Definition of and requirements for case studies of the European energy transition

DELIVERABLE D6.1

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List of acronyms used in this document

CAPEX: Capital Expenditure

CCS: Carbon Capture and Storage

CHP: Combines Heat and Power

CS: Case Study

DER: Distributed Energy resource

DH: District heating

EC: European Community

EU: European Union

EU-28: 28 countries forming EU before Brexit

EUC: European Unit Commitment MOdel

EV: Electric Vehicle

GDP: Gross Domestic Product

GHG: Green House Gases

HP: Heat Pump

OPEX: Operational Expenditure

P2G: Power to Gas

PV: PhotoVoltaic

RES: Renewable Energy System

SSV: Seasonal Storage Valuation

V2G: Vehicle to Grid

WP: Work Package

ZEN: Zero Emmission Neighbourhood research center

Executive Summary

9 case studies will be performed during the project, as a real-size proof of concept of the project, applied to the main topics of the energy transition. Through the case studies, the model connections will be validated and the modelling assumptions and results will be evaluated.

The 9 case studies are the following:

- **Case study 1** will be dedicated to Demand-Response from household consumers. It will evaluate the potential flexibility from demand response from household consumers and study its impact on the integrated European electricity system cost, operation and investments needs.
- **Case study 2** will be dedicated to behaviour of communities of actors. It will study shared energy management in different local energy community concepts, taking into account the individual preferences of the actors involved. Based on comprehensive modelling, the quantitative results will be up-scaled on country and European level.
- **Case study 3** will be dedicated to flexibilities and storage. It will analyse how the uses of flexible hydropower and more generally of different kinds of storages (pumped-hydro, batteries, gas….) can tackle some of the main challenges of the energy transition.
- **Case study 4** will be dedicated to cross-sector integration, with a specific focus on the flexibilities provided by electric vehicle owners to the electricity system.
- **Case study 5** will compare different levels of geographic coordination for investment decisions, both at regional and European level, focusing on the topic of decentralisation. In particular regional decisions with local objectives will be compared with national or European coordinated decisions.
- **Case study 6** will analyse the use of innovative technology in terms of underground rocks for seasonal storage of heat from summer to winter in a district in Oslo, Norway. The analyses will show the impact on the energy system in the district. Relevance for other European regions will be discussed.
- **Case study 7** will evaluate how the use of flexibilities from the heating sector at different time scales (short-time planning with hourly to 5 minutes resolution) may have an impact on the system operation costs and network expansion needs.
- **Case study 8** will investigate the role of natural gas storage in current and future energy systems in transition.
- **Case study 9 (from WP7)** will address regulatory barriers and market design options in shaping the future energy system.

Each of those case studies is detailed in this deliverable along the following dimensions:

- Overall objective and research Question;
- Main assumptions, geographical & time horizon perimeter & granularity, technical scope;
- Challenge(s) beyond-state-of-the-art;
- Modelling approach, models used, linkages;
- Expected results and Limitations
- Input Data needed;
- Methodology of the case study (modus operandi).

0. Introduction

0.1 Project Summary

The EU has set the ambition to reduce greenhouse gas emissions to the point of becoming climate neutral by 2050 and prevent the negative and irreversible effects of climate change. This goal includes shifting the energy system to renewable and clean system, as well as technological, behavioural and organisational changes in the economy and society. For doing so, the coordination of relevant technologic solutions, policies, funding and actors, with well-defined targets based on scientific analyses will be required.

In response, openENTRANCE is developing an open-source modelling platform that will:

- Allow carrying out scientific calculations and assessments for different future options of a low-carbon Europe.
- Link and integrate macro-economic and energy system models, and provide economic (e.g. GDP, employment) and human behavioural data (e.g. energy consumption habits) relevant for the energy transition to be used in modelling analyses.
- Support stakeholders to determine macro-economic consequences of the energy transition and identify the best ways to transition to a 'low-carbon' economy.
- Be openly available to use by any interested users, targeting mainly researchers and modellers.

This open platform will be demonstrated by carrying out case study simulations covering different key aspects of the enrgy transition in Europe, based on the targets for the EU Energy Union.

0.2 Objective and scope of this deliverable

Within the work package "Case Studies", 9 case studies will be performed to cover the main topics of the energy transition. The main objectives of the proposed case studies can be summarised as follows:

- Show the adequacy and relevance of the Open ENTRANCE platform. For this purpose, the case studies will be demonstrated by using scenarios, assumptions and data developed within Work Package 3 "Scenario Building Exercises", and the suite of modelling tools supplied by Work Package 5 "Suite of Modelling tools".
- Show the ability of the proposed approach to answer specific questions related to the evolution of the energy system. This will be done with a specific focus on the effects of decentralisation, variability, the need for flexibility, real market functioning, integration of energy sectors, behaviour of individuals and communities of actors.
- Provide complementary inputs (data) to Work Package 3 "Scenario Building Exercises".
- Provide knowledge regarding barriers and determinants of investments within WP7 "Transition Pathways" (Note: The last case study belongs to WP7).

In order to perform the case studies, simulations will be run using the linked models developed within WP5 "Suite of Modelling tools" and the scenario dataset developed within WP3 "Scenario Building Exercises". As for the scenario dataset, in order to ensure consistency among studies, supplemental data, which may be needed on specific items, may be added to the platform while performing the case studies. Therefore, it will be possible to easily re-run case studies or derive variants or challenge them by using other models/data.

- **Case study 1** will be dedicated to Demand-Response from household consumers. It will evaluate the potential flexibility from demand response from household consumers and study its impact on the integrated European electricity system cost, operation and investments needs.
- **Case study 2** will be dedicated to behaviour of communities of actors. It will study shared energy management in different local energy community concepts, taking into account the individual preferences of the actors involved. Based on comprehensive modelling, the quantitative results will be up-scaled on country and European level.
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- **Case study 9 (from WP7)** will address regulatory barriers and market design options in shaping the future energy system.

The above case studies will also act as a real-size proof of concept of the project. Through the case studies the model connections will be validated and the modelling assumptions and results will be compared.

Within the following nine chapters, each of the case studies is deeply described, including:

- Explanation of the overall objective of the case study: which questions does it aim to answer?
- Baseline of the case study: main assumptions, perimeter of the study, target user;
- Challenge(s) in the case study (beyond-state-of-the-art);
- Modelling approach;
- Expected results;
- Limitations of the study;
- Data requirements including data coming from WP3 and complemental data and data sources;
- Models requirements: models to be used, required linkages, needed model enhancements;
- Methodology of the case study (modus operandi).

1. Case Study 1: Demand response – behaviour of individuals

Leader: EI-JKU; Contribution; EDF, NTNU

1.1 Overall Objective and Case study baseline

This case study focuses on different modelling paradigms for residential electricity demand in both the short (hourly) and long (annual) term within the electricity system. The objective is to analyse the potential of consumers to shift electricity demand under different measures for flexibility. Data from real-life field-tests, recently carried out in several EU nations, will be used. Such data directly reflect human behaviour and individual choices related to electricity consumption and will contribute to an improved understanding of the potentials of demand response for the system and for individuals. The improved understanding of flexibility potentials will be input into the EMPIRE and plan4EU energy system models to assess the system level impacts of flexibility under various scenarios and regimes.

Through this case study, national and European policy makers will be provided with significantly improved insights on demand response measures that support the effective and efficient integration of variable renewable electricity generation into the European grids and markets.

The baseline for this case study is the existing modelling frameworks of the EMPIRE and plan4EU models. Prior research also forms the baseline, firstly including Gils (2014) who has estimated *theoretical* demand response potential for all European countries, differentiated by sector – which includes a "residential" sector. The study and EMPIRE module developed in Maranon-Ledesma and Tomasgard (2019) is the baseline demand response module, using the quantities estimated in Gils (2014), that will be updated in this Case Study. Finally, as a baseline guidance for how to input empirical, social science estimates of human behavior into energy system models, we refer to past work in McKenna et al. (2019; 2020).

1.2 Challenges (beyond the state of the art)

The central challenges of CS1 are:

i. Generating empirically-validated representations of demand response that are consistent with behavioral data and theory regarding residential load-shifting.
ii. Adapting energy system models to the improved representation of demand response.

The beyond state-of-the-art elements of CS1 are:

i. Using empirically-informed demand response potential consistent with behavioral realities instead of purely theoretical ones.

ii. Coupling of large scale pan-european quantitative micro-datasets (ECHOES survey and PEAKapp field test data) with large scale energy system models.

1.3 Expected results and limitations

The focus of this case study is to gain new insights into:

- What affects the choices of individuals and how can this be used to improve modelling of short-term dynamics in electricity demand. Human behaviour is not always rational as assumed by the optimization models. Recent survey data helps us identify the human preferences with respect to the energy market, and analyse the rationality of energy consumers (e.g. household consumers may prefer "green" electricity contracts despite higher prices than conventional contracts);
- What is the potential of demand response, including sector integration;
- What are the needed policies and incentive systems to unleash the flexibility potentials in electricity consumption in the most effective and beneficial way;
- What are the long-term system effects of demand response in the transformation of the electricity system.

A key limitation is that CS1 is only considering the demand response potential in the residential electricity sector.

1.4 Modelling approach & Models requirements

Understanding the potential system–level impacts of household flexibility.

plan4EU model (partner: EDF)

An integrated planning and operation model for the Pan-European electricity system.

- Short-term: hourly representation of flexibility assets, e.g. households
- Regional granularity, and aggregates to pan-European electricity system
- Elicitation of household demand-response potentials and relevance for EU electricity system
- Focused on the European electricity system, with its interactions with other energy vectors: gas, heat, cold, mobility (via eg flexiilities from P2G, Evs….)
- Realistic representation of the system operation: dynamics, operational constraints, interconnections
- Variable renewable integration
- Uncertainties modelling, especially related to climate
- Timeframe: Focus on one specific year, Hourly
- Technical constraints:
  - Dynamic constraints of generation plants
  - Seasonal storage and short-term storage flexibilities
  - Demand flexibilities

- Coupling constraints:
    - Active demand
    - Primary and secondary reserves services
    - Inertia requirements
    - Pollutant limits CO2 emissions
- Uncertainties
    - meta-scenario corresponding to climate change trajectories
    - mid-term/short-term uncertainties corresponding to demands (power and reserve), inflows, renewable generation (PV, wind, hydro)
- Inputs
    - Powerplant characteristics: capacity, costs, technical constraints, availability
    - Storage characteristics: Inflows, capacities, volumes constraints
    - *Demand response characteristics: Curtailment; Load-shifting; Centralized OR distributed*
    - Electricity demand, inflows, CO2 prices, transmission grids, distribution network flow limits, seasonal storage values.

EMPIRE model (partner: NTNU)

A multi-horizon stochastic programming model for the European power system.

- Dual short and long-term decision nodes: capacity and transmission extensions modelled up to 50 years in the future
    - Focuses on investments in energy generation capacity and transmission
    - Optimized capacity and transmission investments to minimize operational cost
    - Long term decisions are made every 5 years
    - Short term decisions are made for representative operational hours
- Spatial scope: EU-28 + Bosnia, Norway, Serbia, Switzerland, and excludes Cyprus
- Addresses European transmission system
- Elicitation of investments costs for demand-response expansion
- *Inputs related to demand response characteristics:*
    - Demand response capacity as a function of the time period (operational hour) and the level of the country's load. This is done through influencing α in (3) of Maranon-Ledesma and Tomasgard (2019).
    - Quantification of demand response rebound effects and inefficiencies (y_{loss} in Maranon-Ledesma and Tomasgard (2019)).
    - Cost estimates for units of demand response.

1.5 Data requirements

Input data for CS1 includes the macro level indicators and energy system information that are already integrated into the EMPIRE and plan4EU models. These indicators will flow out of the scenarios in WP3. Data from Gils (2014) is used as a starting point for demand response potentials, as done in Maranon-Ledesma and Tomasgard (2019).

Additionally, data collected in two other Horizon 2020 projects will be used, PEAKapp and ECHOES. In PEAKapp a fully operational demand flexibility system was tested across 1,590 Austrian households. In addition, electricity consumption data was collected from 1,687 households across 3 Baltic countries (Estonia, Latvia, Sweden). Both datasets allow for statements regarding the price elasticity of short-run electricity demand, while the Austrian field test allows for strong statements regarding the effect of purposeful demand flexibility price incentives on electricity consumption and consumer behavior across seasons and hours of the day.

The ECHOES dataset surveyed 18,037 Europeans across 31 nations (EU28 + Switzerland, Norway and Turkey). These data may be useful for characterizing energy behavior and plans to purchase flexibility-enabling technology. Included in this dataset is a single-bounded willingness to accept (WTA) compensation experiment where respondents were asked: “Would you allow your grid operator to remotely switch on and off non-critical appliances in your home if you were offered an annual discount of [€X]?” Where €X is a value that varied between countries based on purchasing power parity. The number of respondents per nation to this question are given in Table 1.

Country	no. of respondents to WTA question
Austria	251
Belgium	197
Bulgaria	151
Croatia	204
Cyprus	80
Czech Repub	191
Denmark	218
Estonia	160
Finland	202
France	194
Germany	214
Greece	204
Hungary	187
Ireland	255
Italy	221
Latvia	199
Lithuania	206
Luxembourg	205
Malta	101
Norway	134
Poland	197
Portugal	195
Romania	220
Slovakia	206
Slovenia	185
Spain	193
Sweden	197
Switzerland	204
The Netherla	213
Turkey	167
United Kingc	219
TOTAL	5970

Table 1: ECHOES - Number of respondents per country

1.6 Detailed methodology of the case study (modus operandi)

The plan4EU model will be used to simulate the short-term (hourly) integrated operation of all flexible assets and potentials of the pan-European electricity system with a regional geographical granularity, thus allowing the capture of cross-effects of different flexibility inputs. Plan4EU provides a modelling of household demand-response, including load shifting and load curtailment, taking into account accurate dynamics and constraints (e.g. the time-scale within the day for load shifting). However, up until now there has not been realistic, empirically-based, measures of household demand response potentials across EU countries. EI-JKU will provide estimates of demand response potentials at the country level, using the Gils (2014) theoretical potentials as a starting point and scaling these potentials down based on the observed demand response program participation in the PEAKapp data and the stated willingness for automated demand response. This represents a theoretical shift in the methodology - where previous studies looking into demand flexibility look at the technical side, including the appliances owned by households in the nation and the residential load profile – CS1 includes then the behavioral side of demand response. This includes the willingness and ability to participate in behavioral demand response programs, and estimates of the payments that are required to 'buy' units of demand response through household participation. The methods for estimating participation rates follow those laid out in McKenna et al. (2019; 2020), and are described as econometric panel data models. The precise quantities estimated will be chosen based on the quantities represented in the plan4EU and EMPIRE models and will include those listed under the input data requirements in the preceding section. This analysis will incorporate a new addition to grid flexibility modelling: the risk (variance) of demand response flexibility estimates for each country. As econometric models can take account of the variance in estimated quantities and plan4EU has a module for stochastic quantities as inputs.

Demand response and load shifting potentials will be produced at the national level for scenarios chosen in concert with WP3 teams.

Additionally, the *structure* of demand response representation in both of the models will be assessed based on the behavioral insights from the econometric exercise, social science literature, and the expertise of the EI-JKU team. For example, based on the representation of demand response in Maranon-Ledesma and Tomasgard (2019) three open questions arise:

i. Can there be an interaction between demand flexibility and non-dispatchable renewable generation, such as solar, wind, and tidal? This would more accurately represent consumer preferences and the cost to buy units of demand response as past research has shown that the consumers are more willing to increase electricity consumption during times of renewable production in order to use 'green' electrons.
ii. Are the types of load defined under shiftable, curtailable and interruptible load types defined correctly and proportionately for residential consumers? PEAKapp preliminary estimations suggest that most loadshifting behavior leads to overall increases or decreases in electricity demand – this will be further assessed in CS1.
iii. What is the shape of the marginal cost curve for purchasing units of demand response from residential consumers? Maranon-Ledesma and Tomasgard (2019) assume an increasing marginal cost curve, but preliminary PEAKapp estimations often assume a constant marginal cost curve. This will be empirically tested using PEAKapp data and compared to leading literature on the subject.

Plan4EU simulations will be run with the new estimates of demand response included (volumes of potential load curtailment and load shifting with dynamic characteristics and variability, for each nation). The output will describe the value of demand response to the European grid. EI-JKU will then calculate the expected cost, in terms of discounted electricity prices, for the level of demand response employed by the model. This will allow for a never-before-possible comparison of the value of certain levels of demand response to their costs.

As demand response will influence the evolution of the electricity system in the long-term, the case study will also include an assessment on the role of demand response in future capacity-expansion-investment decisions and in supporting renewable balancing. For this purpose, the EMPIRE model will be used. It includes a modelling of Demand-Response expansion (strategic decision variables with investment costs) for different kinds of demand responsive loads. EI-JKU inputs will expand the capabilities of EMPIRE to estimate different amounts of demand response flexibility potentials and allow the model to more accurately reflect behavioral realities in the household sector.

Finally, comparisons on different scenarios will be performed, including simulations with plan4EU based on results from EMPIRE, both based on the new demand-response inputs and in accordance with WP3 scenario input data and guidelines.

1.7 References

Gils, Hans (2014). Assessment of the theoretical demand response potential in Europe. *Energy 67,* pp. 1-18.

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McKenna, Russell, Diana Hernando, Till ben Brahim, Simon Bolwig, Jed Cohen and Johannes Reichl (2020). Analyzing the energy system impacts of price-induced demand-side-flexibility with empirical data. *Zenodo Preprint*. https://zenodo.org/record/3674642#.Xk0BfntCeUk

2. Case Study 2: Communities of actors

Leader: TU Wien

2.1 Overall Objective and Case study baseline

The concept of optimizing local PV self-generation and consumption on 'prosumers' level is already well established in many European countries. Recently, a further development of this concept beyond individual prosumer boundaries to neighbourhood and district level has been triggered not least by the 'EC Clean Energy Package' (the establishment of energy communities and further 'democratization' of the energy system is explicitly mentioned). Moreover, favourable amendment of legislation and regulations in this context have been made in some European countries (e.g. Germany, Austria).

Baseline:

- Participation is on a voluntary basis: fully democratic participation, considering the individual needs of the actors
- Diversity of actors involved with different individual objectives
- Different manifold, e.g. in terms of renewable technologies, system boundaries (building level, spatial extent, distribution grid anatomy, peer-to-peer matching/trading in a wider context, etc.)
- No self-sufficiency of the community is intended

2.2 Challenges (beyond the state of the art)

- Individual willingness-to-pay of different actors involved
- No closed system (the energy communities are part of the local distribution grid)
- Analyzing different settlement patterns and upscaling the potential for energy communities for a whole country
- Upscaling the community potential for Europe as a whole

2.3 Expected results and limitations

Expected results

- Optimal design of the renewable technology portfolio for the community
- Time series of total and shared hourly local generation, storage operation, load, and purchases needed from the public grid
    - For each community actor
    - For the community as a whole

- Revenues streams of community actors, distribution grid operator, and external supplier
    - Sustainable business model making
- Determination of the net present value of investment and operational results up to 15 years
- Analyses for Austria and 4 European 'reference countries'
- Quantitative upscaling of the short- and long-term local energy community potential is conducted for Europe as a whole

Limitations of scope:

- The only energy carrier is electricity
- The model is an economic model, not considering the physical power flow within the community

2.4 Modelling approach & Models requirements

The local energy community model FRESH:COM (FaiR Energy Sharing in local COMmunities) will be used. The modelling approach is as follows:

- Implementation of the linear optimization tool FRESH:COM in Python using Pyomo and Gurobi
- Conducting an optimal techno-economic design of the local renewable technology portfolio (PV system, battery storage) depending on the composition of community actors (described by the individual characteristic load profiles)
- Different allocation and clearing mechanisms of shared local generation:

    1.) static (individual actor's optimum according to predefined allocation scheme)

    2.) dynamic (hourly/real time global community optimum exploiting several synergies among actors' load profiles and preferences)

- Studying a variety of energy community patterns and set-ups (incl. annual phase-in and phase-out of community actors resulting in frequent reallocations of the default set-up)

2.5 Data requirements

For this case study, it is important to define the involved actors first. The following data is required for all the actors involved:

- Electricity demand (hourly values, in kWh)
- PV generation data (hourly values, in kWh)
- Battery parameter: maximum capacity (in kWh), maximum (dis)charging power (in kW)

- Willingness-to-pay for the community's PV generation (in EUR/kWh)

Further we need:

- Prices: average retail electricity price and wholesale electricity market price (EUR/kWh)
- Marginal emissions (kg CO2/kWh)

2.6 Detailed methodology of the case study (modus operandi)

1-Defining the communities:

The first step of this case study will be the definition of the different system boundaries of local energy communities, starting from a single prosumer. The different concepts include shared local energy management (matching renewable electricity self-generation and consumption, supported by battery storage) within a:

- multi-apartment building,
- a local neighbourhood/district,
- a small village.

The technology portfolio includes:

- PV (rooftop, building integrated, small-scale ground mounted)
- supported by small battery storage

2-Defining actors and settlement patterns:

Set-ups in terms of actor portfolios, e.g.

- tenant/owner structure multi-apartment building,
- building/population/small businesses structure in a village

Considering also diversity of settlement patterns in

- dense cities,
- sub-urban and
- rural areas.

In addition, the individual objectives of the actors to join the community are determined (e.g. maximizing local self-generation, minimizing electricity purchase costs, avoiding emissions and/or externalities).

3-Determining the energy community potential for Austria:

In terms of geographic coverage, a thorough quantitative assessment of the short- and long-term local energy community potential is planned for Austria (considering several important structural indicators necessary to describe the communities in a tailor-made metrics).

4-Determining the energy community potential for 4 reference countries in Europe

On higher aggregation level (in terms of empirical indicators necessary to describe the communities) additional 4 European 'reference countries' (representing e.g. the Iberian Peninsula, South-Eastern Europe, UK, Scandinavia) are also quantitatively analysed.

5-Upscaling on European level

Finally, a quantitative upscaling of the short- and long-term local energy community potential is conducted for Europe as a whole, again using a metrics with a variety of country-specific structural and energy sector-related data as well as assessments in terms of different barriers, different in nature (technical, economical, regulatory, etc.). Matching this metrics with the countries where detailed quantitative results have been computed, accompanied by plausibility considerations, enable upscaling on European level.

3. Case Study 3 - Need for flexibility: Storage

Leader: Comillas, Contribution: SINTEF, TU Wien, EDF, Khas

3.1 Overall Objective and Case study baseline

Electricity storage is one of the key supporting technologies of the energy transition, as it provides flexibility and thus is needed to facilitate the integration of renewables. Several technologies could be deployed in this context. Pumped-storage hydro is a mature technology with low investment costs for relatively large sizes, but long and difficult (in some cases, impossible) installation of new capacity. However, although there are already significant hydro storage and pumped-hydro storage capacities installed in different regions across Europe, there is still potential to further invest and increase these capacities. In many cases, building new storage is not possible, but there is potential for upgrades (e.g. adding a pumping mode to HS plants). Some of these projects are already in the PCI list (Projects of Common Interest). The maximum stored energy in the present reservoirs in some European countries can be summarized as follows (all Numbers in TWh): Norway (85), Sweden (34), Spain (18.4), Switzerland (8.4), Austria (3.2) and France (9.8) [Lehner B, Czisch G, Vassolo S, Europe's hydropower potential today and in the future. Eurowasser, 2013]. Norway has hardly any pumping capacity in its present system. However, a recent study has shown that it is possible within present regulations (water-flows and levels in reservoirs) to install about 20 GW in the South-Western part of the country. The pumped-storage hydropower can contribute to balance variable wind and solar power production in UK and Germany/Benelux if the transmission capacities are increased.

At the other side of the spectrum, batteries could offer an alternative to complement hydro with smaller (often at the scale of a single consumer), decentralized storage, albeit at a higher current cost. In addition, the differing sizes of these technologies mean that they can be used at different time horizons and levels in the system: while pumping stations with large sizes in terms of energy content (capacities) could be used to shift loads over the weekend periods or even seasons, the smaller batteries could only be used for several hours. In addition, smaller batteries would not be completely controllable by the system operator and would rather respond to the needs and behavior of consumers.

As seen, both technologies represent different avenues for the use of storage. On the one hand, batteries have traditionally been associated to smoothing short-term fluctuations in demand or renewable generation. Their size is directly related to the scope of this smoothing: smaller batteries support a single consumer, while larger ones can minimize the local power excess or deficits of a community over longer time periods. Therefore, battery storage supports the relative independence of prosumers and is linked to the development of decentralized structures in energy markets. Large-scale pumped-hydro, on the other hand, can be used to balance renewables at the European level. These two alternative uses of storage and schemes of centralization/decentralization will lead to diverging needs for market integration, which will be reflected in transmission network needs.

Hence, the main objective of this case study is the analysis of the widespread deployment of pumped-hydro storage and batteries in terms of system operation costs and transmission network development. Several options for the upscaling of pumped-hydro storage will be considered in combination with the wide-scale adoption of small-scale batteries. For the latter, several operation strategies will be considered:

1) profit maximization by single consumers, communities, or companies

2) minimization of local excess-deficit by prosumers

3) dumb or smart EV charging

The analyses will contemplate different time scales (seasonal, weekly, daily), associated with different storage capacities.

The case study will focus on two regions where the possibilities of these technologies are particularly interesting: the Iberian Peninsula and the Nordic countries. However, the analyses will consider the impact of these developments at a European level. This means that, in order to keep the calculations manageable, the focus regions will be studied in detail, while the rest of Europe will be represented at an aggregate level.

3.2 Challenges (beyond the state of the art)

A myriad study has focused on the potential of battery storage for improving the flexibility of the system and for increasing renewable penetration. However, the tradeoffs between different technologies are only beginning to be explored. Furthermore, most studies focus on a relatively small region, so that large-scale benefits remain undetected. In this case study, we would like to incorporate all the key elements of the problem so that their combined effects can be assessed as accurately as possible:

- **Hydro storage vs. batteries**: both technologies bring the flexibility of storage to the system albeit with opposing profiles in terms of market integration needs.

- **The local vs. the regional:** we model the strategies at the prosumer level and calculate impacts at the European level. In order to be able to calculate them, we model our focus regions in a detailed manner and keep an aggregate description of the remaining of the EU.
- **The short vs. the long term:** our analyses include several time horizons that span from hours to a year, so that the profiles of different technologies can be taken into account.
- **A detailed model for transmission**: the impact on transmission network needs will be assessed by means of a detailed model that considers the physics of power flows.
- **Consideration of different strategies for battery use:** the impact of battery storage will be greatly affected by the strategy that is followed in its use, for instance, whether it corresponds to a profit maximization rule or to minimize excess or defect for prosumers or small communities.

Including all these elements will enable us to provide a comprehensive perspective on the effects of the large-scale deployment of storage at the European level.

3.3 Expected results and limitations

Each of the storage-deployment scenarios will represent a combination of hydro-storage, batteries, and their operation strategy. For each of these, we will calculate the optimal operation of the power system, at aggregate and local level, and its associated cost. In addition, we will compute the corresponding optimal development of the transmission network and its cost. The interactions between the scenario-defining elements will be explored. These results will illustrate the potential advantages of these storage technologies and highlight possible synergies.

The main limitations of the study will be linked to the simplifications carried out in the generation of scenarios and system planning and operation.

3.4 Modelling approach & Models requirements

The case study will pivot between several models that, together, will be able to provide the necessary details of system planning and operation. FANSI will undertake the general definition of the hydrothermal systems studied, while HERO and OSCARS will deal with the deployment and optimal use of batteries under several different strategies and TEPES will incorporate the impact of the transmission grid, which can enable the long-range use of resources across the European Union.

- **FANSI**: Computation of the **long-to-medium term operation of hydrothermal power Systems**
    - Optimal dispatch considering stochastic weather-related variables: wind and solar gross output and inflows to hydropower reservoirs
    - Manages separately individual water reservoirs computing individual water values
    - Considers aggregate power flow constraints (at corridor level)
- **HERO**: **Optimal capacity allocation and dispatch** (for distributed generation and energy storage) to meet the energy needs of **local communities**

    - Considers sector coupling (electricity, heating/cooling, and gas) at the distribution level
- **OSCARS**: Optimal **utilization of small batteries and flexible loads** at prosumer level **under various operation strategies**
- **TEPES**: Computation of the **optimal expansion of large electricity transmission grids**
    - Network model with detailed granularity
    - Full representation of Kirchoff laws and network losses
    - Both long and short-term uncertainty can be represented
    - Suitable for the analysis of the impact of the implementation of specific energy policies on the development of the transmission network.

3.5 Data requirements

The main data requirements for this case study are complete scenarios for:

- **Generation,** with capacities per technology per region and costs in the case of thermal generation. In the case of hydro, the definition of reservoir structure, capacities and inflow scenarios will be needed, as well as their operation constraints. Gross power production scenarios for intermittent generation will also be needed. The expansion of generation will be calculated within the scope of the project by models such as GenesysMOD, SCOPE or EMPIRE.
- **Demand,** which includes the data that are needed to model prosumer strategies in OSCARS and HERO.
- **Transmission,** which should include the starting network in a detailed manner for the focus regions and aggregated for the rest of the European Union.
- **Storage,** data on all the storage units, or the equivalent aggregate ones to be represented in the analyses, need to be provided as well, including their injection/withdrawal capacity in terms of power and energy, and their efficiency.

3.6 Detailed methodology of the case study (modus operandi)

The case study will be structured as a comparative analysis, across two different dimensions:

• Level of deployment of storage, which will consider several situations for the upscaling of hydro pumping and batteries. This will assess the flexibility they can provide for the system comparing their performance and evaluating their synergies.

• Operating strategy associated to the agent in charge of the operation of the batteries. This will include an analysis of the types of agents involved and their multiple utilization objectives: single consumers, communities (e.g. municipalities), or small companies operating storage for maximum profit and other entities that can take into account physical prosumer energy management (e.g. mitigation of local generation excess/deficit) or electric vehicle charging management. The different operating strategies will be translated into output curves (e.g. charging/discharging patterns and changing load profiles over time) that describe the use of storage.

The effectiveness of storage deployment and utilization will, in this case study, be measured as reduced needs for transmission network expansion and reduced overall system costs. Pumped hydro and batteries provide the same functionality at different levels in the system and we will observe the impact on transmission network expansion.

For each considered deployment possibility, the model FANSI will calculate the optimal medium-to-short-term operation of the system, which implies solving the hydrothermal coordination problem at the European level considering a detailed model for focus regions (that is, the Iberian Peninsula and Norway) and an aggregate perspective for the remaining countries. Then, the models OSCARS/HERO will be employed to compute the optimal operation of battery storage based on the electricity prices generated by FANSI. The operation of these battery storage devices will be represented through output curves. Then, the model TEPES will take the operation of both pumped hydro and battery storage to determine the optimal expansion of the transmission network needed to provide additional flexibility in the form of an increase in the level of integration across markets. Subsequently, the new transmission network will be fed back to FANSI, which will adapt the operation of hydro storage and the system to take into account the new transmission lines. FANSI will produce new electricity prices to be considered by OSCARS/HERO to compute new battery operation output curves, to be considered by TEPES together with the new operation of pumped hydro. The process will iterate among FANSI, OSCARS/HERO, and TEPES to ensure the stability of results indicated as convergence (see Figure 1: FANSI-TEPES-OSCARS/HERO)

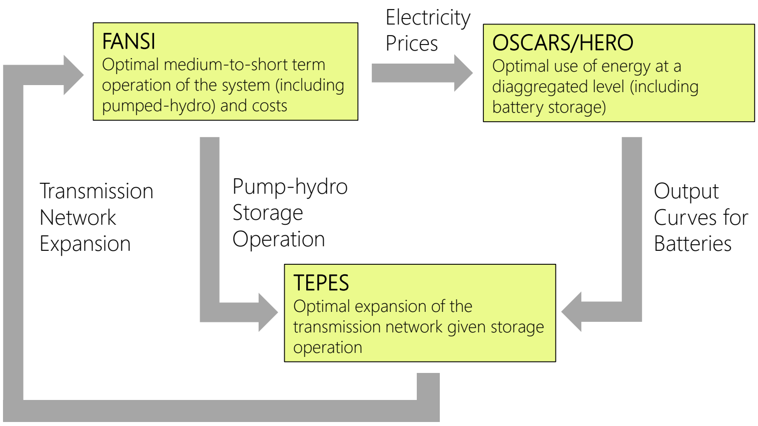

Figure 1: FANSI-TEPES-OSCARS/HERO

4. Case Study 4 – Need for cross-sectoral flexibility

Leader: IEE; Contribution: EDF

4.1 Overall Objective and Case study baseline

In this case study, simulation over the whole pan-European energy system will be run with the models SCOPE SD and Plan4EU. SCOPE SD model simulations will include a high sectoral and temporal resolution and a medium spatial (country level) while Plan4EU will focus on the electricity sector only but with a high temporal and spatial resolution (regions), including also a modelling of aggregated distribution constraints. SCOPE SD and Plan4EU will be linked together as to run Plan4EU simulations with inputs out of SCOPE SD.

General assumptions:

- Low-carbon energy systems in Europe need to be based on cross-sectoral integration to meet climate protection goals
- Cost-efficient coupling of the power with heat and transport sectors implies additional demands for renewable electricity but integrating technologies at the interfaces between those sectors may also provide a valuable source of flexibility
- Multiple studies have been carried out on a one-node-per-country level – but how does the integration of cross-sectoral technologies play out in the local but interconnected domain?
- Objective is to simulate the expansion and operation of the pan-European power system with a particular focus on transport sector technologies (i.e. (hybrid) electric vehicles, hybrid electric overhead-line highway trucks), while integrating all relevant flexibility assets, network costs and constraints on a local and decentralized level
- Flexibility considerations also focus on the consumer behaviour perspective, by investigating a different willingness to provide flexibility for electric vehicle owners
- Baseline is still to be defined but it should feature some cross-sectoral integration technologies including available (decentralised) flexibility

4.2 Challenges (beyond the state of the art)

By analysing the impact of a high electric vehicle penetration on the low-carbon electrical systems in Europe, the case study addresses an important challenge of increasing sectoral integration that can be characterised as follows:

- Comprehensive analysis of the impact on the electrical system of a high penetration of electric vehicles (allowing or not flexible charging) under the consideration of local/regional feasibility and dynamical constraints

- Explicit representation of vital cross-sectoral links and flexibility potential for low-carbon energy pathways, particularly hybrid technology configurations for industry, heat, and transport sector demand applications.
- Extending the one-node-per-country focus to better spatial granularity required to evaluate how flexibility plays out in the more detailed regional domain.
- Accounting for willingness to provide flexibility with a sufficient number of transport sector option instances to capture full technology range (niche applications).
- Concurrent analysis of hourly time-series data for multiple signals from the power sector (e.g. wind, solar PV, electricity demand, hydro inflow), building and industry heat sector (e.g. heat demand, heat pump COP profiles), as well as the transport sector (e.g. transport demands, potential charging power, battery SOC limits).
- Providing regional data for German and French market areas by defining consistent market areas for power grid and other sector coupling technologies.
- Providing regional data for German and French market areas, by defining consistent market areas for power grid and other sector coupling technologies.

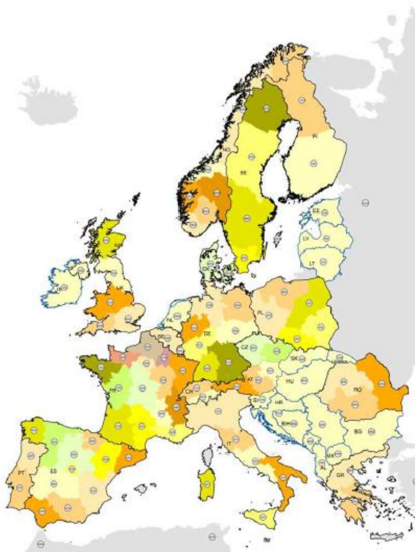

Figure 2: Potential spatial resolution for Germany and France

4.3 Expected results and limitations

Expected results cover the flexibility and integration potential of transport sector technologies in the country domain and the more constrained regional domain. Based on a predefined storyline, the following scenario configuration is to be investigated:

- European scenario with high share of flexible charging behaviour across Europe / Germany / France
- European scenario with low share of flexible charging behaviour across Europe / Germany / France

General results

- Comparison of flexibility and integration potential of transport sector technologies at the country level
- Can transport sector technology integration potential in the country domain be realised in the more constrained regional domain of Europe?
- Cross-validation of the scenario results of the WP3, especially those with high levels of decarbonisation and cross-sectoral integration

Specific results for the SCOPE SD modelling framework

- Possible EV flexibility variants, including with different willingness to provide flexible charging (non-flexible, flexible, V2G)
- Investment and system operation decisions in all relevant energy sectors
- Other flexibility decisions and backup utilisation
- Price impacts (wholesale electricity, potentially carbon price)
- Core region impacts and repercussions in Germany and France
- Optimal electricity generation capacity mix
- Optimal heat generation capacity mix
- Optimal transport sector capacity mix
- Electricity demand (MWh for 2050 per country)
- Flexibility potentials for electric road transport technologies

Specific results for the Plan4EU modelling framework

- Indicators: Plan4EU will provide several indicators allowing to evaluate the value of flexible charging for the electrical system in terms of operation costs; renewable curtailment level; pollutant/CO_2 emissions; network congestions; dual variables (that can be interpreted as prices) related to demand constraints or capacity limits of power lines.
- Strategic decisions under uncertainties: one interesting aspect of Plan4EU is the ability to take into account mid-term uncertainties (e.g. variable renewable production, inflows, demand) when designing strategic decisions related large scale storage (e.g. water reservoirs). This seems to be a crucial point since solar and wind production may significantly vary from one year to another which requires to carefully manage large scale storage w.r.t. that uncertainty.
- Impact of mid-term uncertainties: beyond the strategic decision issue, it is also interesting to investigate the variability of the computed indicators by simulating the operation decisions on several scenario of uncertainties.
- Reference run with non-/low-flexible EV.
- Impact of optimising EV-flexibility.

- Details of sensitivities need to be further defined.

Limitations

- Modelling the power system on a single year operation (e.g. 2050 horizon).
- Uncertainty consideration (SCOPE SD model), particularly long-term uncertainty.
- SCOPE SD does not feature intrazonal grid congestions as it is only a market-based CEP model
- Modelling of hydro generation is aggregated (equivalent hydropower valleys in SCOPE SD; one lake by country/region, no hydro valleys in Plan4EU).
- Modelling of transmission network is simplified (clustering).
- Modelling of distribution network is limited to the reinforcement's costs and global constraints at each node of the transmission network (maximum amount of power injected into the distribution network at each hour).
- Aggregation of heterogeneous vehicles storage into a single representative storage per node (Plan4EU).
- Short-term uncertainties are not taken into account (everything in supposed to be known within a day): arrival and departure of electric vehicles to the parking station are not taken into account, variable renewable generation are not taken.
- Network model: the primary implementation of the case study entails a simplified modelling of the network. Even if several nodes per country will be considered, the model will only consider nodes of the transmission network. Besides, the power flow will be approximated by a Net Transfer Capacity (NTC) model intended to represent commercial trades only, taking into account the capacity limits of the power lines, without any physical representation of the electrical power flows.

4.4 Modelling approach & Models requirements

By linking the SCOPE SD (Fraunhofer IEE) and plan4EU (EDF) modelling frameworks, the case study combines a proprietary with an open-source modelling framework via the openENTRANCE platform.

SCOPE SD modelling framework

The SCOPE SD model is used to develop a long-term low-carbon energy system scenario [PH1] for Europe. By minimizing the generation, storage, and cross-sectoral consumer technology investment and system operation cost, this large-scale linear programming approach features representations for the traditional power system as well as all relevant bi- and multivalent technology combinations at the sectoral interfaces with the heat, industry, and transport sectors.

Model type and problem

SCOPE SD is used for cost-optimised target scenarios of future energy systems with energy and emission targets while capturing a wide range of technology combinations. The modelling framework can be characterised as follows:

- Static deterministic partial equilibrium techno-economic bottom-up [HP2] mathematical optimization model
- Cross-sectoral Capacity Expansion Planning (CEP)
- With/ without expansion decisions (pure system operation model/ or only sector-specific expansion)

Spatial scope and granularity

- EU27+NOR/CHE;
- One node per country

Temporal scope and granularity

- Full-year, i.e. historical (or potentially future) meteorological year
- Hourly resolution
- “Static planning”, i.e. only single scenario years and no pathway (“dynamic planning”)

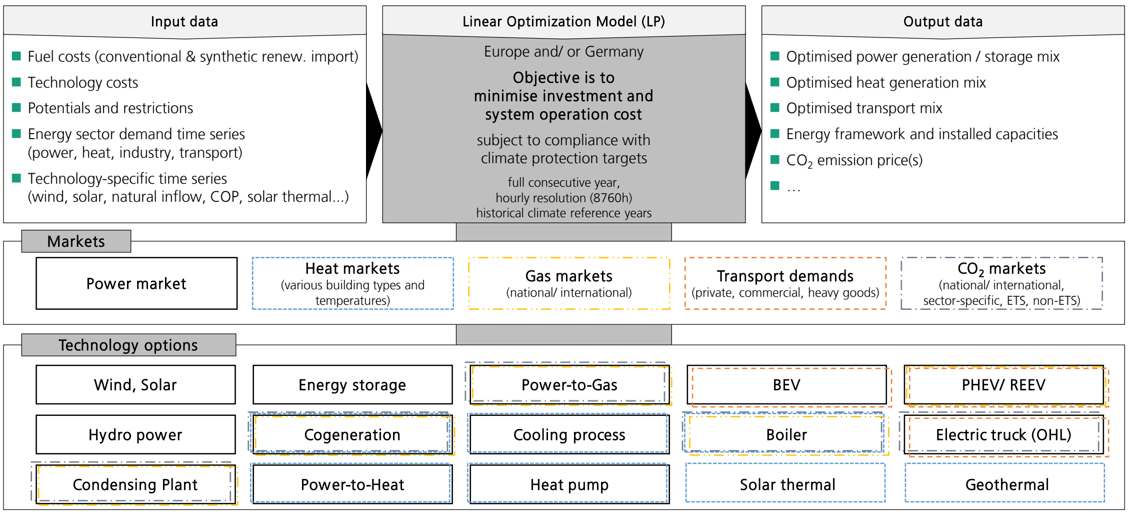

Figure 3: Schematic overview of the SCOPE SD modelling framework developed at Fraunhofer IEE.

Plan4EU modelling framework

CS4 will make use of the scenario valuation layer of Plan4EU. The Scenario valuation layer evaluates the investment decisions from the capacity expansion model by means of modelling the operation of the existing assets in the energy system. This layer contains two distinct models, the first model is referred to as the seasonal storage valuation (SSV) model and the second model is referred to as the European unit commitment (EUC) model.

- ***Seasonal storage valuation model (SSV)***

The objective of the seasonal storage valuation model is to provide an accurate account of "the value" that seasonal storage can bring to the system. Indeed, such seasonal storage (e.g., cascaded reservoir systems) can be used to store energy over large spans of time and use this "stored" energy when most needed. The actual use may in particular depend on adverse climatic situations (intense cold), but the ability to store the energy may in turn also depends on climatic conditions (e.g. draught). It is therefore clear that such a vision of value should be transferred in an appropriate way to shorter time span tools, such as the EUC model. In turn computing an accurate value intrinsically depends on the value of substitution, and thus ultimately on the EUC tool as well.

- ***European Unit Commitment (EUC)***

The EUC model computes an optimal (or near optimal) schedule for all the system assets on a typical period of one year, with a typical granularity of one hour in order to satisfy demand and ancillary services at the lowest cost. It ensures that the given system is « feasible » in the sense that at each hour of the year, including peak hours, it is able to fulfill the following constraints

  - power demand supply;
  - ancillary services supply;
  - minimal inertia in the system;
  - maximum transmission and distribution capacities between clusters;
  - technical constraints of all assets.

4.5 Data requirements

The main data requirements for this case study are complete scenarios for:

- Transmission grid (capacities between nodes)
- Boundaries: electric power exchanges with not-accounted for neighbouring countries
- Generation profiles for wind, PV, hydro correlated to meteorological time series
- Other generation profiles (biomass for example)
- Electricity Demand profiles correlated to temperature time series (including electric vehicle profile)
- Power technologies with their financial and technical parameters
- Storage technologies
- Fuel prices and CO_2 emission price (or budget)
- Hydro technologies with their technical parameters (lakes, run of river, pumped storage)
- Demand response technologies and potentials

Data requirements specific to the Plan4EU model

- At each node of the network, a reference load profile corresponding to the standard aggregate consumption of electric vehicles connected to that node with a time step of one hour for some typical days (e.g. working day or week-end in spring/summer/winter).

- Flexibility is specified by an upper and lower deviation allowed around the reference load profile that should also be specified with a time step of one hour for some typical days (e.g. working day or week-end in spring/summer/winter).

4.6 Detailed methodology of the case study (modus operandi)

First, pan-European reference scenarios will be implemented from WP3 in both model environments to determine further assumptions necessary for the detailed case study. Simulations will then be performed with SCOPE SD, including sensitivities regarding the share of flexible charging in all or selected European countries (i.e. uncontrolled versus system-friendly charging behaviour). Then, the flexibility information from SCOPE SD will be integrated into the plan4EU modelling framework to run more detailed simulations regarding the electricity sector.

The primary approach is to run the SCOPE SD model in a first step focussing on the national level, and use these aggregate results as input for the Plan4EU model. In a second step, the Plan4EU model processes and disaggregates the country-specific input data to then perform the electricity market simulations in the more detailed regional domain.

A potential extension of this modelling chain is to already include a more detailed regional focus of Germany and France in the SCOPE SD model (based on the initial Plan4EU results). By increasing the spatial resolution in terms of multiple bidding zones per country, some limitations regarding internal transmission grid effects could be alleviated. A more detailed spatial resolution allows for a more accurate aggregation (i.e. not to the national but only regional level) of the transport sector flexibility parameters. The Plan4EU model can use the new results from the SCOPE SD model with better assumptions on local potentials for flexibility in a second run. As a consequence, the two versions of running the models can be compared to provide insights into the impact of decentralised flexibility of electric vehicles on the grid and expansion planning.

Further aspects to investigate in optional analyses include a refined modelling approach of the power flow in the Plan4EU model, i.e. using a DC power flow approximation instead of a transport model (NTC). Another aspect focuses on the capacity limits between distribution and transmission network, which is particularly relevant since large shares of renewable power generation as well as electric vehicle charging is connected to the distribution grid level.

The following figure presents a schematic overview of the case study methodology and linkage of modelling frameworks.

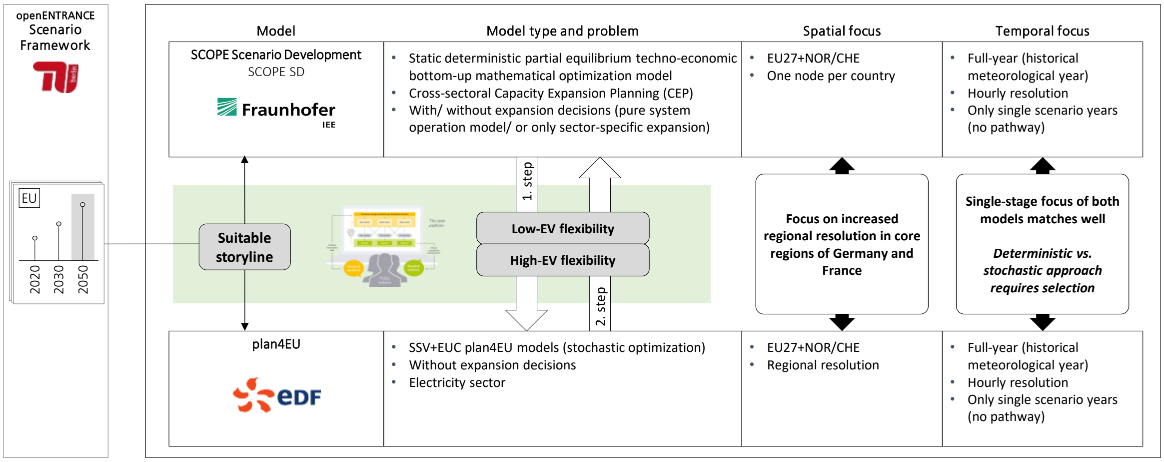

Figure 4: Schematic overview of the case study methodology and model linkage

5. Case Study 5 - Decentralization

Leader: EDF

5.1 Overall Objective and Case study baseline

EU global objectives related to global warming, renewable energy, and cuts in GHG are to be instantiated by states, which themselves may transfer their own objectives to lower decision levels (eg. regions may have their own objectives or targets in terms emissions limits)….

The objective of this case study is to assess the (modelled) impact of decentralization. Decentralization can be interpreted as:

- Decentralization of targets: eg. Member state targets for GHG emissions or RES share in the generation mix vs. European global targets
- Decentralization of decisions: local optimization vs global optimization

In this case study we will compare the three following variants:

1. Global decision and global target: in terms of mathematical optimization, the problem is formalized with a single cost function representing investment and operational costs and constraints related to technical constraints as well as ecological targets in terms of emissions or renewable penetration (proportion of renewable sources in the electricity mix);
2. Global decision and local target: this setting corresponds to an optimization problem with the same cost function and technical constraints as above, except that ecological targets are locally imposed to each region instead of globally to the whole system;
3. Local decision and local target: this framework differs from the previous ones because it involves several optimization problems since each region aims at minimizing her own costs under technical constraints while guarantying her own ecological targets. However, we have to make assumptions on potential exchanges between regions or between regions and a central operator.

Each variant performs the role of fictional central planners with all information and making investment decisions at the global level (variant 1 and 2), or at local levels (Variant 3) in order to minimize total (global or local) system costs.

This case study should then illustrate that different decision levels (region, country, Europe) with specific objectives may lead to different investment decisions.

Scope of technologies:

- Nuclear Power Plants
- Combine Cycle Gas Turbine with and without CCS (carbon capture and storage)
- Open Cycle Gas Turbine
- Hard coal steam power plant with and without CCS

- Lignite steam power plant with and without CCS
- Biomass and waste incineration (steam power plant)
- Hydro generation (storage reservoir, pumped storage and run-of-river)
- Solar PV
- Wind Onshore and Offshore
- Electric transmission and distribution grid
- Storages: including batteries and e-mobility

5.2 Challenges (beyond the state of the art)

Most of the existing capacity expansion models rely on deterministic linear programming approach. The variables that typically would be uncertain (electricity demand, inflows, variable renewable production profiles, etc.) are taken as given, and the model optimizes with perfect foresight over some representative days or along successive time steps. Similarly, to avoid complexity, network power flows and power plants technical constraints are also usually excluded (ramping constraints, minimum uptime and minimum downtime constraints).

However, the cost of renewable sources integration into the electrical system is mainly due to the fact that it naturally increases the flexibility needs of the system in order to guarantee feasibility. Indeed, new flexibilities are required to be able to achieve the balance between supply and demand at each time step, in spite of the deterministic and stochastic variability of variable renewable generation.

It is then crucial to fully integrate this increase of flexibility needs in investment decisions. To this end, one must rely on a capacity expansion tool with both

- a refined description of technical constraints related to the flexibility levers (such as power plants, batteries, demand side management or network);
- a stochastic framework allowing to model uncertainties inherent to variable renewable generation.

This setting is strongly challenging, in various aspects

- data and model aspects: providing a detailed and comprehensive description of the system requires to gather a large amount of data (eHighWay, ???) and to be judiciously agregated according to relevant models;
- algorithmic and computational aspects: the size of the related optimization problem is huge and requires cutting-edge tools to be able to obtain results in reasonable times.

The present case study will rely on the openEntrance Scenarios (from WP3) and on the plan4res public dataset to propose an attempt in that challenging direction.

5.3 Expected results and limitations

The expected results are a quantification of the impacts of decentralization, in particular on the prices and the technical operation of the electric system, and some recommendation as for the coordination/alternative structures to set up in order to minimize de-optimizations of the system.

Limitations of scope:

- Modelling of electricity only
- Modelling the power system on a single year operation (2050 horizon), without providing any pathway to reach the final electricity mix
- Modelling of hydro generation is aggregated (one lake by country/region, no hydro valleys)
- Modelling of transmission network is simplified (clustering)
- Modelling of distribution network is limited to the reinforcement's costs and global constraints at each node of the transmission network (maximum amount of power injected into the distribution network at each hour)
- Synthetic inertia is not modelled

5.4 Modelling approach & Models requirements

The model implemented in Plan4EU simultaneously optimizes investment decisions and hourly dispatch over the course of one year (2050) relying on the two following modelling layers.

- ***Capacity expansion model:***

The capacity expansion model will compute a better or ideally optimal set of assets including electric generation plants, storages, interconnection capacities between clusters and distribution grid capacities, for the considered time horizon (the year 2050). Here optimal means, providing the least-cost set of assets, while accounting at best for the modelled constraints.

- ***Scenario valuation layer:***

The Scenario valuation layer will evaluate the investment decisions from the capacity expansion model by means of modelling the operation of the existing assets in the energy system. This layer contains two distinct models, the first model will be referred to as the seasonal storage valuation model and the second model will be the European unit commitment (EUC) model.

The objective of the seasonal storage valuation model is to provide an accurate account of "the value" that seasonal storage can bring to the system. Indeed, such seasonal storage (e.g., cascaded reservoir systems) can be used to store energy over large spans of time and use this "stored" energy when most needed. The actual use may in particular depend on adverse climatic situations (intense cold), but the ability to store the energy may in turn also depends on climatic conditions (e.g. draught). It is therefore clear that such a vision of value should be transferred in an appropriate way to shorter time span tools, such as the EUC model. In turn computing an accurate value intrinsically depends on the value of substitution, and thus ultimately on the EUC tool as well.

The EUC model will compute an optimal (or near optimal) schedule for all the system assets satisfying the set of constraints:

  - power demand supply;
  - ancillary services supply;
  - minimal inertia in the system;
  - maximum transmission and distribution capacities between clusters;
  - technical constraints of all assets.

5.5 Data requirements

- Transmission grid (capacities between nodes)
- Boundaries: electric power exchanges with not-accounted for neighbouring countries:
- Generation profiles for wind, PV, hydro correlated to meteorological time series
- Other generation profiles (biomass for example)
- Electricity Demand profiles correlated to temperature time series (including electric vehicle profile)
- Power technologies with their financial and technical parameters
- Storage technologies
- Fuel prices and CO_2 emission price
- Hydro technologies with their technical parameters (lakes, run of river, pumped storage)
- Ancillary services demand
- Demand response technologies and potentials
- Installed capacity in reference
- Assumptions on the shares of uses (cooling, heating, EVs, other) in electricity demand and the demand volume (MWh) in 2050

5.6 Detailed methodology of the case study (modus operandi)

This Case study will focus on the Pan-European electricity sector in the single year, e.g. 2050 and include the countries which are TO BE DECIDED.

In order to obtain the total system costs we have to determine the fixed and variable costs. As we simulate only one single year, we will compute annual costs:

- annual fixed costs are the annualized investment costs and the annual fixed operational costs;
- variable costs are the annual power plant operational costs (fuel & CO_2 emission price).

Then the operational costs (related to the optimal dispatch) will be computed by the scenario valuation layer of Plan4EU while the investment decision will be provided by the capacity expansion layer.

The geographical perimeter is to be decided (and will depend of the computation feasibility and data availability) eg. Europe vs Countries / France vs French regions / Germany vs German landers…

3 variants will be run (from the European/member states example):

1. Global European Renewable capacity target (% of the electricity mix), global optimization of the European electricity mix (=as if all decisions were centralized at European level)
   ⇨ 1 Full plan4EU run with a global constraint on RES target
2. "Local" Member-state Renewable capacity targets (% of each country electricity mix), global optimization of the European electricity mix (=as if all decisions were centralized at European level)
   ⇨ 1 Full plan4EU run with constraints on RES target at the level of each country
3. "Local" Member-state Renewable capacity targets (% of each country electricity mix), each country optimizes its electricity mix (with import/export assumptions)
   ⇨ N (number of countries) runs of Full plan4EU at country-scale
   ⇨ 1 run of plan4EU SSV+EUC to evaluate the costs

The following steps will be performed first :

a/ chose the geographical scope: which global region, which local regions. A first run of this case study will be done on France and its regions. Potential extension to Europe and its member state may be performed later.

b/ define the set of possible investments at global or local level (in which technology may each level invest? This will deeply depend on the chosen level as countries may have different opportunities than local sub-country regions)

c/ investigate the question: which level is deciding of grid extensions? (this will of course also depend of the geographical scope chosen).

d/ chose the starting point. It could be a reference mix for 2050 in the chosen region.

6. Case Study 6 – Innovative Technologies

Leader: SINTEF

6.1 Overall Objective and Case study baseline

The main objective of this case study is to investigate and develop a better understanding of the potential of innovative technology, specifically the use seasonal storage of heat, in a local micro energy system. This case study aims to quantify how seasonal heat storage can reduce the surplus heat in the district heating system as well as from solar heating during summer. Furthermore, it seeks to quantify the potential of thermal seasonal storage to cover peak loads in heat demand during winter and thereby reduce the need for investment in heating infrastructure, both for the current and the future system. The case study will also include a cost/benefit analysis for the application of the novel storage technology as well as offer insight on how this technology can be relevant on a European level. This will be done through a qualitative discussion of the relevance of the results on the European level. The case study will also identify drivers as well as barriers for investment into this novel heat storage technology.

In particular, the case study will focus on the district Furuset in Oslo and evaluate the innovative technology of seasonal storage in underground rocks in this particular setting. The interactions between the district heating system of the city of Oslo and the local heating grid will be investigated with hindsight to the impacts especially on the energy system at Furuset.

In the light of Europe's ambition to decarbonize its energy system, ever more intermittent energy sources will penetrate the energy market. It is likely that in many parts of Europe there will be an excess of energy supply during periods in the summer months from both solar and wind power. Short term storage challenges might well be solved by the deployment of batteries on a large scale but for seasonal storage other technologies will be needed. With pumped storage being very limited to specific geographical conditions and hydrogen production and storage facing efficiency issues, there is a clear need to assess other options. The results of this case study will give qualitative insights into what role local, seasonal heat storage can play on a pan-European scale in the transition to a decarbonized energy system.

It will furthermore inform the Norwegian national research centre on zero emission neighbourhoods in smart cities (ZEN), as well as the government in Oslo on the potential and benefits of seasonal thermal storage in connection with local energy system solutions across the country.

The model that will be used for the analysis is the energy investment model eTransport (Bakken et al. 2007, Kohlstadt et al. 2018). A representation of the micro energy system of Furuset, created in the ZEN centre will be adapted to incorporate a module to represent the planned seasonal thermal energy storage unit (Kauko 2019). This adapted version will serve as the baseline scenario and will be compared to a micro energy system without such a storage unit.

6.2 Challenges (beyond the state of the art)

The central challenges of CS6 are:

i. The ambitious plan to upgrade Furuset to a climate-neutral neighbourhood, with its own micro energy system, is a challenge in itself. To mirror this highly cite specific micro energy system combined with the planned installation of a novel energy storage technology using an existing energy systems model is a major challenge.
ii. A central challenge is the need to balance the level of detail in the energy systems description of the different energy carriers with the need for rather high time resolution in order to capture the effects of intermittent renewable energy integration as well as demand peaks.

The beyond state-of-the-art elements of CS6 are:

i. Including seasonal thermal storage into the energy system analysis
ii. Data from a real world test case on a zero emission neighbourhood with its own micro energy system that includes novel technology elements
iii. Discussion of the relevance of local results from a real world test case of novel storage technology on the pan-European level

6.3 Expected results and limitations

This case study is to yield quantitative results as well as qualitative insights on the impacts of a seasonal thermal storage unit on a local micro energy system.

Quantitative results include:

- The estimated, potential reduction of unused surplus heat produced in summer from - in this case study - a waste treatment plant, as well as from solar heating through the use of a thermal seasonal storage unit.
- The capacity of such a storage unit to supply peak demand of heat during winter.
- The reduction in infrastructure investment compared to a case without seasonal thermal storage.
- A cost/benefit analysis for this type of novel technology for thermal seasonal storage.

Qualitative insights include:

- A better understanding of the possibility and related impacts of the use of this type of thermal seasonal storage in suitable locations across Europe
- A better understanding of drivers and limitations/barriers of investments in thermal seasonal storage units

A limitation within the assessment in CS6 is that the total storage capacity is a user-defined input to the seasonal thermal storage module that will be used. This means that the size of the storage is predefined and hence cannot be optimized. This is a key limitation to the available module, since – in case of modelling a not yet existent case – a good understanding of the technology used is necessary to ensure sensible input arguments for charge/discharge amounts of heat as well as heat losses. This poses a limitation since it is not always given that the modeller is sufficiently familiar with the characteristics of all the technologies modelled.

A further limitation in CS6 is that only already existing modules will be used in the modelling of the micro energy system of Furuset and hence only already coded technologies and connections/interactions can be modelled.

6.4 Modelling approach & Models requirements

eTransport model:

A tool for energy system planning within a confined area (taking surroundings into account)

- Multiple energy carriers (electricity, heat, cooling, biomass, waste, hydrogen, natural gas and oil)
- Optimizes hourly operation and future investments (type, time)
- Minimizes total energy system costs
- Models a confined area but included interactions with outside energy system
- Models a full year through four representative days, one for each season
- Each representative day is modelled at an hourly resolution
- Considers energy needs as well as peak loads
- Different sub-modules for different technologies
- New technology can be incorporated to assess its impact on the existing energy system demands
- Experts from each technology develop the corresponding sub-modules
- Operational optimization in AMPL
- Investment optimization in C++
- Realistic representation of the system operation: dynamics, operational constraints, interconnections
- Possibility for end-to-end modelling, i.e. from generation to consumption, also parts
- Timeframe: long term planning horizon
- General technical constraints
    - Hourly resolution for optimization
    - Representative time slots to model a full year
- Specific constraints to each technology module
- Coupling constraints: Time coupling between seasons
- Uncertainty:

  - input data for the scenarios for 2050, inherent uncertainty on macroeconomic future trajectories
  - Representative time slices
- Inputs (the inputs are dependent on which particular modules will be used in the description of the case Furuset and will include the following)
  - Demand: power, heating, hot water, gas, cooling, hydrogen (in MWh/h)
  - Prices: power, gas, waste, oil, biomass (Euro/MWh)
  - Installed capacity: rooftop PV, heat supply, heat pumps, wind capacity, different storage types (battery, heat seasonal, heat daily, hydrogen) in MW and MWh
  - Investment costs: battery, PV, energy efficiency in buildings, heat pumps

Sub-model: module for seasonal thermal storage in rock

- The storage is supplied with heat through a supply point (heat exchanger to the district heating grid)
- The storage supplies heat to the local energy system
- The storage can either be charged or discharged
- 24-hour time horizon
- The total amount of heat supplied and extracted over one full year needs to be zero
- Inputs:
  - Amount of heat supplied/extracted/lost during the seasons
  - Storage characteristics: size, max charge/discharge rate, total daily flow, charge/discharge choice

6.5 Data requirements

Data used in the modelling of this case study include data on the actual energy flows in Furuset, data on energy supply that is provided from outside Furuset as well as data on the technologies used, e.g. novel storage technologies. Some of this data will be provided by the ZEN centre and will already be in the model presentation of Furuset, which will be adopted to include thermal seasonal storage, more data will be provided by the electricity companies supplying Furuset and the relevant district heating company.

Furthermore, data used for the scenarios developed in WP3 will be used as indata to model the energy system as well as the interconnection with outside infrastructure and supply in Furuset in 2050. The four scenarios were developed around the three key concepts of policy exertion, technology novelty and smart societies. Each scenario has a unique combination of these concepts as key drivers.

Price data for the relevant energy carriers for the Furuset case will be needed and included price data on power, gas, waste, oil and biomass. Furthermore, the model requires input of installed capacity of electricity supply units inside the system and for backup from outside the micro energy system analyzed. Additionally, data on the battery and hydrogen storages units in Furuset is needed. To assess savings on investments and maintenance of infrastructure, data on costs of PV installations, batteries, heat pumps will be used as well as data on prices for energy efficiency measures in buildings. The majority of this data will be provided by the ZEN centre, who will collect it from the Furuset project partners as well as the relevant electricity and heat suppliers. The data from the ZEN centre must be adjusted for analysis of 2050. If relevant data is available from the openENTRANCE scenarios, this data will be used.

The capacity and characteristics for the seasonal storage unit planned in Furuset have been dimensioned by SENS Sustainable Energy Solutions AB in a study in 2018. This study supplies the indata on capacity, max charge/discharge rate and expected losses.

6.6 Detailed methodology of the case study (modus operandi)

The eTransport model will be used to simulate the impact of a seasonal storage unit on the case of Furuset, Oslo. Within the ZEN centre a representation of the energy system of Furuset has been developed in eTransport. This will be used as the starting point and will be adjusted to include a seasonal thermal storage unit. This model description will function as the baseline throughout the case study. Analysis will be conducted on the ability of the pre-dimensioned thermal storage unit to supply peak demands of heat, especially during winter. This will be followed by a calculation of how much excess heat that without the thermal storage unit cannot be used, can be stored in the planned unit. As one of the important co-benefits of the installation of a seasonal thermal storage unit, less investment in expensive heating infrastructure to supply the new district with access to the district heating system is expected. We analyse the additional cost for the adjustment of existing infrastructure in the district heating system to supply Furuset with sufficient heating in absence of the thermal storage unit.

As a complementary element of the case study a cost/benefit analysis will be conducted of the thermal seasonal storage. This will include private economic costs to the company building the storage unit but also societal/communal costs regarding the installation phase. On the benefit side, environmental benefits as well as potential health and climate benefits also down the supply chain will be considered and elaborated on.

To better understand what affects investments beyond rational economic reasoning, the key actors in the Furuset case are interviewed. A qualitative assessment of the interviews is to yield better insight in the underlying drivers and barriers for investments which are until now not captured in the model.

Finally, we will conduct a qualitative discussion of the potential when taking this type of seasonal storage to a pan-European level. Since the seasonal storage in bed rock is dependent on the proximity of a high temperature heat supplier, the ground conditions and sufficient space, we will give an idea where in Europe this technology could be deployed. Given this insight, the results obtained from the Furuset case can be discussed on the European level to give a rough idea of the potential importance of this type of storage. Furthermore, we will provide an elaboration on challenges and advantages of this type of seasonal challenge in comparison to other seasonal storage types.

6.7 References

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7. Case Study 7 – Innovative Technologies

Leader: DTU; Contribution: EDF

7.1 Overall Objective and Case study baseline

The EU is committed to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050 [1]. To accomplish this goal the share of renewable energy sources (RES) have to increase significantly. In addition, the RES (wind, solar, etc.) prediction techniques are not capable enough to consider power production variations, and therefore huge unpredicted RES power production variations might happen in the power system in the near future. Challenges related to keeping a high security of supply have raised while the share of intermittent renewable electricity generation is increasing. These variations must be handled in an optimal way. Some sector coupling, conventional generation units and demand response must be used to compensate RES power production variations in the power system and in this way, maintain the balance between production and consumption. Recently, a number of work have focused on investigating different options to unlock available flexibility from not only generators but also distributed energy resources (DERs).

Having a huge share of wind power, Denmark is an international leader in the implementations of a renewable, efficient and secure energy system. The intermittent and not predictable characteristics of wind power leads to imbalances between power generation and consumption in the grid. To keep the power system management reliable and balanced flexible sources are needed on different time scales. The further increase in wind power integration will cause the extra need for flexibility to maintain the system secure and balanced in every instant in the time [2].

To support increasing share of wind power in the system, Denmark has undertaken efficient measures to enable a secured and balanced system. Through combined heat and power (CHP) plants, electric boilers and heat pumps (HP), the Danish power system has a close cooperation with the heating sector [3]. In the process of integrating wind power in the system, a potential flexibility can be offered by the consideration of CHP plants. Moreover, CHP units have an important role in the Danish distinct heating (DH) network [4]. In addition, the electricity taxes wereas profoundly reduced in 2013, bringing incentives to produce heat from electric boilers and HPs [5]. To conclude, unlocking flexibility from the heating sector creates a solid ground for Denmark to integrate even more wind in the system.

Therefore, the Danish case study aims at investigating whether the integration of the heat sector enables us to unchain enough flexibility to ensure smooth and secure operation of future Danish energy system. (National level)

7.2 Challenges (beyond the state of the art)

The central challenges of CS7are:

- Generating representative scenario of 2050 for Danish power system.
- Scaling up the local pilot results for the whole Denmark

7.3 Expected results and limitations

The main expected results are evolved from the investigation of the impacts of sector coupling in the Danish energy system considering a 2050 scenario. Particularly, to analyse whether the integration of the heating and the power sector enables us to unchain enough flexibility to meet the Danish government targets in 2050 an efficient and secure way.

Limitations of the scope:

- Obtaining Danish power system data (power system, generation mix, demand, power grid, etc.) representative for 2050 scenario.
- Obtaining price based control results from a local pilot and scaling up for the whole Denmark.
- The plan4EU model is going to be used for CS7 analysis, where :
  - Modelling of hydro generation is aggregated (one lake by country/region, no hydro valleys)
  - Modelling of transmission network is simplified (clustering)

7.4 Modelling approach & Models requirements

The investigation of CS7 will be carried out in two steps:

- simulating balancing market with hourly resolution and
- applying price-based control with five minutes resolution.

The plan4EU model (EDF, linked) will be used for the implementation of the 1st step. Description of plan4EU model is provided in section 6.4. The 2nd step will be carried out using the results from the pilot study at DTU (see the detailed pilot description in the methodology section 8.6). The local pilot results will be scaled-up for the whole Denmark and integrated with the openENTRANCE database. Finally, the impacts will be assessed by running the plan4EU model.

Plan4EU modelling framework

CS7 will make use of the The European Unit Commitment model of Plan4EU which computes an optimal (or near optimal) schedule for all the system assets on a typical period of one year, with a typical granularity of one hour in order to satisfy demand and ancillary services at the lowest cost. It ensures that the given system is « feasible » in the sense that at each hour of the year, including peak hours, it is able to fulfill the following constraints

- power demand supply;
- ancillary services supply;
- minimal inertia in the system;
- maximum transmission and distribution capacities between clusters;
- technical constraints of all assets.

7.5 Data requirements

Data requirement are related to Danish power system for the scenario of 2050.

- Transmission grid with physical characteristics
- Generation profiles for wind, PV, biomass and others (correlated to meteorological time series if it refers)
- Diurnal industrial load profiles
- Diurnal residential load profiles correlated to temperature time series (including electric vehicle profile)
- Storage technologies
- Demand response technologies and potentials (as well as the spread of summer houses with indoor swimming pool).

7.6 Detailed methodology of the case study (modus operandi)

As it is stated above, the implementation of this case study will be carried out in two steps 1) simulating balancing market with hourly resolution and 2) applying price-based control with five minutes resolution.

Simulating balancing market: hourly resolution

The electricity is different from other commodities since it requires stable frequency and voltage in the transmission system. In real-time, energy demand and supply might deviate from the amount scheduled in the day-ahead bases. Hence, flexible power sources, flexible consumption and a balancing market are needed to keep the balance between production and consumption. Central dispatch, therefore, is needed to operate real-time physical trading smoothly. Balancing markets are continuous, hourly markets. In Denmark balancing market closes 45 minutes before the delivery hour. By simulating balancing market with Danish target scenario for 2050, we aim to investigate and discover challenges and bottleneck in the Danish power system, which might rise having massive renewable energy sources integrated.

Applying price-based control: five minutes resolution

We indicated that in Denmark the balancing market closes 45 minutes before the delivery hour. Being intermittent and hard to forecast renewable energy sources, namely wind power; on real-time might deviate from the submitted bid amount creating extra need for flexible power. Price-based control aims at unlocking flexibility from Danish heat sector to compensate real-time variation with 5 minutes resolution. The idea of price-based control with 5 minutes resolution is tested in a pilot in SmartNet project, and more investigations will be carried out in CITIES project. The local pilot results will be scaled-up for the whole Denmark and integrated with the Open Entrance database. Finally, the impact of sector coupling will be assessed by running the plan4EU model.

Pilot description:

Summer houses with swimming pools consume relatively large amounts of electricity for heating water, humidity control and heating. The electricity demand from summer houses is particularly flexible. For example, swimming pools have a large thermal mass. Thus the load to heat pool water can be disconnected or shifted with little consequences on the comfort of the occupants. The Danish pilot case aims at assessing and demonstrating to what extent flexibility from summer houses can be exploited to provide ancillary services both at the distribution and transmission level. Novasol is a rental company that operates about 900 summer houses with an indoor pool in Denmark, with an average annual power consumption of about 30.000 kWh per house. Although the summer houses are not occupied permanently, they have a year-round base load, e.g., in order to guarantee that the pool water temperature does not fall below a certain threshold, should a customer wish to rent the house with short notice. The location of the houses, coupled with their thermal inertia, make their load a suitable candidate for the provision of grid services. At the same time, a large capacity for wind power production is installed in the area, making summer houses a suitable candidate for the provision of congestion management services. Exploiting a small but representative sample of the summer houses operated by Novasol, the Danish pilot will demonstrate their value in providing ancillary services.

7.7 References

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8. Case Study 8 – Gas storage for flexibility

Leader: KHAS; Contribution: DIW Berlin, TU Berlin

8.1 Overall Objective and Case study baseline

This case study will investigate the role of natural gas storage in current and future energy systems in transition. Like other case studies, Case Study 8 will also explore a policy option aimed at stimulating the transition to a low-carbon energy system.

This case study will investigate the role of natural gas storage in the current and future energy systems in transition. The cases of Turkey and Germany are exemplary. The result of the case study will promote the use of renewables and therefore lead to a low-carbon energy system.

Power-to-gas injects a new level of flexibility into the energy supply system through the production of hydrogen and/or methane. Renewable gas from power-to-gas conversion of surplus renewable electricity can potentially be stored in natural gas storage. For the cases of Germany and Turkey, the processes' costs and capacities as well as the model and its applications will be analyzed.

8.2 Challenges (beyond the state of the art)

GeneSysMod will be used in this case study. European version of the GAMS-programmed OSeMOSYS-model, GENeSYS-MOD, is developed and maintained at TU Berlin.

8.3 Expected results and limitations

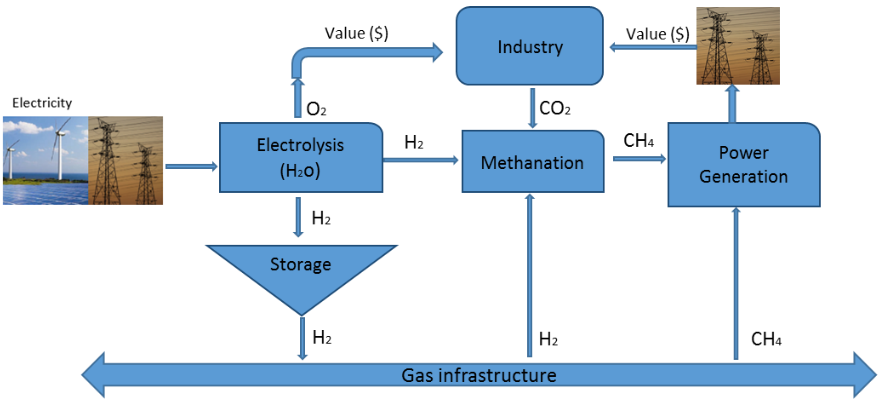

Figure 5: An overview of power to gas technology

- The objective is to use electricity for the electrolysis when the electricity prices are low.
- Use methane to generate power especially when the prices are high
- The final objective is to maximize profit or minimize system cost
- The operational constraints and limitations will be considered
- Parameters: storage level, max storage and discharge rates…
- Variables: (daily/ yearly) storage time start and end, rate of storage charge and discharge, storage level…
- Constraints: max charge/discharge constraints…

8.4 Modelling approach & Models requirements

The model, called GENeSYS-MOD, is a full-fledged energy system originally based on the open-source energy modeling system, called OSeMOSYS. The model uses a system of linear equations of the energy system to search for lowest-cost solutions for a secure energy supply, given externally defined constraints on greenhouse-gas (GHG) emissions. In particular, it takes into account increasing interdependencies between traditionally segregated sectors, e.g., electricity, transportation, and heating. OSeMOSYS itself is used in a variety of research to provide insights about regional energy systems and their transition towards renewable energies Inıtial model, written in GNU MathProg (GMPL), was translated into the widely used and available GAMS software. TU Berlin team extended the code and implemented additional functionalities, e.g., a modal split for the transportation sector or relative investment limits for the single model periods. Both the code and the data used by GENeSYS-MOD are open-access and freely available to the scientific community.

8.5 Data requirements

- Detailed energy data for Turkey is available in KHAS-OseMOSYS model
- Gas transmission and storage infrastructure of Turkey
- Hourly generation profiles, hourly load profiles
- Energy demand, import/export data
- Transportation data
- Installed capacities and generation/production mix per technology and sector
- Energy balances, trade, storage operation
- Emissions
- Generation/production costs

8.6 Detailed methodology of the case study (modus operandi)

The modelling will investigate the potential for gas storage to provide additional flexibility to the energy system.

Power-to-gas functionality will be added to GENeSYS-MOD. Models GENeSYS-MOD-Turkey (KHAS, linked) and GENeSYS-MOD-Germany (linked) will be compared.

Depending on the costs and capacities of power-to-gas facilities and gas storage, natural gas storage will play a more or less strong role. For energy systems without much natural gas storage yet, considering the low-carbon energy transition will be crucial for a sound assessment of the economic viability of new–built gas storage.

9. Case Study 9 – Effective policies for investment incentives

Leader: NTNU; Contribution: SINTEF, DIW Berlin, TNO

9.1 Overall Objective and Case study baseline

Achieving a large share of renewables in the energy system requires incentives and new market-regulatory frameworks to support different actors to invest in the energy transition. Understanding the impact that different shocks exert on different sectors of the economy is an important step to evaluate the effectiveness of energy policies. Nevertheless, the implementation of such policies requires a clear representation of regulatory barriers.

We establish the goal of analysing different policies to study

- The design of capacity markets under a high RES scenario,
- The evolution of cross-border trade regulation for the efficient deployment of RES,
- The evolution of electricity pricing schemes in European countries, incl. network charges, locational prices etc. for an effective deployment of RES,
- The role of subsidies, taxes and distributional welfare effects in investment decisions.
- Identify the regulatory barriers for effective investments in the energy transition.

For each policy we will analyse the allocation of investments and the spillover effects between different sectors, as well as effects on the overall economy.

The full European technology mix will be represented by the EMPIRE model which has a 'copper plate' representation of the European power network along with long-term capacity expansion decisions. EMPIRE covers all the technological features of a power system model. Then, to perform a more in-depth analysis of the effects of the energy transition in the overall economy, this case study uses the REMES model.

9.2 Challenges (beyond the state of the art)

Linking Bottom-up energy system models with Top-down macroeconomic models is not a new trend. It has been carried out in different studies. Nevertheless, the linking process can be quite subtle and does not always lend itself to convergence. Moreover, there is no clear established methodology to establish a linking between two models which might have quite different starting points in terms of data evaluation. Therefore, one of the main challenges will be finding a suitable methodology to obtain a fruitful exchange of information between the models whether a full convergence takes place or not. A key state-of-the-art accomplishment will be the development of a full-fledged European scale bottom-up to top-down energy model.

9.3 Modelling approach & Models requirements

The REMES model will be linked to the EMPIRE model for dynamic analysis of the energy system and the interaction with the overall economy. REMES provides a macroeconomic market analysis with focus on the energy system. REMES includes EU country details of supply, demand, trade, transport, households, employment and government. The model linkage will be done by exchanging parameters between REMES and EMPIRE models such as projected power generation technology mix, demand for energy and price for CO2 allowances. REMES will provide an analysis of the impact of different environmental policies on the overall economy in terms of GDP, household's consumption, energy infrastructure investment and employment. As the changing economic activity will have some impacts on the energy system, REMES will communicate to EMPIRE the variables that reflects this changing activity such as GDP and/or sectorial value added or any other activity indicator. This interaction will allow to study policy incentives and subsides to promote investment in low-carbon technologies. Linking investment decisions between REMES and EMPIRE models will enhance the representation and analysis of investment determinants and potential barriers.

9.4 Expected results and limitations

We expect the modelling framework to provide insights on the allocation of investments into different energy generation technologies, as well as its economic impacts on the other sectors. For the first sets of analyses we expect the capacity markets to redefine the different Countries as nodes of a large virtual power network where, depending on the availability of natural and technological resources, it will be possible to contribute on a large scale on the generation and delivery of a stable energy supply. The second sets of analyses will shed light on the effects of policies aiming at the reduction of power transmission from Countries employing large share of fossil fuels and the technical and economic effects on the other countries as well as possible carbon leakage effects. The third set of analyses is expected trigger different responses by the bottom up model into the top down economic model in terms of technology mix, which, will impact differently on the economies. The last set of analyses will provide insights on how the Countries can participate in the investments to drive the green transition.

9.5 Data requirements

The following data input is necessary for the top-down and bottom-up models involved in the analyses:

REMES_EU:

- Social Accounting Matrix
- Elasticities of substitution and transformation
- Policy and Development (Taxes and Subsidies, CO2 budget, population growth, gdp growth in base case)
- New sectors
    - Cost allocation per unit output

    - Assumed curent price for new products and services
    - Sectors purchasing new products and services
- From Bottom-Up model: Technology mix for energy sectors.

EMPIRE:

- Demand projections 2020-2050 for all EU countries
- Energy technology CAPEX and OPEX
- Technologies efficiency and conversion
- Grid transmission expansion: investment costs and candidate lines considered
- Renewables potentials and profiles

9.6 Detailed methodology of the case study (modus operandi)

The two models will be initialized to the handling of common policies and will include common assumptions for the future technical and socio-economic development. A necessary assumption homogeneization phase is to be considered prior to establish the linking. This means that an initial storyline will be mapped to shocks that both models can understand and handle. The mapping needs to be transparent and shared between the modellers in order to enhance mutual comprehension of the initial state

EMPIRE will run first using standard assumptions on electricity demand growth, which will be based on GDP growth per Country. The results will be collected in the OpenENTRANCE template and be passed on to REMES_EU, which will read them and use these technology structures to map the technological change over time of the power sectors. Thus, REMES_EU will proceed computing a new economic equilibrium over the years and produce an output with the development (in percentage) of the electricity demand over the years and the CO2 price. This information will be collected in the OpenENTRANCE template and fed back to EMPIRE, which will apply the demand percentage change on the its demand on the base year to reconstruct the electricity demand over the modelling horizon. The models will proceed exchanging information in this manner until reaching a convergence. We claim the convergence to be satisfied when the norm of the percentage difference in output to be delivered from one model to another is smaller than a predetermined threshold .

The Top-Down REMES_EU model will provide information on GDP development, unemployment rate, sectoral value added, price variations per commodity, allocation of energy consumption per sector and final utilisation and reallocation of the investments as a consequence of the implemented policies.

The Bottom-Up EMPIRE model will provide decarbonization strategies and changes over time on the overall technology mix. That is, EMPIRE will estimate the necessary technology to accomplish a given CO2 target. It determines endogenous investment decisions on generation and transmission expansion. It also provides hourly profiles on supply-demand operations per country.

Both models work with a country level granularisation and consider the European continent.