within the electricity sector and also across other sectors which adopt hydrogen as an energy carrier. The 2030 results show modest investments in hydrogen storage, with daily storage cycles rather than seasonal. However, by 2040 the large energy storage capacities are used effectively to balance demand across the seasons (again under all assumptions taken in this case study).

## 3.3 Studying inter-annual fluctuations of variable renewables when planning for enhanced security of supply

The case studies did not implement multi-year optimization at this stage (this is important future work), but Spine Toolbox and SpineOpt have been built in a way that makes multi-year optimization more feasible through a very flexible temporal structure of the model.

## 4. Energy Efficiency

### 4.1 The cost efficiency of energy efficient buildings when analysed as part of the larger energy system

The heating and cooling of the built environment accounts for almost 40% of the final energy demand in the EU\(^2\), and as such is under constant pressure to reduce this impact on the climate. Improving the energy efficiency of the built environment and the electrification of heating and cooling sectors are seen as the main two avenues for reducing the carbon emissions of the heating sector, of which the latter can have profound impacts on the operation of power systems.

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\(^2\) [https://publications.jrc.ec.europa.eu/repository/handle/JRC114758](https://publications.jrc.ec.europa.eu/repository/handle/JRC114758)
Case study A4 demonstrates the ability of SpineOpt to model the heating and cooling demand of building stocks as an integral part of the overarching energy system. This way it is made possible to study the potential impacts of energy efficiency improvements and electrification, including the operational costs of the modelled system. Furthermore, the demonstrated methodology captures potential flexibility in the modelled heating/cooling demand, making it easier to study the energy system impacts of potential demand response measures in the heating sector.

The remaining main challenges in modelling the impact of energy efficiency improvements and electrification in the heating sector are often related to data availability. While EU-wide data sources for building stock data like the EU Building Stock Observatory\(^3\) exist, data are rarely complete enough to realistically model the heating sector without combining it with national statistics on a country-by-country basis, which can be prohibitively time consuming and lead to inconsistencies.

The derived policy implication is to build on the existing EU-wide building databases to improve their data coverage and to develop tools that allow modellers to utilize the data in a flexible and efficient manner. There are many processing steps required before the data become usable in energy system wide models. Building energy management presents a large potential for flexible use of electrical energy—a pre-requisite for cost-efficient operation.

4.2 Achieving primary energy efficiency gains in transport with increased electrification

The results from case study B3 corroborate findings that show much higher primary energy efficiency in the electrified transport system in comparison to a fuel-based transport system. When the electricity system moves towards variable electricity generation, the primary energy efficiency increases considerably and this is reflected on the transport sector mainly by electric vehicles that have a tank-to-wheel efficiency close to 80%.

5. Market design

5.1 Market designs that consider interactions between the energy sectors

In case study C1, the benefits of the coordination of balancing capacity markets in future European electricity markets have been analyzed. This case study examines the day-ahead energy-only market and the reserve markets. Decisions made in one market will impact the outcome of other markets, be it through the interdependence of operational decisions or through the allocation process of cross-zonal transmission capacity (CZC). To address the issue of transmission capacity allocation, three different methodologies have been proposed in the energy balancing guidelines: the co-optimized allocation; the market-based allocation; and the allocation based on an economic efficiency analysis.

While all three processes require network capacity to be explicitly allocated to either one of these markets, they determine the value of transmission capacity differently: the value of transmission capacity can correspond to actual or forecasted market values. In the co-optimized allocation process, the allocation of transmission capacity will be dependent on the comparison of the actual market values. In the market-based allocation and in the allocation based on economic efficiency, the market revenue from future markets is only

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\(^3\) https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/eu-bso_en#the-database
forecasted, as the timing of market clearings are not aligned. This leads to sub-optimal allocation of resources. To ensure an efficient market design, the co-optimized allocation process should be preferred. In practice, this would imply that the common market clearing algorithm or the European electricity wholesale market, namely EUPHEMIA, would also need to consider the balancing capacity market and other ancillary services.

5.2 Consider the value of new energy transmission links in integrating energy markets

New transmission links can reduce operating costs by allowing the system to bypass a zone of congestion and thus use cheaper generating units to fulfill the demand. In studies that study the integration of energy markets, the value of new links needs to be properly taken into account in order to produce meaningful results. However, capturing that value requires modelling grid investment decisions which increases the computational complexity and may also introduce non-linearities, rendering the problem difficult to solve. A solution is to use decomposition approaches to solve the optimization problem, such as Benders decomposition, as currently implemented by SpineOpt. By using Benders decomposition, SpineOpt can solve optimization problems combining investment and operation decisions in tractable time. All the modeller needs to do is specify certain parameter values in the input dataset to activate the Benders decomposition and control it to a certain extent. An example of this technique is provided by Case Study C2, where we co-optimize system operation and grid investments on a model of the Nordic synchronous power system, with about 490 nodes and 600 transmission lines. First we select 100 candidate transmission lines using an empirical algorithm, and then we model the system’s operation over a 10 years horizon with weekly resolution and using three scenarios of renewable energy penetration, in order to determine the optimal investment time for the candidate lines. In this case, SpineOpt selects 14 out of the 100 candidates to invest in, so as to reinforce an area that happens to (i) be weakly connected to the rest of the system, and (ii) not have sufficient installed capacity. Each Benders iteration takes about three hours to complete on a standard laptop, rendering the solution relatively fast. The conclusion is that state-of-the-art computing techniques and software technologies can effectively help the analysis of complex, large-scale energy systems combining market operation and grid investment decisions.

5.3 Avoid inefficiencies caused by divergent regulations

Efforts are being made to coordinate the activation of balancing energy. The International Grid Control Cooperation (IGCC) platform for imbalance netting is already online. There are also pilot projects for the procurement of automatic and manual frequency restoration reserves (a/mFRR) and replacement reserves: the PICASSO, MARI, and the TERRE projects, respectively. The coordination of procurement however, remains fairly untapped, with the exceptions of the FCR cooperation and the fully integrated Nordic balancing market. In Case study C1 we simulate the co-optimized allocation process of cross-zonal transmission capacity for the exchange and sharing of balancing capacity (BC) in a joint day-ahead energy and BC market clearing, in comparison to the uncoordinated case.

Results show that the exchange of BC enables both more cost-effective procurement of BC resources and more cost-effective scheduling of electricity generation. Sharing of BC, through its associated reduced BC needs, reinforces these impacts and allows the portfolio to be scheduled even closer to an electricity generation cost-driven schedule. System-wide impacts are moderate in terms of both capacity rescheduling and cost savings (somewhat more important for sharing than for exchanging of BC). Country-level impacts are more substantial, with significant impacts on the use of “mid-load” and “peak-load” capacity (e.g., CCGT and
OCGT). Cross-zonal transmission capacity is also substantial, with half of the cross-border flows being related to BC when BC sharing is allowed. However, such flows only mildly displaced energy flows and rather complement them, with BC often flowing one way while energy is flowing the other way.

5.4 Offer new grid services to the grid

In case study C1, we have simulated the co-optimized allocation process of cross-zonal transmission capacity for the exchange and sharing of Balancing Capacity (BC) in a joint day-ahead energy and BC market clearing. This way we analyzed the potential benefits related to coordinated sizing of BC requirements. Following the results of case study C1, the most important impact of introducing cross-border BC coordination as a new market design appears to be on supporting the need for “back-up capacity”. At high renewable generation shares, the functionalities of non-spinning mFRR provision for short-term operational reliability and back-up capacity provision for system adequacy, collapse into a demand for relatively low-CAPEX, high-flexibility capacity (e.g., CCGT and OCGT). Sharing such infrequently used capacity across borders rather than having each control area be self-sufficient, could greatly reduce the power system’s investment needs. Our results showed that cross-border BC coordination, especially when paired with alternative sources of firm and flexible capacity, like infrequently used high-capacity demand response, could significantly reduce the need for back-up capacity.

The level to which the need for back-up capacity could be reduced depends strongly on the effectiveness of the cross-border coordination and the extent to which it can reduce regional BC requirements. This requires further research considering investment models with uncertainty profiles of multiple years, to understand in more detail what the trade-off entails between building more back-up capacity vs. building less but sharing it. It also initiates a range of non-technical questions related to how governments and other actors (TSOs, large industrial consumers, etc.) want to value the loss of load in highly renewable power systems.

It is, however, very clear that pursuing increased coordination of the procurement and sizing of BC is a no-regret option: in the short-term it allows more cost-effective operation of the power system without requiring increased investment in power system assets, whereas in the long term it has the potential to reduce the need for generation capacity that might otherwise require financial support to attract sufficient investment.

6. DATA, METHODS AND TOOLS

6.1 Assess the benefits of data availability for enhanced trading and balancing

Data availability issues can affect the accuracy of an energy system integration model leading to suboptimal results. The availability of data is usually out of the control of the modeller, which means that when designing a model, measures need to be taken in order to accommodate some level of uncertainty in the input data and/or in the access to such data. Ideally, the model should accommodate different ways to handle uncertainty, which can be achieved in at least two ways. First, uncertainty can be explicitly modelled using common mathematical constructs such as stochastic programming. Second, the data collection process can be automated so that whenever there is more data available from the source, the model can immediately make use of that data without any additional effort from the modeller. Spine implements both approaches. The first one is implemented in SpineOpt via a dedicated data structure that allows the definition of branching and/or converging stochastic structures (i.e.,
SpineOpt’s flexible stochastic structure). The second is implemented in Spine Toolbox by means of the *Importer* functionality, which allows the definition of mappings from external data sources into the Spine data structure. That can be applied every time the project is executed, over diverse data sources available at the time. In addition, results from the different executions of the model are stored separately and thus can be compared in order to measure the impact of data availability. Case Studies B3, B4, and B5, as well as C2 illustrate these features.

### 6.2 Include aspects of human behaviour in the tools

Human behavior and social acceptance have a profound impact on the evolution of energy systems. They would be important dimensions to consider when aiming for robust policy advice concerning emission reductions or evaluation of different technologies. However, most energy system models do not cover these aspects. While the Spine project did not include behavioral aspects directly, we have built a modelling environment that is readily expandable. The SpineOpt model can include additional constraints and terms in the objective function. As behavioral aspects can be difficult to monetize, it is also important to have the possibility to operate models that are not based on optimization, but can still inform policy making or modelling efforts that are based on exact formulations. We have tried to build Spine Toolbox in a way that allows both the rapid development of new models and simulation tools as well as linking of modelling tools with different capabilities. Building a bridge between social sciences and energy economics would be an intriguing new direction in future.

### 6.3 Adequate tools for the planning of pan-European energy systems

Case Study C3 considers investment decisions, including a high level of operational detail. For comparison, a number of the scenarios were completed with a lower level of operational detail. When operating reserves and a system inertial floor constraint were not included, variable renewable generation was invested in at significantly higher levels. Large dispatchable plants, which are important for system stability, were no longer selected. By not adequately considering the system flexibility requirements, curtailment levels for a given level of renewable generation capacity were underestimated. Interestingly, while the increased levels of renewable generation prompt increased investments in hydrogen storage, the required electrolyzers for each scenario remained similar or even decreased partly driven by the underestimation of curtailed renewable energy which can power the electrolyzers at very low cost. These results highlight the importance of sophisticated tools for planning the future energy system, with the ability to include sufficient detail and also the ability to capture the interactions between the different sectors which are becoming increasingly integrated.

### 6.4 Enhance innovation capacity by testing energy sector innovations with open-source tools and ready-made cases

It is important to reduce barriers for testing energy sector innovations and assessing their impact on the integrated energy system. These barriers may come from different sources. First, commercial software licenses may be difficult to afford for small to medium size organizations that do not have a consolidated business model and/or continuous source of revenue. Second, the usage of closed-source software tools where the solution comes from a “black-box” reduces the modeller’s ability both to interpret results (leading eventually to wrong conclusions) and to try out new ideas by extending the current formulation. Third, the lack of working examples and proper documentation and support can lead to a situation where the learning curve is so steep that an organization is forced to dismiss a certain tool, especially
if they have constraining short-term goals. Most of these barriers can be effectively removed simply by the adoption of open-source software. Open-source software reduces acquisition costs and improves usability as the modeller now has full access to the source code, and thus can properly diagnose and extend their models at will. If the open-source tool also provides sufficiently documented, ready-made working examples, the situation improves further as newcomers can take up, extend, and even combine such examples in order to implement their own case studies. Spine takes a decisive step in the adoption of the open-source paradigm in combination with state-of-the-art technologies and programming languages, as well as best practices for documentation, support, and automatic testing via continuous integration. Spine also supports sharing projects as online git repositories to increase opportunities for sharing and collaboration. The Spine data structure and the ancillary data conversion tools are also designed so that data can be easily shared across multiple users, as well as reused for multiple purposes.

REFERENCES
