

NAVIGATING THE ROADMAP FOR CLEAN, SECURE AND EFFICIENT ENERGY INNOVATION



D.7.1: Draft methodological working paper documenting the methodological approaches and interlinkages for all supply models and interfaces to other WPs

Author(s): Frank Sensfuß, Gerda Deac, Christiane Bernath (Fraunhofer ISI)
Sara Lumbreras, Luis Olmos, Andres Ramos (Comillas), Peter Kotek, Borbala Toth, Laslo Szabo (REKK), Christian Skar, Ruud Egging (NTNU), Pedro Crespo Del Granado (NTNU/ETH), Blazhe Gjorgiev (ETH), Gustav Resch, Andre Ortner (TU Vienna)

03 / 2017

A report compiled within the H2020 project SET-Nav (work package 7)

www.set-nav.eu

Project Coordinator: Technische Universität Wien (TU Wien)

Work Package Coordinator: Fraunhofer ISI



Project coordinator:

Gustav Resch

Technische Universität Wien (TU Wien), Institute of Energy Systems and Electrical Drives, Energy Economics Group (EEG)

Address: Gusshausstrasse 25/370-3, A-1040 Vienna, Austria

Phone: +43 1 58801 370354

Fax: +43 1 58801 370397

Email: resch@eeg.tuwien.ac.at

Web: www.eeg.tuwien.ac.at



Dissemination leader:

Prof. John Psarras, Haris Doukas (Project Web)

National Technical University of Athens (NTUA-EPU)

Address: 9, Iroon Polytechniou str., 15780, Zografou, Athens, Greece

Phone: +30 210 7722083

Fax: +30 210 7723550

Email: h_doukas@epu.ntua.gr

Web: <http://www.epu.ntua.gr>



Lead author of this report:

Frank Sensfuß

Fraunhofer Institute for Systems and Innovation Research ISI

Address: Breslauer Strasse 48, 76139 Karlsruhe

Phone: +49 721 6809-133

Fax: +49 721 6809-77-133

Email: frank.sensfuss@isi.fraunhofer.de

Web: <http://www.isi.fraunhofer.de>

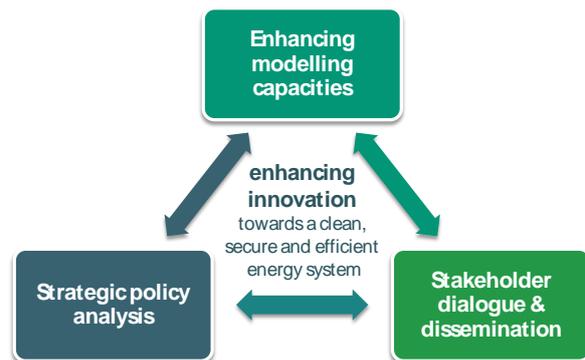
Project duration:	April 2016 – March 2019
Funding programme:	European Commission, Innovation and Networks Executive Agency (INEA), Horizon 2020 research and innovation programme, grant agreement no. 691843 (SET-Nav).
Web:	www.set-nav.eu
General contact:	contact@set-nav.eu

About the project

SET-Nav aims for supporting strategic decision making in Europe’s energy sector, enhancing innovation towards a clean, secure and efficient energy system. Our research will enable the European Commission, national governments and regulators to facilitate the development of optimal technology portfolios by market actors. We will comprehensively address critical uncertainties facing technology developers and investors, and derive appropriate policy and market responses. Our findings will support the further development of the SET-Plan and its implementation by continuous stakeholder engagement.

These contributions of the SET-Nav project rest on three pillars: modelling, policy and pathway analysis, and dissemination. The call for proposals sets out a wide range of objectives and analytical challenges that can only be met by developing a broad and technically-advanced modelling portfolio. Advancing this portfolio is our

first pillar. The EU’s energy, innovation and climate challenges define the direction of a future EU energy system, but the specific technology pathways are policy sensitive and need careful comparative evaluation. This is our second pillar. Ensuring our research is policy-relevant while meeting the needs of diverse actors with their particular perspectives requires continuous engagement with stakeholder community. This is our third pillar.



Who we are?

The project is coordinated by Technische Universität Wien (TU Wien) and being implemented by a multinational consortium of European organisations, with partners from Austria, Germany, Norway, Greece, France, Switzerland, the United Kingdom, France, Hungary, Spain and Belgium.

The project partners come from both the research and the industrial sectors. They represent the wide range of expertise necessary for the implementation of the project: policy research, energy technology, systems modelling, and simulation.



The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 691843 (SET-Nav).

Legal Notice:

The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Union. Neither the INEA nor the European Commission is responsible for any use that may be made of the information contained therein.

All rights reserved; no part of this publication may be translated, reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic,

mechanical, photocopying, re-cording or otherwise, without the written permission of the publisher.

Many of the designations used by manufacturers and sellers to distinguish their products are claimed as trademarks. The quotation of those designations in whatever way does not imply the conclusion that the use of those designations is legal without the content of the owner of the trademark.

Table of Contents

1	Introduction	1
2	Coupling of models involved in WP7	1
2.1	Model coupling and data exchange concept case study 7.2	1
2.2	Model coupling and data exchange concept case study 7.3	1
2.3	Model coupling and data exchange concept case study 7.4	2
2.4	Model coupling and data exchange concept beyond WP7	4
2.4.1	Linkages to WP5	4
2.4.2	Linkages to WP6	4
2.4.3	Linkages to WP8: Macro	4
2.4.4	Linkages to WP9	4
3	Classification of supply side models.....	4
4	Enertile	5
4.1	Model description.....	5
4.2	Model extensions	7
4.2.1	Adapt regionalisation (sub-national zone) to assess grid infrastructure	7
4.2.2	Interaction between the power sector and the heat and transport sector	8
4.3	Model linkages	9
5	EMPIRE	9
5.1	Model description.....	9
5.2	Model extensions	11
5.2.1	Modelling of demand flexibility	11
5.2.2	Representing the interaction between the power sector and the demand for heat	11
5.2.3	Increasing the geographical resolution of EMPIRE to sub-national regions	12
5.3	Model linkages	12
6	TEPES	12
6.1	Model description.....	12
6.2	Model extensions	14
6.2.1	Modelling of innovative transmission technologies	14
6.2.2	Integration with supply-side models: disaggregation procedure	14
6.2.3	Integration with supply-side models: feedbacks for system optimization	15
6.3	Model linkages	15
7	Green-X	16
7.1	Model description.....	16
7.2	Model extensions	18
7.2.1	Incorporate a simplified representation of wholesale electricity markets	18
7.2.2	Incorporate a simplified representation of retail electricity markets.....	18

7.2.3	Update available support mechanisms	19
7.3	Model linkages and role of the model in the overall model framework	19
8	RAMONA	20
8.1	Model description.....	20
8.2	Model extensions.....	21
8.3	Model linkages.....	21
9	EGMM.....	21
9.1	Model description.....	21
9.1.1	Local demand.....	22
9.1.2	Local supply	23
9.1.3	Gas storages	23
9.1.4	External markets and supply sources	23
9.1.5	Cross-border pipeline	24
9.1.6	LNG infrastructure.....	24
9.1.7	Long-term take-or-pay (TOP) contracts	24
9.1.8	Spot trading.....	25
9.1.9	Equilibrium.....	25
9.1.10	Welfare analysis.....	26
9.2	Model extensions.....	27
9.3	Model linkages.....	28
10	Nexus security model.....	28
10.1	Model description.....	28
10.2	Model extensions.....	30
10.3	Model linkages.....	30
11	Summary.....	30
12	Appendix	32
12.1	Case study 7.2 Decentralised vs. centralised development of the electricity sector- impact on the transmission grid” combines TEPES and Enertile to analyse the impact of different supply strategies on the electricity grid	32
12.2	Case study 7.3 Diffusion rate of renewable electricity generation	32
12.2.1	A - Standardized data.....	32
12.2.2	Electricity generation	33
12.2.3	Electricity prices	33
12.2.4	Market values	34
12.2.5	Capital costs.....	34
12.2.6	B - Special data	35
12.2.7	B01 Non market valuation of RES-E generation.....	35
12.3	Case study 7.4 - Unlocking unused flexibility and synergy in electric power and gas supply systems	35
12.3.1	A – Standardized data.....	36

12.3.2	Electricity generation	37
12.3.3	Electricity capacities	38
12.3.4	Investments	39
12.3.5	Electricity Costs	40
12.3.6	Electricity emissions	41
12.3.7	Electricity fuel consumption	42
12.3.8	Detailed grid cost.....	43
12.3.9	Gas infrastructure.....	44
12.3.10	Gas operation	45
12.3.11	Gas Investments	46
12.3.12	Gas costs	47
12.3.13	Gas emissions.....	48
12.4	B - Special data	49
12.4.3	Region definition.....	49
12.4.4	Existing transport capacity between regions	50
12.4.5	Investment Options for the grid	50
12.4.6	Gas production costs.....	50
12.4.7	Gas demand.....	50
12.4.8	Gas prices	50
12.4.9	System security/reliability indices electricity/gas	51

Figures

Figure 1. Simplified structure of the model.	6
Figure 2. Example of the hourly matching of supply and demand.	7
Figure 3. Zonal level. Nodes indicated as dots.	8
Figure 4. EMPIRE geographical coverage. Black lines in this map indicate overhead lines while red lines indicate submarine cables.	10
Figure 5. Stylized illustration of the representative days modelling used in EMPIRE.	10
Figure 6. Multi-horizon stochastic programming structure in EMPIRE	11
Figure 7. Example output for TEPES.	14
Figure 8: Overview structure of Green-X (electricity sector)	16
Figure 9. Multi-horizon tree formulation used in RAMONA. Squares indicate strategic decisions and circles indicate operational decisions.	20
Figure 10. The geographical scope of the European Gas Market Model.	21
Figure 11. Main nodes of production and consumption, interconnectors and LNG infrastructure	28
<i>Figure 12: Nexus security model flow chart.</i>	29

Tables

Table 1: Overview of supply side models in WP7.	4
Table 2: Involvement of Enertile in SET-Nav	7
Table 1: Summary of modelling input parameters and data sources	26

1 Introduction

This report describes all model adaptation, extensions and linkages for the supply side oriented models. The perspective of the different supply side models is used to structure the complex interaction between the models. The resulting classification is also used to structure this report. The aim of all model adaptations and extensions is a comprehensive modelling framework with well-defined linkages that can be used in the case studies and the pathway analysis.

2 Coupling of models involved in WP7

Our activities in WP7 complement the modelling activities in WP5 and WP6, which have special focus on energy demand and the energy infrastructure. The goal of WP7 is to build a strong modelling framework for energy supply with a particular focus on electricity supply. In this context, there is strong interaction with WP6 on energy infrastructure since energy supply cannot be assessed without the perspective on energy infrastructures. This also translates into the fact that one case study on the impact of centralized or decentralized electricity infrastructure is associated to WP6 and WP7. This section describes the model extensions and efforts for increased model coupling in WP7.

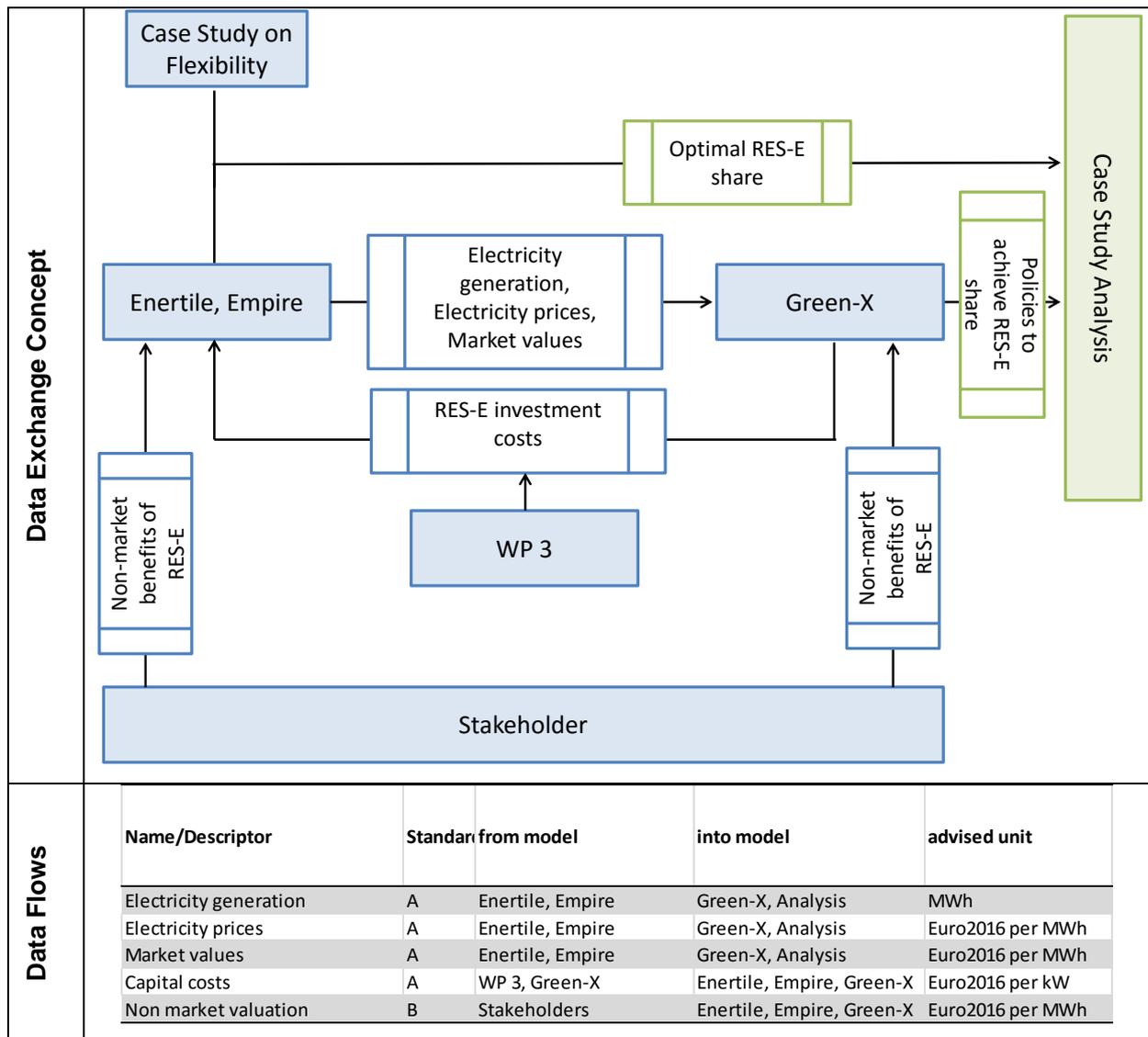
2.1 Model coupling and data exchange concept case study 7.2

The case study is identical to case study 6.2. The developments are described in the working paper on WP6.

2.2 Model coupling and data exchange concept case study 7.3

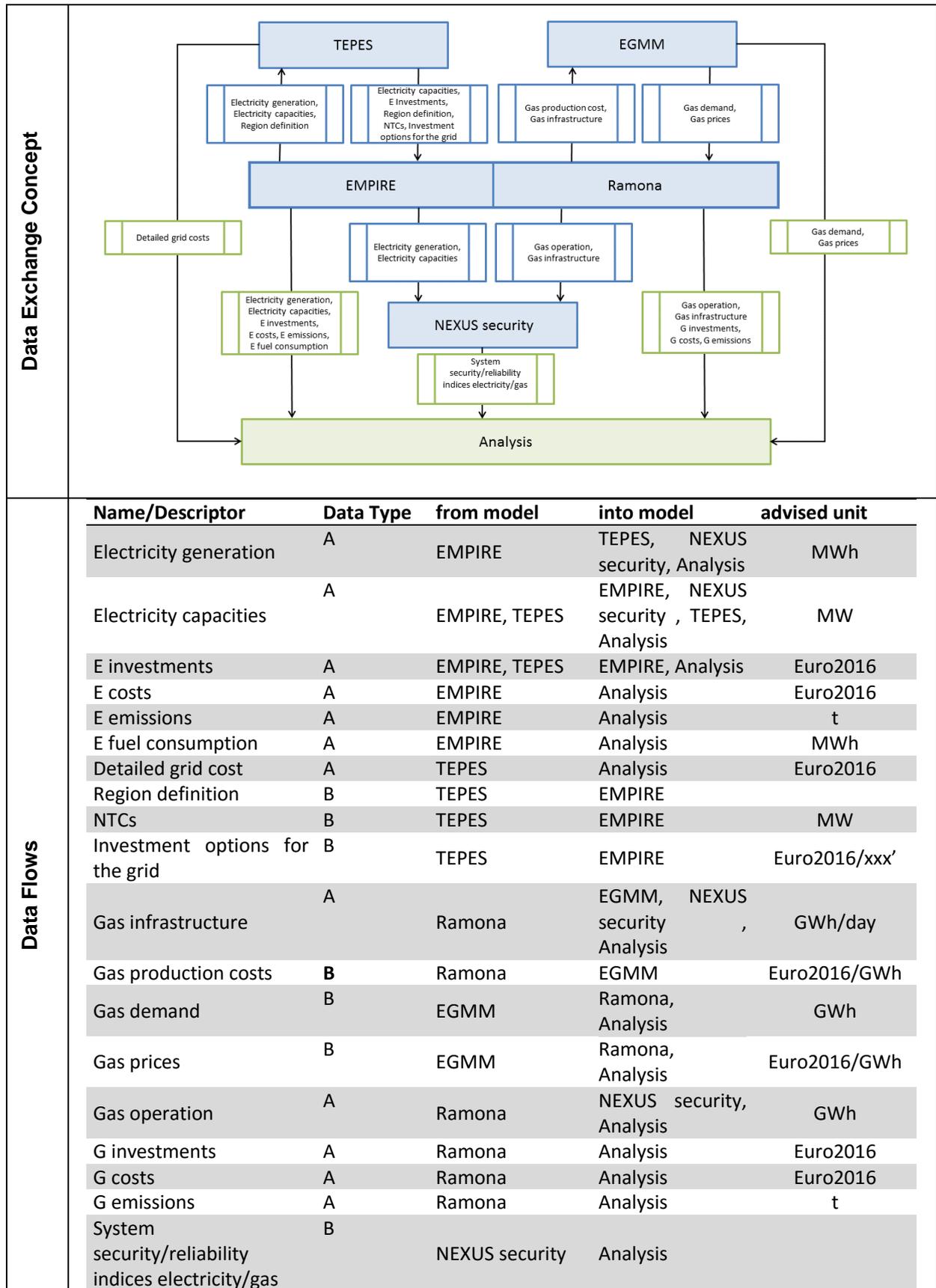
This data exchange concept describes the data flows between the models Enertile, EMPIRE and Green-X. Further input will come from WP3 regarding the impact of the innovation system on learning rates of RES technologies.

In principle, Green-X will be applied to model the required RES premiums / certificate prices and corresponding assumptions on diffusion barriers in order to reach the optimum RES shares delivered by Enertile and EMPIRE. The main input data required from Enertile and EMPIRE are yearly averages of RES market values, electricity prices and RES generation per country. Assumptions for energy and carbon prices will be taken from the overall database.



2.3 Model coupling and data exchange concept case study 7.4

This data exchange concept describes the data flows between the models for the case study “Unlocking unused flexibility and synergy in electric power and gas supply systems”. General assumptions, such as interest rates and overall input data that is only relevant for one model (e.g. O&M costs of power plants, lifetime of power plants, maximal land use factors for renewable electricity generation) are not managed within the data exchange between models. It is necessary to keep these assumptions consistent within each case study, and to reach a certain degree of consistency between case studies in the project. Inclusion of assumptions in the data exchange would just add complexity and result in a loop-through of data without additional benefit.



2.4 Model coupling and data exchange concept beyond WP7

2.4.1 Linkages to WP5

The models Green-X, EMPIRE and RAMONA are utilized in case studies of WP5. The latter deals with flexibility, which can be utilized in the interaction of energy demand and supply.

2.4.2 Linkages to WP6

The supply side models TEPES; RAMONA, EGMM, Enertile are utilized in different case studies of WP6 such as 6.2 on centralized and decentralized electricity supply and 6.3 on gas infrastructure and pricing.

2.4.3 Linkages to WP8: Macro

In the current concept of the case studies no direct data flows to the macroeconomic models are planned. However, macroeconomic data is used in the scenario design of the case studies. In the pathway analysis investment data created by the supply side models can be utilized by the macroeconomic models.

2.4.4 Linkages to WP9

The case studies, model developments and mode linkages established in WP7 will be utilized in the pathways analysis carried out in WP9.

3 Classification of supply side models

System optimisation models are widely used in strategic energy sector analysis. These models try to determine dispatch and investment of generation units and infrastructures. System optimisation models used in SET-Nav are **Enertile** and **EMPIRE**.

Transmission grid models assess the physical feasibility of grid operation and the detailed physical extensions of the grid. **TEPES** is the transmission grid model that is used in SET-Nav.

Renewable policy models cover policies that change the framework conditions in the sector. Renewable policy is a main driver in addition to technical and economic aspects. **Green-X** covers the renewable policy perspective in SET-Nav.

The **demand perspective** is covered extensively in WP5. Demand Perspective models play also a major role in WP7, since demand and supply interact and this interaction will become even stronger in future. In SET-Nav **FORECAST** covers the demand in the industry sector, while **INVERT** has a special focus on the heating sector.

Gas supply models assess the gas networks, gas storages and gas markets. Due to its low carbon content gas can be an important fuel on an emission reduction pathway for the energy system. **Ramona** with a focus on gas infrastructure and **EGMM** with a focus on gas markets are used in SET-Nav.

System security models analyse the vulnerability of gas and electricity networks. **Nexus-Security** is used to assess the energy system resilience and vulnerability in SET-Nav.

Table 1: Overview of supply side models in WP7

Perspective	Models	
System optimisation	Enertile	EMPIRE
Transmission grid	TEPES	

Renewable policy	Green-X	
Gas supply	Ramona	EGMM
System security	Nexus	

4 Enertile



4.1 Model description

Enertile is an energy-system optimization model developed at the Fraunhofer Institute for System and Innovation Research, ISI. The model focuses on the power sector, but also covers the interdependencies with other sectors, especially heating/cooling and the transport sector. It is used mostly for long-term scenario studies and explicitly designed to depict the challenges and opportunities of increasing shares of renewable energies. A major advantage of the model is its high technical and temporal resolution.

Integrated optimization of investments and dispatch

Enertile optimizes the investments into all major infrastructures of the power sector, including conventional power generation, combined-heat-and-power (CHP), renewable power technologies, cross-border transmission grids, flexibility options, such as demand-side-management (DSM) and power-to-heat storage technologies. The model chooses the optimal portfolio of technologies while determining the utilization of these in all hours of each analyzed year.

High spatial coverage

The model currently depicts and optimizes Europe, North Africa and the Middle East. Each country is usually represented by one node, although in some cases it is useful to aggregate smaller countries and split larger ones into several regions. Covering such a large region instead of single countries becomes increasingly necessary with high shares of renewable energy, as exchanging electricity between different weather regions is a central flexibility option.

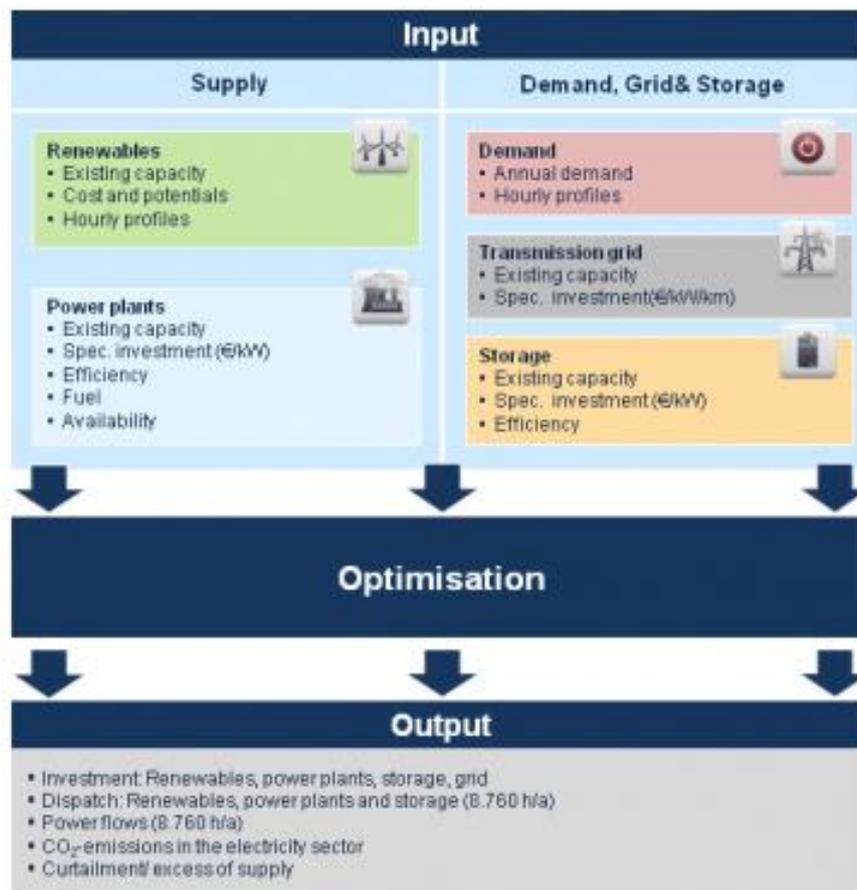


Figure 1. Simplified structure of the model.

High temporal resolution

The model features a full hourly resolution: In each analysed year, 8,760 hours are covered. Since real weather data is applied, the interdependencies between weather regions and renewable technologies are implicitly included.

Detailed picture of renewable energy potential and generation profiles

The potential sites for renewable energy are calculated on the basis of several hundred thousand regional data points for wind and solar technologies with consideration of distance regulations and protected areas. The hourly generation profile is based on detailed regional weather data.

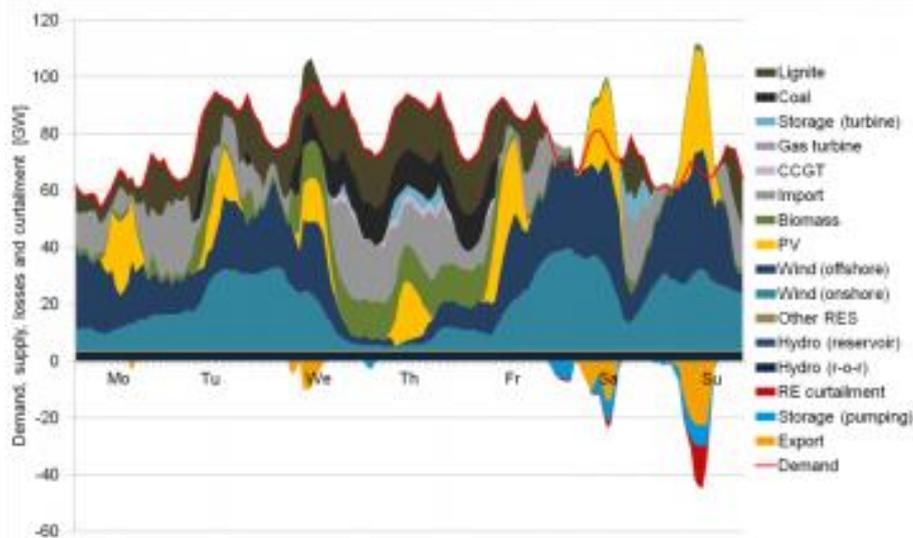


Figure 2. Example of the hourly matching of supply and demand.

The involvement of Enertile in different work packages is shown in Table 2. The role in WP7 is highlighted and focuses on the expansion and operation of the electricity system.

Table 2: Involvement of Enertile in SET-Nav

Work Package	Case Study	Role of Enertile
WP5	Energy demand and supply in buildings and the role for RES market integration	
	The contribution of innovative technologies to decarbonise industrial process heat	
	Ways to a cleaner and smarter transport sector	
WP6/WP7	Decentralised vs. centralised development of the electricity sector - Impact on the transmission grid	<ul style="list-style-type: none"> Assessment of expansion and operation of the electricity system Building consistent generation expansion pathways considering deployment of RES, CCS and nuclear from a cost minimisation perspective
WP7	Diffusion rate of renewable electricity generation	

4.2 Model extensions

4.2.1 Adapt regionalisation (sub-national zone) to assess grid infrastructure

Enertile is a system-optimization tool for the electricity sector that is based on countries as a regional structure. It also includes the electricity grid in terms of transport capacities for electricity between countries.

4.2.1.1 Zonal level

Within this work package, the definition of regions is further developed to also implement sub-national regions. This is necessary to account for important bottlenecks in the electricity grid infrastructure within countries. The definition of the sub-national regions (zonal level) was developed by TEPES with a strong interaction of the Enertile and the TEPES model. The region definition had to meet the following challenges:

- Each country has to be a single region to provide results for each country (EU 27+).
- Important sub-national bottlenecks in the electricity grid infrastructure should be covered
- An increase in zones increases calculation time in Enertile strongly. The number of zones that can be covered in Enertile is limited to 35-40 regions.

Fehler! Verweisquelle konnte nicht gefunden werden. shows the resulting definition of zones.



Figure 3. Zonal level. Nodes indicated as dots.

4.2.1.2 Nodal level

Renewable electricity generation from wind and solar radiation is covered in Enertile in a high spatial resolution. A procedure to supply nodal capacities and hourly generation profiles on a nodal level for TEPES was developed on the basis of the highly disaggregated results of Enertile.

4.2.2 Interaction between the power sector and the heat and transport sector

Enertile has a strong focus on the electricity sector, based on its nature as an optimization model for the electricity sector in Europe and neighbouring regions. The integration of rising shares of renewable electricity in the electricity sector is a crucial task for the next decades. On one hand

this can be addressed by additional flexibility within the electricity sector, on the other hand, a stronger linkage to other sectors could help to integrate renewable electricity. Within the SET-Nav project, Enertile was expanded by different modules to integrate demands and flexibilities from the heating and the transport sector. These modules will be used extensively in work package 5.

4.3 Model linkages

Enertile will be linked to the transmission grid model TEPES within the case study on “Decentralised vs. centralised development of the electricity sector - Impact on the transmission grid” within work package 6. In other work packages Enertile will also be linked to the renewable policy model Green-X and to the demand side models Invert/EE-Lab, Forecast and ASTRA.

5 EMPIRE

5.1 Model description

EMPIRE is a capacity expansion model for the European power system, formulated as a multi-horizon stochastic program. The objective is to minimize system cost for the European power system, including investment cost and expected operational costs, while satisfying its demand for electricity. This formulation is commonly used in energy-system models to represent strategic and operational decision-making in a perfectly competitive market. The main function of EMPIRE is to assess cost-efficient decarbonization pathways for the European power sector, with a particular focus on the interplay between low carbon technologies with different characteristics such as solar PV, wind energy, carbon-capture and storage and nuclear power.

Spatial and temporal resolution

Most of the European countries represented in the ENTSO-E are included in EMPIRE, and each country is represented by a separate node in the transmission system model. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the geographical coverage and spatial detail used. Strategic decisions (e.g. investments) are considered in five-year time intervals, starting from 2020, until the model time horizon of 2050 (expansion this horizon is straightforward). For each strategic period, annual system operation is optimized, at an hourly resolution, using eight representative days split across four seasons. See **Fehler! Verweisquelle konnte nicht gefunden werden.** for a stylized illustration of the level temporal detail used in EMPIRE. In addition to the representative days EMPIRE includes six periods with a duration of five hours each where the system is put under high stress (high-load periods). The main purpose of including high-load periods is to account for those situations during a year where capacity may be scarce, which is important to consider for investments back-up technologies, usually identified by low-to-medium capital costs and high operational costs.

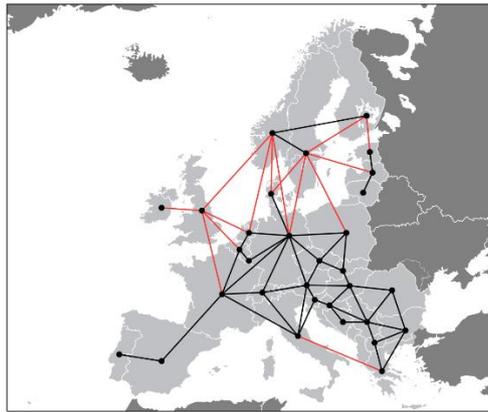


Figure 4. EMPIRE geographical coverage. Black lines in this map indicate overhead lines while red lines indicate submarine cables.

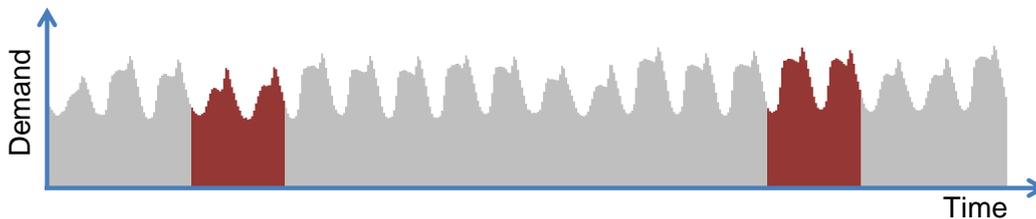


Figure 5. Stylized illustration of the representative days modelling used in EMPIRE.

Technical modelling of generation, transmission and storage

EMPIRE includes a total of 23 generation technologies with various characteristics. These technologies can broadly be grouped into three categories, which have a particular technical implementation. These are: thermal power plants (nuclear, fossil generation, CCS, biomass), intermittent power generation (wind, solar, run-of-the-river hydro) and energy constrained generation (reservoir hydro). All technologies are modelled with a maximum capacity on their power generation output. The thermal generation in addition have fuel costs and technical constraints (e.g. ramping limits). The intermittent power generation are modelled using predefined production profiles, and energy constrained generation have a limit on total output over a time interval (to represent available energy stored in reservoirs). Within each category, the different technologies are distinguished through their technical specifications and costs.

The transmission infrastructure is modelled by cross-border interconnectors and national grids are not explicitly included. As a result, each country is modelled as a copperplate and internal grid bottlenecks are not considered. The flows in the network are computed using a transportation model, which means that loop-flows are not handled.

In addition to the generation and transmission, EMPIRE models electricity storage units. These are implemented with a charging unit (pump), discharging unit (generator) and an energy reservoir, all with their respective capacities. In the operation, the energy balance of the reservoir is respected, and losses are incurred in the charging/discharging process. In terms of investments in new storage there are two types of possibilities in EMPIRE, investment in energy storage units where the power and energy capacity ratio is given (typical for electro chemical batteries), and independent investments in power and energy capacity (possible for pump hydro storage).

Multi-horizon stochastic programming formulation

One of the key strengths of EMPIRE is the use of multi-horizon stochastic programming to design a system, which is optimal over a wide range of annual operational conditions. By operational conditions, we mean load profiles, wind and solar production profiles and hydro reservoir inflow. It is difficult to predict the future outcomes of such parameters at the time strategic decisions are made, and therefore considering several possible outcomes will make the strategic decisions more robust to alternative futures and reduce the risk of sub-optimal performance.

At each strategic decision period, several annual operations are optimized (parametrized using different operational conditions). As an underlying assumption, we do not consider dependence between operational decisions in one year and strategic and operational decisions in future years. As a result, the operational modelling in each strategic time-period is in a sense terminated and thus represent a separate horizon in the full model (thereof the name multi-horizon). **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the structure of the multi-horizon stochastic programming formulation in EMPIRE. In this figure, the following symbols are used:

- x_i - Strategic decisions (investments) in strategic period i (2020, 2025, 2035,...). I is the end of horizon, typically, 2050.
- $y_{i\omega}$ - Collection of all operational decisions (dispatch, flows, etc.) in strategic period i stochastic scenario ω . The stochastic scenario represents different operating conditions (as previously discussed). O is used to denote the number of stochastic scenarios (usually around 10 scenarios are used).

All the strategic and operational decisions are co-optimized in a single optimization problem.

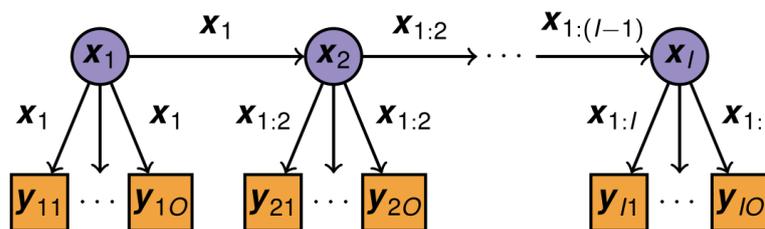


Figure 6. Multi-horizon stochastic programming structure in EMPIRE

5.2 Model extensions

5.2.1 Modelling of demand flexibility

We are implementing two types of demand-side flexibility in EMPIRE, load shedding and peak shifting. This involves:

1. Technical implementation of the logic of the demand side flexibility measures
2. Parameterization of different forms of the demand-side flexibility measures, which mostly involve data collection.
3. Implementation of investment logic for demand-side flexibility measures.

With demand-side flexibility modelling in place, EMPIRE can provide results such as:

1. Deployment of various types of the demand-side flexibility measures
2. Cost-savings related to increased demand-side flexibility
3. Utilization of different types of demand-side flexibility

5.2.2 Representing the interaction between the power sector and the demand for heat

Currently, EMPIRE only considers the power sector, and all other linkages to other parts of the energy system is handled exogenously. With more combined heat-and-power (CHP) plants being

deployed throughout Europe it is important to capture the link between the power sector and centralized heat production. A key target is therefore to implement a logic to endogenously handle investment and operation of CHP plants in EMPIRE. This entails the modelling of heat demand, the operational characteristics of CHP plants.

5.2.3 Increasing the geographical resolution of EMPIRE to sub-national regions

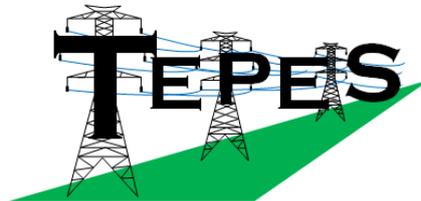
In order to work more seamlessly with more spatially granular models such as CCTS MOD, we disaggregate some of the larger countries in Europe into several sub-national nodes. This disaggregation process involves (for each sub-national region):

1. Acquiring wind and solar production profiles.
2. Developing an inventory of current generation capacities.
3. Gather data about hydro reservoir inflows.
4. Assessing deployment potentials (including determining deployment limits) of wind and solar PV.
5. Gather data about load and develop load profiles.

5.3 Model linkages

EMPIRE will be linked to the TEPES model and the CCTS MOD in case study 6.4. EMPIRE will also be actively used on case studies 7.3 and 7.4 by creating model linkages with RAMONA, Nexus-Security, EGMM and Green-X.

6 TEPES



6.1 Model description

The intermittent nature of the output of most renewable energy resources (RES), its non homogeneous distribution and the deployment of a large share of this generation is expected to result in a significant increase in the power flows among areas in large-scale systems. As a result of this, the development of the transmission network should be planned in an integrated way and the number of operation snapshots to consider in the planning process should probably be high. Identifying the main optimal transmission network corridors to reinforce and the extent of reinforcements needed in them and other operation variables affected by the existence of the grid, like the investment cost of grid additions, network losses incurred, CO₂ emissions produced, overall production by technology and fuel production costs is a major challenge for large-scale systems. Different future RES generation strategies associated with different RES targets may also strongly influence this network development.

Transmission expansion planning (TEP) determines the investment plan for new facilities (lines and other network equipment) for supplying the forecasted demand at minimum cost. Tactical planning is concerned with time horizons of 10-20 years. Its objective is to evaluate the future network needs. The main results are the guidelines for future structure of the transmission network.

TEPES model presents a decision support system for defining the transmission expansion plan of a large-scale electric system at a tactical level. A transmission expansion plan is defined as a set of network investment decisions for future years. The candidate lines are pre-defined by the user, so the model determines the optimal decisions among those specified by the user, or identified automatically by the model. Candidate lines can be HVDC or HVAC circuits.

The model determines automatically optimal expansion plans that satisfy simultaneously several attributes.

Dynamic

The scope of the model corresponds to several years at a long-term horizon.

The model represents hierarchically the different time scopes to take decisions in an electric system: Year, Period, Sub-period and Load level.

This time division allows a flexible representation of the periods where system operation is evaluated. For example, by a set of non chronological isolated snapshots, by a set of representative days for different seasons of the year or by a stepwise load-duration curve covering the duration of a year.

Stochastic

Several stochastic parameters that can influence the optimal transmission expansion decisions are considered. The model considers stochastic scenarios related to operation and to reliability. The operation scenarios are associated to renewable energy sources, electricity demand, hydro inflows, and fuel costs. The reliability scenarios evaluate N-1 generation and N-1 transmission contingencies.

The optimization method used is based on a functional decomposition between an automatic transmission plan generator (based on optimization) and an evaluator of these plans from different points of view (operation costs for several operating conditions, or reliability assessment for N-1 generation and transmission contingencies). The model is based on Benders' decomposition where the master problem proposes network investment decisions and the operation subproblem determines the operation cost for this investment decisions and the reliability subproblems determine the not served power for the generation and transmission contingencies given that investment decisions.

The operation model (evaluator) is based on a DC load flow although a simpler transportation representation is allowed for some or all the lines. Network losses can also be considered. By nature the transmission investment decisions are binary although can also be treated as continuous ones. The current network topology is considered as the starting point for the network expansion problem.

The main results of the model can be structured in these themes:

- Investment: investment decisions and cost
- Operation: output of different units and technologies (thermal, storage hydro, pumped storage hydro, RES), fuel consumption, RES curtailment, hydro spillage, hydro reservoir scheduling, line flows, line ohmic losses, node voltage angles
- Emissions: CO₂
- Marginal: Short-run Marginal Costs, Transmission Load Factors (TLF)
- Reliability: ENS (Energy Not Served)
- Cost to go function or future cost function

The resulting expansion plan for the transmission network can be represented in Google Earth for easy visual inspection.



Figure 7. Example output for TEPES.

TEPES has been used in 6 several projects and appears in over 20 academic publications.

6.2 Model extensions

TEPES had to be extended to link it to the other models in project SET-Nav.

6.2.1 Modelling of innovative transmission technologies

TEPES has been extended to include the option to use innovative transmission technologies in the expansion of the transmission system:

- Phase-Shifting Transformers (PSTs) have been incorporated as a way of alleviating congestion without investing in new lines. These Flexible Alternating Current Transmission Systems (FACTS) are sometimes the most efficient way of alleviating operation problems due to Kirchhoff's Voltage Law.
- Combinations of AC transmission lines and PSTs.
- HVDC (High-Voltage Direct-Current) lines.

The model performs an automatic search of the most attractive investment candidates within these categories, builds an approximation of investment cost and considers them for the most efficient expansion. Then, they are included in the expansion options that are fed back to system optimization.

6.2.2 Integration with supply-side models: disaggregation procedure

TEPES performs a detailed expansion of the transmission grid:

- Considering hundreds or potentially thousands of nodes (*nodal* level).
- Integration with supply-side models: providing useful outputs for integrated system expansion

System expansion is performed at a more aggregate level (we will refer to it as *zonal* level). Therefore, it is necessary to disaggregate this data. The results for the system expansion include conventional generation capacity, demand profiles, installation and use of storage (power

injection and withdrawal) and intermittent generation. These are calculated, in this case, by ENERTILE.

- Generation, demand and storage data at zonal level are allocated to nodes according to previously defined shift keys;
- Conventional generation is located according to their existing locations;
- Demand is disaggregated according the share of the existing nodal consumption from ENTSO-e data;
- Storage and renewable generation are located according to their potential for each node. Each renewable or storage technology (wind onshore, solar PV, run-of-the-river hydro) is disaggregated according to the share of its existing nodal production from ENTSO-e data)

6.2.3 Integration with supply-side models: feedbacks for system optimization

TEPES calculates the detailed network expansion, which is fed back to the system optimization. In addition to this, the best options for increasing net transfer capacity between zones are calculated.

We make a distinction between the unit cost of reinforcing each corridor up to its optimal development state, as computed using TEPES, and the unit cost of reinforcing this corridor beyond this point.

- 1) Computation of the unit cost of reinforcing each corridor up to the optimal amount of transmission capacity:
 - i) TEPES computes the optimal operation of the system in each snapshot and development of the network. The network reinforcements to undertake in the system are determined, as well as the annualized cost of each reinforcement.
 - ii) The fraction of the annualized cost of each reinforcement is allocated to the considered snapshots proportionally to the aggregate size of overflows created in these snapshots in the original network if capacity constraints are relaxed.
 - iii) The cost assigned to each MW of power flowing through a reinforcement in a particular snapshot is assigned according to the net flow through the reinforcement in that particular snapshot.
 - iv) The unit cost of reinforcing each corridor between two zones is calculated by simulating a transaction between these two zones. The use of reinforcements by each transaction gives the proportion of the cost that should be allocated to the corridor.

These calculations result in a unit cost of the reinforcement of each corridor up to the level of optimal expansion.

- 2) Computation of the unit cost of reinforcing the network beyond its optimal capacity level.

In this case, once the optimal expansion of the grid has been computed, the unit cost of reinforcing each corridor is computed as the cost of allowing an incremental transaction between zones A and B, linked by corridor C, in both possible directions of it, on top of the power injections and withdrawals resulting from the economic dispatch in all the snapshots considered.

The unit cost of allowing this incremental transaction is the per-unit cost of expanding the system to allow the incremental transaction between these two zones.

6.3 Model linkages

TEPES is only linked to system optimization tools in this WP. This means that it interacts with ENERTILE in case study 6.2 and with EMPIRE in case study 6.4, where both ENERTILE and EMPIRE play a similar role.

7 Green-X

7.1 Model description

The model Green-X has been developed by the Energy Economics Group (EEG) at the Vienna University of Technology under the EU research project "Green-X–Deriving optimal promotion strategies for increasing the share of RES-E in a dynamic European electricity market" (Contract No. ENG2-CT-2002-00607). Initially focused on the electricity sector, this modelling tool, and its database on renewable energy (RES) potentials and costs, has been extended to incorporate renewable energy technologies within all energy sectors. The general structure of the model is exemplified for the electricity sector in Figure 8.

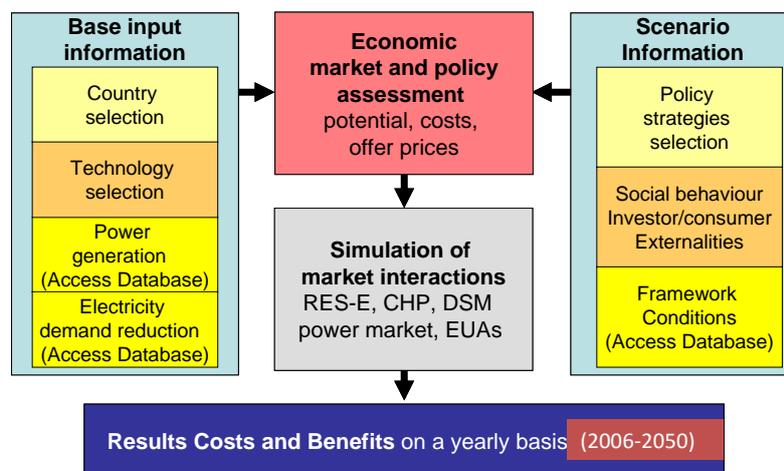


Figure 8: Overview structure of Green-X (electricity sector)

It allows the investigation of the future deployment of energy technologies using renewable energy sources (RES) as well as the accompanying cost (including capital expenditures, additional generation cost of RES compared to conventional options, consumer expenditures due to applied supporting policies) and benefits (for instance, avoidance of fossil fuels and corresponding carbon emission savings). Results are calculated at both a country- and technology-level on a yearly basis. The time-horizon allows for in-depth assessments up to 2050.

Through its in-depth energy policy representation, the Green-X model allows an assessment of the impact of applying (combinations of) different energy policy instruments at both country or European level in a dynamic framework. Sensitivity investigations on key input parameters such as non-economic barriers (influencing the technology diffusion), conventional energy prices, energy demand developments or technological progress (technological learning) typically complement a policy assessment.

Within the Green-X model, the allocation of biomass feedstock to feasible technologies and sectors is fully internalized into the overall calculation procedure. For each feedstock category, technology options (and their corresponding demands) are ranked based on the feasible revenue streams as available to a possible investor under the conditioned, scenario-specific energy policy framework that may change on a yearly basis. Recently, a module for intra-European trade of biomass feedstock has been added to Green-X that operates on the same principle as outlined above but at a European rather than at a purely national level. Thus, associated transport costs and GHG emissions reflect the outcomes of a detailed logistic model. Consequently, competition on biomass supply and demand arising within a country from the conditioned support incentives for heat and electricity as well as between countries can be reflected. In other words, the

supporting framework at MS level may have a significant impact on the resulting biomass allocation and use as well as associated trade.

Coverage and data structure

Green-X covers *geographically* the **EU-28**, the **Contracting Parties of the Energy Community** (West Balkans, Ukraine, Moldova) and selected other EU neighbors (Turkey, North African countries).

Technology-wise the default version of Green-X includes a broad set of energy technologies using renewable energy sources within the various energy sectors (i.e. electricity, heating and cooling as well as transport). The Green-X model develops nationally specific dynamic cost-resource curves for all key RES technologies, including for renewable electricity, biogas, biomass, biowaste, wind on- and offshore, hydropower large- and small-scale, solar thermal electricity, photovoltaic, tidal stream and wave power, geothermal electricity; for renewable heat, biomass, sub-divided into log wood, wood chips, pellets, grid-connected heat, geothermal grid-connected heat, heat pumps and solar thermal heat; and, for renewable transport fuels, first generation biofuels (biodiesel and bioethanol), second generation biofuels (lignocellulosic bioethanol, biomass to liquid), as well as the impact of biofuel imports. Besides the formal description of RES potentials and costs, Green-X provides a detailed representation of dynamic aspects such as technological learning and technology diffusion.

Policy-wise the model offers a broad coverage of different energy policy instruments for incentivizing the market uptake of RES technologies, including quota obligations based on tradable green certificates / guarantees of origin, feed-in tariffs, feed-in premiums, tax incentives, investment incentives, auctions, etc.), and a detailed representation of the instrument-specific functionality. Moreover, Green-X was extended throughout 2011 to allow an endogenous modelling of sustainability regulations for the energetic use of biomass. This comprises specifically the application of GHG constraints that exclude technology/feedstock combinations not complying with conditioned thresholds. The model allows flexibility in applying such limitations, that is to say, the user can select which technology clusters and feedstock categories are affected by the regulation both at national and EU level, and, additionally, applied parameters may change over time.

Outputs from Green-X

Standard outputs from the Green-X model on an annual basis are:

- energy output by sector (RES-E, RES-H, RES-T), by country, by technology
- installed capacity & corresponding capital expenditures by sector, by country, by technology
- share on gross domestic electricity / heat / transport fuel demand
- (average) (additional) generation costs by sector, by country, by technology
- avoided (fossil) primary energy and GHG emissions due to additional RES deployment by sector, by country, by technology
- impact of selected energy policy instruments on supply portfolio, costs & benefits to the society (consumer)– e.g. capital, operational and support expenditures for RES

Moreover, due to the bottom-up character of the model, Green-X offers the possibility to derive more detailed and other type of result evaluations as well.

7.2 Model extensions

Within the course of this project, it is planned to significantly enhance the model functionality of Green-X. The planned extensions are motivated by two intertwined developments. First, since RES-E is not any more considered to be a marginal player in electricity markets a number of increasingly relevant interactions of RES electricity generation and market outcomes need to be taken into account. Second, the increasing market penetration of RES-E requires a shift of energy policy and regulations away from the sole aim of pushing RES development towards more market-oriented approaches. In order to adequately represent and to assess these developments we aim to extend the system boundaries and technology coverage of Green-X in two dimensions. On the one hand, multiple linkages of Green-X with the other models applied in this project will help to incorporate and to assess relevant interactions of RES development with markets, grids and the economy. On the other hand, the model itself needs to be extended in order to endogenously cover new framework conditions und which RES investments take place.

In the following, the targeted model developments are described in more detail. We begin with model extensions that extend the scope of Green-X.

7.2.1 Incorporate a simplified representation of wholesale electricity markets

In market-based environments the profitability of each generation technology is determined by the market value of generated electricity minus total generation costs. One of the core strengths of the Green-X model is its detailed representation of cost-potential curves of RES across Europe and beyond. At present, electricity prices and corresponding market values of RES-E are exogenous to the model. As a consequence, interactions of RES generation with electricity markets had to be assessed via resource-intensive iterations with dedicated electricity market models. Not only the required model iterations, but also associated harmonisation efforts of data, often involving aggregation and simplification, makes this procedure not very effective. The aim of this task is to bring together the value and costs of generated electricity within one model in order to efficiently assess the profitability or required financial support, respectively, for each technology.

A simplified representation of the wholesale electricity market will allow for an endogenous calculation of wholesale electricity prices. These prices will serve to assess e.g. the price-damping effect of RES-E on electricity prices (merit-order effect) and to derive potential revenues of RE generators from different market segments. It is planned to implement a highly resolved generation dispatch model that represents the total electricity generation mix across the EU. This will enable Green-X to more accurately derive the amount of emissions reduced through RES-E. Also, it will be possible to assess the profitability of conventional generators as well. In particular, the assessment focuses on national policies and preferences with regard to nuclear power and the development and the potential of CCS in order to reduce emissions. Of interest with regard to RES-E market integration are also the question how different market design and regulations of wholesale electricity markets (e.g. capacity mechanisms, rules for RES curtailment) impact the business case of RES.

7.2.2 Incorporate a simplified representation of retail electricity markets

The development of decentralised solar PV and storages on the level of distribution grids has become more attractive in recent years. The valuation of decentralised generation needs to consider next to energy costs and revenues also a number of other cost components, like transmission fees and taxes. Also, the profitability of decentralised generation is strongly impacted by regulations and the concrete design of electricity tariffs at retail level. In order to assess the impact of how a certain policy design pushes investments in decentralised (RES)

generation a simplified retail market model will be implemented into Green-X. The model will be enabled to assess the economics and deployment of RES on distribution grid level. It is planned to incorporate a selected number of representative electricity consumers from the residential sector and from industry into the model. This model extension will enable Green-X to assess the impact of different grid tariff designs (capacity- vs. energy-related charges) and energy tariffs (fixed vs. real-time pricing) as well as regulations (e.g. taxation of own consumption) on the investment decision of consumers. The retail market model will be closely coupled to the wholesale electricity market model in order to reflect the interlinkage of prices.

7.2.3 Update available support mechanisms

In the guidelines on state aid the EC stated that premium models and the use of auctions to determine the level of required premiums are the preferred instruments to support RES. The Green-X model will be extended in order to fully cover the effect of different auction designs on RES development across the EU. Furthermore, the option of regional and/or EU-wide cooperation initiatives with regard to RES support will be implemented in the model to assess potential cost savings and benefits from such cooperations. The ability of the model will also be extended with regard to the simultaneous application of multiple support instruments per technology. In particular, technology push instruments like investment support and other SET plan measures should be applicable together with a RES premium scheme.

7.3 Model linkages and role of the model in the overall model framework

The role of Green-X within the framework of this project is to provide feasible pathways for future RES development in the EU until 2050. Moreover, it will allow for a detailed impact assessment of different RES policy instruments with respect to their static and dynamic efficiency and their effectiveness. In particular, within case study 7.3 the Green-X model will be applied to assess to what extent the optimal RES share at a given point in time derived from the cost-minimization model ENERTILE (and EMPIRE) can be achieved given the prevalence of non-economic barriers and other dynamic constraints.

The Green-X model will be coupled with several of the demand and supply models and will also receive relevant input data from the macro-economic models. The demand for energy in the different sectors is provided to Green-X via country-specific yearly values until 2050. The final energy demand in the electricity sector will be derived from the FORECAST model. The future heat demand will come from the INVERT model and demand for the transport sector will be provided by the ASTRA model. The generation mix and corresponding market prices and generator revenues in the electricity sector will be provided by the models Enertile and Empire. The results of these models will already contain dependencies from other crucial input parameters like the transmission grid expansion, or different primary fuel price assumptions. Input data on GDP from the macro-economic model NEMESIS and the primary energy carrier prices as well as carbon prices will come from the model MULTIMOD. In particular, the gas sector models EGMM and Ramona will provide Green-X country-specific gas prices. Location- and technology specific prices for heat delivery will be taken from the INVERT model results. Given this input data, Green-X will calculate a number of relevant indicators assessing direct and indirect costs and benefits of RES deployment.

8 RAMONA

8.1 Model description

RAMONA is a mixed-integer linear optimization model that includes both investment decisions and operational decisions in the gas network. Pressure-flow relationships, compressors, operation of processing facilities as well as multi-commodity flows are optional features in the model. RAMONA can handle different types of objective functions depending on the problem at hand, such as (expected discounted) cost minimization, and maximization of (expected) profit or social welfare. The model can handle several (strategic) infrastructure decisions such as development of new fields, construction and redesign of infrastructure (pipelines, compressors, processing plants). On the operational level, the model can handle the relationship between pressure and flow, gas quality, processing and security-of-supply restrictions. RAMONA, like EMPIRE, is a stochastic programming model using the multi-horizon framework. In RAMONA both long-term strategic uncertainty and short-term operational uncertainty can be defined. The figure below illustrates the stochastic tree formulation used in RAMONA.

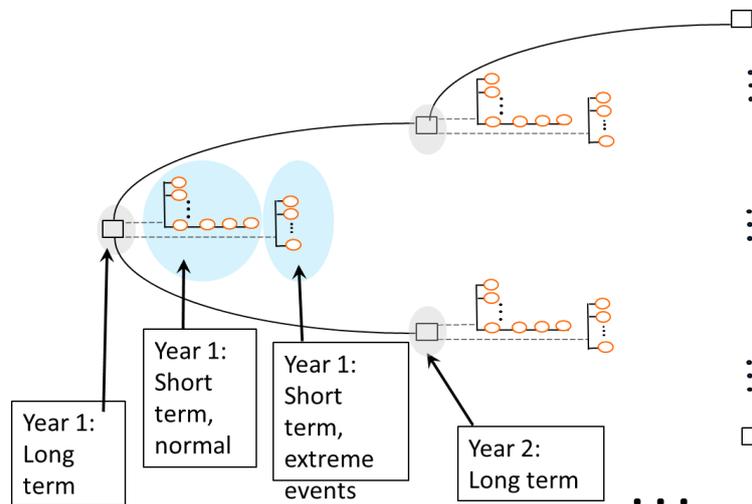


Figure 9. Multi-horizon tree formulation used in RAMONA. Squares indicate strategic decisions and circles indicate operational decisions.

There currently are two different data sets for RAMONA:

1. A detailed dataset of the Norwegian offshore natural gas infrastructure. This data set considers actual pipelines and major components of the natural gas system (compressors and processing plants).
2. An aggregate representation of the European natural gas system. In this data set each country is represented by a separate node in the network, and gas pipelines are aggregated to single cross-border interconnectors.

The following is a list of inputs and output for the RAMONA model

Inputs:

- Technology options (transport and field concepts)
- Resources (gas and oil)
- Production rates / profiles

- Capacities
- Time windows
- Costs
- Prices
- Rate of return

Outputs:

- Investment plan
- Operational decisions
- Cost of investment plan and system operation

8.2 Model extensions

The key ambition with RAMONA is to integrate it with EMPIRE to have common optimization of the infrastructure investments and operation in the electricity and the gas sector.

8.3 Model linkages

The RAMONA model will be linked to the EGMM model in task 6.3 and task 7.4

9 EGMM

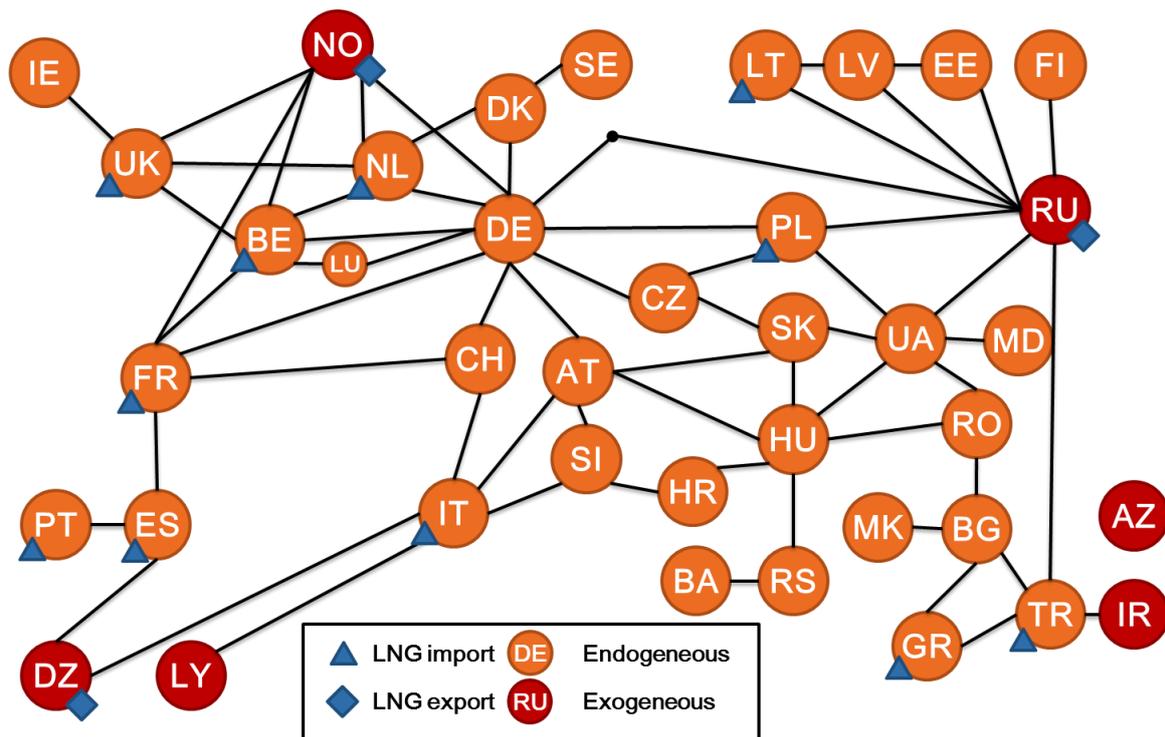
9.1 Model description

The EGMM is a competitive, dynamic, multi-market equilibrium model for natural gas production, trade, storage, and consumption in Europe. It explicitly includes a supply-demand representation of 35 European countries,¹ as well as their gas storages and transportation links to each other and to the outside world. The time frame of the model is 12 consecutive months, starting in April. Market participants have perfect foresight over this period.

REKK's European Gas Market Model has been developed to simulate the operation of an international wholesale natural gas market in whole Europe. 0 shows the geographical scope of the model. Country codes denote the countries for which we have explicitly included the demand and supply side of the local market, as well as gas storages. Large external markets, such as Russia, Iran, Libya, Algeria and LNG exporters are represented by exogenously assumed market prices, long-term supply contracts and physical connections to Europe.

Figure 10. The geographical scope of the European Gas Market Model

¹ Countries covered are EU-27 (not including Cyprus), Energy Community Contracting Parties (Albania, Ukraine, Moldova, Serbia, FYR of Macedonia, Bosnia and Herzegovina), Switzerland and Turkey



Given the input data, the model calculates a dynamic competitive market equilibrium for 35 European countries, and returns the market clearing prices, along with the production, consumption and trading quantities, storage utilization decisions and long-term contract deliveries.

Model calculations refer to 12 consecutive months, with a default setting of April-to-March.² Dynamic connections between months are introduced by the operation of gas storages (“you can only withdraw what you have injected previously”) and TOP constraints (minimum and maximum deliveries are calculated over the entire 12-month period, enabling contractual “make-up”). The European Gas Market Model consists of the following building blocks: (1) local demand; (2) local supply; (3) gas storages; (4) external markets and supply sources; (5) cross-border pipeline connections; (6) long-term take-or-pay (TOP) contracts; and (7) spot trading. We will describe each of them in detail below.

9.1.1 Local demand

Local *consumption* refers to the amount of gas consumed in each of the local markets in each month of the modelling year. It is, therefore, a quantity measure.³ Local *demand*, on the other hand, is a functional relationship between the local market price and local consumption, similarly specified for each month of the modelling year.

Local demand functions are downward sloping, meaning that higher prices decrease the amount of gas that consumers want to use in a given period. For simplicity, we use a linear functional form, the consequence of which is that every time the market price increases, local monthly consumption is reduced by equal quantities (as opposed to equal percentages, for example).

² The start of the modeling year can be set to any other month.

³ All quantities are measured in energy units within the model.

The linearity and price responsiveness of local demand ensures that market clearing prices will always exist in the model. Regardless of how little supply there is in a local market, there will be a high enough price so that the quantity demanded will fall back to the level of quantity supplied, achieving market equilibrium.

9.1.2 Local supply

Local *production* is a similar quantity measure as local consumption, so the corresponding counterpart to local demand is local *supply*. Local supply shows the relationship between the local market price and the amount of gas that local producers are willing to pump into the system at that price.

In the model, each supply unit (company, field, or even well) has either a constant, or a linearly increasing marginal cost of production (measured in €/MWh). Supply units operate between minimum and maximum production constraints in each month, and an overall yearly maximum capacity.⁴

Any number of supply units can be defined for each month and each local market. As a result, local supply will be represented by an increasing, stepwise linear function for which the number, size, and slope of steps can be chosen freely.

9.1.3 Gas storages

Gas storages are capable of storing natural gas from one period to another, arbitraging away large market price differences across periods. Their effect on the system's supply-demand balance can be positive or negative, depending on whether gas is withdrawn from, or injected into, the storage. Each local market can contain any number of storage units (companies or fields).

Storage units have a constant marginal cost of injection and (separately) of withdrawal. In each month, there are upper limits on total injections and total withdrawals. Storage fees are considered in a volumetric manner, which considers injection, withdrawal and working gas tariff items.

There are three additional constraints on storage operation: (1) working gas capacity, (2) starting inventory level, and (3) year-end inventory level. Injections and withdrawals must be such during the year that working gas capacity is never exceeded, intra-year inventory levels never drop below zero, and year-end inventory levels are met.

9.1.4 External markets and supply sources

Prices for external markets and supply sources are set exogenously (i.e. as input data) for each month, and they are assumed not to be influenced by any supply-demand development in the local markets. In case of LNG the price is derived from the forecasted Japanese spot gas price, taking into account the cost of transportation to any possible LNG import terminal. As a consequence, the price levels set for outside markets are important determinants of their trading direction with Europe. When prices of the external markets are set relatively low, European countries are more likely to import from the outside markets, and vice versa.

⁴ Minimum production levels can be set to zero. If minimum levels are set too high, a market clearing equilibrium may require negative prices, but this practically never happens with realistic input data.

9.1.5 Cross-border pipeline

Any two markets (local or outside) can be connected by any number of pipelines or LNG routes, which allow the transportation of natural gas from one market to the other. Connections between geographically non-neighbouring countries are also possible, which corresponds to the presence of dedicated transit routes.

Cross-border linkages are directional, but physical reverse flow can easily be allowed for by adding a parallel connection that “points” into the other direction. Each linkage has a minimum and a maximum monthly transmission capacity, as well as a proportional transmission fee.

Virtual reverse flow (“backhaul”) on unidirectional pipelines or LNG routes can also be allowed, or forbidden, separately for each connection and each month. The rationale for virtual reverse flow is the possibility to trade “against” the delivery of long-term take-or-pay contracts, by exploiting the fact that reducing a pre-arranged gas flow in the physical direction is the same commercial transaction as selling gas in the reverse direction.

Additional upper constraints can be placed on the sum of physical flows (or spot trading activity) of selected connections. This option is used, for example, to limit imports through LNG terminals, without specifying the source of the LNG shipment.

Furthermore, the model allows for constraining spot flows on infrastructure for interconnectors exempted / not under the jurisdiction of the European Regulation or booked long term by a major market player (eg. Trans-Balkans pipeline).

9.1.6 LNG infrastructure

LNG infrastructure in the model consist of LNG liquefaction plants of exporting countries, LNG regasification plants of importing countries and the “virtual pipelines” connecting them. “Virtual pipelines” are needed to define for each possible transport route a specific transport price. LNG terminals capacity is aggregated for each country, which differs from the pipeline setup, where capacity constraints are set for all individual pipeline. LNG capacity constraints are set as a limit for the set of “virtual pipelines” pointing from all exporting countries to a given importing country, and as a limit on the set of pipelines pointing from all importing countries to a given exporting country.

9.1.7 Long-term take-or-pay (TOP) contracts

A take-or-pay contract is an agreement between an outside supply source and a local market concerning the delivery of natural gas into the latter. The structure of a TOP contract is the following.

Each contract has monthly and yearly minimum and maximum quantities, a delivery price, a point of delivery and a monthly proportional TOP-violation penalty. Maximum quantities (monthly or yearly) cannot be breached, and neither can the yearly minimum quantity. Deliveries can be reduced below the monthly minimum, in which case the monthly proportional TOP-violation penalty must be paid for the gas that was not delivered.

Any number of TOP-contracts can be in force between any two source and destination markets. Monthly TOP-limits, prices, and penalties can be changed from one month to the next. Contract prices can be given exogenously, based on oil-indexed long term contract formulae.

The delivery routes (the set of pipelines from source to destination) must be specified as input data for each contract. It is possible to divide the delivered quantities among several parallel routes in pre-determined proportions, and routes can also be changed from one month to the next. The point of delivery may be set to any interconnector within the modelled system.

9.1.8 Spot trading

The final building block, spot trade, serves to arbitrage price differences across markets that are connected with a pipeline or an LNG route. Typically, if the price on the source-side of the connection exceeds the price on the destination-side by more than the proportional transmission fee, then spot trading will occur towards the high-priced market. Spot trading continues until either (1) the price difference drops to the level of the transmission fee, or (2) the physical capacity of the connection is reached.

Physical flows on pipelines and LNG routes equal the sum of long-term deliveries and spot trading. When virtual reverse flow is allowed, spot trading can become “negative” (backhaul), meaning that transactions go against the predominant contractual flow. Of course, backhaul can never exceed the contractual flow of the connection.

9.1.9 Equilibrium

The European Gas Market Model algorithm reads the input data and searches for the simultaneous supply-demand equilibrium (including storage stock changes and net imports) of all local markets in all months, respecting all the constraints detailed above.

In short, the equilibrium state (the “result”) of the model can be described by a simple no-arbitrage condition across space and time.⁵ However, it is instructive to spell out this condition in terms of the behaviour of market participants: consumers, producers and traders.⁶

Local consumers decide about gas utilization based on the market price. Consumers in each market within the region are represented by a linear monthly gas demand function that only depends on the contemporaneous local wholesale price of gas.

Local producers have piecewise linear short-run cost functions, with upper and lower limits on monthly production and a separate upper constraint on yearly output. Local producers decide about their gas production level in the following way: if market prices in their country of operation are higher than unit production costs, then they produce gas at full capacity. If prices fall below costs, then production is cut back to the minimum level (possibly zero). Finally, if prices and costs are exactly equal, then producers choose some amount between the minimum and maximum levels, which is actually determined in a way to match the local demand for gas in that month.

Traders in the model are the ones performing the most complex optimization procedures. First, they decide about long-term contract deliveries in each month, based on contractual constraints (prices, TOP quantities, penalties) and local supply-demand conditions. Importers own long-term take-or-pay (TOP) contracts that are sourced from gas exporters in outside markets, most importantly from Russia, Norway, Algeria, and a number of LNG exporting countries. Each contract specifies a price, a delivery route, and a minimum and maximum delivered quantity per month and per year. The monthly minimum delivery constraint alone is flexible: it can be violated, but most of the undelivered gas must be paid for according to the TOP rules.

Second, traders also utilize storages to arbitrage price differences across months. For example, if market prices in January are relatively high, then they withdraw gas from storage in January and

⁵ There is one, rather subtle, type of arbitrage which is treated as an externality, and hence not eliminated in the model. We assume that whenever long-term TOP contracts are (fully or partially) linked to an internal market price (such as the spot price in the Netherlands), the actors influencing that spot price have no regard to the effect of their behavior on the pricing of the TOP contract. In particular, reference market prices are not distorted downwards in order to cut the cost of long-term gas supplies from outside countries.

⁶ We leave out storage operators, since injection and withdrawal fees are set exogenously, and stock changes are determined by traders.

inject it back in a later month in such a way as to maximize the difference between the selling and the buying price. As long as there is available withdrawal, injection and working gas capacity, as well as price differences between months exceeding the sum of injection costs, withdrawal costs, and the foregone interest, the arbitrage opportunity will be present and traders will exploit it.^{7,8}

Finally, traders also perform spot transactions, based on prices in each local and outside market and the available cross-border transmission capacities to and from those markets, including countries such as Russia, Turkey, Libya, Algeria or LNG markets, which are not explicitly included in the supply-demand equalization.

Besides the actors listed above, the EGMM considers infrastructure operators as well. TSOs, SSOs and LNG operators however are not active actors within our modelling framework. The infrastructure operators merely observe the gas flows utilising their infrastructure and earn revenues based on the utilisation. Since all actors exhibit price-taking behaviour, the equilibrium is welfare-maximising for all market participants.

9.1.10 Welfare analysis

The changes of socio-economic welfare are estimated with the net benefits (benefits minus cost) that the individual projects can bring to the analysed region. Total positive socio-economic welfare accounted for in the NPV of a modelled period (year) is calculated as the sum of welfare change of all market participants:

- Consumer surplus [to consumers]
- Producer surplus (or short-run profit, excluding fixed costs) [to producers]
- Profit on long-term take-or-pay contracts [to importers]
- Congestion revenue on cross-border spot trading [to TSOs]
- Cross-border transportation profit (excluding fixed costs) [to TSOs]
- Storage operation profit (excluding fixed costs) [to SSOs]
- Profit on inter-temporal arbitrage via gas storage [to traders]
- Profit of LNG operators [to LNG operators]

Welfare change for each market participant is assigned with a weight of 1:1.

Table 1: Summary of modelling input parameters and data sources

⁷ Traders also have to make sure that storages are filled up to their pre-specified closing level at the end of the year, since we do not allow for year-to-year stock changes in the model.

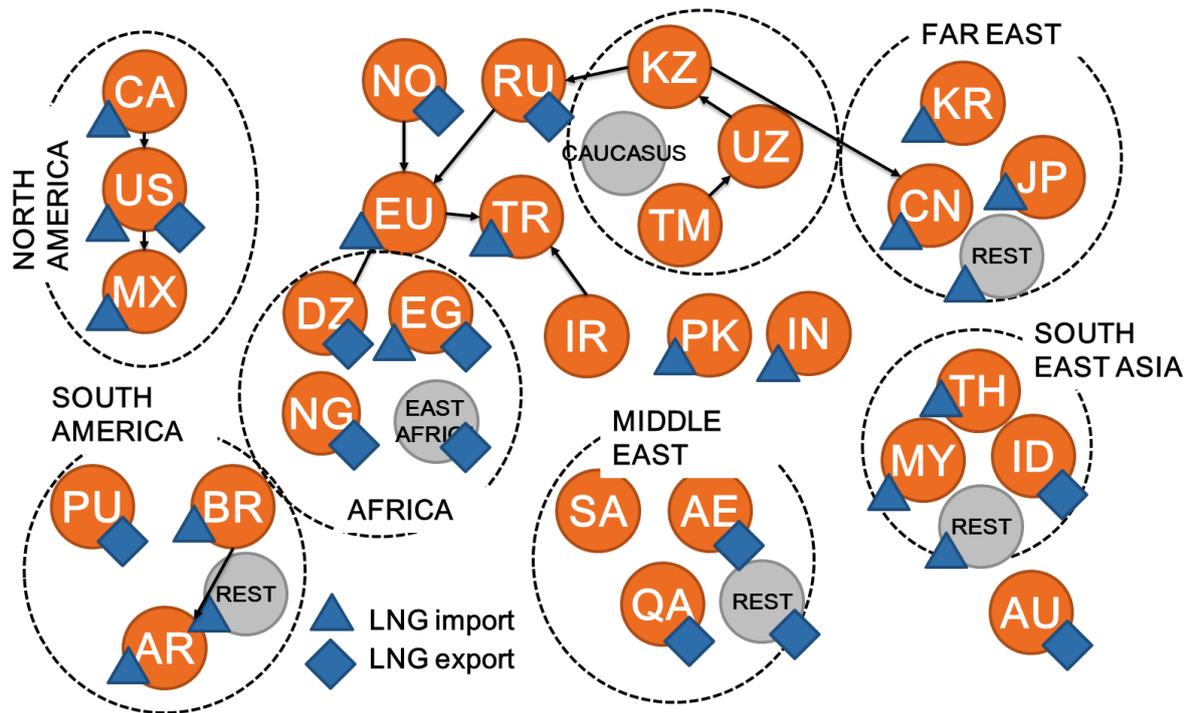
⁸ A similar intertemporal arbitrage can also be performed in markets without available storage capacity, as long as there are direct or indirect cross-border links to countries with gas storage capability. In this sense, flexibility services are truly international in the simulation.

Category	Data Unit	Source
Consumption	Annual Quantity (TWh/year) Monthly distribution (% of annual quantity)	PRIMES Reference, supplemented by Energy Community or Eurostat data if applicable
Production	Minimum and maximum production (GWh/day)	PRIMES Reference, supplemented by Energy Community or Eurostat data if applicable
Pipeline infrastructures	Daily maximum flow (GWh/day)	GIE, ENTSO-G, Energy Community data
Storage infrastructures	Injection (GWh/day), withdrawal (GWh/day), working gas capacity (TWh)	GSE
LNG infrastructures	Regasification capacity (GWh/day)	GLE, GIIGNL
LTC contracts	Yearly minimum maximum quantity, Seasonal minimum and maximum quantity	Gazprom, National Regulators Annual reports, Eurostat, Platts, Cedigaz
Storage, LNG regasification and transmission tariffs	€/MWh	TSO, SSO, LSO webpages

9.2 Model extensions

The EGMM performs well for short and mid-term (up to 10-15 years) infrastructure and tariff analyses. However, on the longer term the results received by the model are more difficult to interpret due to the simplistic representation of the LNG market and major producers' behaviour (Norway, Russia, Algeria and Qatar). For this reason, we aim to extend the geographical scope of the modelling to the global scale, incorporating the major players on both consumption and production side. The mathematical fundamentals and assumptions on market players, equilibria are left intact – i.e. on a global scale, we assume a perfectly competitive gas market, constrained by infrastructure and existing contractual obligations (LTC).

Figure 11. Main nodes of production and consumption, interconnectors and LNG infrastructure



Extending the EGMM to a global scale would allow for the endogenous calculation of LNG supply to Europe and spot flows from major producers.

9.3 Model linkages

EGMM will be linked with RAMONA to get a better understanding of Norwegian offshore investments. Other interlinkages are not envisaged.

10 Nexus security model

10.1 Model description

The Nexus security model is developed by the Reliability and Risk Engineering (RRE) laboratory and is a part of the Nexus energy system platform commenced at the ETH Zurich. The core of the Nexus security model is based on a cascading outages simulation model that is capable of capturing power system operations and automations. The goal of the model is to assess the security of the supply by testing the capability of a power system, which has large share of intermittent generators, to withstand sudden unexpected changes (e.g. loss of power line, loss of generating unit). The model provides insights into the adequacy of the capacity of the transmission system and the adequacy of flexibility providers. The model is instrumental in identifying the regions of the system parameters that have to be avoided in order to prevent the propagation of cascading failures in the system, and in developing mitigating actions against the onset and the propagation of cascading failures.

The Nexus security model is characterized by the following functions: (1) simulates critical scenarios which may trigger a cascading event; (2) identifies if there is island operation in the system; (3) it employs primary and secondary frequency control of generators to restore the power generation/consumption balance in case of power imbalance in the system or in the islands generated [1]; (4) it conducts load shedding when the frequency exceeds the acceptable

threshold or the voltage magnitude at a bus is under the limit; (5) it identifies blackout conditions in island operation when the power imbalance in the island is so large to cause frequency instability [1, 2]; (6) it computes the load flow change on the transmission lines using a linear AC power flow model [3]; (7) it simulates the transient dynamic of line temperature and performs automatic disconnection when the line reaches its failure threshold. The general structural of the model is presented in *Figure 12*.

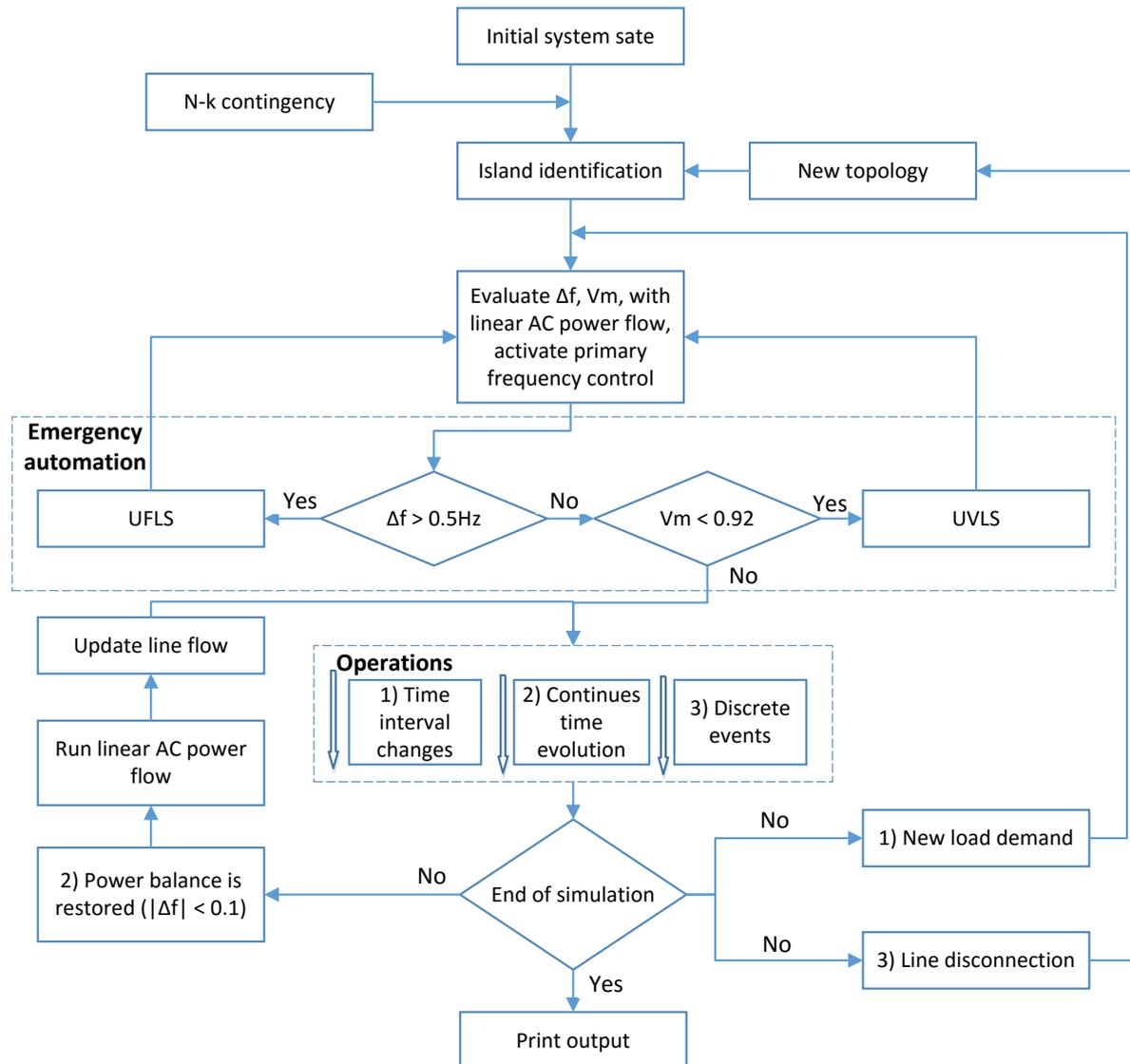


Figure 12: Nexus security model flow chart.

At the initial system state (*Figure 12*) it is considered that all of the devices scheduled for operation in the system are in service and load demands are equal to the forecast. Single or multiple line and generator contingencies are selected to simulated sudden (unexpected) changes with the objective of testing the resilience of the power system. The selected component(s) is removed from the system. The contingencies can be selected by the user or by simulating component failure using the Monte Carlo method. After the contingencies are initiated, the topology of the system is checked for islands. The frequency and voltage deviations are calculated and based on the obtained values certain actions are preformed, as shown in *Figure 12*. These actions are modeled to simulate the power system automation as well as certain protocols undertaken by power system operators.

Coverage and data structure

The Nexus security model can be applied to any power system or interconnected systems. To run the analyses the model requires the electric network topology, power plant characteristics (type, location, capacity, ramp rates, minimum stable generation, minimum up/down time), transmission system data (line parameters, bus parameter, relay parameters), hourly load demands at each bus and hourly air temperatures (average temperatures can be used for simplification).

Model outputs

The Nexus security model is providing assessment of the resilience of the system such that:

- Identifies vulnerabilities in the system
- Regions of the system parameters that have to be avoided
- Based on the performed N-k contingencies provides:
 - the progress of cascading failures
 - the number of lines tripped
 - the amount of load shading at each bus
 - the total demand not served (DNS).

Involvement in SET-Nav

The Nexus security model is involved in Task 7.4: Case Study: Unlocking unused flexibility and synergy in electric power and gas supply systems.

10.2 Model extensions

The model is extended with enhancement of the simulation of the power system automation by including: under voltage load shedding (UVLS) scheme; autotransformer voltage regulation by simulation the on-line tap changer, also a Monte Carlo method is implemented to simulate the contingencies (random failure of component in the system).

10.3 Model linkages

The Nexus security model will be linked with EMPIRE and RAMONA.

References

- [1] Kirschen DS, Bell KRW, Nedic DP, Jayaweera D, Allan RN. Computing the value of security. IEE Proceedings - Generation, Transmission and Distribution. 2003;150:673-8.
- [2] Alizadeh Mousavi O, Bozorg M, Cherkaoui R, Paolone M. Inter-area frequency control reserve assessment regarding dynamics of cascading outages and blackouts. Electric Power Systems Research. 2014;107:144-52.
- [3] Bolognani S, Dörfler F. Fast Power System Analysis via Implicit Linearization of the Power Flow Manifold. 53rd Annual Allerton Conference on Communication, Control, and Computing 2015.

11 Summary

In WP7 a variety of supply side and infrastructure models are utilized in order to analyse developments in energy supply. Among these are the electricity supply models such as **Enertile** and **EMPIRE**, which are complemented by the security of supply model **NEXUS-Security** and **Green-X** model, which is specialized on the development of renewables. Both electricity models

are complemented by the gas infrastructure model **RAMONA**, the gas market model **EGMM** and the electricity grid model **TEPES**. These models are combined in different case studies. Case study 6.2/7.2 on “Decentralised vs. centralised development of the electricity sector- impact on the transmission grid” combines TEPES and Enertile to analyse the impact of different supply strategies on the electricity grid. The models Green-X, Enertile and Empire are combined to analyse the interaction between diffusion of renewable electricity generation and the electricity system in case study 7.3. Case study 7.4 “Flexibility and synergy in electric power and gas supply systems” analyses the interactions between the electricity sector and the gas sector. In this case study, the models Empire, Ramona, TEPES, EGMM and Nexus security are combined.

12 Appendix

This appendix details the data flows in the case studies.

12.1 Case study 7.2 Decentralised vs. centralised development of the electricity sector- impact on the transmission grid” combines TEPES and Enertile to analyse the impact of different supply strategies on the electricity grid

The detailed data flows of case study 6.2/7.2 are documented in the working paper on WP6.

12.2 Case study 7.3 Diffusion rate of renewable electricity generation

One important aspect of the model interaction is the different time resolution of the exchanged data. Whereas the power system models Enertile and EMPIRE mostly works with hourly data resolution, Green-X works on a yearly time resolution. However, since hourly resolution is necessary to derive market value of fluctuating RES, Enertile delivers market values, electricity prices and RES generation and Green-X will take the yearly averages of these values as input.

Green-X covers all years from present to 2050. Enertile covers only certain years (5 or 10 years time steps depending on the area and flexibility options covered). For this case study, covering EU 28, N, CH, Balkans, 10 year time steps will be calculated. Input data for intermediate years have to be determined by interpolation.

12.2.1 A - Standardized data

This first category of datasets (“Standardized data”) contains data that is relevant for the pathway analysis and the energy balance or emission balance of the system. In the end, this data should be part of a predefined data structure, which will be **the same for all case studies**. When the data exchange structure for all case studies is defined, the data that is general for the project needs to be revised carefully. The following table gives a first suggestion. We also recommend a revision of the terminology at this point.

Catagory	Structure	Level	Keys
Dataset key	Model	General	Enertile, Empire, Green-X, WP3, Case Study
Dataset key	Unique ScenarioID	General	xxxx
Dataset key	Output/Secondary		
Dataset key	Fuel	specific for each data flow	
Data keys	Perspective	specific for each data flow	
Data keys	Supertype	specific for each data flow	
Data keys	Type	specific for each data flow	
Data keys	Subtype	specific for each data flow	
Data keys	Param/Fuel	specific for each data flow	
Data keys	subparam	specific for each data flow	
Time Key	Year	general	Yearly from 2006 to 2050
Time Key	Hour	specific for each data flow	0,1,2,...,8759 in UTC+1 or empty
Time Key	Country	general	EU 28, N, CH, Balkans
Data	Region	general	n.a.
Data	Value		
Data	Unit	specific for each data flow	

12.2.2 Electricity generation

Optimization models report electricity generation to Green-X.

Catagory	Structure	Keys
Dataset key	From	Enertile, Empire
	To	Green-X
	Unique ScenarioID	xxxx
	Output/Secondary Fuel	Electricity
Data key	Perspective	Electricity Sector
	Supertype	Generation
	Type	Generation
	Subtype	
	Param/Fuel	
	subparam	
Time Key	Year	2020, 2030, 2040, 2050
	Hour	empty
Geographical key	Country	EU 28, N, CH, Balkans
	Region	n.a.
Data	Value	
	Unit	MWh

12.2.3 Electricity prices

Optimization models report electricity prices to Green-X.

Catagory	Structure	Keys
Dataset key	From	Enertile, Empire
	To	Green-X
	Unique ScenarioID	xxxx
	Output/Secondary Fuel	Electricity
Data key	Perspective	Electricity Sector
	Supertype	Prices
	Type	Electricity prices
	Subtype	
	Param/Fuel	
	subparam	
Time Key	Year	2020, 2030, 2040, 2050
	Hour	empty
Geographical key	Country	EU 28, N, CH, Balkans
	Region	n.a.
Data	Value	
	Unit	Euros 2016 per MWh

12.2.4 Market values

Optimization models report market values to Green-X.

Catagory	Structure	Keys
Dataset key	From	Enertile, Empire
	To	Green-X
	Unique ScenarioID	xxxx
	Output/Secondary Fuel	Electricity
Data key	Perspective	Electricity Sector
	Supertype	Prices
	Type	Market value of RES-E
	Subtype	
	Param/Fuel subparam	
Time Key	Year	2020, 2030, 2040, 2050
	Hour	empty
Geographical key	Country	EU 28, N, CH, Balkans
	Region	n.a.
Data	Value	
	Unit	Euros 2016 per MWh

12.2.5 Capital costs

Capital costs will be assessed for different learning sensitivities. First input will come from WP3. Then Green-X will provide Learning rates for a given optimal share of RES-E that has been determined by optimization models. The altered cost structures feedback to optimization models until robust equilibrium is achieved.

Catagory	Structure	Keys
Dataset key	From	WP3, Green-X
	To	Enertile, Empire, Green-X, Analysis
	Unique ScenarioID	xxxx
	Output/Secondary Fuel	Electricity
Data key	Perspective	Electricity Sector
	Supertype	Costs
	Type	Capital costs
	Subtype	
	Param/Fuel subparam	
Time Key	Year	2020, 2030, 2040, 2050
	Hour	empty
Geographical key	Country	EU 28, N, CH, Balkans
	Region	n.a.

Data	Value
	Unit Euros 2016 per kW

12.2.6 B - Special data

This second category of datasets deals with specialized data that needs to be exchanged between models but is not necessarily needed in the aggregate pathway analysis within this project. These data should only be documented but not forced into a defined structure.

12.2.7 B01 Non market valuation of RES-E generation

From the stakeholder consultation non-market values for RES-E generation will be assessed, to account for positive externalities. In order to determine the optimal share of RES-E accounting for these externalities the valuations will be used to reduce capital costs in the optimization models, respectively to increase the market value in Green-X.

Catagory	Structure	Keys
Dataset key	From	Stakeholder
	To	Enertile, Empire, Green-X, Analysis
	Unique ScenarioID	xxxx
	Output/Secondary	
Data key	Perspective	Economy
	Supertype	
	Type	
	Subtype	
	Param/Fuel	External benefits
	subparam	
Time Key	Year	2020, 2030, 2040, 2050
	Hour	
Geographical key	Country	EU 28, N, CH, Balkans
	Region	n.a.
Data	Value	
	Unit	Euros 2016 per kW / MWh

12.3 Case study 7.4 - Unlocking unused flexibility and synergy in electric power and gas supply systems

The detailed documentation includes a short description of the data as well as proposed data keys for the standardized data structure. Short examples for data exchanges are provided in an Excel Sheet.

12.3.1 A – Standardized data

This first category of datasets (“Standardized data”) contains data that is relevant for the pathway analysis and the energy balance or emission balance of the system. In the end, this data should be part of a predefined data structure, which will be **the same for all case studies**. When the data exchange structure for all case studies is defined, the data that is general for the project needs to be revised carefully. The following table gives a first suggestion. We also recommend a revision of the terminology at this point.

As EMPIRE and RAMONA represents the electricity/gas operation using representative seasons (days) with an hourly resolution the ‘Time Key’ will differ from what is used with Enertile. Furthermore, due to the stochastic programming formulation of these models the operational hours are indexed by stochastic scenarios. This creates an additional deviation from the originally proposed format.

Category	Structure	Level	Keys
Dataset key	Model	general ⁹	TEPES, EMPIRE, Ramona
	Unique ScenarioID	general ¹	xxxx
	Output	specific for each data flow	
Data keys	Perspective	specific for each data flow	
	Supertype	specific for each data flow	
	Type	specific for each data flow	
	Subtype	specific for each data flow	
	Param/Fuel	specific for each data flow	
	subparam	specific for each data flow	
Time Key	Year	general ¹	2050
	Hour	specific for each data flow	0,1,2,...,8759 in UTC+1 or empty
Geographical key	Country	general ¹	as defined in Region-Shapefile
	Sub-Region	general for case study	as defined in Region-Shapefile
Data	Value		
	Unit	specific for each data flow	

⁹ general for the project, super-regions can be defined for the overall project but don’t have to be declared, if all countries are declared. If your case study/model cannot cover countries but only super-regions consisting of two or more countries, this need to be discussed

12.3.2 Electricity generation

This dataflow contains all annual and hourly generation data for a given region. This data has to follow two important rules. Firstly, energy that is put into the system (electricity generation, pump storage electricity generation) is always positive and energy that is taken out of the system (demand/export/pumping) is always negative. Secondly, the sum of all generation data is always zero for all timescales and regions¹⁰.

Category	Structure	Keys
Dataset key	from model	EMPIRE
	into model	TEPES, NEXUS Security, Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Heat
Data keys	Perspective	Electricity Sector, Heat Sector
	Supertype	Generation
	Type	Generation
	Subtype	Renewables, Conventional, Demand, Storage, Trading
	Param/Fuel	Wind, PV, Gas, Coal, Lignite, Demand, Pump storage, Export, Import,...
	subparam	onshore, offshore, rooftop, open-field, GT, CCGT, CHP, ST, pump, generation, Heat pump, el. Vehicle, DE_0, DE_1, FR_0...
Time Key	Year	2050
	Hour	empty for annual data, or following EMPIRE's operational resolution (hourly in representative seasons)
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	MWh

¹⁰ This may be confusing if you look at this system from the perspective of a different sector, but for a case study with a strong focus on the electricity system. This approach has the advantage, that it is easy to check the simultaneous generation and consumption for all time steps. For other sectors with less restrictive time constraints, it may not be necessary to include demand and generation in one data flow.

12.3.3 Electricity capacities

This dataflow contains all capacity data for generation units and NTC capacities of interconnectors

Category	Structure	Keys
Dataset key	from model	EMPIRE, TEPEs
	into model	EMPIRE, TEPEs, NEXUS Security, Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Heat
Data keys	Perspective	Electricity Sector, Heat Sector
	Supertype	Capacity
	Type	Capacity
	Subtype	Renewables, Conventional, Storage, Trading,
	Param/Fuel	Wind, PV, Gas, Coal, Lignite, Demand, Pump storage, Export, Import, ...
	subparam	onshore, offshore, rooftop, open-field, GT, CCGT, CHP, ST, pump, generation, Heat pump, el. Vehicle, DE_0, DE_1, FR_0...
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	MW

12.3.4 Investments

This dataflow contains all investments into generation units, storage and NTC capacities

Category	Structure	Keys
Dataset key	from model	TEPES, EMPIRE
	into model	EMPIRE, TEPES, Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Heat
Data keys	Perspective	Electricity Sector, Heat Sector
	Supertype	Investment
	Type	Investment
	Subtype	Renewables, Conventional, Storage, Trading
	Param/Fuel	Wind, PV, Gas, Coal, Lignite, Demand, Pump storage, ...
	subparam	onshore, offshore, rooftop, open-field, GT, CCGT, CHP, ST, pump, generation, Heat pump, el. Vehicle, DE_0, DE_1, FR_0...
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	Euro

12.3.5 Electricity Costs

This dataflow contains all annual cost (Annuity of investments, O&M, fuel cost) of electricity generation, storage and interconnectors

Category	Structure	Keys
Dataset key	From model	EMPIRE
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Heat
Data keys	Perspective	Electricity Sector, Heat Sector
	Supertype	Cost
	Type	Capital Cost, OandM Cost, CO2-Cost, Fuel Cost
	Subtype	Renewables, Conventional, Storage, Trading
	Param/Fuel	Wind, PV, Gas, Coal, Lignite, Demand, Pump storage, ...
	subparam	onshore, offshore, rooftop, open-field, GT, CCGT, CHP, ST, pump, generation, Heat pump, el. Vehicle, DE_0, DE_1, FR_0...
Time Key	Year	2050
	Hour	empty
Geographic al key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	Euro

12.3.6 Electricity emissions

This dataflow contains all emissions (CO₂ equivalents) of power generation

Category	Structure	Keys
Dataset key	From model	EMPIRE
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Heat
Data keys	Perspective	Electricity Sector, Heat Sector
	Supertype	Emissions
	Type	CO2
	Subtype	Conventional
	Param/Fuel	Gas, Coal, Lignite, ...
	subparam	GT, CCGT, CHP, ST
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	t CO2 eq

12.3.7 Electricity fuel consumption

This dataflow contains all fuels consumed for electricity and heat generation covered by the model

Category	Structure	Keys
Dataset key	From model	EMPIRE
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity, Heat
Data keys	Perspective	Electricity Sector, Heat Sector
	Supertype	Fuel consumption
	Type	Fuel consumption
	Subtype	Conventional
	Param/Fuel	Gas, Coal, Lignite
	subparam	GT, CCGT, CHP, ST
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	MWh

12.3.8 Detailed grid cost

This dataflow contains an estimation of all cost related to the electricity grid

Category	Structure	Keys
Dataset key	From model	TEPES
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Electricity
Data keys	Perspective	Electricity Sector
	Supertype	Grid
	Type	??
	Subtype	??
	Param/Fuel	??
	subparam	DE_0, DE_1, FR_0...
Time Key	Year	2020, 2030, 2040, 2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	Euro

12.3.9 Gas infrastructure

This dataflow contains the natural gas infrastructure data available from Ramona.

Category	Structure	Keys
Dataset key	from model	Ramona
	into model	EGMM, NEXUS security, Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Natural Gas
Data keys	Perspective	Natural Gas
	Supertype	Infrastructure
	Type	Infrastructure
	Subtype	Storage, Trading
	Param/Fuel	Import, Export, Storage
	subparam	?
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	GWh/day

12.3.10 Gas operation

This dataflow contains an estimation the various operational elements of the natural gas sector.

Category	Structure	Keys
Dataset key	From model	RAMONA
	into model	EGMM, NEXUS security, Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Natural Gas
Data keys	Perspective	Natural Gas Sector
	Supertype	Operation
	Type	Operation
	Subtype	Production, Demand, Storage, Trading
	Param/Fuel	Gas producer, Storage, Pipelines...
	subparam	?
Time Key	Year	2020, 2030, 2040, 2050
	Hour	empty for annual data, or following RAMONA's operational resolution (hourly in representative seasons)
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	MW

12.3.11 Gas Investments

This dataflow contains all investments into generation units, storage and NTC capacities.

Category	Structure	Keys
Dataset key	from model	Ramona
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Natural Gas
Data keys	Perspective	Natural Gas
	Supertype	Investment
	Type	Investment
	Subtype	Storage, Trading
	Param/Fuel	Import, Export, Storage
	subparam	?
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	Euro

12.3.12 Gas costs

This dataflow contains all annual cost (Annuity of investments, O&M, fuel cost) from the natural gas sector.

Category	Structure	Keys
Dataset key	From model	Ramona
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Natural Gas
Data keys	Perspective	Natural Gas
	Supertype	Cost
	Type	Capital Cost, OandM Cost, CO2-Cost, Production Cost
	Subtype	Production, Storage, Trading
	Param/Fuel subparam	Gas producer, Storage, Pipelines... ?
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	Euro

12.3.13 Gas emissions

This dataflow contains all emissions (CO₂ equivalents) of the natural gas sector.

Category	Structure	Keys
Dataset key	From model	Ramona
	into model	Analysis
	Unique ScenarioID	xxxx
	Output/ Secondary Fuel	Natural Gas
Data keys	Perspective	Natural Gas
	Supertype	Emissions
	Type	CO2
	Subtype	Production, Demand
	Param/Fuel	Gas producer, Demand
	subparam	?
Time Key	Year	2050
	Hour	empty
Geographical key	Country	as defined in Region-Shapefile
	Region	as defined in Region-Shapefile
Data	Value	
	Unit	t CO2 eq

12.4B - Special data

This second category of datasets deals with specialized data that needs to be exchanged between models but is not necessarily needed in the aggregate pathway analysis within this project. These data should only be documented but not forced into a defined structure.

12.4.3 Region definition

GIS Shape file containing all regions. Shapefiles include countries as well as sub-regions

Example:



12.4.4 Existing transport capacity between regions

NTC Transport capacity that can be utilized throughout the year.

Example:

B) Existing NTC between regions			
FROM region	TO region	Capacity	Unit
DE_1	DE_2	1000	MW

12.4.5 Investment Options for the grid

Investment options for the extension of the grid

Example:

C) Invest Options grid									
FROM region	TO region	STEP	Available in year	Invest €/kW	Maximum MW	Lifetime	O&M €/kW a	Interest rate	Losses
DE_1	DE_2	1	2030	250	1000	50	20	7%	3%
DE_1	DE_2	2	2040	500	3000	50	20	7%	3%

12.4.6 Gas production costs

Production costs from RAMONA

	Marginal production costs
	Euro/Sm3
DE	6

12.4.7 Gas demand

Natural gas demand from EGMM. Demand has low elasticity.

	Yearly quantity
	TWh/month
DE	

12.4.8 Gas prices

Natural gas prices from EGMM.

	Monthly average price
	Euro/GWh
DE	

12.4.9 System security/reliability indices electricity/gas

Output from NEXUS for the overall analysis:

- Demand not served (DNS)
- Cascading failures occurrences;
- Estimation of gas curtailments;
- Linepack variations.