

École polytechnique de Louvain

Study of the electricity transition for Western Europe: a comparison between EROI and ROI

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Academic year 2018–2019

Master [120] in Electro-mechanical Engineering

Abstract

Driven by concerns about global warming and limited energy resources, the European Union has set ambitious targets for the reduction of greenhouse gas emissions. The electricity sector is projected to play a key role in this decarbonisation. For analysing possible transition pathways for the decarbonisation of the energy system, long-term planning and careful research is required. Energy system optimisation models are often used to model power systems and plan future investments. Frequently, these models minimise the Levelised Cost Of Energy (LCOE). In 2018, a model that maximises the Energy Return On Investment (EROI) was developed at UCLouvain to simulate the energetic transition of Western-Europe. This model is compared to a state-of-the-art commercial model, PLEXOS by Energy Exemplar. Thanks to this comparison between an LCOE based energy system optimisation model and an EROI based model, this study was able to highlight notable results. The impact of not having a cheap storage solution in a system with a 100% renewable energy sources penetration has been shown. The optimal energy systems from both models have been compared to the European Commission's Reference Scenario. Finally, the LCOE has been shown to increase with an increasing share of renewables.

Acknowledgements

First of all, I would like to thank my master thesis supervisor Professor Hervé Jeanmart for the advices he gave me during the writing of this thesis.

As readers, I would like to thank Professor Emmanuel De Jaeger, Véronique Dias, Élise Dupont and Professor Gian-Marco Rignanese.

My gratitude goes to Gauthier Limpens for always being there to help me when I needed it. His advices always gave me the strength to pursue this thesis.

A special thanks goes to Oscar de Giey with whom I spend some time refactoring and improving the EROI model.

Thank you to my parents and brothers who supported me through these 5 years at the EPL.

Finally, I would like to thank Lugovine Louchez, her parents and Christian Courtois for the support they gave me during the writing of this thesis.

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List of abbreviations

BI	British Isles
CCGT	Combined Cycle Gas Turbine
EROI	Energy Return On (energy) Investment
ESOI	Energy Stored On (energy) Investment
EU	European Union
EURS	European Union Reference Scenario
EROMI	Energy Return On Monetary Investment
FOM	Fixed Operation and Maintenance (costs)
FR	France
GB	Germany & Benelux
HVDC	High Voltage Direct Current
IA	Italy & Alpine States
IP	Iberian Peninsula
LCOE	Levelised Cost Of Energy
LCOS	Levelised Cost Of Storage
LDC	Load Duration Curve
LP	Linear Programming
LT	Long-Term
OECD	Organisation for Economic Co-operation and Development
PHES	Pumped Hydroelectric Energy Storage
PtG	Power to Gas
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
SC	Scandinavia
VOM	Variable Operation and Maintenance (costs)
WT	Wind Turbine
WToff	Offshore Wind Turbine
WTon	Onshore Wind Turbine

Chapter 1

Introduction

1.1 Context

Concerns are raised about global warming and limited energy resources. In 2010 the energy supply sector was responsible for approximately 35% of all greenhouse gas emissions [1] and at the end of 2018, oil and natural gas reserves accounted for only 50 years of current production while coal reserves accounted for 132 years [2]. The International Energy Agency even stated that “no more than one-third of proven reserves of fossil fuels can be consumed prior to 2050 if the world is to achieve the 2 °C goal, unless carbon capture and storage (CCS) technology is widely deployed” [3].

Driven by these concerns, the European Union has set ambitious targets for the reduction of greenhouse gas emissions. In 2009, the leaders of the European Union announced an objective to reduce greenhouse gas emissions by at least 80% below 1990 levels by 2050. The feasibility and challenges of realizing this objective are discussed in the Energy Roadmap 2050 [4]. Several possible pathways to achieve this level of decarbonisation have been analysed. In all considered pathways, the electricity sector is projected to play a key role, with greenhouse gas emissions reductions in this sector projected to be in the range of 93-99% by 2050. This decarbonisation of the electricity sector relies strongly on renewable energy sources such as wind power generation and solar photovoltaic (PV) power generation.

For analysing possible transition pathways for the decarbonisation of the energy system, long-term planning and careful research is required. Energy system optimisation models are often used to model and understand modern power systems. These models consider the complex inter-temporal, inter-sectoral and inter-regional relationships of the power system spanning over multiple countries and multiple decades [5].

Frequently, these models are formulated as optimisation models where the objective is to minimise the levelised cost of energy (LCOE) [6–11]. The LCOE is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis. It is defined as the ratio of the total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. In the case of energy systems, this metric is often adapted to the ratio of the total cost to generate electricity, including build and operation costs, over the electricity consumed. This adaptation considers the curtailment of the electricity sources and the costs of storage technologies. On an annual basis, the adapted LCOE would be

defined as follows:

$$\text{LCOE} = \frac{\text{Annualised total system costs}}{\text{Annual energy consumption}}$$

The energy return on investment (EROI) is another metric that can be used by energy system optimisation models [12]. It is defined as the ratio of the useful energy delivered from a process to the energy required to get it [13]. Like the LCOE, this metric can be adapted to fit energy systems by considering the energy consumed instead of the energy delivered. The adapted EROI would be defined as follows:

$$\text{EROI} = \frac{\text{Energy consumed}}{\text{Total energy invested}}$$

1.2 Previous research

In the literature a large choice of energy system optimisation models can be found. An extensive review of these modelling tools can be found in [14].

The EROI model used in this study is based on the work of Limpens [15], Ramelot & Martinelle [12] and de Giey [16]. Limpens first developed an EROI based model to study the electricity storage needs for the energy transition of Belgium. Ramelot & Martinelle further developed the model and studied 100% renewable electricity systems for Western Europe. Finally, de Giey implemented typical days capabilities to the model and conducted studies on the Western Europe energy system.

The LCOE model used in this study is based on the work of Brouwer [11] who studied least-cost options for integrating intermittent renewables in a low-carbon Western-Europe in 2050. His study was conducted with the PLEXOS hourly power system simulation tool. The same tool will be used in this study. PLEXOS is one of the most used commercial models with applications in the academia [17–19].

1.3 Our contribution

In this thesis, we develop an LCOE based energy system optimisation model with PLEXOS and compare it with an EROI based model. The comparison is performed on multiple scenarios:

- A two-cells 100% renewable energy system composed of France and Germany & Benelux where the economic costs used to calculate the LCOE have been adapted to try to obtain similar results from both models.
- A two-cells 100% renewable energy system composed of France and Germany & Benelux where the real economic costs are used.
- A six-cells 100% renewable energy system of Western-Europe.
- A scenario where the non-renewable production of Western Europe is fixed and corresponds to the EU Reference Scenario for the year 2030.
- A transition scenario where the minimum renewable production share increases from 40% to 100% every year.

This master thesis is articulated as follows: Chapter 2 describes both the EROI and PLEXOS model and the main differences in their implementation is detailed. In Chapter 3, the implementation of the Western Europe electricity system and its input data is detailed. A comparison between EROI and LCOE is also performed. Next, Chapter 4 presents the results of the comparison of both models for all the scenarios listed above. Finally Chapter 5 discusses the results of these comparisons.

Chapter 2

Model Description

In this chapter, the models used to represent the system is detailed. First, the model which optimises the renewable energy (RE) and storage assets by maximising the energy return on energy invested (EROI) is presented. This model is based on [15] and [12]. Second, the PLEXOS model which optimises the assests by minimising the total system cost is presented. This model is based on [11]. Finally, the main differences between the two models and the hypotheses made are detailed.

2.1 EROI model

The EROI model is based on the work of Ramelot and Martinelle [12] which is an extension of the work of Limpens [15].

2.1.1 Description

The model studies the electricity system of a given area for a given period and time step. In this model, the aera is divided in “*cells*” and the complete electricity system gathering all cells and their interconnections is refered to as the “*system*”. A cell is represented by producers, storage systems, transmission lines, pipelines and a consumption profile. A graphical representation of a cell is given in Figure 2.1 and of a three-cell system in Figure 2.2.

Four different renewable electricity production systems are considered in this model:

1. *Photovoltaic panels*, characterised by the technical characteristics of a photovoltaic (PV) panel (efficiency, lifetime and energy cost), irradiance data, an average load factor, an already-installed capacity and a technical potential.
2. *Wind turbines*, characterised by a wind turbine (WT) model (cut-in, cut-off and rated wind speed, rated power, lifetime and energy cost), wind speed data, an average load factor, an already-installed capacity and a technical potential.
3. *Dams*, characterised by local inflow data and installed storage and output power capacities.
4. *Run-of-the-river power stations*, characterised by local inflow data and installed capacity.

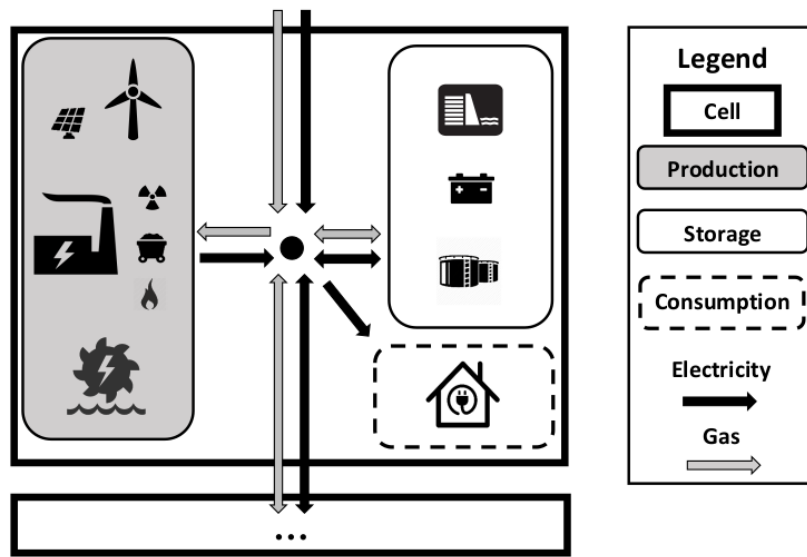


Figure 2.1: Representation of a cell. Adapted from [15].

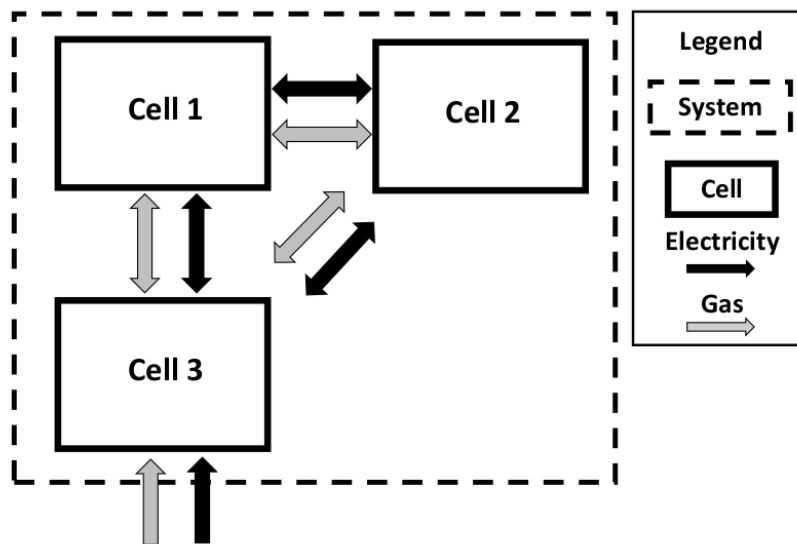


Figure 2.2: Representation of a system. Adapted from [15].

Three different non-renewable (conventional) electricity production systems are considered in this model: *combined cycle gas turbine (CCGT) power plants*, *Coal power plants* and *Nuclear power plants*. All three electricity production systems are characterised by their total installed capacity and the fuel to electricity efficiency of the CCGT is also specified. In this model, both CCGT and coal electricity production is assumed to vary instantaneously while the production from nuclear power plants is assumed to be non-flexible.

For storing the electricity, three storage systems are considered: batteries for short-term, pumped hydroelectric energy storage (PHES) for mid-term and power to gas (PtG) for long-term storage. Storage systems are characterised by a storage capacity, a charge and discharge rate, an input and output efficiency, a depth of discharge and a “leak”. In addition, batteries are characterised by the cost of the batteries, their maximum number of cycles, the already-installed capacity and a technical potential. The power-to-gas and the gas storage are characterised by an energy cost and lifetime. PHES is characterised by its energy stored on energy invested (ESOI).

Exchange between countries and imports from outside the system of electricity and gas is possible through transmission lines and pipelines. These exchanges are supposed to be lossless and are characterised by a maximum exchange capacity. Imports are characterised by a maximum percentage of the total consumption (at the cell or at the system level).

2.1.2 Objective function and constraints

The EROI of the previously described model is maximised using linear programming. Thus, the objective function of the model must be linear and subject to linear equality and linear inequality constraints.

Objective function In this model, the net EROI is maximised, which corresponds to the ratio between the end user consumption and the energy invested in renewable and storage assets. End user consumption is fixed while the energy invested is minimised. The energy invested is defined as the sum of the following investments:

1. energy invested in PV panels and WT;
2. energy invested in the installation of battery parks, PtG plants and gas storage facilities;
3. energy invested in the utilisation of battery park, PtG plants and PHES.

In the case of batteries and PtG units, the energy investment is split between installation and utilisation by the mean of a weighting factor to avoid unrealistic behaviours such as a huge park of batteries only used once.

Constraints The linear programming problem is subject to some constraints. The most important constraint is the power balance at every time step and in every cell. Indeed, inside every cell, the production and import of electricity needs to be at least equal to the consumption and export of electricity combined. Then, a minimum RE share of the total electricity production has to be respected in every cell and in the whole system. Similarly,

a maximum electricity and gas import share of the total electricity consumption is set at the cell and system level.

Next, a storage balance is imposed for batteries, PHES, dams and gas storage facilities. Indeed, the energy contained inside a storage system at time t needs to match the energy stored and the energy transfers to or from the storage system at time $t - 1$. In addition to this constraint, a minimal use of PtG is imposed in every cell. This minimum utilisation constraint defines a minimum ratio between the energy which goes through the PtG unit and the maximum energy that could be absorbed at full load.

Finally, the system and the cells are constrained by technical limits: the transmission capacity for both electricity and gas between cells is limited and each technology is limited by its minimal installed capacity for RE and its maximal potential.

The full mathematical description of the objective function and the constraints is available in [12].

2.1.3 Implementation

The model is implemented using the Python programming language. The PuLP library is used to write and solve the linear programming problem. PuLP has the ability to interface with multiple solvers such as COIN CBC or CPLEX. This study will use the CPLEX solver from IBM available on the IBM website¹. The simulations have been performed on a Lenovo Thinkpad T470 with an Intel Core i5 7200U 3.10 GHz processor and 16 GB of RAM running on a Windows 10 Professional platform with a 64 bits operating system. The model also supports other operating systems and has been tested on MacOS and Ubuntu 18.04 LTS.

Code adjustments Since the release of the EROI model by Ramelot and Martinelle [12], several adjustments have been conducted with the help of Oscar de Giey. Two errors have been corrected, three improvements implemented and the architecture of the model has been completely redesigned without affecting the results. The complete changes can be found in A.1. The complete code can be found on Github².

2.2 PLEXOS model

In this model, the same electricity, storage and transmission technologies as in the EROI model are used (with the exception of Power-to-Gas). The main difference between the two models is the objective function. This time, the objective is to minimise the total system cost, which includes annualised build costs, fixed O&M (FOM) and variable O&M (VOM). The modelling software used in this analysis is PLEXOS developed by Energy Exemplar [20]. PLEXOS is an optimisation tool that can be used to determine the optimal size and timing of new investments in electric generation and transmission and to optimise hydro and battery operation.

¹<https://www.ibm.com/analytics/cplex-optimizer>

²<https://github.com/oscardegiey/EROI-OMES>

2.2.1 Description

PLEXOS allows the energy system to be described as a set of objects with input properties and memberships (also called relationships). The object classes used in this study are the following:

Generator : All types of generation resource e.g. thermal, nuclear, hydro, pump storage, RES, etc. are modelled with the Generator class. A simple fossil fuel generator is defined by its Units and Max Capacity properties. More complex generators such as solar panels or wind turbines are also defined by Rating Factor, Build Cost, Max Units Built and Min Units Built properties.

Storage : the Storage class represents water storage reservoirs with short, medium, or long-term storage and generator head-ponds and tail-ponds. Each storage can connect to one or more generators. In this study, three Storage objects are created for each cell: a dam storage and two pumped storage reservoirs (head and tail reservoirs). Storages are defined by their Max Volume, Initial Volume and Natural Inflow properties.

Battery : a Battery is very similar to a Generator but with a built-in storage function. Additional properties are Max Power, Max Load, Charge and Discharge Efficiency.

Region : Regions represent transmission areas. As such they are the top-level object in the transmission system.

Node : Nodes are transmission buses. They are required to connect Generators, Batteries and transmission Lines. A Node can have a Load property.

Line : Lines represent physical or notional AC or DC transmission lines in the network. Each Line object must have a unique Node From and a Node To. They are defined by their Max Flow and Min Flow properties.

Constraint : The Constraint class allows the user to define generic constraints. An example of a user-made constraint is the minimum renewable energy production share set to 100%.

Data File : The Data File class can be used to create any type of data (such as loads, solar panel ratings, wind turbine ratings or natural inflows) based on external data contained in CSV files.

Scenario : Scenario objects allow data to be labelled with a particular scenario name. Any property can be tagged with a scenario name. That property will only be used if the scenario is selected.

An example of the objects and memberships used in a two cell system is available in Figure 2.3 Different types of optimisations can be performed by PLEXOS, such as:

LT Plan : Long Term Plan finds the optimal combination of generation new builds and retirements, AC and DC transmission upgrades (and/or retirements) and gas system

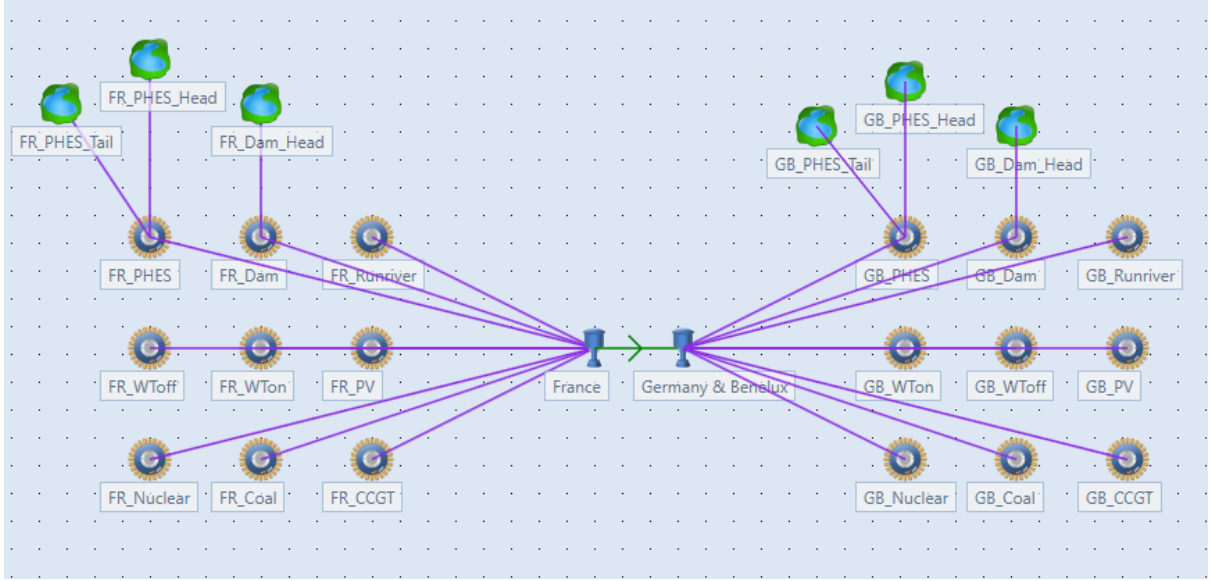


Figure 2.3: Graphical visualisation of a two cell PLEXOS model. This case represents *France* and *Germany & Benelux*, each node has 6 generators, 2 storages (PHES and dams) and 1 battery.

upgrades (and/or retirements) that minimises the net present value³ of the total system costs over a long-term planning horizon like 20-30 years subject reliability and/or other constraints. LT Plan by default spans the whole simulation planning horizon in a single optimization “step”. For realistically-sized power systems and long planning horizons this may lead to extremely big linear programming problems. To make this problem tractable, the load duration curve (LDC) methodology can be used. This method is explained in subsection 2.2.2.

PASA : Projected Assessment of System Adequacy schedules maintenance events such that available generation capacity is optimally shared between interconnected regions.

MT Schedule : Medium Term Schedule is a simulation based on a temporal simplification, with choice of partial or full chronology which can include a representation of the generation and transmission system and constraints to a level of detail the user desires. It is able to simulate over long horizons and large systems in a short execution time.

ST Schedule : Short Term Schedule is a chronological unit commitment and economic dispatch model based on mixed-integer programming. It is able to resolve time periods as short as one minute and model the full detail of the electric and gas systems.

³The net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment or project. In the case of the LT Plan, the NPV of the costs represents the present value of future costs considering a discount rate.

These tools can be integrated in sequence, in this case PLEXOS will feed information from one process to the next.

An introduction on how to use PLEXOS is available in Appendix D.

2.2.2 Formulation of the LT Plan

The objective function of the LT Plan seeks to minimize the net present value of build costs plus fixed operations and maintenance costs plus production costs. The core formulation for the LT Plan is thus:

Minimise

$$\begin{aligned} & \sum_y \sum_g DF_y \times (\text{BuildCost}_g \times \text{GenBuild}_{g,y}) \\ & + \sum_y DF_y \times \left[\text{FOMCharge}_g \times 1000 \times \text{PMAX}_g \left(\text{Units}_g + \sum_{i \leq y} \text{GenBuild}_{g,i} \right) \right] \\ & + \sum_t DF_{t \in y} \times L_t \times \left[\text{VoLL} \times \text{USE}_t + \sum_g (\text{SRMC}_g \times \text{GenLoad}_{g,t}) \right] \end{aligned} \quad (2.1)$$

subject to

$$\sum_g \text{GenLoad}_{g,y} = \text{Demand}_t \quad \forall t \quad (2.2)$$

$$\text{GenLoad}_{g,t} \leq \text{PMAX}_g \left(\text{Units}_g + \sum_{i \leq y} \text{GenBuild}_{g,i} \right) \quad (2.3)$$

$$\text{MinUnitsBuilt}_{g,y} \leq \sum_{i \leq y} \text{GenBuild}_{g,i} \leq \text{MaxUnitsBuilt}_{g,y} \quad (2.4)$$

with the variables and parameters defined in Table 2.1.

Build cost annual charges The Generator Build Cost property represents the (per kW) overnight cost of building a new unit. The above formulation shows this cost being incurred in the year the plant is built. This capital cost approach is really only suitable if the planning horizon is long enough to fully amortize the build cost e.g. at least the Economic Life of the plant. If the horizon is not long enough to cover the economic life of the last new build then this cost model is incorrect.

The approach used for projects whose life extends past the end of the planning horizon, is to annualize the build costs i.e. convert them to an equivalent annual charge which is applied in the year of build and every subsequent year across the economic life of the generator. We transform the build cost input into an annualised charge suitable for the LT Plan formulation as follows:

$$\text{Annuity}_{g,y} = \text{BuildCost}_{g,y} \times 1000 \times \text{MaxCapacity}_{g,y} \times \frac{D}{\left(1 - \left[\frac{1}{(1+D)} \right]^{\text{EconomicLife}_g} \right)} \quad (2.5)$$

The build cost coefficient in the objective function (i.e. BuildCost_g) is thus replaced by the sum of the discounted annual charges, starting from the given year y until the end of

Variable	Description	Type
GenBuild _{<i>g,y</i>}	Number of generating units build in year <i>y</i> for Generator <i>g</i>	continuous
GenLoad _{<i>g,t</i>}	Dispatch level of generating unit <i>g</i> in period <i>t</i>	continuous
USE _{<i>t</i>}	Unserved energy in dispatch period <i>t</i>	continuous
Parameter	Description	Unit
<i>D</i>	Discount rate. We the derive $DF_y = 1/(1 + D)^y$ which is the discount factor applied to year <i>y</i> , and DF_t which is the discount factor applied to dispatch period <i>t</i>	
<i>L_t</i>	Duration of dispatch period <i>t</i>	Hours
BuildCost _{<i>g</i>}	Overnight build cost of generator <i>g</i>	€
MinUnitsBuilt _{<i>g,y</i>}	Minimum number of units of generator <i>g</i> to be built by the end of year <i>y</i>	
MaxUnitsBuilt _{<i>g,y</i>}	Maximum number of units of generator <i>g</i> allowed to be built by the end of year <i>y</i>	
PMAX _{<i>g</i>}	Maximum generating capacity of each unit of generator <i>g</i>	MW
Units _{<i>g</i>}	Number of installed generating units of generator <i>g</i>	
VoLL	Value of lost load (energy shortage price)	€/MWh
SRMC _{<i>g</i>}	Short-run marginal cost of generator <i>g</i> which is composed of $HeatRate \times FuelPrice + VOMCharge$	€/MWh
FOMCharge _{<i>g</i>}	Fixed operations and maintenance charge of generator <i>g</i>	€/kW
Load _{<i>t</i>}	Average power demand in dispatch period <i>t</i>	MW

Table 2.1: Variables and parameters used in the LT Plan formulation

the economic life of the unit. In this study, we will consider no discount rate, meaning that annual build costs correspond to the build cost divided by the economic lifetime of the generator:

$$Annuity_{g,y} = \frac{BuildCost_{g,y} \times 1000 \times MaxCapacity_{g,y}}{EconomicLife} \quad (2.6)$$

End-year treatment It is important, in the LT Plan formulation that the model does not inappropriately consider the end of the planning horizon to also be the end of time. In the above basic formulation we have implicitly assumed that the LT Plan has an infinite horizon. In practice, the model will have a finite horizon. We therefore have to take account of so-called end-year effect.

Without some method for dealing with end-year effects, the model will in the last years of the horizon only build generators with low build costs even if their marginal generation costs are high. This is because the average cost of generation between build year and the end of the planning horizon, including build costs, will be lower for such generators.

By default, the end effects method assumes that the last year of the horizon is repeated an infinite number of times. The objective function is expanded by the cost of the years after the final horizon year, which equals the sum of the present values of generation costs and annualized build costs. By including annualized build costs in the perpetuity we are assuming that the system continues to expand after the final year.

Partial vs Fitted chronology In long planning horizons, the LT Plan may lead to extremely big linear programming problems. To reduce this problem, partial chronology can be used. In this chronology, the LT Plan divides the horizon by either day, week, month or year, according to the setting chosen by the user. A load duration curve (LDC) is created for each of these periods by ordering the original dispatch intervals by the total of all load from highest to lowest. The intervals in each duration curve are then grouped into a number of blocks which are created by slicing the duration curve using the weighted least-squares fit method. For example, a 25-year horizon solved with monthly LDC each with 12 blocks will have $12 \times 12 \times 25 = 3600$ blocks (or periods) in total. The procedure is visually explained in Figure 2.4. This method has two downsides:

1. In partial chronology all system constraints are applied, except those that deal with unit commitment. Storage is balanced between duration curves, but not within the curves e.g. for weekly duration curves the storage bounds are enforced at the boundary between weeks. Therefore, if the LT Plan uses partial chronology, an ST Schedule is needed afterwards for unit commitment and storage balance.
2. Partial chronology is not suited for systems with a large amount of renewable generation and may result in power unbalance and unserved energy.

In this study, the planning horizon is short, only one year, and systems with only renewable generation are studied. We therefore use a fitted chronology instead of the partial chronology. In an LT Plan with a fitted chronology, all system constraints are applied including generator unit commitment and storage is balanced every hour. This chronology simulates every hour of the planning horizon and creates large linear programming problems, but has no risk of power unbalance. Also, in this case, the LT Plan combines both long-term and short-term planning.

2.2.3 Implementation

The model is built using PLEXOS by Energy Exemplar. Multiple solvers can be used to solve the linear programming problem. The academic license only includes open-source solvers such as GLPK [22] and the free-for-academic SoPlex/SCIP LP/MIP solver [23]. In this study, PLEXOS will be used to generate the LP problem of the LT Plan. This problem is solved outside of PLEXOS, with the CPLEX solver from IBM. A performance comparison between CPLEX and open-source solvers has been conducted in [24].

2.3 Limitation of both models

Both models have their own strengths and weaknesses. In this section we will list some of them and explain the adaptations brought to the EROI model to match the PLEXOS model as closely as possible.

Strengths and weaknesses A detailed overview of the strength and weaknesses of both models is available in Table 2.2.

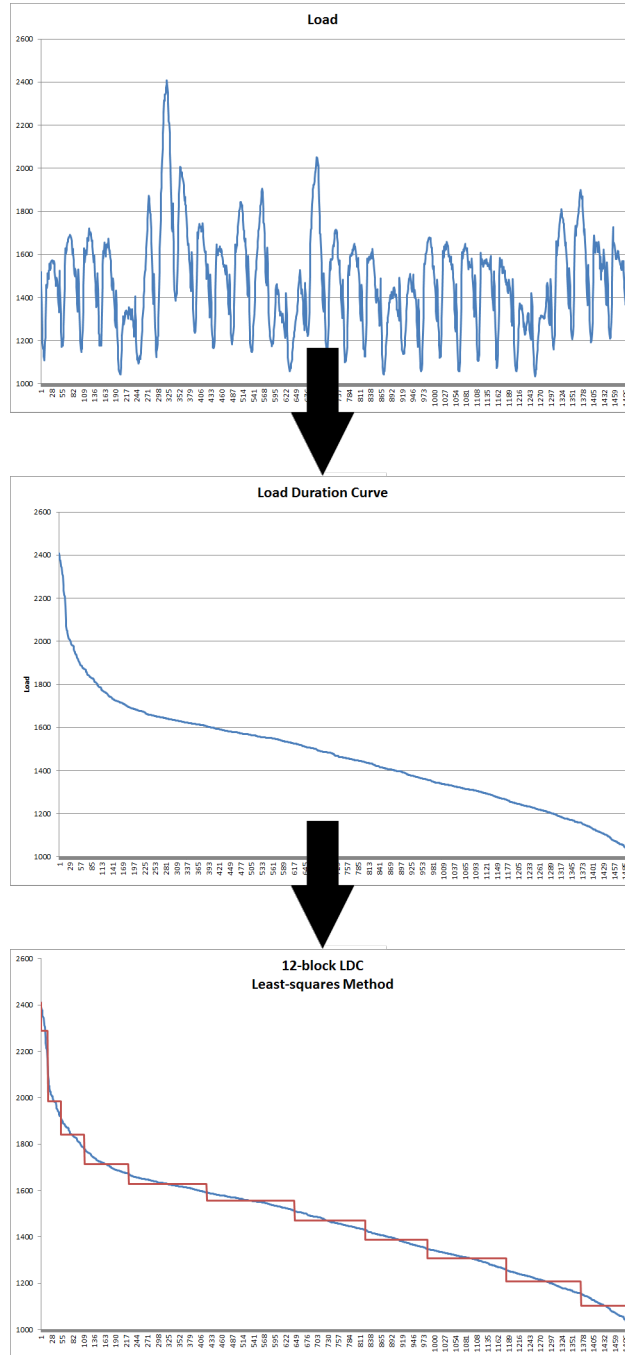


Figure 2.4: Load duration curve slicing used in the partial chronology of the LT Plan.
Source [21]

EROI model	PLEXOS model
Open-source The code for the EROI model is free and available, meaning that you can adapt it to your own requirements. An error in the solution can be tracked down in the code and easily fixed.	Energy Exemplar does not provide end users with access to PLEXOS' source code. The black box system of PLEXOS makes it hard to track down an error in the solution and generally requires the help of the support team.
Capabilities & Features The model is easy to scale by adding or removing a cell. Every cell has all of its properties inside a single configuration file. Thanks to the PuLP library, there are no restrictions on which solver to use. It support a wide range of solvers such as GLPK, COIN, CPLEX, XPRESS, Gurobi... The model may not include as much features as the PLEXOS model but the open-source code makes it possible to implement any feature but can be very hard without a good knowledge of Python.	There are practically no limits to the application of the optimization and simulation approach in PLEXOS. Its object-oriented design makes it easy to learn and use these capabilities, and extend the feature set as required. But the academic license of PLEXOS does not include all components of PLEXOS. Missing components are for example support for commercial solvers, gas modelling, distributed computing...
Interface Currently, the model implementation only exports the solution in a non-readable format that can only be read and viewed with Python. Coding knowledge is therefore necessary to analyse the solution.	PLEXOS has a user interface, making it easy for new users to rapidly create models. It also has a solution viewer, a reporting tool and the possibility to export the solution in a readable format (e.g. <code>.xlsx</code> or <code>.csv</code>).
Support and documentation The EROI model offers no support and no document is yet available.	PLEXOS has a support team available for any question or problem encountered with the software. An extensive documentation is also available online (only approved clients may view the documentation).

Table 2.2: Comparison of both models' strengths and weaknesses.

EROI model adaptation The EROI model was adapted to match as closely as possible the PLEXOS model. The modifications are the following:

- Remove the possibility to invest in PtG plants and gas storage. PLEXOS' academic license does not include gas modeling;
- Batteries have no more "leak". This function is not yet implemented in PLEXOS;
- Battery's depth-of-discharge is always set to 100%. Using another value in PLEXOS would cause a solver error;
- PHES has $\eta_{\text{out}} = 100\%$ while η_{in} represents the round trip efficiency.

Chapter 3

Western Europe energy system

In this chapter, the implementation of the Western Europe electricity system is detailed. The objective of this implementation is to represent as closely as possible the actual electricity system.

3.1 Definition of the cells

In both the EROI and ROI model, the spatial resolution of the system affects the computational time. This study only focus on the analysis of Western Europe's electricity system at a macro scale. Therefore, six cells are defined (Figure 3.1):

- Scandinavia (SC): Norway, Sweden and Denmark;
- British Isles (BI): United Kingdom and Ireland;
- Germany & Benelux (GB): Germany, Belgium, Netherlands and Luxembourg;
- France (FR);
- Iberian Peninsula (IP): Spain and Portugal;
- Italy & Alpine states (IA): Italy, Switzerland and Austria.

The same division of Western Europe is found in other studies [11, 12]. This division is based on multiple considerations: size of the cells, policies, energy mixes, interconnections, geography and climate. These considerations are detailed in [12]. The characteristics of the cells are summarised in Table 3.1 and in Figures 3.2, 3.3 and 3.4. This model of Western-Europe is convenient in terms of data collection and system comprehension but lacks precision due to the electricity transmission between cells and the copper plate hypothesis. This hypothesis could be questioned with countries like Germany developing recurrent congestion between the electricity producing north and the industrial south regions of the country. Extensive description of the Western-Europe model and its different cells can be found in [12]. Only one modification was brought to the Western-Europe model, namely a new interconnection between the British Isles and Germany & Benelux, the Nemo Link. The Nemo Link is an HVDC submarine power cable between the United Kingdom and Belgium. It is capable of transmitting 1000 MW in both directions for an annual transmission capacity of 8.76 TWh.

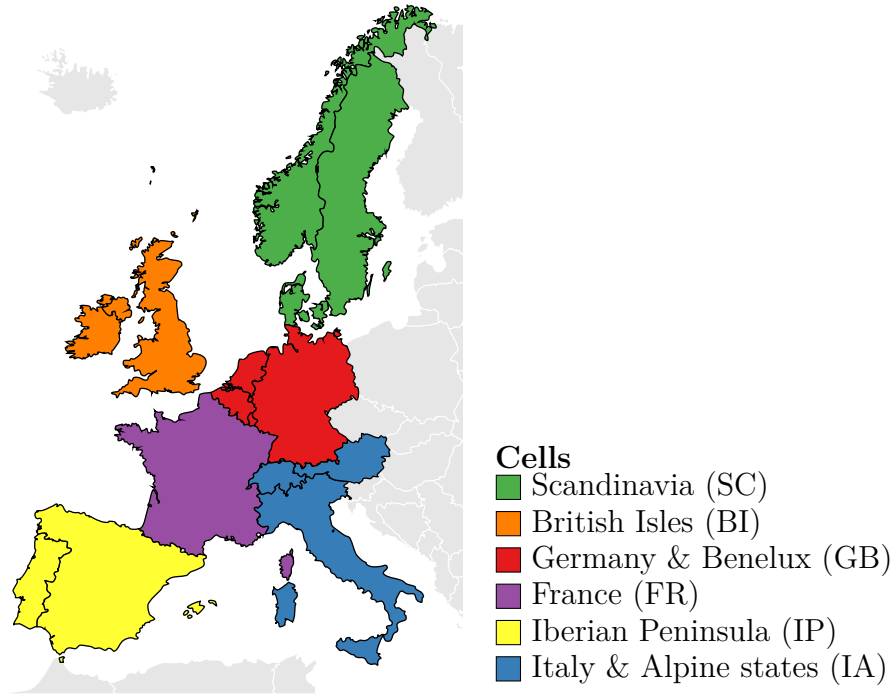


Figure 3.1: Definition of the cells for the Western Europe model

Cell Country	Area [km ²]	Population [millions]	Annual electricity consumption [TWh]	Annual electricity production [TWh]
Scandinavia	878431	21	303	334
Denmark	4.89%	27.37%	10.86%	9.01%
Norway	43.85%	25.04%	45.21%	43.34%
Sweden	51.26%	47.59%	43.93%	47.65%
British Isles	315000	70	370	366
Ireland	22.47%	6.78%	7.78%	8.36%
United Kingdom	77.53%	93.22%	92.22%	91.64%
Germany & Benelux	432000	112	724	840
Belgium	7.08%	10.18%	11.41%	10.04%
Germany	82.51%	73.98%	72.51%	76.04%
Luxembourg	0.60%	0.53%	0.87%	0.26%
Netherlands	9.81%	15.31%	15.21%	13.66%
France	644000	69	479	550
Iberian Peninsula	598000	57	302	328
Portugal	15.41%	18.14%	16.46%	17.74%
Spain	84.59%	81.86%	83.54%	82.26%
Italy & Alpine state	427000	78	452	410
Austria	19.67%	11.28%	15.13%	16.78%
Italy	70.65%	77.90%	69.95%	69.47%
Switzerland	9.68%	10.83%	14.92%	13.75%

Table 3.1: Area, population and annual electricity consumption and production of the cells and their corresponding countries in 2017. Data from [25–28]

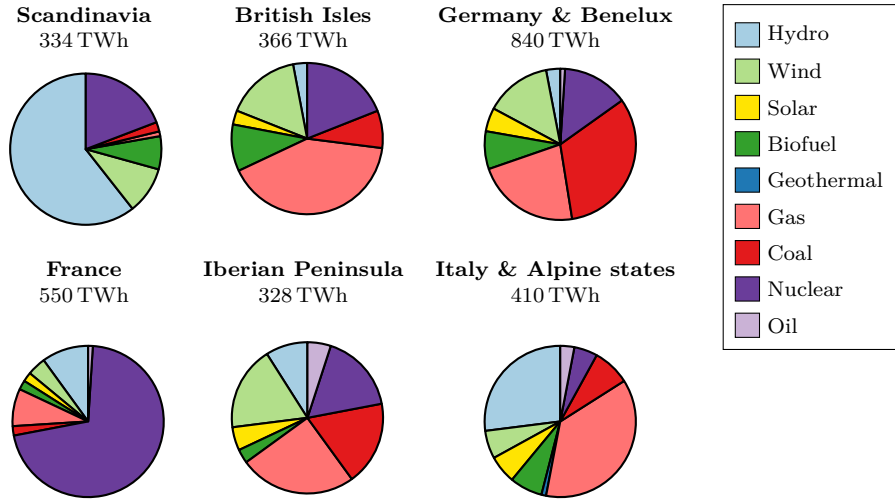


Figure 3.2: Electricity production mix in Western Europe in 2017. Data from [25–28]

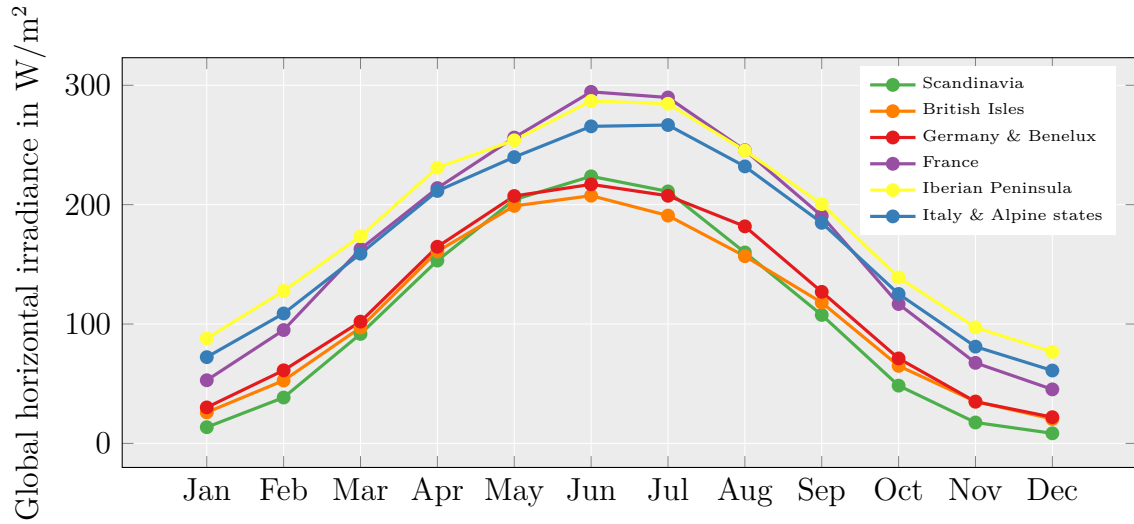


Figure 3.3: Monthly mean irradiance profile for every cell

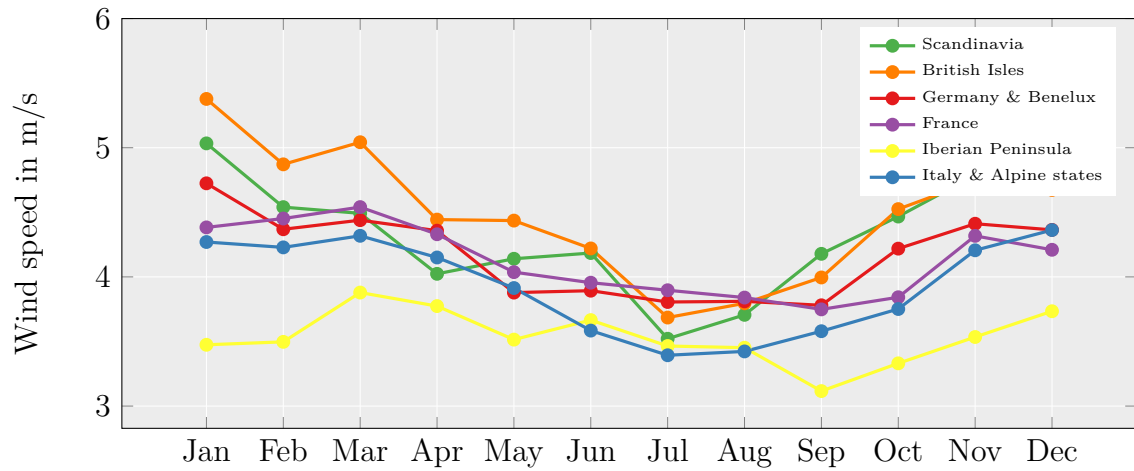


Figure 3.4: Monthly mean wind speed profile for every cell

3.2 Energy cost and techno-economic parameters

In this section, the energy cost for the EROI model and the techno-economic parameters for the PLEXOS model are explained and discussed.

3.2.1 Energy cost

The energy cost of the different electricity production and storage systems used in this study are the same as in [12]. In Table 3.2, these costs have been converted into the same units. We distinguish two different types of energy costs: the lifetime energy cost, corresponding to an energy cost per kW of installed capacity and the storage cost, corresponding to the energy invested per energy entering the storage.

Generator type	Lifetime energy cost kWh/kW	Storage cost kWh/MWh _{in}	Lifetime years
Solar PV	4280	-	30
Wind onshore	3743	-	25
Wind offshore	7964	-	25
PHES	-	1.42	-
Battery	330	9.9	15

Table 3.2: Energy cost converted to the same units. From [12]

3.2.2 Techno-economic parameters

This study considers 7 types of electricity production systems and 2 types of electricity storage systems. These are shown in Table 3.3 and 3.4 along with their techno-economic parameters based on Brouwer’s research [11]. These parameters reflect the average parameters of the electricity production and storage systems in the year 2050.

	Build cost €/kW	FO&M €/kW	VO&M €/MWh	Efficiency % LHV	Fuel cost €/GJ	Lifetime years
CCGT	902	11	1.2	63%	6.5	30
Coal	2088	29	4.6	49%	1.7	40
Nuclear	4841	103	0.0	33%	1.0	50
Solar PV	700	17	0.0	-	-	30
Wind onshore	1402	37	0.0	-	-	25
Wind offshore	2655	83	0.0	-	-	25
Hydropower	2059	52	0.0	-	-	40

Table 3.3: Projected techno-economic parameters of electricity production systems. From [11].

3.2.3 EROI and LCOE comparison

We will now compare the EROI and LCOE of the 7 types of electricity production technologies: CCGT, Coal, Nuclear, Solar PV, Wind onshore, Wind offshore and Hydropower.

	Build cost €/kW	Build cost €/kWh	FO&M cost €/kW	Energy to power ratio	Round-trip efficiency %	Lifetime cycles	Lifetime years
PHEs	1101	67	1% ¹	14.30 ²	76.5	35000	40
Li-ion	541	344	3% ¹	5.00	90	6000	15

1. Storage O&M costs are expressed in % of invest.

2. Average value of the six cells.

Table 3.4: Projected techno-economic parameters of electricity storage systems. From [11].

For the LCOE, no discount rate is taken into account. As a reminder, the EROI and LCOE are calculated as follows

$$\text{EROI} = \frac{\text{LifetimeEnergyGeneration}}{\text{LifetimeEnergyCost}} = \frac{\text{Lifetime} \times \text{LoadFactor} \times 8760}{\text{LifetimeEnergyCost}} \quad (3.1)$$

$$\text{LCOE} = \frac{\text{LifetimeCost}}{\text{LifetimeEnergyGeneration}} = \frac{\text{LifetimeCost}}{\text{Lifetime} \times \text{LoadFactor} \times 8760} \quad (3.2)$$

For Solar PV, Wind onshore, Wind offshore and Hydropower, the load factor used to calculate the EROI and the LCOE corresponds to the average load factor of the six cells. For CCGT, Coal and Nuclear, the load factors for OECD Europe are taken from [29].

Generator type	Lifetime energy cost kWh/kW	Lifetime years	Average load factor %	EROI
Solar PV	4280	30	13.172	8.088
Wind onshore	3743	25	23.040	13.480
Wind offshore	7964	25	39.808	10.947

Generator type	Lifetime cost €/kW	Lifetime years	Average load factor %	LCOE €/MWh
CCGT	5161.84	30	39.000	50.363
Coal	6302.02	40	51.000	35.265
Nuclear	13 670.20	50	77.000	40.544
Solar PV	1210.00	30	13.172	34.955
Wind onshore	2327.00	25	23.040	46.119
Wind offshore	4730.00	25	39.808	54.256
Hydropower	4139.00	40	30.981	38.126

In order to compare both metrics, we need to invert the LCOE to obtain an Energy Return On Monetary Investment (EROMI), expressed in MWh/€. This new metric can easily be compared with the Energy Return On Energy Investment (EROEI) once normalised. To normalise these metrics, we divide them by the respective metrics of PV (EROEI/EROEI_{PV} and EROMI/EROMI_{PV}). The normalised metrics are available in Table 3.5. A normalised metric greater than one means that the technology is energetically or economically cheaper than Solar PV.

From Table 3.5 we can see that Solar PV is considered as the most expensive electricity production technology in the EROI model, but as the cheapest one in the ROI model.

Generator type	EROI model	PLEXOS model
	EROEI/EROEI_{PV}	EROMI/EROMI_{PV}
CCGT	-	0.694
Coal	-	0.991
Nuclear	-	0.862
Solar PV	1.000	1.000
Wind onshore	1.667	0.758
Wind offshore	1.353	0.644
Hydropower	-	0.917

Table 3.5: Normalised Energy Return On Energy Investment (EROEI) and Energy Return On Monetary Investment (EROMI) comparison.

The differences between the normalized metrics EROEI and EROMI will have a significant impact on the optimal power generation investments of the system, whether it is optimised with respect to the energy or money invested.

3.2.4 ESOI and LCOS comparison

We will now compare the Energy Stored On (Energy) Invested (ESOI) and Levelised Cost Of Storage (LCOS) of the 2 types of electricity storage technologies. The ESOI is calculated as follows:

$$\text{ESOI} = \frac{\text{LifetimeEnergy}_{\text{in}}}{\text{LifetimeEnergyCost}} \quad (3.3)$$

The LCOS is calculated as formulated in [30], which is analog the LCOE formulation, but uses the electricity that entered the storage instead of the generated electricity. Again, no discount rate is used.

$$\text{LCOS} = \frac{\text{LifetimeCost}}{\text{LifetimeEnergy}_{\text{in}}} \quad (3.4)$$

Generator type	Lifetime energy cost kWh/kW	Lifetime years	Lifetime cycles	Round-trip efficiency %	ESOI
PHES	928.38	40	35 000	76.50	704.23
Battery	660	15	6000	90.00	50.51

Generator type	Lifetime cost €/kW	Lifetime years	Lifetime cycles	Round-trip efficiency %	LCOS €/MWh_{in}
PHES	2881.81	40	35 000	76.50	62.988
Battery	3278.45	15	6000	90.00	491.768

Like for the EROI and the LCOE, we need to invert the LCOS and normalise the ESOI and the LCOS. This time we will normalise the metrics with respect to PHES. Again, a normalised metric greater than one means that the technology is energetically or economically cheaper than PHES. According to Table 3.6, both models consider batteries as the most expensive storage system with the same order of magnitude.

Generator type	EROI model	PLEXOS model
	ESOI/ESOI _{PHER}	LCOS _{PHER} /LCOS
PHER	1.000	1.000
Battery	0.072	0.128

Table 3.6: Normalised ESOI and LCOS comparison.

Chapter 4

Models comparison

The goal of this chapter is to compare the PLEXOS model with the previously developed EROI model. First, we verify that both models use the same methodology. For this, we set up our models with the same techno-economic parameters. Next, we perform a comparison with a small energy system consisting of France and Germany & Benelux. Afterwards, a comparison is presented with the six cells of the Western Europe energy system. Next, we apply the non-renewable energy production from the European Union Reference Scenario and observe how the EROI and PLEXOS models optimised the RE energy mix. Finally, a transition scenario is performed with PLEXOS in a system with a growing minimum RE share from 40% to 100%.

4.1 Verification of the methodology: a two-cells analysis

In this section, we will validate the methodology used by both models. By validation, we mean trying to obtain similar results from our models when both are set up with the exact same parameters. An energy system optimisation of France and Germany & Benelux is performed with a period of study of one year and a time step of one hour. These cells were chosen to compare the PLEXOS model with the two-cells analysis performed previously in [12].

To set up our models with the same parameters, we consider the economical cost of the system as a scaling of the energy cost. We keep the same costs as in the EROI model, but we express them in a new unit, the equivalent investment unit U_e . This unit represents a certain quantity of investments. The build and utilisation costs of the PLEXOS model are adapted to have the same factors between technologies as in the EROI model. This way, both models should give the same results in U_e . In the EROI model, the lifetime energy cost of the different electricity production and storage systems are divided by their lifetime in order to have an annual investment cost. The same will be done to the economic build cost in the PLEXOS model.

Cost calculation The *lifetime cost* of the different electricity production and storage technologies needs to be converted to an *annual build cost*. In order to obtain this annual build cost, we change the units of the lifetime costs of Table 3.2 to U_e/kW and apply the

following formula:

$$\text{BuildCost} = \frac{\text{LifetimeCost}}{\text{Lifetime}} \quad (4.1)$$

The resulting build cost is therefore expressed in Ue/kW/yr. For the *utilisation costs* of PHES and Li-ion batteries, we keep them equal to the storage costs from Table 3.2 but express them in Ue/MWh_{in}.

The results of the cost calculations of all electricity production and storage technologies is available in Table 4.1.

	Annual build cost Ue/kW/yr	Utilisation cost Ue/MWh _{in}
Solar PV	142.667	-
Wind onshore	149.707	-
Wind offshore	318.541	-
PHES	-	1.42
Battery	22.000	9.90

Table 4.1: Build and utilisation costs of both models expressed in equivalent investment units.

Results and discussion The results from the energy system optimisation of France and Germany & Benelux are available in Table 4.2. Both models are investing in the same electricity production and storage technologies. If we analyse the investments made

	Units	FR		GB	
		EROI	PLEXOS	EROI	PLEXOS
Solar PV	GW	7.65	7.65	48.11	48.11
Wind onshore	GW	13.54	13.54	141.31	139.70
Wind offshore	GW	122.90	122.90	119.20	119.20
Battery	GW	1773.20	2066.61	4166.40	4279.92
Battery	TWh _{in}	193.55	195.79	324.14	324.41
PHES	TWh _{in}	11.52	11.67	7.01	7.19
Curtailment	%	2.84	3.51	2.01	1.09

Table 4.2: RE and storage assets builds, storage utilisation and curtailment in the case of a two-cells 100% RE scenario with scaled economic costs

in the energy system as done in Table 4.3 and Figure 4.1, we see that both models give nearly equivalent solutions: 244.076 GUE invested in the EROI model and 252.812 GUE in the PLEXOS model. This difference can be explained by a limitation of PLEXOS. In PLEXOS the initial volume of the different storage systems is set to 50% of the capacity. In the EROI model, the initial volume is not constrained, which leads to a different initial volume for every storage system. Optimum operation will try to maximise the energy stored at the beginning of Fall. As an example from Swiss Dams, at the 1st of January the level is around 60% of its maximum capacity¹. We can work around this limitation

¹Weekly reports of the water levels of Switzerland's reservoirs available at <https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/electricity-statistics.html>

	FR		GB	
	EROI	PLEXOS	EROI	PLEXOS
PV	1090.83	1090.83	6863.99	6863.99
WToN	2026.88	2026.88	21 155.64	20 914.14
WToff	39 147.16	39 147.10	37 968.56	37 968.49
Battery inst.	39 010.35	45 465.32	91 660.90	94 158.17
Battery util.	1916.15	1938.30	3209.02	3211.63
PHES util.	16.36	16.57	9.95	10.20
Sum	83 207.73	89 685.00	160 868.06	163 126.63

Table 4.3: Investments made in RE and storage assets in the case of a two-cells 100% RE scenario with scaled economic costs, expressed in MUE.

by using the results from the EROI model and setting the initial volume of the storage systems in PLEXOS to the same as in the EROI model results. These initial volumes are available in Table 4.4.

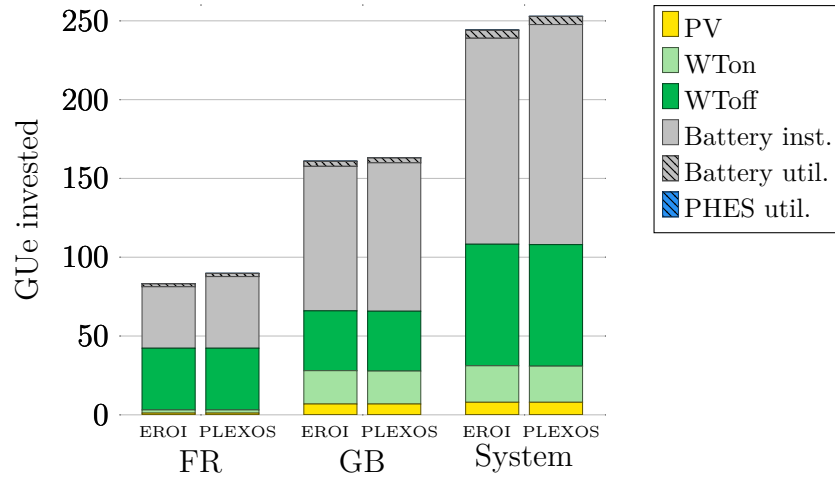


Figure 4.1: Investments made in RE and storage assets in the case of a two-cells 100% RE scenario with scaled economic costs.

	FR	GB
Dam	4.53%	11.74%
PHES	82.77%	62.20%
Battery	71.66%	63.88%

Table 4.4: Storage levels of the different storage systems of the EROI model on the 1st of January.

The new results from the PLEXOS model is available in Table 4.5. It can be underlined that the two models now give the same results for the study of a two-cell, 100% RE scenario.

	Units	FR		GB	
		EROI	PLEXOS	EROI	PLEXOS
PV	km ²	76.46	76.46	481.12	481.12
W_{Ton}	5MWeq	2707.80	2707.80	28 262.73	28 262.83
W_{Toff}	5MWeq	24 579.04	24 579.00	23 839.04	23 839.00
Battery inst.	GWh	8865.99	8866.01	20 832.02	20 832.03
Battery util.	GWh _{in}	193 550.10	194 216.44	324 143.11	323 476.99
Curtailment	%	2.84	3.73	2.01	1.31

Table 4.5: RE and storage assets builds, storage utilisation and curtailment in the case of a two-cells 100% RE scenario with scaled economic costs and adapted initial storage level.

4.2 Two-cells 100% RE scenario

In this section, we are now using the real economic costs (Table 3.3) of an energy system. We will run both models with their own sets of parameters on an energy system consisting of France and Germany & Benelux. A time step of one hour and a period of study of one year are used. The optimised energy system will have to have a 100% RE electricity production.

First, a comparison of the costs of the system is made. Second, the RE and storage assets of each cell are presented and analysed. Third, a global analysis of the annual production and exchanges is conducted and finally, the energy flows on an annual timescale are detailed.

Costs Table 4.6 shows the total annual system costs. The investment costs represent the annual build costs of the RE and storage technologies while O&M costs includes both variable and fixed O&M costs. In the EROI model, the O&M costs of electricity production systems are already included in the build costs. For storage systems like batteries, The way O&M is implemented in EROI is wrong. Half of the total overall technology cost is put in the installation of the battery and the other half is put in the utilisation. More detailed data on these system costs are available in Tables B.1 and B.2. RE assets comprise 44.4% of the total costs in the EROI model, but only 28.93% in the PLEXOS model. More importantly, the share of storage O&M costs in the total storage costs is only 3.8% in the EROI model but 31.1% in the PLEXOS model. This shows the high utilisation costs of batteries in the PLEXOS model. A summary of the costs is available in Figure 4.2.

If we were to use the EROI model’s solution and apply the economic costs to it, we would obtain an annual system cost of 1361.31 bn€/yr or 2.17 times the cost of the PLEXOS model’s solution. We can do the same with PLEXOS model’s solution and apply the energy costs to it. We obtain an annual system cost of 421.44 TWh/yr or 1.73 times the cost of the EROI model’s solution.

	FR		GB		System	
	EROI	PLEXOS	EROI	PLEXOS	EROI	PLEXOS
	TWh/yr	bn€/yr	TWh/yr	bn€/yr	TWh/yr	bn€/yr
RE investment	42.27	45.86	65.99	60.03	108.26	105.89
RE O&M	0.00	33.86	0.00	41.98	0.00	75.85
Storage investment	38.93	96.88	91.66	210.92	130.59	307.80
Storage O&M	1.93	43.71	3.22	95.05	5.15	138.76
Total	83.13	220.32	160.87	407.99	244.00	628.30
EROI	5.76	-	4.50	-	4.93	-
LCOE [€/MWh]	-	459.96	-	563.52	-	522.28

Table 4.6: Total system costs for the case of a two-cells 100% RE scenario.

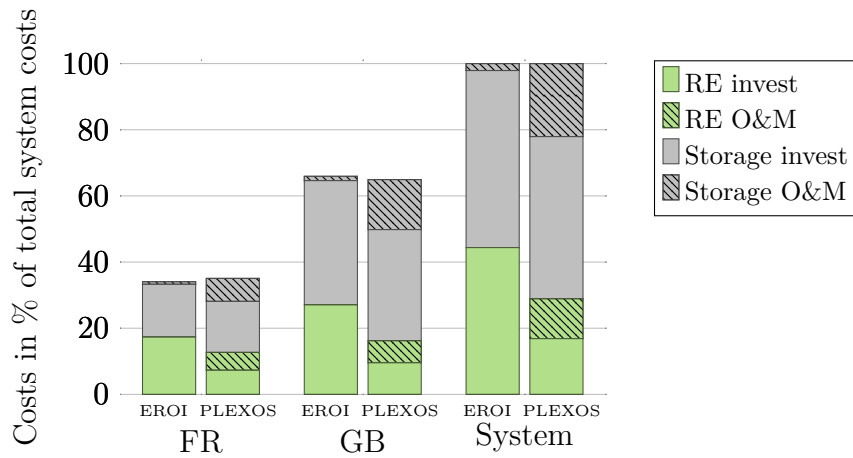


Figure 4.2: Distribution of the different costs expressed in % of the total system costs (244 TWh for the EROI model and 628.30 bn€ for the PLEXOS model).

RE and storage assets Figure 4.3 shows the difference in RE assets between the EROI model and the PLEXOS model. In both cases, all offshore wind potential is used. We observe that the PLEXOS model installed an important quantity of renewables, reaching the maximum potential of every technology in every cell with the exception of onshore wind in France. The important renewable capacity of the PLEXOS model is mainly due to the high costs of batteries. This results in lower storage capacity. Indeed, the PLEXOS model only has 10.21 TWh storage capacity while the EROI model has 29.68 TWh.

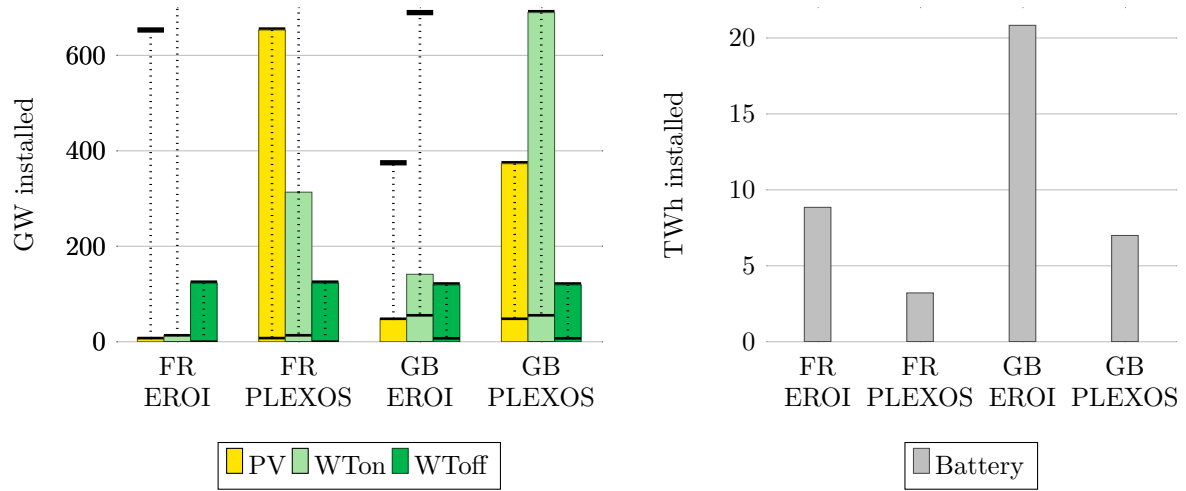


Figure 4.3: Installed RE and storage capacity in the case of a two-cells 100% scenario.

Analysis of the production and exchanges Figures 4.4 and 4.5 resumes the production and the annual exchanges between the cells. In the arrow is presented the annual energy exchanges as well as the net value. Curtailed energy is not shown in these figures.

In the EROI model, France relies mainly on offshore wind turbines (85% of its production) while Germany & Benelux is more diversified: 57% from offshore wind, 33% from onshore wind, 7% from solar PV and the remaining production from hydropower. In this model, Germany & Benelux is an electricity importer (28.5 TWh or 3.9% of its electricity needs).

In the PLEXOS model, both countries have a diversified production. Solar and onshore wind turbines plays a bigger role in this model than in the EROI model. This can be explained by the important RE capacity installed.

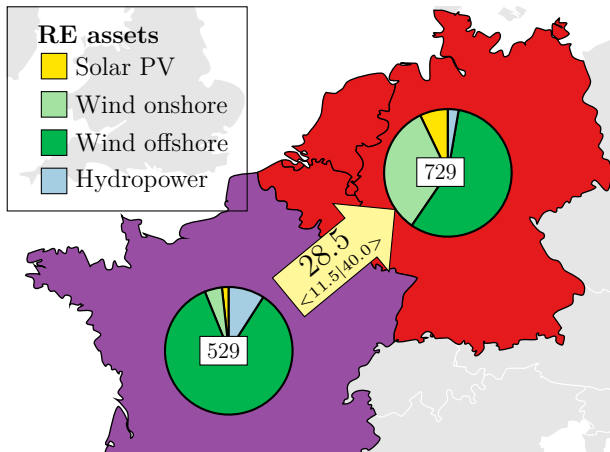


Figure 4.4: EROI model: RE production and annual exchange (total exchanges and net exchange) in TWh

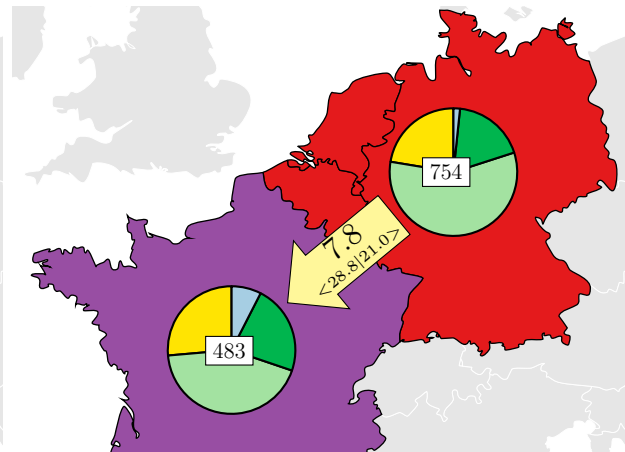


Figure 4.5: PLEXOS model: RE production and annual exchange (total exchanges and net exchange) in TWh

Energy flows In this section, the energy flows of the system is presented and studied. Figures 4.6, 4.7, 4.8 and 4.9 resume the global energy flows of the cells for the period studied. They highlight the part of production directly consumed, exchanged, stored and curtailed. In the EROI model, we observe that an important quantity of the consumed energy comes from storage (35% for France and 40% for Germany & Benelux). This is not the case in the PLEXOS model where more consumed energy comes directly from renewable energy source. The share of consumed energy coming from storage is 18% for France and 25% for Germany & Benelux. One can notice also notice in the PLEXOS model the large amount of curtailed energy in both cells. Indeed, almost 70% of the energy produced is curtailed. This is mainly due to the large installed capacity of renewables.

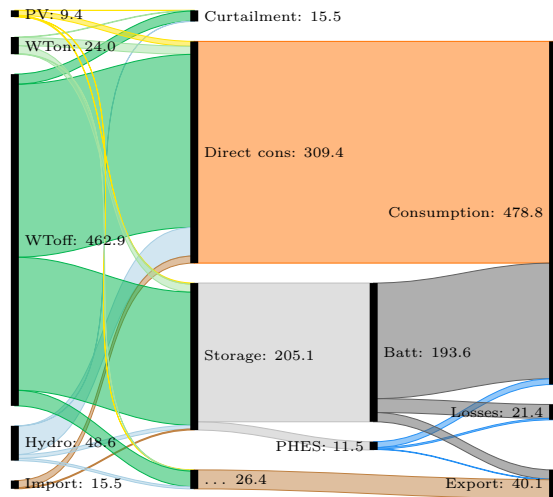


Figure 4.6: EROI model: Sankey diagram of France annual energy flow in TWh.

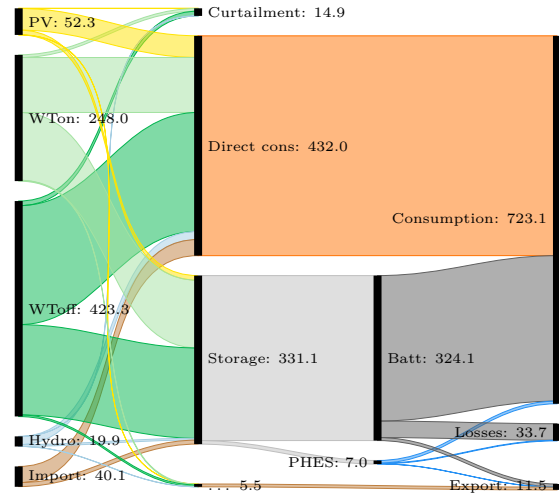


Figure 4.7: EROI model: Sankey diagram of Germany & Benelux annual energy flow in TWh.

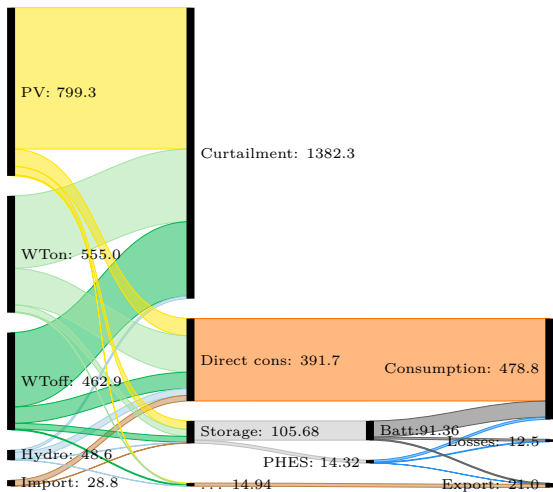


Figure 4.8: PLEXOS model: Sankey diagram of France annual energy flow in TWh.

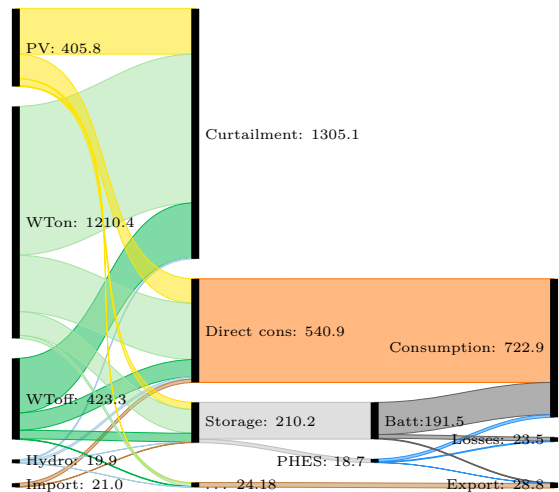


Figure 4.9: PLEXOS model: Sankey diagram of Germany & Benelux annual energy flow in TWh.

The utilisation of the storage systems is presented in Table 4.2. It presents the number of cycles achieved by a given storage system over the year for different cycle durations. The number of cycles is determined the same way as in [12]. First, the total annual energy cycled in the given time range is computed. The energy cycled in a storage corresponds to the quantity of energy which entered and left the storage within a certain period. The storage is considered as a stack, meaning that the last energy unit that entered the storage is the first one to leave. Then, this energy is divided by the storage capacity of the technology studied to obtain the number of cycles. Figure 4.2 shows how this method works.

From Table 4.7, we can observe that batteries are used for different durations, from less than 24h (short-term storage) to more than a month (seasonal storage). This is due to the lack of PtG solutions in the system. PHES on the other hand is mainly used for short-term storage. Energy is usually stored there for less than a week. This storage technology is used a lot more in the PLEXOS model than in the EROI model. (131 and 288 cycles in the PLEXOS model for France and Germany & Benelux respectively, 105 and 108 for the EROI model).

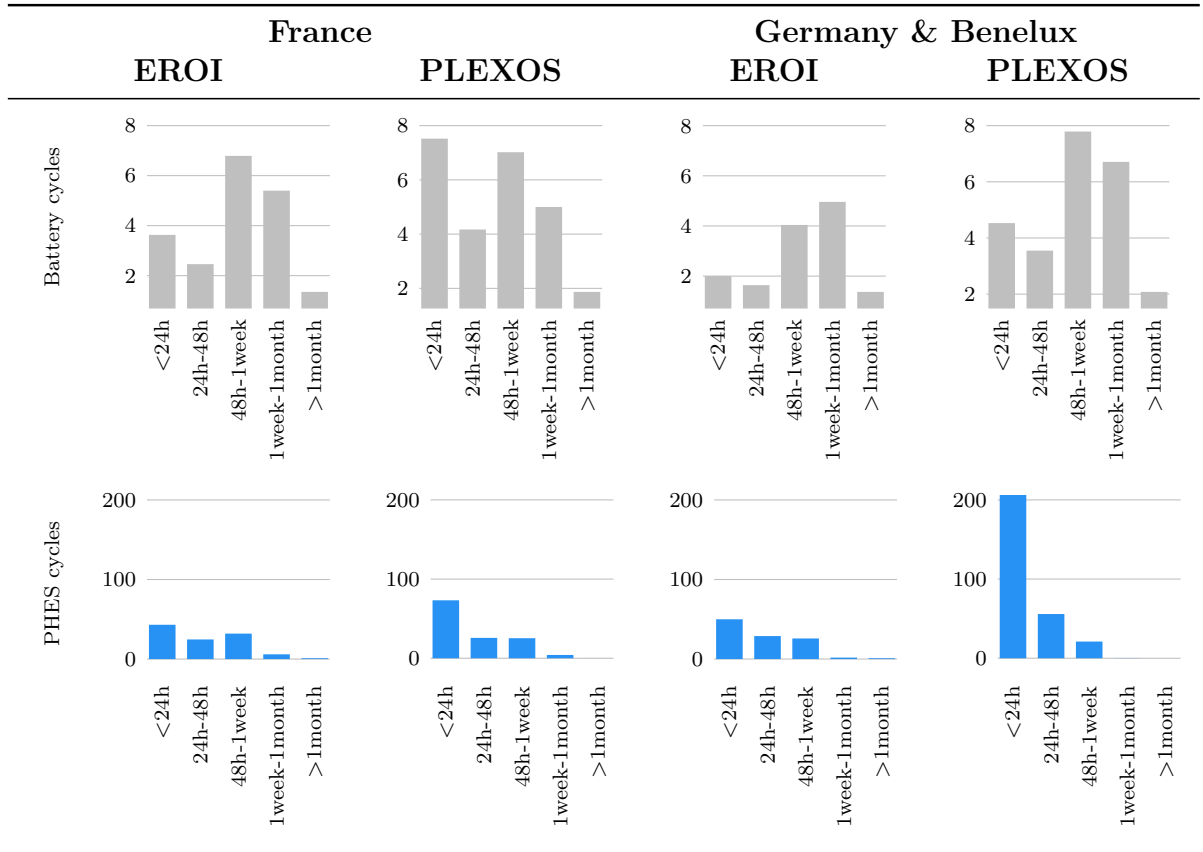


Table 4.7: Number of cycles of the storage assets.

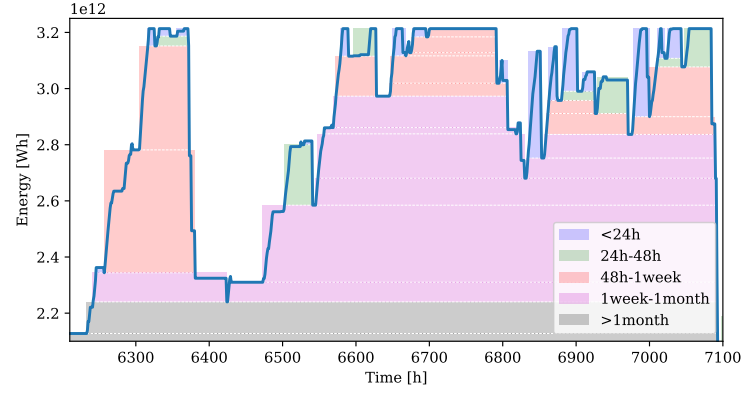


Figure 4.10: Energy evolution inside a lithium-ion battery. Colored blocks represent fractions of cycles and the color indicates their duration.

4.3 Six-cells analysis: A 100% RE scenario

In this section, we show the results from both models with their own sets of parameters on an energy system consisting of the complete Western-Europe model. A time step of one hour and a period of study of one year are used. The optimised energy systems have a 100% RE electricity production.

First, a comparison of the costs of the system is made. Second, the RE and storage assets of each cell are presented and analysed and finally, a global analysis of the annual production and exchanges is conducted.

Costs Tables 4.8 and 4.9 shows the total annual system costs of the EROI and PLEXOS model respectively. The investment costs represent the annual build costs of the RE and storage technologies while O&M costs includes both variable and fixed O&M costs. RE assets comprise 59.3% of the total system costs in the EROI model while it only represents 29.2% in the PLEXOS model. Like in the two-cells scenario, the high cost of batteries is here again highlighted. Figure 4.11 summarises the distribution of the different costs.

When compared to the two-cells scenario, the EROI of the EROI model improved from 4.93 to 6.66 and the LCOE of the PLEXOS model decreased from 522.28 €/MWh to 316.62 €/MWh. In both cases, one can notice that even if the consumption is doubled from the two-cells to the six-cells system, the costs did not follow the same growth.

	BI	FR	GB	IP	IA	SC	System
RE investment	55.45	42.27	64.06	28.88	37.14	6.44	234.32
RE O&M	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage investment	24.01	42.08	65.78	8.40	11.02	0.09	151.37
Storage O&M	1.86	2.09	3.07	0.99	1.53	0.02	9.57
Total	81.32	86.44	132.91	38.27	49.69	6.54	395.17
EROI	4.55	5.54	5.45	7.89	9.10	46.33	6.66

Table 4.8: EROI model: Total system costs. All costs are expressed in TWh/yr.

	BI	FR	GB	IP	IA	SC	System
RE investment	31.04	35.73	46.32	8.88	11.65	2.34	135.96
RE O&M	23.82	27.18	32.94	7.62	11.03	4.24	106.83
Storage investment	89.65	87.68	202.75	10.26	15.24	0.36	405.95
Storage O&M	40.40	39.57	91.37	4.78	7.36	0.49	183.97
Total	184.91	190.16	373.39	31.54	45.28	7.44	832.71
LCOE [€/MWh]	499.76	396.99	515.73	104.44	100.18	24.55	316.62

Table 4.9: PLEXOS model: Total system costs. All costs are expressed in bn€/yr.

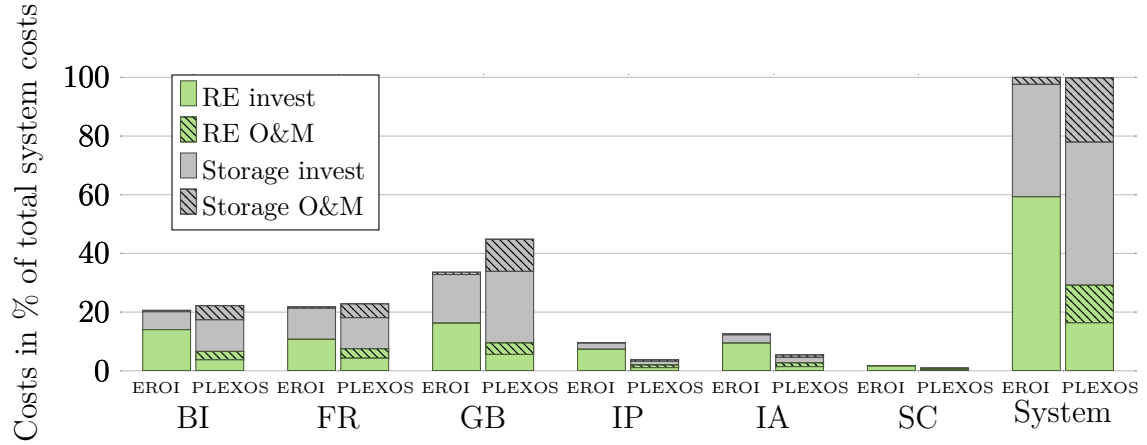


Figure 4.11: Distribution of the different costs expressed in % of the total system costs (395.17 TWh for the EROI model and 832.71 bn€ for the PLEXOS model).

RE and storage assets Figure 4.12 and 4.13 displays the RE assets of the cells in the 100% RE system from both models. The upper and lower limits are represented. We observe that the PLEXOS model tends to invest massively in solar PV while the EROI model prefers wind turbines (onshore or offshore depending on the cell). This reflects the EROI and LCOE of the different technologies. Solar PV has a lower LCOE than wind turbines while its EROI is less important. The total capacity invested is also significantly different in both models. The PLEXOS model builds a lot of RE capacity in order to avoid having to store the electricity into expensive storage systems. This effect is not present in the EROI model where the cost of batteries is less important.

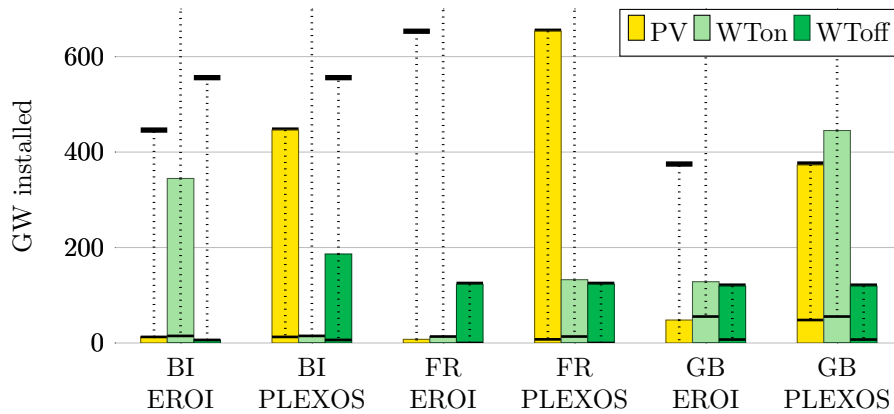


Figure 4.12: Installed RE capacity in the British Isles, France and Germany & Benelux. The horizontal black lines correspond to the upper (technical potential) and lower limits (already installed capacity).

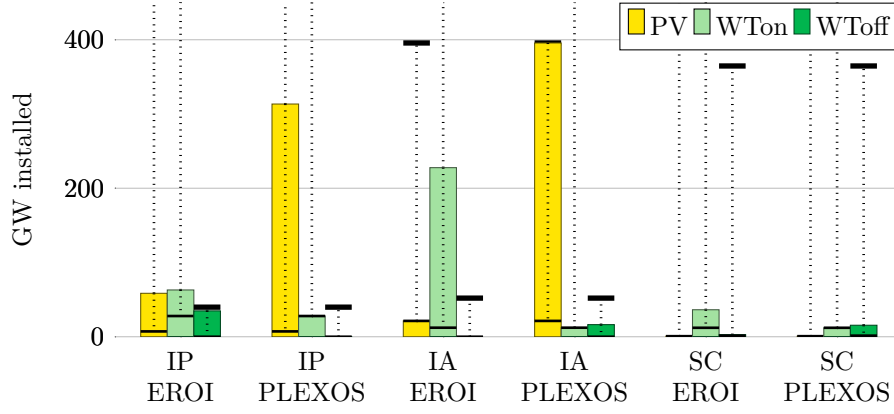


Figure 4.13: Installed RE capacity in the Iberian Peninsula, Italy & Alpine States and Scandinavia. The horizontal black lines correspond to the upper (technical potential) and lower limits (already installed capacity).

Figure 4.14 presents the battery storage capacity of the 100% RE Western-Europe system. Two groups of cells are emerging: cells with a lot of storage capacity (British Isles, France and Germany & Benelux) and cells with a small amount of storage capacity (Iberian Peninsula, Italy & Alpine States and Scandinavia). We can also observe that the PLEXOS model prevents the expansion of batteries due to their high costs compared to production units like solar PV or wind turbines.

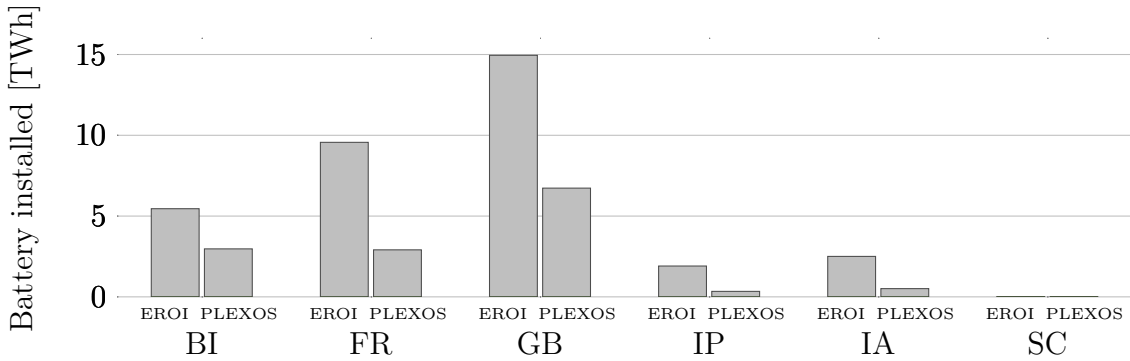


Figure 4.14: Installed battery storage capacity of the different cells.

Analysis of the production and exchanges Figures 4.15 and 4.16 resumes the production and the annual exchanges between the cells.

In the EROI model, the production relies mainly on wind turbines: offshore in France and Germany & Benelux and onshore in the British Isles and Italy & Alpine States. The Iberian Peninsula has an balanced production that uses all four RE sources. Finally, Scandinavia generates its electricity from hydropower and onshore wind turbines with almost no solar energy being produced. We observe that 4 cells (British Isles, France, Italy & Alpine States and Scandinavia) relies on one single technology for at least 65% of their production. Germany & Benelux needs two technologies and the Iberian Peninsula even need three of them. In this model, the British Isles, France, the Iberian Peninsula and

Italy & Alpine States are electricity exporters while Germany & Benelux and Scandinavia imports electricity from neighbouring cells.

In the PLEXOS model, the electricity production of all cells is more balanced than in the EROI model. Only the Iberian Peninsula and Scandinavia relies on a single technology for at least 65% of their production. The British Isles, Germany & Benelux and Italy & Alpine States need two technologies and France is the most balanced cell with three technologies needed to produce at least 65% of its electricity. We observe that solar energy is more present in this model than in the EROI model. In this model, the British Isles, France and Germany & Benelux are electricity exporters while the Iberian Peninsula, Italy & Alpine States and Scandinavia are importers.

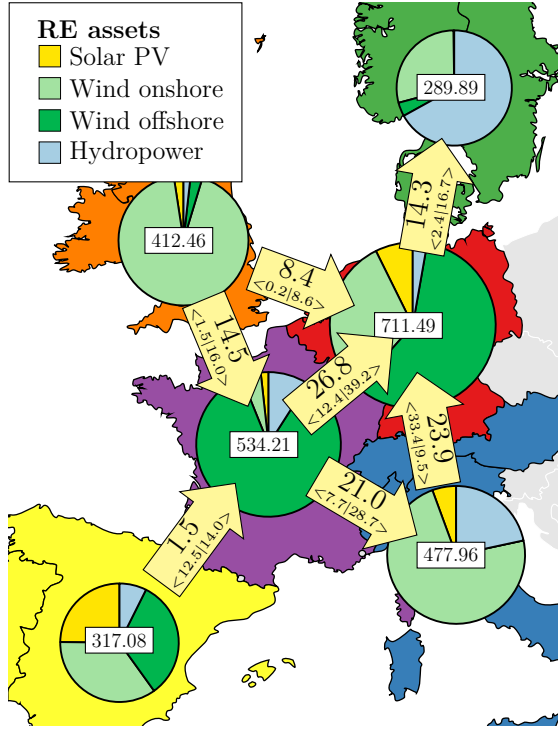


Figure 4.15: EROI model: RE production and annual exchange (total exchanges and net exchange) in TWh

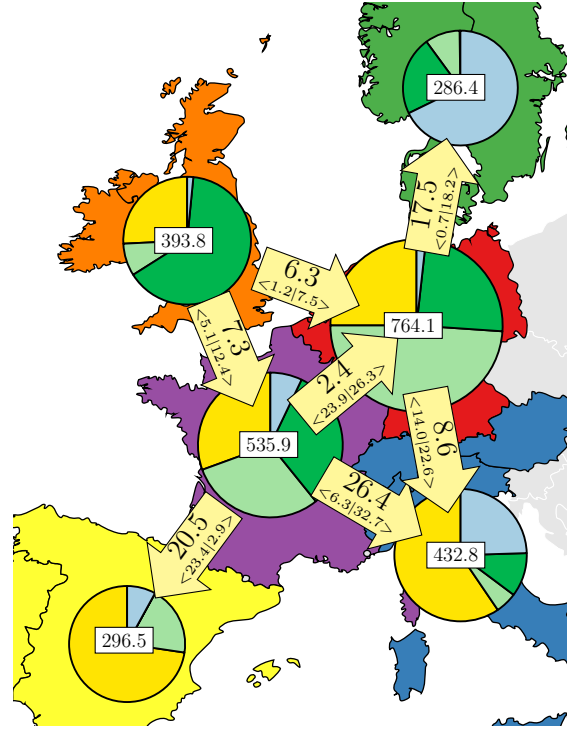


Figure 4.16: PLEXOS model: RE production and annual exchange (total exchanges and net exchange) in TWh

4.4 Commission's proposal

The European Commissions energy policy decisions are underpinned by thorough analyses and impact assessments. Mathematical models and tools are used to assess policies' effectiveness and evaluate the potential consequences of policy proposals. The *EU Reference Scenario* [31] is one of the European Commission's key analysis tools in the areas of energy, transport and climate action. It allows policy-makers to analyse the long-term economic, energy, climate and transport outlook based on the current policy framework.

Both the EROI and the PLEXOS model will be compared to the EU Reference Scenario (EURS) for the year 2030, year chosen for its numerous available data and its occurrence in

a foreseeable future. We will compare these three models by fixing the non-RE production sources installed capacity to their values in the EURS model. This way, we can simulate the optimal renewable energy mix (with regard to EROI and LCOE) to produce the rest of the electricity.

It is to be noted that a separate methodology has been used for Norway and Switzerland, as these countries are not part of the EU and are not mentioned in the EU Reference Scenario. In the case of Norway, a Norwegian study from the Institute for Energy Technology proposing three future scenarios has been adopted [32]. The scenarios predicted trends for Scandinavia in 2030, we thus took the scenario for Norway which was closer to the European Commissions trends for Sweden and Denmark. In the case of Switzerland, a detailed government 2050 roadmap for the electricity system and its nuclear phase-out has been used [33].

4.4.1 Non-RE energy mix and consumption

The non-renewable energy mix and the consumption of the different cells is common to the three models. This data is taken from the EU Reference Scenario and is available in Table 4.10 and 4.11. In these tables, biomass is considered in the same production mix as CCGT. In the EROI and PLEXOS model, nuclear energy is considered as non-flexible, with a fixed generation set at 77% of the maximum capacity. This is not entirely correct as the French nuclear power plants were specifically designed to allow for more flexibility than conventional plants [34]. The renewable sources minimum installed capacity and potential of the EROI and PLEXOS model remain the same as in the previous sections.

	BI	FR	GB	IP	IA	SC
Electricity consumption	446 265	608 391	824 432	335 296	480 082	392 999
Nuclear energy	107 051	385 062	4047	57 521	9000	49 738
CCGT energy	182 352	32 303	292 840	66 893	183 652	46 647
Coal energy	3676	69	252 734	15 179	47 957	3859

Table 4.10: Electricity annually consumed by the cells and electricity annually produced by nuclear, CCGT and coal in 2030. Expressed in GWh. From the EU Reference Scenario.

	BI	FR	GB	IP	IA	SC
Nuclear	15 871	57 087	600	8528	1334	7374
CCGT	56 545	11 775	60 337	35 046	50 863	10 310
Coal	1343	3780	41 220	3968	5876	1600

Table 4.11: Non-renewable production sources installed capacity in 2030. Expressed in MW. From the EU Reference Scenario.

4.4.2 RE energy mix and annual exchanges

The production and annual exchanges between the different cells is resumed in Figure 4.17 for the EURS model, Figure 4.18 for the EROI model and Figure 4.19 for the PLEXOS model.

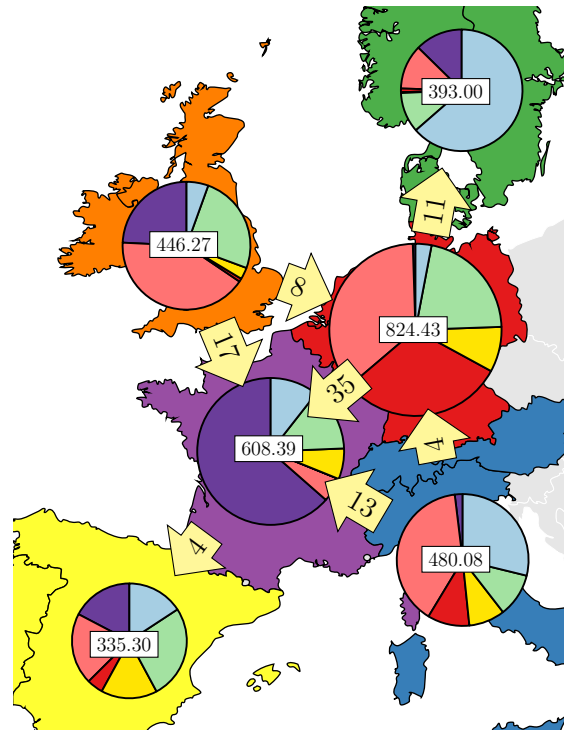
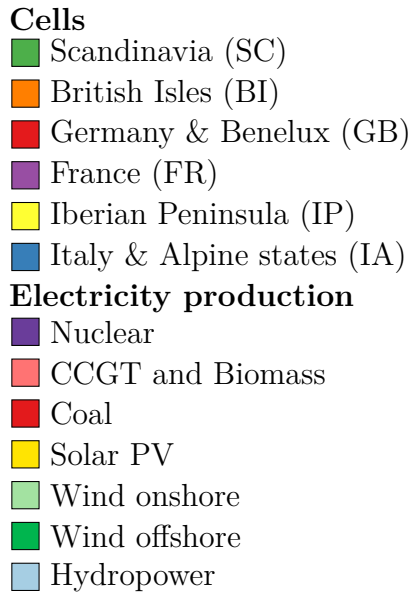


Figure 4.17: **EURS model**: Electricity production and annual net exchange in TWh.

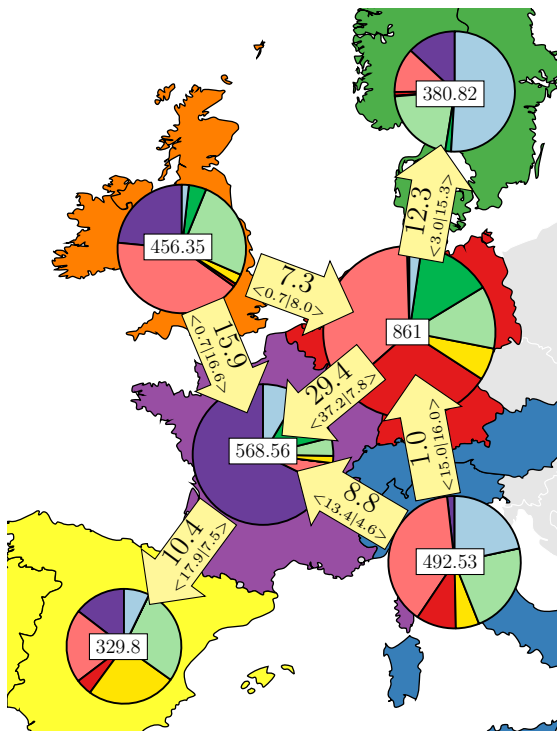


Figure 4.18: **EROI model**: Electricity production and annual exchange (total exchanges and net exchange) in TWh.

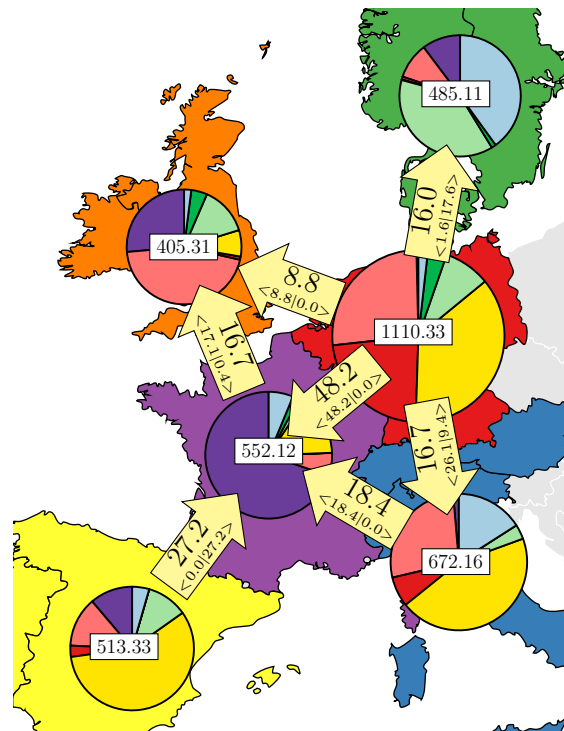


Figure 4.19: **PLEXOS model**: Electricity production and annual exchange (total exchanges and net exchange) in TWh.

Renewable production In the EROI and PLEXOS model, only the renewable energy mix is optimised. A detailed overview of the renewable energy mix is available in Table 4.12.

	Wind			Solar PV			Hydropower		
	EURS	EROI	PLEXOS	EURS	EROI	PLEXOS	EURS	EROI	PLEXOS
BI	25%	30%	18%	3%	3%	7%	6%	2%	2%
FR	14%	17%	3%	7%	2%	15%	11%	9%	6%
GB	21%	26%	12%	8%	6%	36%	3%	2%	2%
IP	26%	28%	11%	16%	25%	58%	16%	7%	4%
IA	11%	22%	3%	9%	6%	45%	29%	22%	16%
SC	11%	23%	39%	0%	0%	0%	64%	51%	40%
System	18%	24%	13%	7%	6%	30%	18%	13%	10%

Table 4.12: Comparison of the RE shares for the EU Reference Scenario (EURS), the EROI model and the PLEXOS model. Expressed in % of the electricity production.

Some observations can be made from this table.

First, the EU Reference Scenario does not mention electricity storage, meaning that the annual production and the net exchange of a cell is equal to its annual consumption. This is not the case with the EROI and PLEXOS model where some of the produced electricity is sent to storage systems such as batteries and PHES. The annual electricity production is thus higher in the EROI and PLEXOS model than in the EURS. As the NRE electricity production is fixed, RE electricity will have to produce the supplementary electricity needed for storage. This is the reason why we observe a 43% RE electricity production in the EURS, 43% in the EROI model and 53% in the PLEXOS model. We can deduce that a small amount of electricity is stored in the EROI model (only 144.8 TWh or 4.7% of the electricity production) and a lot more in the PLEXOS model (610.6 TWh or 16.3% of the electricity production).

When compared to the EURS, the wind power share in the EROI model is more important for every cell and solar power is less important with an exception in the Iberian Peninsula. Conversely, the PLEXOS model shows a small interest in wind power than the EURS, and a more important interest in solar power. These investment decisions reflect the cost analysis we did in Section 3.2. In the EROI model, wind power is energetically more interesting than solar power while in the PLEXOS model it is the opposite. This explains why the PLEXOS model needs more storage than the EROI model, as solar power only produce electricity during the day.

Finally, it may seem from the table that hydropower produced less in the PLEXOS model than in the EROI model but this is only due to the fact that the first model produced more electricity than the latter. In the PLEXOS model, hydropower produced 387 TWh while in the EROI model it produced 401 TWh. In both models, hydropower produced less than in the EURS (550 TWh). This can be explained by the difference in installed capacity. In the EURS there is no distinction between dams and run-of-the-river plants. Therefore, we could not use the installed capacity data from the EURS and implement them into the two other models. We observe that the EURS uses a higher hydroelectric installed capacity than in our Western-Europe model.

Power exchanges In the EROI and PLEXOS model, power is exchanged between cells to improve the EROI or reduce the LCOE. Figure 4.20 shows the correlation between net exchange and coal and gas production share. A positive net exchange indicates that the cell is exporting electricity while a negative net exchange indicates that the cell is importing. In the EURS and EROI model a cell with a low coal and gas production share is importing its electricity from cells with a higher coal and gas share. This correlation can be explained by the fact that coal and CCGT plants are the only flexible generation electricity sources in a cell. Dams could also be included in the list of flexible generation electricity sources, but is constrained by its water reservoir while coal and CCGT plants are truly flexible. Therefore, the coal and gas production share represents the flexibility of the electricity production of a cell. Flexible cells can help less flexible cells to balance their electricity production. This is no longer true in the PLEXOS model where the cell British Isles has a high coal and gas production share (45.9%, second highest after Germany & Benelux) but is importing 5.8% of its consumption. This can be explained by the large amount of electricity stored (610.6 TWh). In systems with large amounts of stored electricity, PHES and batteries can be considered as flexible electricity sources. In the PLEXOS model, British Isles is the only cell without batteries while the other cells have at least 600 GWh of storage capacity. This could explain why the British Isles cell needs to import electricity from other cells even though it has a high coal and gas production share. The complete data on power exchange is available in Tables C.1, C.2 and C.3.

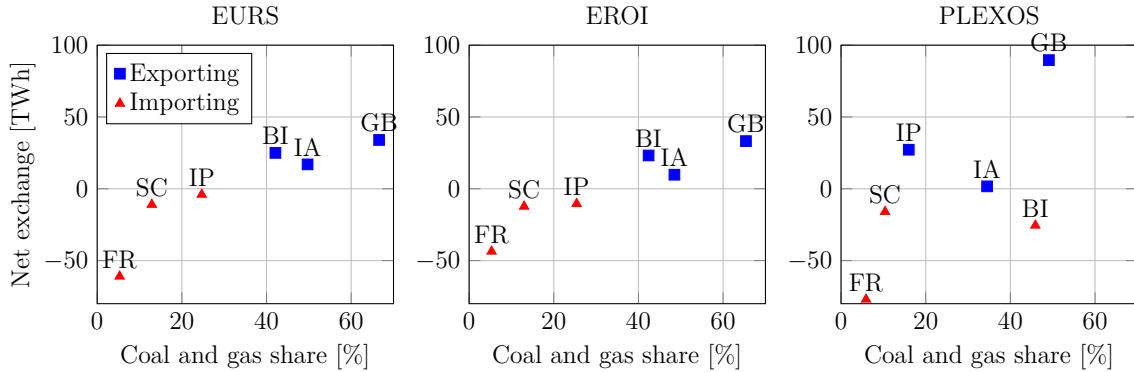


Figure 4.20: Correlation between net exchange and coal and gas production share in the different models.

4.4.3 Production and storage assets

In this section, an overview of the installed capacity of both production (Figure 4.21) and storage (Figure 4.22) is given for every cell and compared between the different models.

One can observe that the EURS and the EROI model follows the same trends. In most cells, wind power is preferred over solar. In two cells, the trends are not the same, namely Iberian Peninsula where the EROI model prefers solar power while the EURS suggests installing wind power and Italy & Alpine States where the EROI model installed three times the solar capacity in wind power while the EURS has slightly more solar power than wind power. In the PLEXOS model, the trend is completely different. Solar power

is privileged over all other electricity sources with the exception of Scandinavia where wind power is profitable. Looking at the installed battery capacity in Figure 4.22, we can observe more installed capacity in the PLEXOS model than in the EROI model, probably due to the high installed capacity of solar power in the PLEXOS energy system.

4.4.4 Cost analysis

In this section we analyse the energy cost of the EROI model and the economic cost of the PLEXOS model.

EROI model Distribution of the yearly system costs is available in Table 4.13. We can observe that 83% of the costs are from investments in new solar and wind electricity production units. The total system costs are here only a quarter of those of a 100% RE system. Less investments in storage were made when compared to a 100% RE system. The EROI of the different cells lies between 20 and 68. Cells without storage like Italy & Alpine States and Scandinavia profits from a higher EROI. The EROI of the complete system is 31.36 but the energy cost of non-renewable technologies like nuclear, coal and gas was not taken into account in the calculation. If we were to apply the energy costs to the system obtained with the PLEXOS model, we would have an EROI of 10.89.

Detailed distribution of the yearly system costs is available in Table C.4.

	BI	FR	GB	IP	IA	SC	System
Production investment	12.15	9.17	26.36	15.52	11.97	5.76	80.94
Storage investment	1.76	7.06	6.31	0.84	0.00	0.00	15.97
Storage O&M	0.11	0.18	0.16	0.15	0.01	0.00	0.62
Total	14.01	16.42	32.83	16.52	11.98	5.76	97.53
Consumption	441.62	606.04	819.62	332.18	466.03	392.93	3058.41
EROI [-]	31.51	36.91	24.97	20.11	38.89	68.16	31.36

Table 4.13: EROI model: yearly system costs expressed in TWh/yr, consumption and EROI.

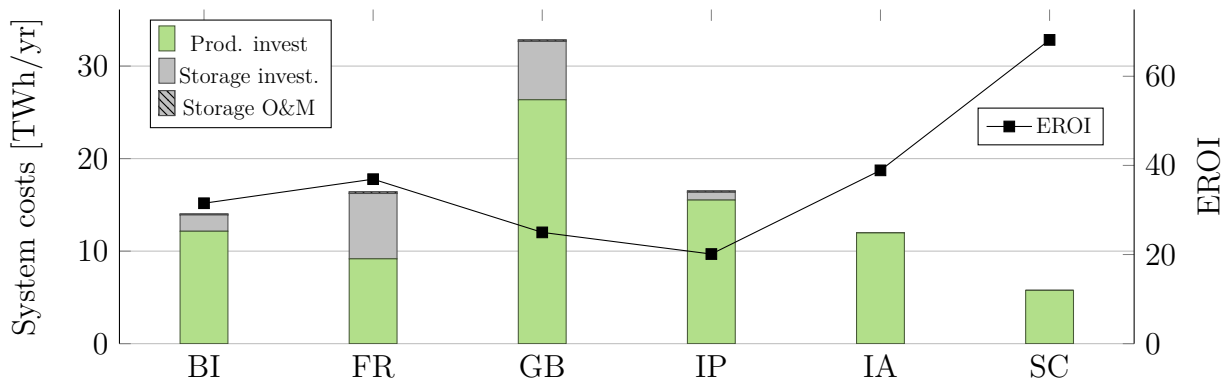


Figure 4.23: EROI model: distribution of the system costs expressed in TWh/yr and EROI of all cells.



Figure 4.21: Installed RE capacity of the different cells for all three models.

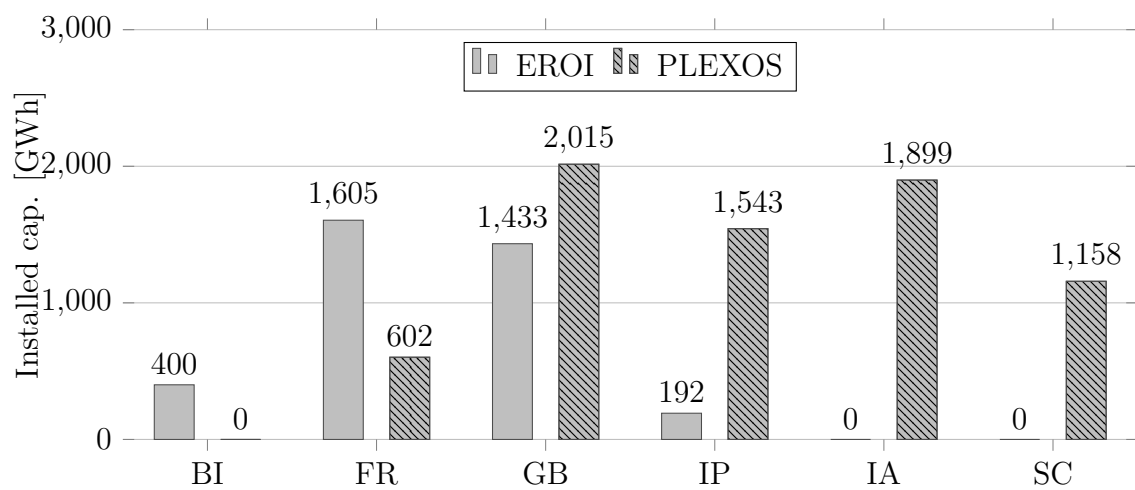


Figure 4.22: Installed storage capacity of the different cells for the EROI and PLEXOS.

PLEXOS model Distribution of the yearly system costs is available in Table 4.14. We can observe that most of the costs are from the storage investments (55.4% of total costs). The total system costs corresponds to 47.9% of those of a 100% RE system. Conversely to the EROI model, the economic costs of NRE electricity production is here taken into account. The LCOE of the different cells lies between 43.83 €/MWh and 205.35 €/MWh.

	BI	FR	GB	IP	IA	SC	System
Production investment	6.43	22.29	17.26	9.35	9.98	7.97	73.28
Production O&M	12.79	23.46	27.07	10.54	15.46	8.78	98.28
Storage investment	0.13	18.44	61.10	46.92	58.49	35.74	220.83
Storage O&M	0.00	0.55	1.83	1.40	1.73	1.06	6.56
Total	19.36	64.91	107.26	68.21	85.66	53.55	398.95
Consumption [TWh/yr]	441.62	606.04	819.62	332.18	466.03	392.93	3058.41
LCOE [€/MWh]	43.83	107.11	130.86	205.35	183.81	136.28	130.44

Table 4.14: PLEXOS model: yearly system costs expressed in bn€/yr, consumption and LCOE.

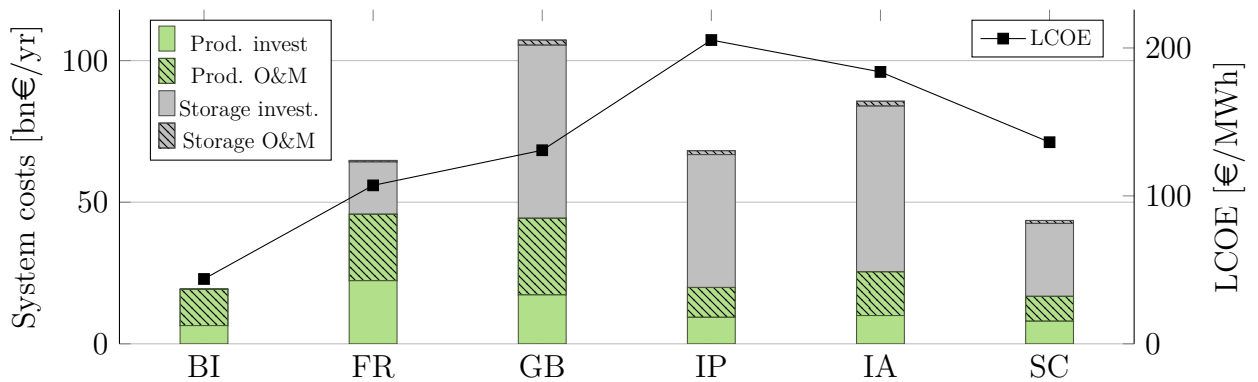


Figure 4.24: PLEXOS model: distribution of the system costs expressed in bn€/yr and LCOE of all cells.

In the EURS, the cost of electricity generation is given. We can compare this value to the LCOE of the PLEXOS model. This comparison is given in Table 4.15. We observe that the LCOE of the PLEXOS model is almost always higher than the LCOE of the EURS. This could be explained by the consideration of storage technologies in our study.

	BI	FR	GB	IP	IA	SC	System
EURS	114.09	72.15	100.89	88.74	93.18	65.90	90.03
PLEXOS	43.83	107.11	130.86	205.35	183.81	136.28	130.44
Variation	-61.6%	+48.5%	+29.7%	+131.4%	+97.3%	+106.8%	+44.9%

Table 4.15: Comparison of the LCOE of the EURS and the PLEXOS model, in €/MWh.

4.5 A transition scenario with PLEXOS

This section will study the transition of the Western-Europe system from 40% RE to a 100% RE system. Only the PLEXOS model is used for this study. The milestones used to study this transition are 40%, 60%, 80% and 100% of renewable electricity production. This constraint of minimum RE production was applied to the whole system and not on each individual cell. We will analyse the following decisions of the PLEXOS model at every milestone and in every cell:

- Built generation capacity (PV, WTon and WToff).
- Retired generation capacity (Nuclear, CCGT and Coal).
- Built storage capacity (Battery).

These decisions are made to minimize the system costs and to respect the minimum RE production constraint of the system.

First, we will analyse the electricity production of the different cells. Next, we will take a look at the evolution of the storage capacity. Finally, we will analyse the evolution of the LCOE with the minimum RE production.

4.5.1 Electricity production

Figure 4.25 shows the evolution of the production of electricity in Western-Europe. At 40% of renewable electricity production, most of the renewable electricity comes from hydropower (37.8%) and solar PV (32.8%). Offshore wind turbines are not yet a main sources of electricity, only 2% of the total production. The more the system evolves towards a 100% RE production, the more electricity is produced from solar PV and offshore wind turbines. During the transition, the quantity of energy produced with onshore wind turbines decreases. This is due to cheaper electricity sources like solar and offshore wind being introduced into the system and forcing the onshore wind turbines to be curtailed. It is only at 100% RE production that onshore wind turbines become a major electricity source.

One may notice that the total amount of energy produced slightly increases with the share of renewables, from 2645 TWh at 40% to 2709 TWh at 100%. The consumption of the system remained the same during the transition (2630 TWh annually). This is explained by the increasing quantity of energy that needs to be put into storage systems, rising the amount of energy lost during the storage.

Details of the evolution of the production of every cell is available in Figure C.1.

Figure 4.26 gives the evolution of the RE production share of every cell. We can compare this with the RE production share of the Western-Europe system. During the transition, three cells drives the renewable energy transition, namely Scandinavia, Italy & Alpine States and Iberian Peninsula. These three cells have their RE production share above the system RE production share at any time during the transition. Then Iberian Peninsula and Italy & Alpine States have a very good solar load factors (16.7% and 15.3% respectively) and early on in the transition they are leveraging this advantage to reduce the system's costs. Scandinavia benefits from an impressive already installed hydropower capacity (48 GW) that helps the cell achieve a 74% RE production share early in the

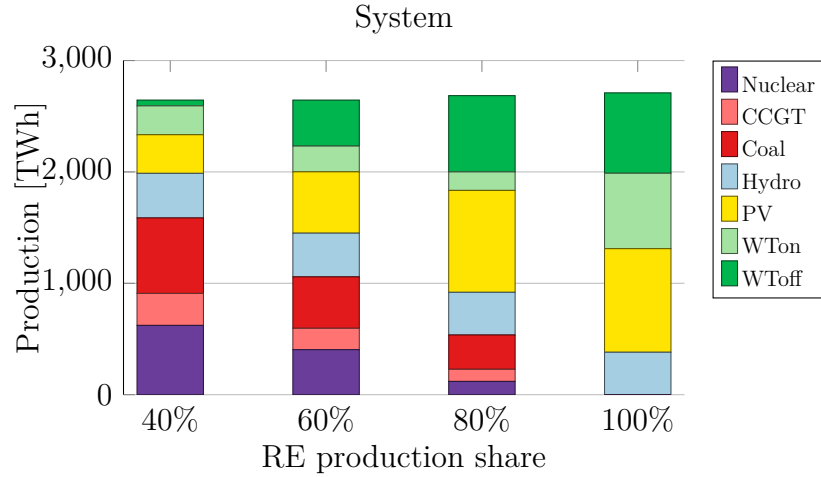


Figure 4.25: Transition with PLEXOS model: Evolution of the production of electricity of the complete system.

transition. On the other hand, the British Isles, France and Germany & Benelux have a RE production share below the system's average RE share during the transition.

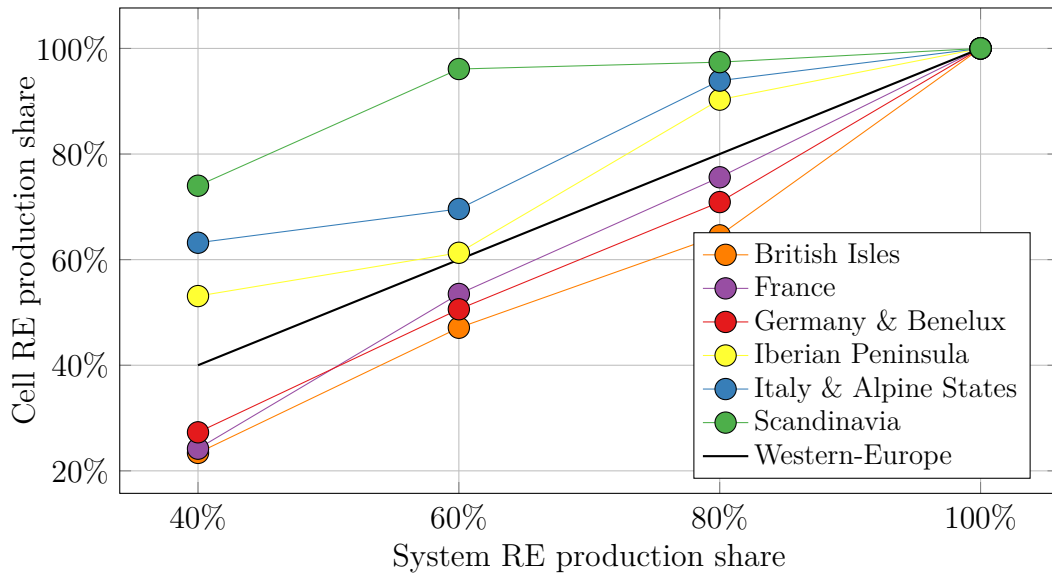


Figure 4.26: Evolution of the RE production share of each cell with the RE increase of Western-Europe.

4.5.2 Installed storage capacity

In Figure 4.27, we can observe the evolution of the installed storage capacity of battery in each cell. The storage capacity of PHES units is not shown in this graph as their capacities remain constant during the transition. One can notice the surge of installed capacity after 80%. This shows the difficulty of a system to reach a 100% RE energy system without inexpensive storage technologies. In the PLEXOS model, batteries are

expensive and power-to-gas is not available, resulting in a system that choose the last moment to install the necessary storage to support a 100% RE electricity production.

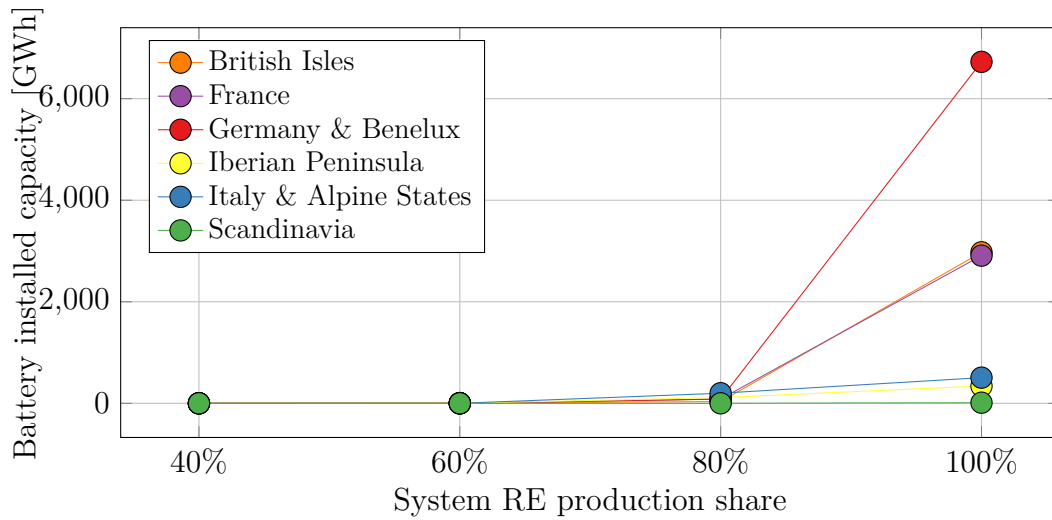


Figure 4.27: Evolution of the installed battery storage capacity in each cell with the RE increase of Western-Europe.

4.5.3 Evolution of the LCOE

The LCOE of every cell at every step of the transition has been calculated and put into Figure 4.28. At 40% RE production share, the LCOEs of the cells are between 29.66 €/MWh (Scandinavia) and 44.13 €/MWh (France), with a global LCOE of 35.90 €/MWh. At 80% RE production share, the global LCOE has increased to 51.95 €/MWh, with no significant different between the cells' LCOEs. At 100% RE production, we start to see a important difference between cells with a small amount of batteries and cells with a significant amount. The combined LCOE of the British Isles, France and Germany & Benelux is 340.94 €/MWh while the combined LCOE of the Iberian Peninsula, Italy & Alpine States and Scandinavia is only 72.51 €/MWh.

The distribution of the costs of Western-Europe is available in Figure 4.29. As already explained, the high cost of batteries is the main source of costs in a 100% RE system, 68.8% of the total system costs in this case.

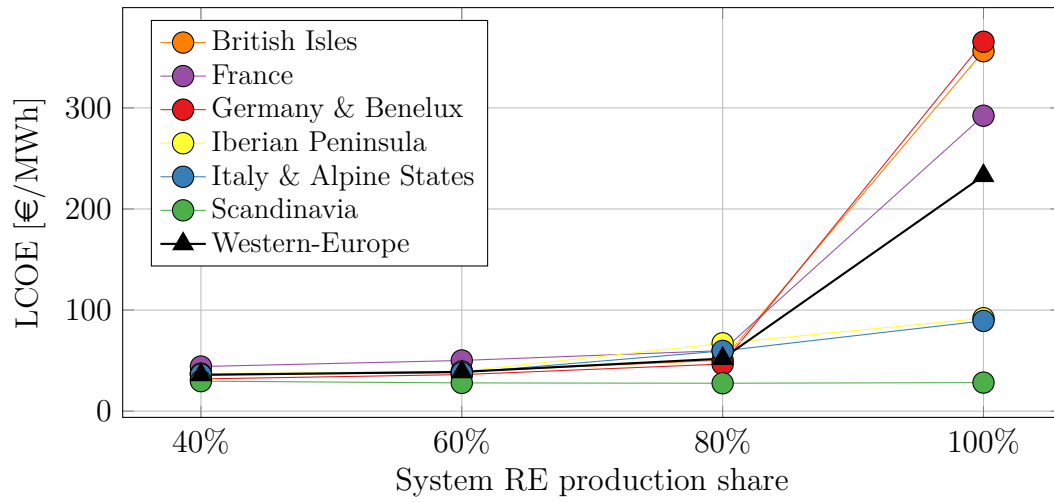


Figure 4.28: Evolution of the LCOE of each cell and the system with the RE increase of Western-Europe.

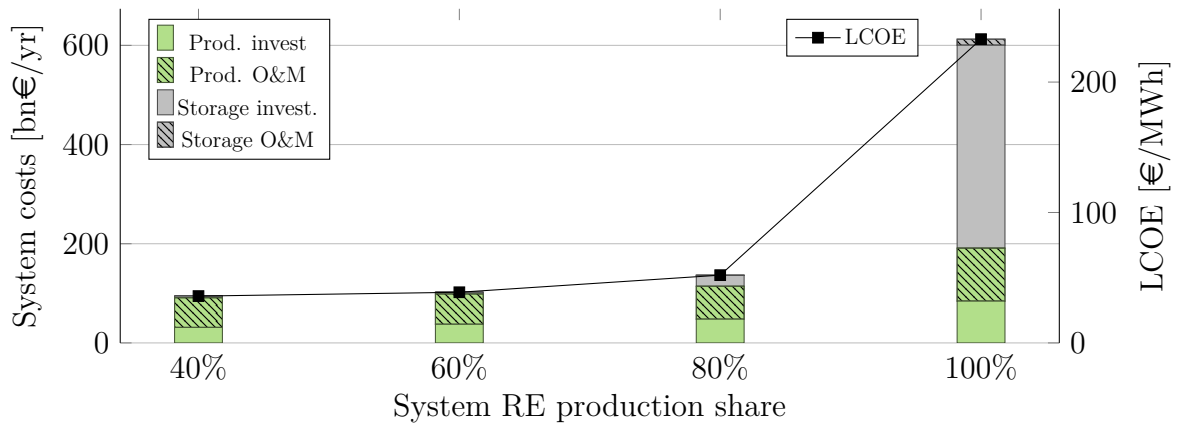


Figure 4.29: PLEXOS model: distribution of the system costs expressed in bn€/yr and LCOE of Western-Europe.

Chapter 5

Discussion

Several conclusions can be drawn from the multiple comparisons that are presented in Chapter 4.

First, in the case of a 100% RE energy system, on one hand the installed RE capacity was much higher in the PLEXOS model than in the EROI model and on the other hand the installed battery storage capacity was much lower in the PLEXOS model than in the EROI model. We can see that the PLEXOS model tries to limit as much as possible the installation of batteries even if it means that a lot of the produced energy will be curtailed. To convince ourselves of this, we can take a look at the final cost of 1 MWh. In the EROI model, a MWh directly consumed will have on average a cost of 92 kWh. If that same MWh was coming from a battery, its cost would have been 125 kWh, including production and storage costs. Stored energy is thus 1.36 more expensive than direct energy. In the PLEXOS model, one MWh of direct energy costs on average 43.46 €. Stored, it would have cost 594.59 €. This means that stored energy is 13.7 times more expensive than direct energy. This important price difference between direct and stored energy explains why the PLEXOS model prefers to curtail most of its production instead of having to build batteries to store it.

The absence of cheap storage solutions like Power-to-Gas has a negative effect on the EROI and LCOE of our models. In Ramelot & Martinelle's study [12], Power-to-Gas was available. A two-cells system had an EROI of 7.88 and a six-cells system an EROI of 9.90. In our study, we have an EROI of 4.93 and 6.66 respectively. This shows that an energy system with a high share of RE needs a cheap storage solution in order to be energetically profitable. Studies suggests that Power-to-Gas may not be attractive until about 80% of intermittent renewable energy sources penetration [35]. The comparison with the EU Reference Scenario and the transition scenario are therefore more realistic systems than the 100% RE systems presented in the two-cells and six-cells analysis.

The comparison of our models with the European Union Reference Scenario showed used that the EROI model was closer to what the European Commission expects from the energy system in 2030 than the PLEXOS model. The suggested electricity mix to adopt in 2030 is similar in the EURS and EROI model with the exception of a slightly lower hydropower production compensated by wind power in the EROI model. The PLEXOS model on the other hand decided to invest in solar power instead of other technologies. This resulted in a lot of the produced energy being curtailed or stored. The LCOE of the PLEXOS model could be compared with the LCOE given in the EURS. The electricity in

the PLEXOS model is 44.9% more expensive than in the EURS model.

The comparison with the EURS also confirmed the correlation observed by de Giey [16] between the net exchange and the gas and coal share of a cell. In cells with storage systems like batteries, the PLEXOS model showed us that this correlation is no longer valid. Instead, we observe a correlation between the net exchange and the amount of flexible generation capacity, which includes gas, coal, dams, PHES and batteries. The more flexible generation capacity a cell has, the more energy it exports to its neighbours.

Finally, the transition scenario with the PLEXOS model showed that the LCOE of the system increases with the minimum RE share. We could also observe that increase of the total system costs with the minimum RE share were exponential. A 8% increase in costs was necessary to go from 40% RE to 60% RE, again a 34% increase to go from 60% RE to 80% RE and finally a 348% increase to go from 80% RE to 100% RE. In total the system costs increased by 549% between 40% and 100% RE. This impressive increase is mainly due to the necessity of storage technologies in high RE systems and the high costs of batteries.

Chapter 6

Conclusion

The objective of this master thesis was to compare a novel model developed at the UCLouvain that used the EROI metric as objective function with the state-of-the-art optimisation tool for energy systems PLEXOS by Energy Exemplar. This objective was fulfilled by first validating the methodology of both models. We proved that when feeded with the same inputs, both models would give the same optimal energy system. Afterwards, we compared how the two-cells energy systems of both models behaved under a 100% RE production constraint. Next, the same analysis was done with a complete six-cells energy system. These two analyses showed us the importance of the availability of cheap electricity storage. We then took our models to the next level and used them to model Western-Europe in 2030 with the same non-RE energy mix as the EU Reference Scenario. This analysis highlighted that the EROI model was closer to what the European Commission suggests than the PLEXOS model. Finally a transition towards a 100% RE energy system was performed with the PLEXOS model.

PLEXOS energy system optimisation tool has some interesting features like partial chronology or a more detailed heat rate (with run up and run down rates) that could be implemented into the EROI model in order to have a more realistic system and reduce the complexity of the optimisation. But the use of a proprietary software like PLEXOS sometimes reduces our freedom to develop the ideal energy system optimisation model to compare to the EROI model. Our academic license lacked some important features of an energy system optimisation model, like Power-to-Gas.

The future work on this subject would include a sensitivity analysis on the different input parameters. The sensitivity of the optimal energy system to certain cost parameters could be of key importance in the long-term planning of our energy system.

This study highlights the importance of energy system optimisations in the long-term planning of the energy transition of our society. The decrease of the EROI and the increasing trend of the LCOE with the increasing share of renewables raise concerns about whether or not our society is willing to transition towards an energy system with discouraging energetic prospects (considering the EROI) and economical prospects (regarding the LCOE).

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Appendix A

Model Description Appendix

A.1 Changes and validation of the EROI model

A.1.1 Changes

The EROI model used in this study is very similar to the one used in [12] and there program is available here: <https://github.com/sramelot/memoire2018>. Two errors have been spotted and three precisions have been added for more realistic approximations by the author and Oscar de Giey [16].

Errors The two errors concerned local inflow and the run-of-the-river energy production. The first was omitting a max limit on the run-of-the-river variable producing unrealistic results in some simulations. This correction is in the initialization in the file `lp_problem.py` (line 93). The second error was the initialization of the local inflow before normalizing it to the annual production. This can be found in the file `producers.py` (line 188-189 and 214-215).

Precisions While the power curve of the wind turbines in the previous program was computer as a sum of an exponential between the cut-in and cut-out wind speed, the new method suggests an approximation with cubic splines. This has been modified in the class `Producers.py` (line 96-120). A comparative illustration can be found in Figure A.1. The cut-in, rated and cut-out speed have been respectively set at 4.5, 14 and 25 m/s. One can observe the smoother transition between the increasing curve and the rated speed for the cubic splines approximation. The power curve of the Enercon E82/2300 is used in the model. This change affects the system in the power generation for WT's but does not change fundamentally the different global trends.

Two other precisions were the irradiance and wind velocity adaptations to the load factor. The previous method used an iterative method with a fixed tolerance of 1×10^{-3} whereas the new method uses the `fsolve` function from SciPy, which has a default tolerance of 1.49012×10^{-8} .

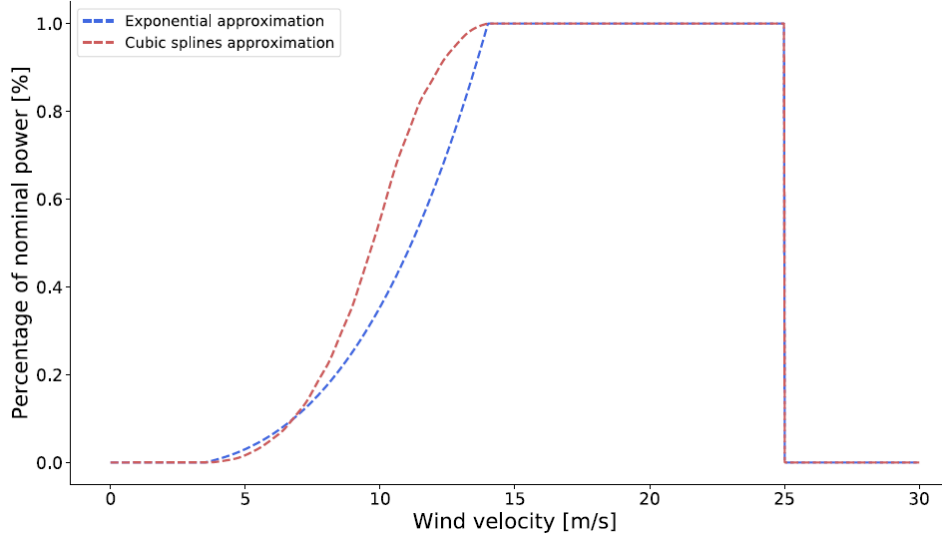


Figure A.1: Power curves of the two different approximations

A.1.2 Validation of the new program

As the program has been completely redesigned, the new program has to be validated in order to be sure that design and utilization changes did not affect the systems results. The only changes that should affect the results are the aforementioned “precisions” and “errors”. Please find in Table A.1 the difference induced by the previously cited changes. Once these changes are reset to old approximations, the system, even with a different architecture, produces the exact same linear programming problem.

	Invested energy TWh	EROI -
Ramelot & Martinelle’s version	42.1	8.78
Couplet & deGiey’s version	42.6	8.68

Table A.1: Comparison of the objectives with the new approximations and corrections.

Appendix B

Two-cell analyses

B.1 Tables

	FR		GB		System	
	EROI TWh/yr	PLEXOS bn€/yr	EROI TWh/yr	PLEXOS bn€/yr	EROI TWh/yr	PLEXOS bn€/yr
RE investment	42.27	45.86	65.99	60.03	108.26	105.89
Solar PV	1.09	15.24	6.86	8.70	7.95	23.94
Wind onshore	2.03	17.57	21.16	38.67	23.18	56.24
Wind offshore	39.15	13.05	37.97	12.66	77.12	25.71
RE O&M	0.00	33.86	0.00	41.98	0.00	75.85
Solar PV	0.00	11.10	0.00	6.34	0.00	17.44
Wind onshore	0.00	11.59	0.00	25.51	0.00	37.11
Wind offshore	0.00	10.20	0.00	9.89	0.00	20.09
Hydropower	0.00	0.97	0.00	0.24	0.00	1.20
Storage investment	38.93	96.88	91.66	210.92	130.59	307.80
Battery	38.93	96.88	91.66	210.92	130.59	307.80
Storage O&M	1.93	43.71	3.22	95.05	5.15	138.76
Battery	1.92	43.59	3.21	94.92	5.13	138.51
PHES	0.02	0.12	0.01	0.14	0.03	0.25
Total	83.13	220.32	160.87	407.99	244.00	628.30

Table B.1: Yearly system costs for the case of a two-cell 100% RE scenario.

	FR		GB		System	
	EROI	PLEXOS	EROI	PLEXOS	EROI	PLEXOS
	%	%	%	%	%	%
RE investment	17.32	7.30	27.05	9.55	44.37	16.85
Solar PV	0.45	2.43	2.81	1.39	3.26	3.81
Wind onshore	0.83	2.80	8.67	6.15	9.50	8.95
Wind offshore	16.04	2.08	15.56	2.01	31.61	4.09
RE O&M	0.00	5.39	0.00	6.68	0.00	12.07
Solar PV	0.00	1.77	0.00	1.01	0.00	2.78
Wind onshore	0.00	1.85	0.00	4.06	0.00	5.91
Wind offshore	0.00	1.62	0.00	1.57	0.00	3.20
Hydropower	0.00	0.15	0.00	0.04	0.00	0.19
Storage investment	15.96	15.42	37.57	33.57	53.52	48.99
Battery	15.96	15.42	37.57	33.57	53.52	48.99
Storage O&M	0.79	6.96	1.32	15.13	2.11	22.09
Battery	0.79	6.94	1.32	15.11	2.10	22.05
PHES	0.01	0.02	0.00	0.02	0.01	0.04
Total	34.07	35.07	65.93	64.93	100.00	100.00

Table B.2: Yearly system costs in % of the total system costs for the case of a two-cell 100% RE scenario.

Appendix C

Six-cell analyses

C.1 Commission's proposal: tables

Exporting cells	Net export TWh	Export share %	Gas and Coal share %
Germany & Benelux	34	4.15	66.56
British Isles	25	5.66	42.12
Italy & Alpine States	17	3.65	49.70
Importing cells	Net import TWh	Import share %	Gas and Coal share %
France	61	10.07	5.34
Scandinavia	11	2.80	12.85
Iberian Peninsula	4	1.20	24.71

Table C.1: Exporting and importing cells in the EURS with their export and import share. The correlation with their Gas and Coal share is highlighted.

Exporting cells	Net export TWh	Export share %	Gas and Coal share %
Germany & Benelux	33.2	3.85	65.37
British Isles	23.2	5.09	42.42
Italy & Alpine States	9.8	2.00	48.48
Importing cells	Net import TWh	Import share %	Gas and Coal share %
France	43.6	7.20	5.31
Scandinavia	12.3	3.12	13.04
Iberian Peninsula	10.4	3.12	25.38

Table C.2: Exporting and importing cells in the EROI model with their export and import share. The correlation with their Gas and Coal share is highlighted.

Exporting cells	Net export TWh	Export share %	Gas and Coal share %
Germany & Benelux	89.6	8.07	49.14
Iberian Peninsula	27.2	5.29	15.99
Italy & Alpine States	1.7	0.25	34.46
Importing cells	Net import TWh	Import share %	Gas and Coal share %
France	77.0	12.71	5.86
British Isles	25.5	5.76	45.90
Scandinavia	16	4.07	10.41

Table C.3: Exporting and importing cells in the PLEXOS model with their export and import share. The correlation with their Gas and Coal share is highlighted.

	BI	FR	GB	IP	IA	SC	System
Production investment	12.15	9.17	26.36	15.52	11.97	5.76	80.94
Solar PV	1.81	1.09	6.86	8.46	3.04	0.11	21.37
Wind onshore	8.30	2.03	8.67	7.06	8.93	5.19	40.18
Wind offshore	2.03	6.05	10.83	1.59	0.00	0.47	19.39
Storage investment	1.76	7.06	6.31	0.84	0.00	0.00	15.97
Battery	1.76	7.06	6.31	0.84	0.00	0.00	15.97
Storage O&M	0.11	0.18	0.16	0.15	0.01	0.00	0.62
Battery	0.11	0.18	0.16	0.15	0.00	0.00	0.60
PHES	0.00	0.00	0.00	0.01	0.01	0.00	0.02
Total	14.01	16.42	32.83	16.52	11.98	5.76	97.53
Consumption	441.62	606.04	819.62	332.18	466.03	392.93	3058.41
EROI	31.51	36.91	24.97	20.11	38.89	68.16	31.36

Table C.4: EROI model: yearly system costs expressed in TWh/yr, consumption and EROI.

	BI	FR	GB	IP	IA	SC	System
Production investment	6.43	22.29	17.26	9.35	9.98	7.97	73.28
Nuclear	1.54	5.53	0.06	0.83	0.13	0.71	8.79
CCGT	1.70	0.35	1.81	0.60	1.15	0.17	5.78
Coal	0.07	0.20	2.15	0.15	0.29	0.02	2.78
Solar PV	0.78	13.54	8.70	4.97	5.25	0.02	33.26
Wind onshore	1.46	0.76	3.11	1.57	0.68	4.42	11.99
Wind offshore	0.68	0.96	1.19	0.00	0.00	0.16	2.98
Hydropower	0.21	0.96	0.23	1.25	2.48	2.47	7.59
Production O&M	12.79	23.46	27.07	10.54	15.46	8.78	98.28
Nuclear	2.80	10.08	0.11	1.51	0.24	1.30	16.03
CCGT	7.61	1.37	11.89	2.78	7.46	1.85	32.97
Coal	0.10	0.11	5.51	0.34	0.98	0.08	7.12
Solar PV	0.57	9.86	6.34	3.62	3.83	12.63	24.24
Wind onshore	0.96	0.50	2.05	1.03	0.45	2.92	7.91
Wind offshore	0.53	0.75	0.93	0.00	0.00	0.12	2.33
Hydropower	0.21	0.97	0.24	1.26	2.50	2.49	7.67
Storage investment	0.13	18.44	61.10	46.92	58.49	35.74	220.83
Battery	0.00	18.15	60.76	46.52	57.25	34.91	217.59
PHES	0.13	0.29	0.34	0.40	1.25	0.83	3.24
Storage O&M	0.00	0.55	1.83	1.40	1.73	1.06	6.56
Battery	0.00	0.45	1.82	1.40	1.72	1.05	6.53
PHES	0.00	0.00	0.00	0.00	0.01	0.01	0.03
Total	19.36	64.91	107.26	68.21	85.66	53.55	398.95
Consumption [TWh/yr]	441.62	606.04	819.62	332.18	466.03	392.93	3058.41
LCOE [€/MWh]	43.83	107.11	130.86	205.35	183.81	136.28	130.44

Table C.5: PLEXOS model: yearly system costs expressed in bn€/yr, consumption and LCOE.

C.2 Transition with PLEXOS: figures

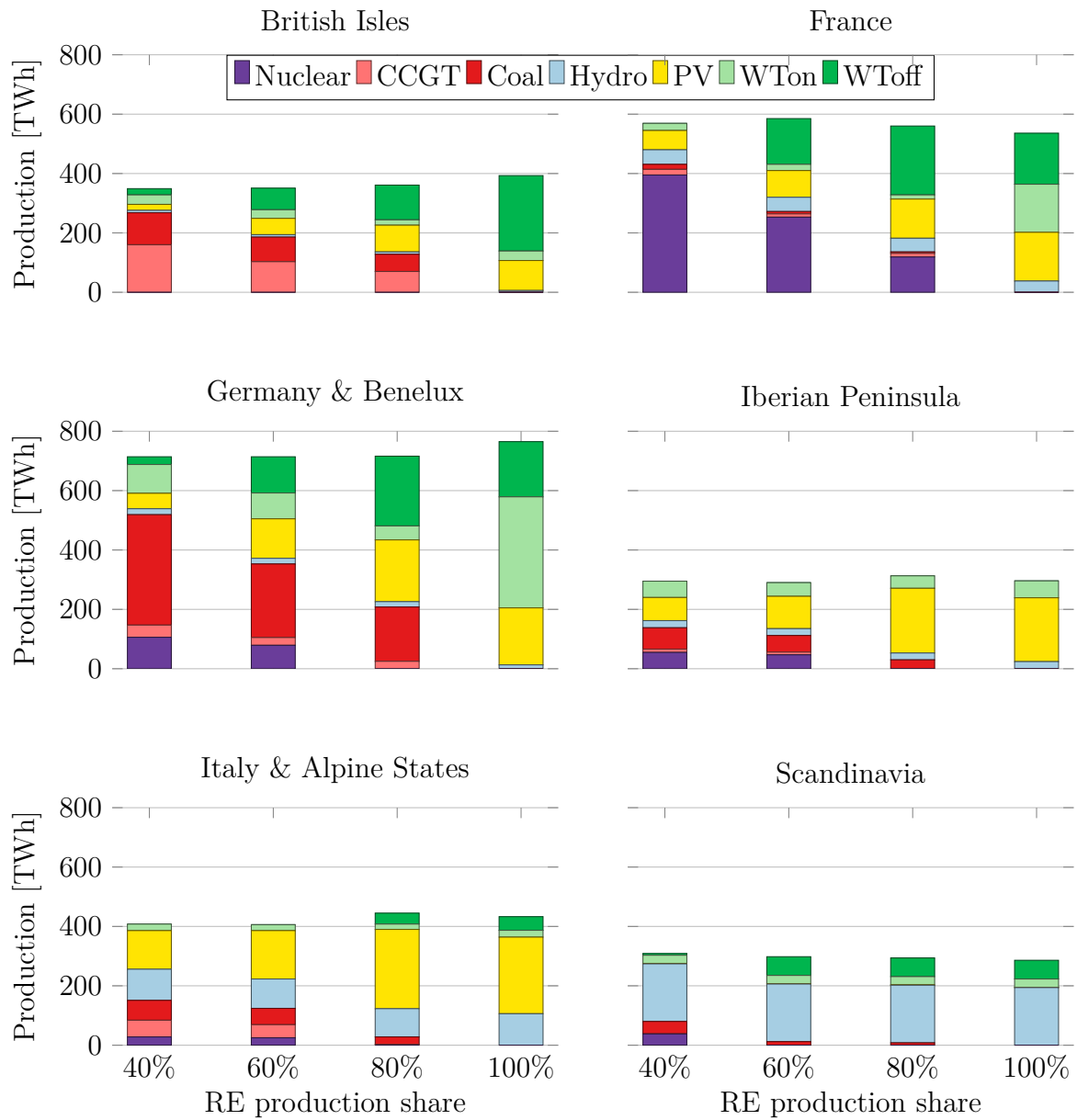


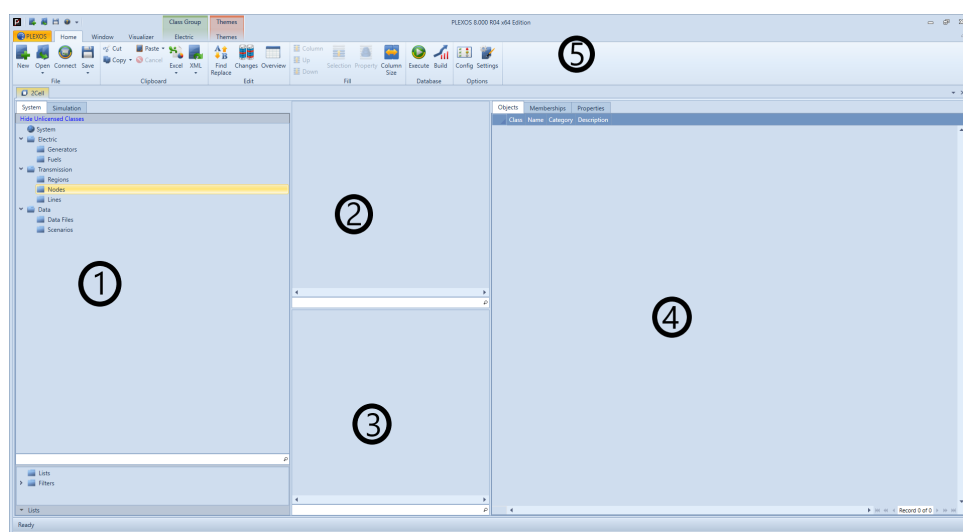
Figure C.1: Transition with PLEXOS model: evolution of the production of electricity of the different cells.

Appendix D

Introduction to PLEXOS

The goal of this appendix is to be a step-by-step guide into the creation and optimisation of a simplified two-cell model. This way, first-time PLEXOS users can familiarise themselves with the object-oriented software design of PLEXOS. This guide was made with PLEXOS Version 8.000 R04 x64 Edition and was inspired by a tutorial from the Iowa State University¹.

1. **Launch PLEXOS:** If this is the first time you launch PLEXOS, a valid license file will be asked by the License Manager. Use the License Wizard to create a local license file. Next, request a license activation to support@energyexemplar.com and attach your local license file to the email. Once you have received a valid license file from the support, delete the existing license file and copy the attached one to the same folder location. You are now ready to use PLEXOS.
2. **Create a new file:** Click on “New” from top left-hand menu. Then click on the “Save” icon above the word “Save” on the top left-hand menu. Choose a directory to save to, and name your file “2Cell.xml”.
3. **Observe:**

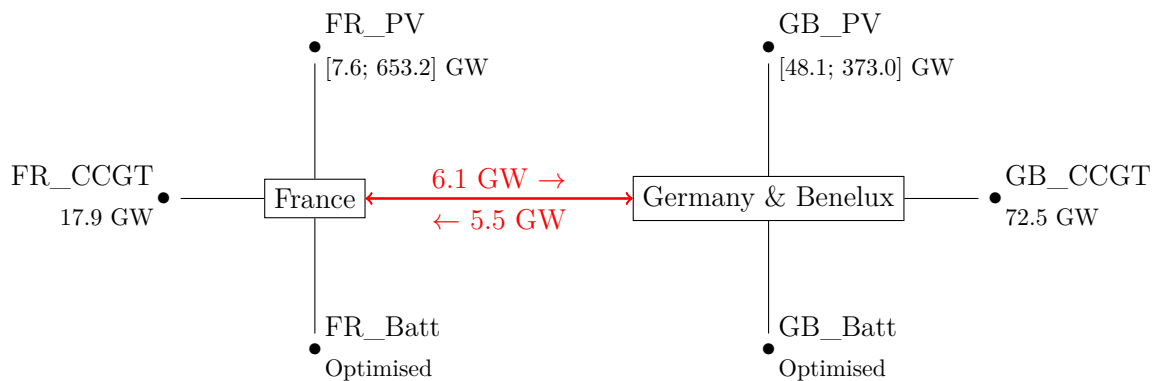


¹Available at <http://home.engineering.iastate.edu/~jdm/ee552/PlexosTutorial1-2016.pdf>

The numbers 1 to 5 refers to

1. The Main Tree: This tree shows you all the Objects in the database organized into Collections shown as folders. This tree is your primary means of navigating the data in the system. The other interface elements respond to your selections in this tree.
2. The Membership Tree: Shows the relationships (called Memberships) between objects. The contents of this tree change according to your selection in the Main Tree.
3. The Properties Tree: Lists the properties available for the type of objects selected in the Main Tree.
4. The Data Grid: There are three tabs for the grid (Objects, Memberships, Properties). Each presents a standard Access datasheet where you can edit/add/delete data. You can also use the standard Access filtering and sorting commands to organize the data presented.
5. The Menu Bar: Provides the action commands for PLEXOS such as Execute to begin execution of a simulation.

Now we are going to create the following power system:



We will do seven types of operations:

- Set configuration: **Step 4**
- Create objects: **Step 5 to 11**
- Add objects to collections and set memberships: **Step 12 to 16**
- Set properties: **Step 17 to 22**
- Set up simulation: **Step 23 to 28**
- Execute model
- Examine solution.

We start with the configuration:

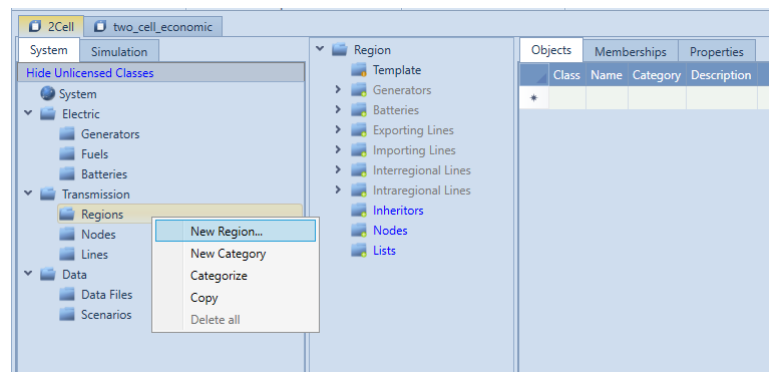
4. **Set configuration** Click on “Config” in the menu bar. In this window, you will select all the properties you are going to use in the system. First click on the checkbox in the bottom left-hand-corner to enable “All Dynamic”. In the left panel, you will enable the following checkboxes:

- Electric.Generator.Generators.Production.VO&M Charge
- Electric.Generator.Generators.Production.Rating Factor
- Electric.Generator.Generators.Capacity.FO&M Charge
- Electric.Generator.Generators.Expansion.Build Cost
- Electric.Generator.Generators.Expansion.Economic Life
- Electric.Generator.Generators.Expansion.Max Units Built
- Electric.Generator.Generators.Expansion.Min Units Built
- Electric.Generator.Generators.Expansion.Max Units Retired
- Electric.Battery
- Electric.Battery.Batteries.Production.Max Load
- Electric.Battery.Batteries.Production.Initial SOC
- Electric.Battery.Batteries.Capacity.FO&M Charge
- Electric.Battery.Batteries.Expansion.Max Units Built
- Electric.Battery.Batteries.Expansion.Build Cost
- Electric.Battery.Batteries.Expansion.Economic Life
- Transmission.Node.Nodes.Production.Load
- Transmission.Line.Lines.Production.Min Flow

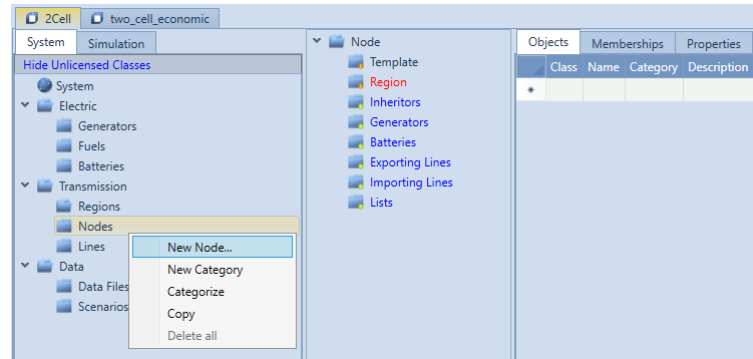
Once you have enabled all these properties, click on “OK” at the bottom right-hand-corner of the screen.

The next type of operation is the creation of the objects:

5. **Create region Western-Europe:** Right click on “Region” (from main tree) and select “New Region”. A dialog box will appear where you will need to provide your new region with a name. Name it “Western-Europe”. Click “OK”, and a “Western-Europe” Properties window will appear. Click “OK” at the bottom right-hand corner of this window.

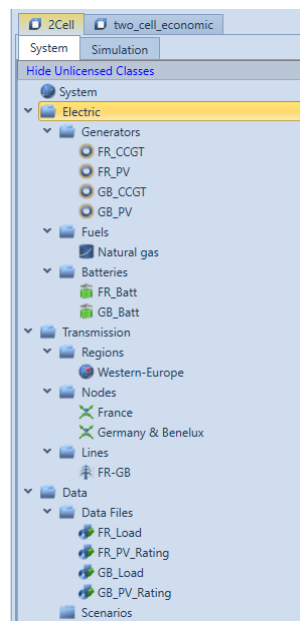


6. **Create node France:** Right click on “Nodes” from main tree and select “New node”. A dialog box will appear, where you will need to provide your new node with a name. Name it “France”. Click “OK”, and a “France” Properties window will appear. Click “OK” at the bottom right-hand corner of this window.



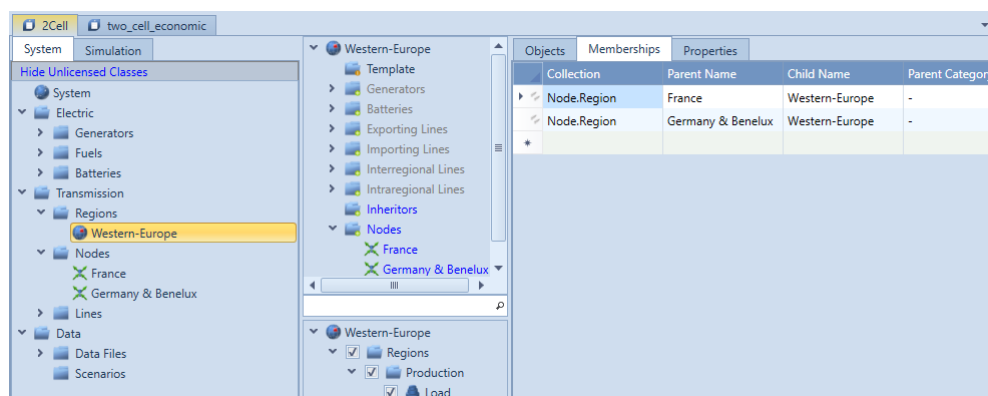
7. **Create node Germany & Benelux:** Repeat step 6 except name the new node “Germany & Benelux”.
8. **Create line FR-GB:** Right click on “Lines” from main tree and select “New line”. A dialog box will appear, where you will need to provide your new line with a name. Name your new line “FR-GB”. Click “OK”, and a “FR-GB” Properties window will appear. Click “OK” at the bottom right-hand corner of this window.
9. **Create generators:** Right click on “Generators” from main tree and select “New generator”. A dialog box will appear, where you will need to provide your new generator with a name. Name your new generator “FR_CCGT”. Click “OK”, and a “FR_CCGT” Properties window will appear. Click “OK” at the bottom right-hand corner of this window. Repeat this process to create generators FR_PV, GB_CCGT and GB_PV.
10. **Create fuel Natural gas:** Right click on “Fuels” from main tree and select “New fuel”. A dialog box will appear, where you will need to provide your new fuel with a name. Name your new fuel “Natural gas”. Click “OK”, and a “Natural gas” Properties window will appear. Click “OK” at the bottom right-hand corner of this window.
11. **Create batteries:** Right click on “Batteries” from main tree and select “New battery”. A dialog box will appear, where you will need to provide your new battery with a name. Name your new battery “FR_Batt”. Click “OK”, and a “FR_Batt” Properties window will appear. Click “OK” at the bottom right-hand corner of this window. Repeat this process to create battery GB_Batt.
12. **Create data file objects:** Right click on “Data Files” (from main tree) and select “New Data File”. A dialog box will appear, and you will need to provide your new datafile with a name. Name your new data file “FR_Load”. Click “OK”, and a “FR_Load” Properties window will appear. Click “OK” at the bottom right-hand corner of this window. Repeat this process to create data files FR_PV_Rating, GB_Load and GB_PV_Rating.

At this point, your system should look like this:

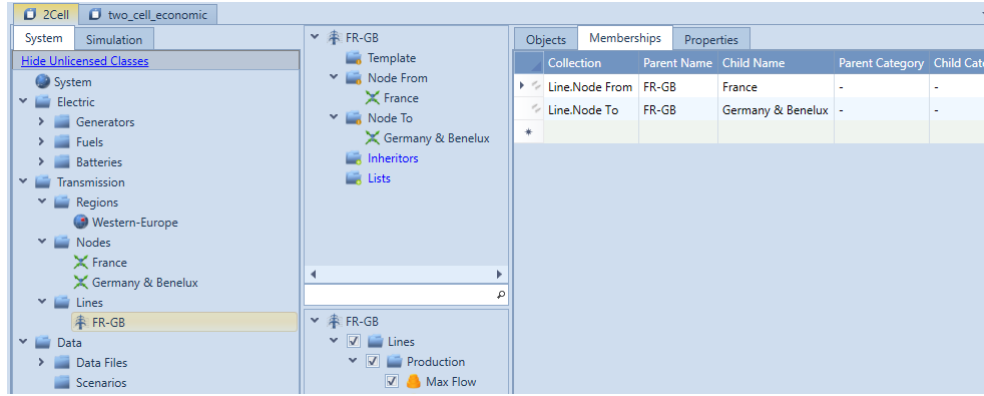


We will now add these objects to collections:

12. **Add nodes to node collection of region:** Left click on “Western-Europe” in main tree. Left click on the “Memberships” tab of the data grid. Left click beneath the “Collection” column in data grid. When you do this, you will see a drop-down menu appear on the right-side of the cell. Select “Node.Region”. Left click on the “Parent Name” column, and select “France”. Left click on the “Child Name” column, and select “Western-Europe”. Add a second “Node.Region” membership between “Germany & Benelux” and “Western-Europe”.

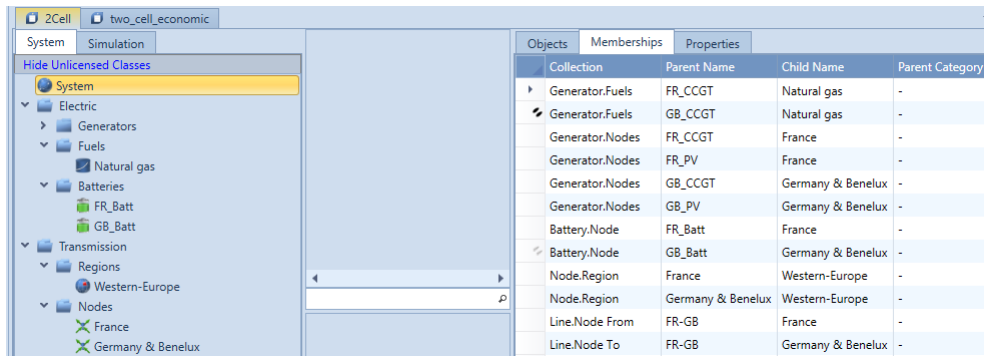


13. **Add nodes to node collection of line:** Left click on “FR-GB” in main tree. Left click on the “Memberships” tab of the data grid. Left click beneath the “Collection” column in data grid. When you do this, you will see a drop-down menu appear on the right-side of the cell. Select “Line.Node From”. Left click on the “Parent Name” column, and select “FR-GB”. Left click on the “Child Name” column, and select “France”. Add a “Line.Node To” membership between “FR-GB” and “Germany & Benelux”.



14. **Add generators to generator collection of nodes:** Left click on “France” in main tree. Left click on the “Memberships” tab of the data grid. Add a “Generator.Nodes” membership between “FR_CCGT” and “France”. Repeat the operation for the “Generator.Nodes” memberships between “FR_PV” and “France”, “GB_CCGT” and “Germany & Benelux” and “GB_PV” and “Germany & Benelux”.
15. **Add batteries to battery collection of nodes:** Repeat step 14 except the memberships to add are: a “Battery.Node” membership between “FR_Batt” and “France” and a second “Battery.Node” membership between “GB_Batt” and “Germany & Benelux”.
16. **Add generators to generator collection of fuel:** Left click on “Natural gas” in main tree. Add a “Generator.Fuels” membership between “FR_CCGT” and “Natural gas” and a second “Generator.Fuels” membership between “GB_CCGT” and “Natural gas”.

Left click on System in main tree to check all existing memberships



We will now set the properties of the different objects:

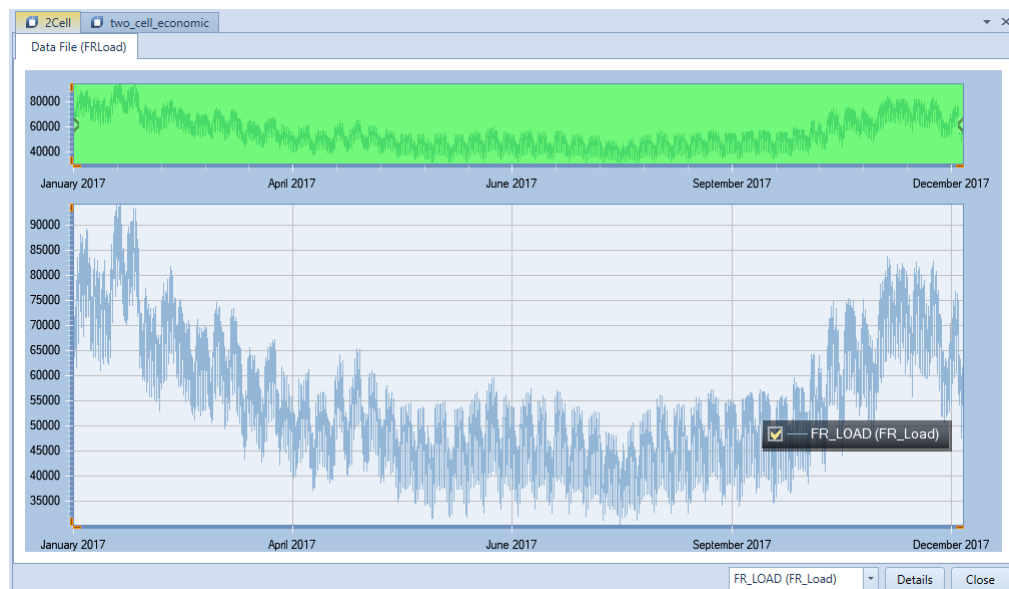
17. Set data file properties:

- (a) Prior to setting the data file properties, you need to create a load data file. To do this, create a .csv file having the following format:

Year	Month	Day	1	2	3	4	...	24
2017	1	1	72916	72169	69699	66467	...	71234
2017	1	2	66704	65627	63510	61607	...	75040

The load data, in MW, is specified one 24 hour day per row. It is possible to model as many days as desired. Create a `data\` directory at the same location as your model. Download the data files for this system from <https://github.com/acouplet/masterthesis/PLEXOS/guide> and put them in the `data\` directory.

- (b) Left click on “FR_Load” in main tree. Left click on the “Properties” tab of the data grid. Left click beneath the “Property” column in the second data grid. When you do this, you will see a drop-down menu appear on the right-side of the cell. Select the “Filename” property. In the “Filename” column of the property, fill `data\FR_Load.csv`.
- (c) Repeat steps 17(b) for “FR_PV_Rating”, “GB_Load” and “GB_PV_Rating”.
- (d) Data files can be viewed within PLEXOS. Left click on “Build” in the menu bar. Left click on “FR_Load” in the “Data Files defined in Database” list and then on “Add >” to add it to the “Data Files to be Built” list. Left click on “FR_Load” in the second list and then on “View”. You now have a view of the “FR_Load” data file.



You can also view details by left clicking on “Details”. Once you have finished viewing the data file, left click on “Close” to close the “View” window, and again on “Close” to close the “Build” window.

18. **Set node properties:** Left click on “France” in main tree. Left click on the “Properties” tab of the data grid. Left click beneath the “Property” column in the second data grid. When you do this, you will see a drop-down menu appear on the right-side of the cell. Select the “Load” property. In the “Data File” column select “FR_Load”. Repeat the operation for the “Load” property of “Germany & Benelux”.
19. **Set line properties:** Left click on “FR-GB” in main tree. Create the properties “Max Flow” and “Min Flow” and set their value to 6100 and -5500 respectively.

20. **Set fuel properties:** Left click on “Natural gas” in main tree. Create the property “Price” and set its value to 6.5.
21. **Set generator properties:** Left click on the “Generators” directory in main tree. Create the following properties:

Objects	Memberships	Properties	
Generator	Property	Value	Data File Units
FR_CCGT	Units	1	-
FR_CCGT	Max Capacity	17898	MW
FR_CCGT	Min Stable Level	0	MW
FR_CCGT	Heat Rate	5.71428571	GJ/MWh
FR_CCGT	VO&M Charge	1.2	\$/MWh
FR_CCGT	FO&M Charge	11	\$/kW/yr
FR_CCGT	Build Cost	902	\$/kW
FR_CCGT	Economic Life	30	yr
FR_CCGT	Max Units Retired	1	-
FR_PV	Units	0	-
FR_PV	Max Capacity	100	MW
FR_PV	Rating Factor	100	FR_PV_Rating %
FR_PV	FO&M Charge	17	\$/kW/yr
FR_PV	Build Cost	700	\$/kW
FR_PV	Economic Life	25	yr
FR_PV	Max Units Built	6531.62	-
FR_PV	Min Units Built	76.46	-
GB_CCGT	Units	1	-
GB_CCGT	Max Capacity	72469	MW
GB_CCGT	Min Stable Level	0	MW
GB_CCGT	Heat Rate	5.71428571	GJ/MWh
GB_CCGT	VO&M Charge	1.2	\$/MWh
GB_CCGT	FO&M Charge	11	\$/kW/yr
GB_CCGT	Build Cost	902	\$/kW
GB_CCGT	Economic Life	30	yr
GB_CCGT	Max Units Retired	1	-
GB_PV	Units	0	-
GB_PV	Max Capacity	100	MW
GB_PV	Rating Factor	100	GB_PV_Rating %
GB_PV	FO&M Charge	17	\$/kW/yr
GB_PV	Build Cost	700	\$/kW
GB_PV	Economic Life	25	yr
GB_PV	Max Units Built	3729.55	-
GB_PV	Min Units Built	481.12	-

22. **Set battery properties:** Create the following properties for both batteries:

Objects	Memberships	Properties	
	Property	Value	Data File Units
▶	Units	0	-
	Capacity	2000	MWh
	Max Power	400	MW
	Max Load	400	MW
	Initial SoC	50	%
	Charge Efficiency	90	%
	Discharge Efficiency	100	%
	FO&M Charge	67.83	\$/kW/y
	Max Units Built	1000000	-
	Build Cost	2261	\$/kW
	Economic Life	12	yr

Our system is now complete. Next, we have to setup the simulation of our model:

23. **Create model:** Click left on the “Simulation” tab of the main tree. Create a new model by right clicking on “Models” in the main tree and selecting “New Model”. A dialog box will appear, where you will need to provide your new model with a name. Name your new model “LTST”. Click “OK”, and the “LTST” Properties window will appear. Click “OK” at the bottom right-hand corner of this window.

24. **Set Planning Horizon:** Click right on “Horizons” in the main tree and select “New Horizon”. Name your new horizon “1ydt1” and click “OK”. A window will appear where you have to add the model that run this horizon. Add “LTST” model to the “Horizon.Models” members. Left click on “Close”. A new window will appear where you can setup your planning horizon. Use these properties:

Click on “OK”.

25. **Set Report:** Click right on “Reports” in the main tree and select “New Report”. Name your new report “Custom” and click “OK”. Add “LTST” to the “Report.Models” members and click “OK”. Use these properties:

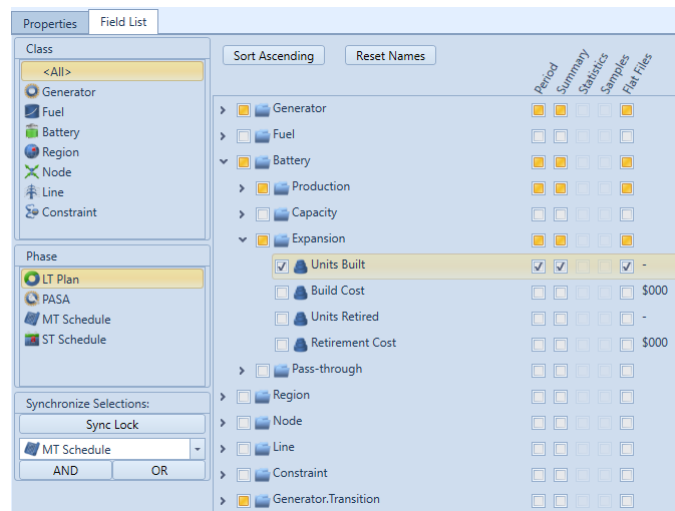
Click on the “Field List” tab of the Report properties window. This window will let you decide which output property you want to be written out in the solution files. Select for “Period”, “Summary” and “Flat Files” columns and the “ST Schedule” phase the following properties:

- Generator.Production.Generation

- Generator.Production.Undispatched Capacity
- Battery.Production.Energy
- Battery.Production.SoC
- Battery.Production.Generation
- Battery.Production.Load
- Node.Production.Load
- Node.Production.Native Load
- Node.Production.Generation
- Line.Production.Flow

And for the “LT Plan” phase, select the following properties:

- Generator.Capacity.Units
- Generator.Expansion.Units Built
- Generator.Expansion.Units Retired
- Battery.Production.Units
- Battery.Production.Units
- Battery.Expansion.Units Built



Click on “OK”.

26. **Set LT Plan:** Click right on “LT Plan” in the main tree and select “New LT Plan”. Name your LT Plan “r=8” and click “OK”. Add “LTST” to the “LT Plan.Models” members and click “OK”. Use these properties:

The screenshot shows a complex configuration window with multiple tabs and sections. Key settings include:

- Step Size:** Step Size (years) = 1, Overlap (years) = 0.
- Chronology:** Fitted (selected), Slicing Method: Peak/Off-peak Bias (selected).
- Discounting:** Discount Rate (%) = 8, End Effects Method: Perpetuity (selected), Discount/Expansion Period: Year (selected).
- Expansion Algorithm:** Expansion Decisions Integer Optimality: Linear (selected), Integerization Horizon (years) = -1.
- Stochastic Method:** Deterministic (selected).
- Transmission:** Nodal (selected).
- Heat Rate:** Detailed (selected).
- Pricing:** Generation Pricing Method: Average (selected).

Click on “OK”.

27. **Set ST Schedule:** Click right on “ST Schedule” in the main tree and select “New ST Schedule”. Name your ST Schedule “ST” and click “OK”. Add “LTST” to the “ST Schedule.Models” members and click “OK”. Use these properties:

The screenshot shows the Transmission Detail configuration window with the following settings:

- Transmission Detail:** Nodal (selected).
- Heat Rate:** Detailed (selected).
- Stochastic Method:** Deterministic (selected).
- Discounting:** Discount Rate (%) = 0, End Effects Method: Perpetuity (selected), Discount Period: Week (selected).

Click on “OK”.

28. **Set Performance:** Click right on “Performance” in the main tree and select “New Performance”. Name your Performance “SCIP” and click “OK”. Add “LTST” to the “Performance.Models” members and click “OK”. Select the GLPK solver and click on “OK”.

You are now ready to execute your model. You can check every settings of your model by double-clicking on it in the main tree.

29. **Execute model:** Click on “Execute” in the menu bar. Add “LTST” to the models you want to execute. Finally, click on “Execute” in the bottom right-hand corner of the window.

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