Electricity storage needs for the energy transition : an EROI based analysis illustrated by the case of Belgium

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Abstract

To face climate changes and energy dependency, governments encourage their industries and communities to increase the share of renewable energy (RE). However, the RE production is mostly inflexible. The risk of unmatching electricity market grows. Tools such as power plant flexibility, import/export, demand side management, storage and RE curtailment are developed to handle this problem. This study focuses on the energy storage mix required for the energy of the electricity system to high RE shares. An hour based model is developed in order to optimise the renewable energy and storage assets by maximising the energy return on investment (EROI) while respecting power fluxes constraints. The model is used to quantify the storage needs for the energy transition of Belgium. An in-depth analysis is performed for four scenarios. Depending on the RE deployment and nuclear share, EROI between 5 and 10.5 are obtained. Large scale storage is required as soon as the energy mix has more than 30% of RE. With more than 75% of RE, power to gas becomes unavoidable. This study highlights that curtailment can be limited to less than 5% of RE production. These values are the result of the optimum between increasing storage, RE capacity and curtailment.

Keywords: Energy storage, EROI, Power to gas, seasonal storage, energy transition, energy management.

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1. Introduction

In 1917, an engineer wrote : "It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were devised for storing power from the intermittent sources of nature ... [The] problem of storing them in a practical way ... has for many years engaged the attention of the most eminent engineers, among whom may be mentioned Edison, Lord Kelvin, Ayrton, Perry..." [1].

This problem is resurfacing nowadays because of the energy transition which aims at decarbonising energy sources. To face climate changes and energy dependency, the European Union, among others, drives its members towards an energy transition from fossil fuels to renewable and low carbon energy.

Renewable energies (REs) are intermittent and irregular. They do not fit the electricity demand. A risk of unmatching market grows and tools such as power plant flexibility, import/export, demand side management, storage and RE curtailment are developed to face this issue.

Recent works focusing on the energy transition evaluated storage needs for a fully renewable electricity in Europe [2–4]. They highlighted a needed storage capacity of around 100-300 TWh with an optimal RE mix. Nowadays the only large scale technology for electricity storage is Pumped Hydro Energy Storage (PHES). Gross PHES European potential is estimated at around 11.4 TWh and is reduced to 4 TWh if land use constraints are respected [5]. Approximately half of it is in the Alps and another half in the Scandinavian countries [5–7]. Therefore, the well-known gravity storage potential is one order of magnitude lower than the required amount of storage for Europe. Hence, other technologies will be required to answer the energy transition storage needs.

Storage of electricity can be done with different technologies, at different scales and for different applications. The most promising technologies are summarised in Figure 1 (adapted from other works [8–11]).

These technologies are split in two families: "chemical" and "mechanical". In the "chemical" family, batteries and flow batteries use ions to store electrons, and Power to Gas (PtG) uses electrolysers to transform electricity into hydrogen. Hydrogen can be transformed, to improve storage properties, into ammonia or, by assuming an available source of carbon dioxide (CO_2), into methane or synthetic liquid fuels such as methanol or dimethyl ether. In the "mechanical" family, energy can be stored into inertia form as in flywheels, gas potential energy as in Compressed Air Energy Storage (CAES) or based on gravity as in Pumped Hydro Energy Storage (PHES).

Each technology is suitable for a specific time scale. Short and long-term are defined as periods shorter than a couple of hours or longer than weeks, respectively. Figure 1 sorts storage technologies by power and energy capacity for a typical unit. The duration is the time required to empty the storage at full load. The competitive edge between the technologies should be the round trip efficiency. Indeed, short-term storage is used very often throughout the year and must have a high round trip efficiency. This requires large numbers of batteries and flow batteries (bottom left of Figure 1) with limited unit capacity. However, the efficiency of long-term storage is less relevant. In that case, the size of the reservoir becomes the key parameters. These large reservoir are used for seasonal storage or to backup production during a lack of RE for a couple of days or even weeks. PHES and PtG have naturally this specification (top right in Figure 1).

Some technologies are geographically dependent such as CAES that needs caves or PHES that needs a significant difference in height.

Power to gas exists at demonstration scale and can produce hydrogen, methane, methanol, dimethyl ether or ammoniac [12, 13]. Storing these molecules is industrially mature, at low cost and at an energy denisty of the same order of magnitude as fuel oil.

An ideal storage mix is composed of an efficient daily storage and a large energy reservoir seasonal or backup storage. A mix of PHES, batteries and PtG is promising with high efficiency batteries for short-term, PHES depending on geography for mid term and PtG for large energy storage and seasonal needs. This storage mix is relevant and used in other works studying high RE share in Germany or Europe [14–16]. Still such a mix has never been optimized regarding the EROI.

This paper estimates the storage needs for energy management. It focuses on time scales ranging from one hour to one year. At very small time scales, energy storage is also required for power quality management but that will not be investigated in this study. Energy storage taken into account in this study is used for different applications as

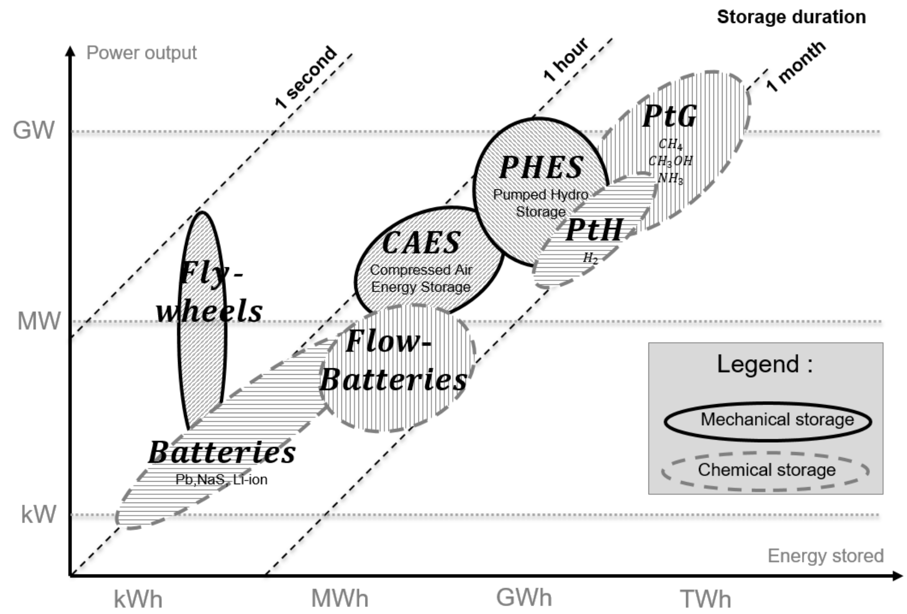


Figure 1: Overview of energy storage capacity of different storage systems including PtG. There are 2 families: mechanical and chemical storage. Adapted from Ibrahim *et al.* 2008 [8].

listed in [17, 18]. Applications are sorted in seven categories. (1) Renewable energy support, small scale storage is installed close to the RE device and buffers production (as solar panels in dwellings). (2) Commodity arbitrage, large scale storage absorbs excess during peaks and provides power during deficit. It ensures a production and consumption match at large time scale and decreases the spread in electricity prices. (3) Transmission support, storage avoids congestion on the transmission grid. (4) Distribution deferral, storage is used to arbitrage at distribution grid level (similar to (2) but at the distribution level). (5) Power quality, storage is used to control the frequency. This is equivalent to matching the production and consumption at a small time scale. (6) Distribution grid support, which avoids congestion on the distribution grid (similar to (3) but at the distribution level). (7) Off grid, system is not connected to the grid.

Common metrics used to evaluate energy systems are the Levelized Cost Of Energy (LCOE) and the financial investment (the money Return On Investment, ROI). Analysing an energy system based on ROI requires to take into account economical assumptions such as inflation and growth. Moreover, some energy source prices are biased by subsidies, policies and lobbies. To avoid these problems, this study uses the Energy Return On Investment (EROI).

EROI is the ratio between the energy produced throughout the lifetime of an energy system and the energy mobilized to produce, maintain and dismantle the same energy system. This dimensionless factor allows a comparison between energy sources, if the same boundaries for calculating inputs and outputs are used.

A high EROI is desirable because it is directly correlated to the standard of living in our society, which is based on energy-intensive machines. It is an indicator of society welfare and economy development [19–21]. The quality of energy sources matters because they have different EROI. David Ricardo's first principle is then verified: highest EROI sources are exploited first because they provide the most energy for the less effort. Therefore, the best fossil sources (EROI around 100) have been exploited in the past. Today, these sources are still exploited but with lower EROI (around 15) due to depletion [19, 20, 22]. Nowadays, wind and solar energies become competitive based on their respective EROI around 10-20 and 2-9 [19–24].

With a lower EROI and a decentralised RE production, the energy sector becomes more asset and worker intensive. Thus, an increasing proportion of the economy has to be devoted to obtain the same amount of energy available for the rest of the economy.

In scientific papers, EROI is a widely used metrics to measure the energy efficiency of energy sources [20, 22, 24]. To compute the EROI of the society, all actors from the primary energy to the end users must be taken into account.

Thus EROI is negatively impacted by energy storage, conversion and transport. The goal of this paper is to estimate the best electricity energy storage mix for the energy transition. The approach is illustrated by the case of Belgium. Similar case studies exist for Europe [16, 25], Germany [15] or even Belgium [26, 27]. But, they are all focusing on the ROI and not the EROI as the metric. Also, the studies about Belgium [26, 27] consider only one type of storage without geographical constraints. In the present work, as explained above, three storage technologies are taken int account. Only one other study analyses the impact of the energy storage on the EROI for the specific case of an isolated RE farm with a limited transmission line [28].

The work is organised as follows. a methodology, presented in Section 2, has been developed in order to analyse an electricity system based on RE and storage capabilities. Then the focus case of Belgium energy transition is detailed in Section 3 and solved in Section 4. Finally, the results are discussed in section 5 and general trends are highlighted for similar countries.

2. Methodology

In this section, a generic future electricity system and its components are defined. The system is split into several cells that exchange electricity. Cells represent a city, a region or even a country depending on the size of the whole system. This mimics an electricity system with limited transmission line capacities between neighbouring areas.

Inside a cell, production, consumption and storage capacities are well connected. They exchange electricity without losses, the so-called copper plate hypothesis. Given the detailed assumptions and key parameters in every cell, the maximization of the EROI at the whole system level is expressed as the solution of a linear optimization problem.

The whole methodology is further described in the following subsections and, schematically in Appendix A, where model inputs and outputs are detailed.

2.1. The electricity system and its components

2.1.1. Definition of the electricity system

Smart energy systems for European countries or similar areas are defined in different studies [15, 16, 25, 29]. They usually combine two main energy vectors, electricity and fuels (either liquid or gaseous). Here the focus is on the electricity. However, conversion of electricity into fuels and back is taken into account. Fuel fed to power plant is also taken into account, see Figure 2 that illustrates a generic implementation of an electricity system with three cells. The cells are interconnected by transmission lines. Cells at the border of the electricity system are connected to the outside by import/export transmission lines.

This implementation allows the model to take into account many different scenarios, such as large consumers, critical transmission lines or isolated producers, in quite complex systems.

The aim of the electricity system is to supply the demand of the end users that is given in the model as an input parameter. To reach this goal, the electricity system is made of four different components in each cell: supply, conversion, storage and demand. Considering all cells, the electricity system represents a bounded area that can still import or export electricity to, non modelled, neighbouring areas.

In each cell, the supply provides primary energy from three different sources: RE (Photovoltaic (PV) and Wind turbines (WT)), fossil fuel (e.g. natural gas) and nuclear power plants. Conversion units allow fuel to be converted into electricity or the opposite, using PtG. Storage concerns mainly electricity, but fuel is also stored either from PtG units or as a buffer from a constant supply coming from outside the system. The nature of the fuel and its chemical state (gas or liquid) are not specified in the model because only the quantity of chemical energy matters, independently of the fuel (natural gas, methanol, gasoline...).

2.1.2. Cell components

Each cell has its own consumers. Each consumption is hourly specified and must be balanced by the electricity production, storage or imports.

In each cell, the energy storage mix is composed of three representative technologies, batteries, PHES and PtG. Each technology is separately implemented. The PtG storage is split into three parts. First, the power to gas unit with an electrolyser and a synthetic fuel production unit (such as a methaniser). Second, a gas storage unit. Third, a gas to power unit assimilated to a power plant (PP).

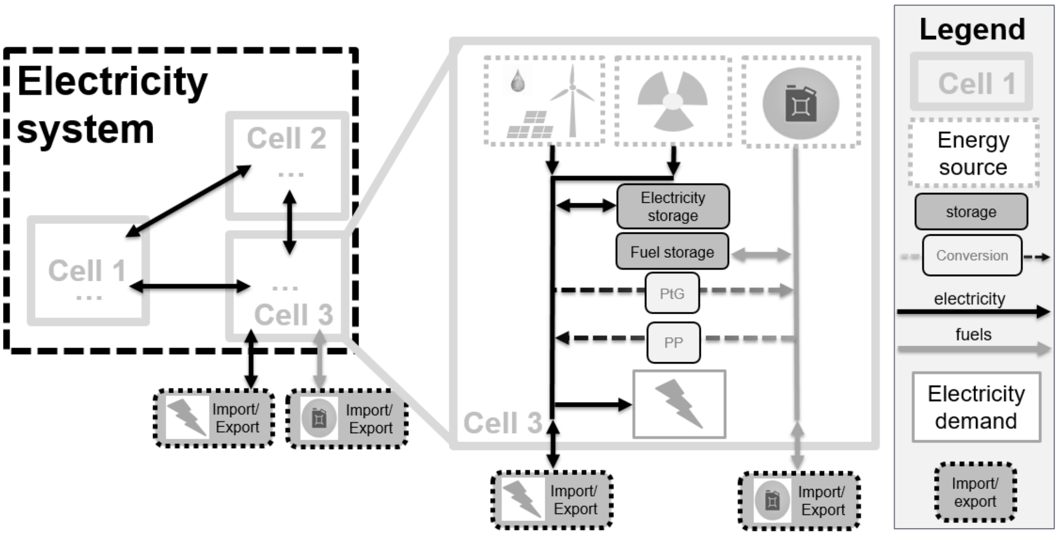


Figure 2: 3 cells system architecture (left) with a focus on cell 3 components (middle) and a legend (right). Cell 1 is represented by a bordering cell that is connected to the outside of the electricity system. Cell 3 is detailed with its energy suppliers, end-users, storage, conversion (dash arrows) and transport (plain arrows). There are 3 different types of energy supply (from top left to bottom) RE, nuclear and fossil fuels. Black and grey plain arrows represent respectively electricity and fuel fluxes. 2 conversion units have been represented, power to gas (PtG) and power plant (PP). There are 2 types of storage: fuel/gas storage and electrical storage. The last one includes batteries, PHES and CAES. The thick black dash lines isolate the electricity system from the shaded rest of the energy system.

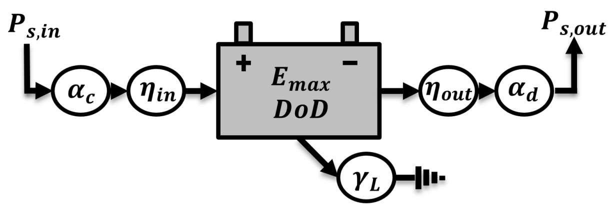


Figure 3: Representation of a generic storage system. 9 variables characterise the properties of the storage system and are listed in Table 1. Adapted from [28].

Storage units are defined by several parameters adapted from a study by Ghiassi-Farrokhfal *et al.* [28], see Figure 3. The following characteristics are implemented: round trip efficiency [-], charge and discharge power [MW], energy capacity [MWh], depth of discharge [-], self discharge [MW/MWh], energy cost per unit of installed capacity [MWh/MWh], storage cycle life [cycles] and life time [years]. The proposed model is improved by splitting the round trip efficiency into inlet and outlet efficiencies. All main storage technologies can be abstracted using these parameters, as summarised in Table 1.

Nuclear and Fuel power plants are characterised by an operating range [MW] and a load ramp [MW/s], and, for the units burning fuel, a fuel to electricity efficiency [-].

PV and WT production are defined by specific parameters. Photovoltaic panels are characterised by an efficiency giving the electrical output based on irradiation. Wind turbines are characterised by a power curve giving the electrical output based on wind velocity. The specific velocities of the power curves are: a cut in wind velocity of 3.5 m/s, nominal power at wind velocity of 14 m/s and cut off wind velocity of 25 m/s. Moreoever, PV and WT energy depends on the weather. Hourly discretizations of wind and of solar irradiation are required as inputs by the model.

Hydro plants are integrated into the PHES units by adding an additional power inlet (a fluid source, for example: a river).

Concentrated solar power (CSP), tidal and wave energy are not integrated in this study.

Parameters	Symbol	Units	Li-ion
Power storage inlet	$P_{s,in}$	[MW]	-
Maximum power charge	α_c	[MW]	-
Charge efficiency	η_{in}	[-]	95%
Maximum storage size	E_{max}	[MWh]	-
Depth of Discharge	DoD	[-]	20%
Self discharge	γ	[MW/MWh]	4e-6
Power storage outlet	$P_{s,out}$	[MW]	-
Maximum power discharge	α_d	[MW]	-
Discharge efficiency	η_{out}	[-]	95%
Storage cycle life	λ	[cycles]	6 000
Energy invested to create each unit of energy storage	ε	[MWh/MWh]	120
Life time	y	[years]	15

Table 1: Storage characteristic parameters. Numerical values are given for Lithium-ion batteries (data from [30, 31]).

2.1.3. Energy transport

Each cell is interconnected to some of the other cells by a number of transmission lines and pipes. The cells can hourly exchange electricity and fuel between each other, respecting the transmission line and pipe maximum power capacities and losses. The system is also connected to the outside and can import or export electricity and fuel. The yearly total imports are considered as an input parameter of the model.

2.2. Mathematical representation and optimisation

All the unknowns, the constraints and the objective function of the electricity system are formalized into a large linear system. They are defined in the following sections.

2.2.1. Variables

The model solves, hourly, the power fluxes of the electricity system based on unknown variables, such as the power plant production in each cells, the power stored in each cell, but also WT and PV installed capacities, battery capacities, etc.

The variables are shown in Figure 4 for a single cell. Most of the assets are purposely variable in order to avoid results to be only correlated to user-defined parameters. Assets and parameters which constrain the system are the hourly consumption, the non RE power plant capacities and the transmission line capacities.

2.2.2. Constraints on the system

The electricity system is constrained by two physical laws. First, power fluxes must be hourly balanced. For example, the model decides to import electricity or discharge a storage if there is a lack of electricity production. Conversely, the model charges storage, exports, or even decreases temporarily RE production (curtailing) if there is an excess of electricity production. Second, the cell topography constrains the size or number of RE or storage assets such as the local potential for PHES, the available windy spots, and the available areas for photovoltaic panels.

Four additional input parameters which constrain the system are: RE production share, electricity import share, PtG minimum capacity factor and fuel imports. The share of RE and electricity imports are user defined because the aim of this study is to analyse the energy transition under various energy dependency policies. Given the total RE production share, the model distributes the RE production over the available RE technologies in the system. Each cell can have a specific share of RE production given by the model. Similar to the RE share, the electricity imports is the annual electricity that could be imported compare to the annual consumption.

To avoid ridiculously huge PtG units, a minimum capacity factor over a whole year is imposed.

Fuel can be imported at a constant flow rate. This specification avoids to import massively during winter and very little during summer. The size of the fuel storage is thus designed for the seasonal storage needs including importation.

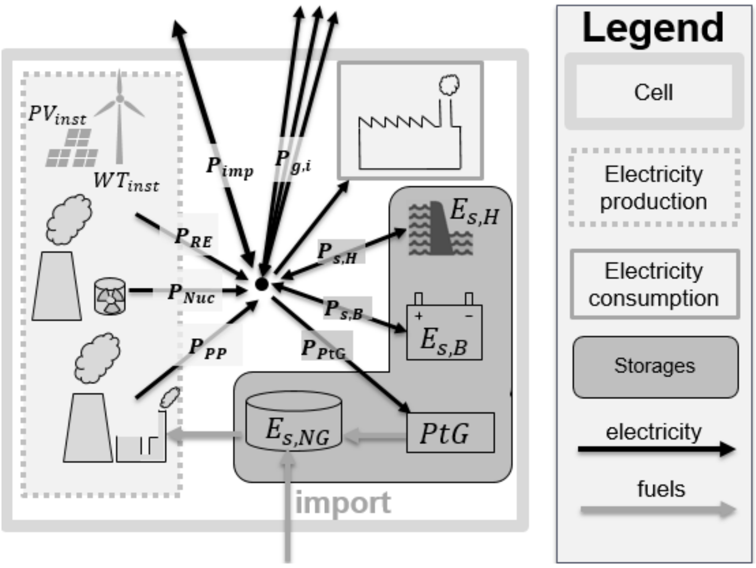


Figure 4: Representation of the variables of a cell, its power and gas fluxes. Variable hourly defined (such as power) are in bold. Three groups are identified: production, storage and consumption. There are two energy flows, electricity (black arrows) and gas (grey arrows). The installed capacity is variable for solar PV (PV_{inst}) and wind (WT_{inst}). The electrical power variable fluxes are production from RE (P_{RE}), nuclear (P_{Nuc}) and power plant (P_{PP}), transmission from neighbouring cells i ($P_{g,i}$), import (P_{imp}) and finally storage in PHES ($P_{s,H}$), batteries ($P_{s,B}$) or PtG (P_{PtG}). Storage is characterised by internal properties represented in Figure 3. Only the maximum storage size (energy capacity) are represented, they are for PHES ($E_{s,H}$), batteries ($E_{s,B}$) and natural gas ($E_{s,NG}$).

2.2.3. *Periodicity conditions*

The model solves a typical year supposed to be periodically reproduced. The amount of energy stored must verify this condition. The energy invested for an asset is supposed to be equally spread over the years.

2.2.4. *Toward EROI maximization*

As this study focuses on the energy transition, nuclear and gas shares are user defined, and thus they are not taken into account in the computation of the EROI.

A difference is made between gross and net EROI. The gross EROI is the energy that could have been produced by renewable energy sources (RES) (including the energy curtailed) divided by the energy invested for the RE assets. The net EROI is the ratio between the renewable energy consumed by the end user and the energy invested for RE and storage assets. A difference with the gross EROI, curtailment, storage cost and storage efficiency (energy waste) are taken into account in the net EROI. Therefore the gross EROI is higher or equal to the net EROI.

The amount of RE consumed is fixed by the RE production share. Therefore, maximising the EROI is equivalent to minimising the energy invested in the RE, storage and PtG units.

Hence, to compute the EROI, the energy invested to produce RE devices, storage and PtG are required as inputs parameters. They depend on cell topographies and are computed for each cell based on Life Cycle Assessment (LCA) studies, that analyse the energy required and carbon dioxide equivalent ($CO_{2,eq}$) emitted from cradle to grave [24, 28, 30].

Each RE technology has a specific energy cost [MWh] per unit of capacity [MW]. Storage devices have two contributions to the energy cost, first from the installed capacity and second from the actual use. Splitting the energy cost in two prevents unrealistic solutions such as using once a year a battery or using a battery thousands of time per month. PtG being at lab scale, it has a low readiness level. Consequently, there are not many studies for the energy invested for a PtG unit [32]. Hence, an educated guess value is taken for PtG at 100 MWh per installed power capacity of 1 MW. It is verified that this value has a very low impact on the results (see Section 5.1).

An exhaustive list of parameters, variables, constraints and outputs is given in Figure A.16.

3. Case study : Belgium energy transition

The case of Belgium is well defined while challenging. It is well defined because the exogenous parameters needed by the model are well-known. The weather is also quite homogeneous over the country simplifying the modelling approach. Yet, it is challenging due to the high population density and the consequent low RE potential per capita, especially for wind energy.

3.1. Cells division, imports and consumption

A cell is defined by a homogeneous weather and a good internal interconnection (electricity/gas). These assumptions are satisfied for the country as a whole, which is thus the first cell. Another cell is defined for offshore wind parks because weather is different with stronger winds.

These two cells representative of Belgium are interconnected by a transmission line. The transmission line can become the bottleneck if extra offshore capacities are installed without upgrading it. The capacity of the line is set at 2800 MW. This value is four times larger than today offshore WT installed capacity but only 75% of the maximum potential capacity. With an increasing offshore park, the transmission line will become the bottleneck condition. To face this problem, the model can increase the offshore battery storage as analysed in a study [28].

No losses in electricity transmission are considered between Belgium mainland and the offshore wind parks. The overall system representing Belgium is connected to its neighbours (France and The Netherlands) by transmission lines with a total capacity of 4500 MW (from Belgium Transmission System Operator (TSO) ELIA [33]), this capacity limits the imports.

The hourly electricity consumption corresponds to Belgium in 2015 (from European TSO: ENTSOE). The consumption varies between 6 at night and 12 GW during the day in summer and between 7 at night and 13 GW during the day in winter. The average consumption is 9.7 GW.

The average consumption during the energy transition is considered steady at around 9.7 GW. This is justified by two arguments. First, electricity efficiency[1] is estimated to increase as fast as the electricity consumption growth (such as electric cars or heat pumps) until at least 2025 as predicted by the ENTSOE [34]. Second, Belgium has an electricity trade deficit. An increasing consumption will result in increasing importation which will not impact the results of the model.

Belgium has imported on average 10% of its electricity consumption these last 10 years (based on Belgian Federation of Electric and Gas Companies (FEBEG) statistics). Hence, 10% of import is given as an input parameter to the model.

The gas network is strongly connected to The Netherlands and France in order to route gas from North sea to France. Therefore, the model allows a very high gas power capacity of 100 GW (from Belgium gas TSO Fluxys), which represents 50 m^3/s of methane at 60 bars.

3.2. Production

Belgium electricity production is a mix of nuclear, RE and fossil fuels, see Table 2 (Belgium installed capacity in July 2017 except PV and WT, data from Belgium TSO ELIA).

The non renewable production park is simplified in the model to its major components. Considering a load factor of 75% for nuclear, we assume an available nuclear capacity of 4440 MW. Hence, inputs for the model are 4440 MW nuclear and 5190 MW of flexible plants which regroup CCGT, CHP, OCGT, recycled waste and hydroelectric. This panel of flexible plants are assimilated to CCGT using natural gas with 58% efficiency. The flexible production mix is diversified enough to assume that it can be used from 0 to 100% of its power.

Large scale renewable energies in Belgium are solar, wind and biomass, since the small share of hydroelectric its included in the flexible plants. Tidal and geothermal are negligible. Biomass is mostly imported. Hence, biomass, geothermal and tidal are not considered. Finally, the two Belgian renewable energy sources implemented in this study are wind and solar.

[1]Electricity efficiency is defined as the useful power output divided by the total electrical power consumed.

Hourly weather data are used to compute WT and PV production profiles. Hourly distributions are taken at the coast (Zeebrugge and Koksijde) and in Brussels [35]. Capacity factors are summarised in Table 3 and are similar to data from other sources such as from ELIA and the international energy agency (IEA) [36]. RE installed capacity in Belgium in 2017 produces around 13% of the electricity consumed. Based on ELIA and Febeg[2] statistics, there is an installed capacity of 3.7 GW for PV and 1.7 GW of WT. The offshore and onshore wind potential are 3.5 GW [37] and 10 GW [24], respectively.

3.3. Storage

Belgian PHES installed capacity is 5 GWh with 1.2 GW of power and 77% roundtrip efficiency. There is no more room for another substantial PHES plant [5]. There are no available geographical resources for CAES. The storage mix during the Belgian energy transition will be composed of batteries, PtG and the existing PHES.

Batteries considered for the study are Li-ion with 90% efficiency, 6000 cycles, 15 year lifetime, 80% depth of discharge, 0.1% self discharge per day as summarised in Table 1 [30, 31]. An equivalent cycle is define as the sum of charge and discharge equal to a full cycle. For example, charging and discharging twice half the battery is equal to an equivalent cycle. The model assumes no difference between a cycle or an equivalent cycle.

Assuming power to methane technology, the efficiency from electricity to gas is around 63% [25, 38]. The PtG units size is limited to 1GW with a minimum yearly capacity factor of 15%. These last two values are arbitrary and define the reference scenario. A sensitivity analysis is performed in Section 5.1 to identify the role of these parameters.

3.4. EROI

The model requires as input parameters the energy invested for WT, PV and storage in order to compute the system EROI. The energy invested are based on a recent study [24]. In this work, the estimated energy invested per installed capacity for offshore and onshore wind turbines are 28.7 MJ/W and 20.2 MJ/W, respectively. The energy invested for solar panels is 1.5 GJ/m^2 which is equivalent, assuming an efficiency of 10% to 10 MJ/Wp for the Belgian weather. These values lead to an EROI of around 11-12 for wind and around 7 for solar PV. These values are coherent with other works estimating an EROI around 14 for wind and between 3 and 8 for solar PV [22, 28].

The energy invested for Li-ion battery storage is 120 MWh/MWh [30] for onshore and is more expensive for offshore reaching 200 MWh/MWh. The energy invested for PHES is computed based on the Energy Stored On energy Invested (ESOI) coming from other studies [30, 31]. The ESOI is the ratio between the energy stored during the lifetime and the energy invested to create this storage. The ESOI for PHES is around 700 MWh/MWh.
The model will optimise the capacity of the batteries and the number of cycles. The storage energy cost is the average of the capacity energy cost based on the ESOI and the cost of using the storage. Based on the energy invested for batteries, their ESOI are around 22 and 36 for offshore and onshore, respectively.
The energy invested for gas storage is very low and considered five order of magnitude lower than the energy invested for batteries.

[2]FEBEG : Federation Belge des Entreprises Electriques et Gazieres asbl.

Type	Fuel	Capacity [MW]
nuclear	Uranium	5 919
CCGT	Natural gas	3 519
CHP	Natural gas	706
OCGT	Natural gas	400
Recycled waste	Waste	335
Biomass	Wood pellets	363
Hydroelectric	Water	230
Turbo jet	Oil	200
Others	Mix	471

Table 2: Installed Belgian electricity production capacity in july 2017 (from Belgium TSO ELIA), except for solar and wind.

3.5. $CO_{2,eq}$ emissions

In the study, the greenhouse gas emissions are given as CO_2 equivalent emissions (simplified as $CO_{2,eq}$ emissions). These emissions for electricity production and storage are estimated based on LCA studies [39–42] and summarised in Table 4 . $CO_{2,eq}$ emissions for batteries are estimated to 61 tons of equivalent $CO_{2,eq}$ per MWh of installed capacity [41, 42].

3.6. Solver and performances

some textThe model has been implemented in Matlab® using the function `linprog`. No initial solution was provided to the solver. All runs have been performed on a Intel®Core^{TM} Quad i7-6600U CPU @2.60GHz, with a memory of 8 Go, and a 64-bit system. A run is performed in 30 minutes in average.

4. Results

In this section, results for all the possible designs of the Belgium electricity transition are evaluated and EROI-optimised. First, scenarios representative of four main steps in the transition are presented and in-depth analysed. Second, results for different RE and nuclear shares are analysed.

4.1. Detailed analysis of 4 scenarios

Four scenarios representative of the Belgium transition from nowadays to 100% RE are studied. Electricity import is fixed at 10% of the electricity consumption, therefore the production mix supply 90% of the consumption. The first scenario is a representation of a near-future society with a production mix of 50% nuclear, 20% RE and 30% gas. The second scenario presents a society in 15-20 years with a production mix of 10% nuclear, 50% RE and 40% gas. The third scenario presents a speculative case with a high share of renewable. The production mix is 0% nuclear, 80% RE and 20% gas. The fourth scenario presents a production mix of 100% renewable electricity for Belgium. Summary of the scenarios, results and storage specifications are given in Tables 5 and 6.

Capacity factors [%]	Wind	Solar
Offshore	41.2	10.5
Onshore	20.8	9.8

Table 3: Capacity factors of offshore and onshore RE in Belgium.

	Value	Units
Gas CCGT	490	[$kg_{CO_{2,eq}}$/MWh]
Nuclear	12	[$kg_{CO_{2,eq}}$/MWh]
Wind	12	[$kg_{CO_{2,eq}}$/MWh]
PV	45	[$kg_{CO_{2,eq}}$/MWh]
Li-ion Battery	61 300	[$kg_{CO_{2,eq}}$/$MWh_{installed}$]

Table 4: $CO_{2,eq}$ emissions per MWh production based on Life Cycle Assessments. For electricity production, $CO_{2,eq}$ emissions are given per MWh of electricity produced. For electricity storage, $CO_{2,eq}$ emissions are given per MWh of installed capacity. From [39–42].

	Scenarios			WT [5MW$_{eq}$]		PV		EROI		Curtailment	CO_2
	RE [%]	Nuc.[%]	Gas.[%]	On	Off	[km^2]	[GW$_c$]	gross	net	[%]	[Mt/year]
1	20	50	10	999	151	24	3.7	9.83	9.70	0.2	12.1
2	50	10	40	2007	658	58	8.8	9.85	9.44	2.1	16.2
3	80	0	20	2007	754	201	30.6	8.53	7.46	3.4	10.3
4	100	0	0	2007	754	427	65.8	7.92	5.37	19.0	4.6

Table 5: Synthesis of the four scenarios. Wind potential are 2007 and 754 WT 5 MW$_{eq}$ for onshore and offshore, respectively. PV has a 10% efficiency and is counted in square kilometres. 1 km^2 has a peak power of around 150 MW and an average power of around 15.7 MW.

Scenarios	Battery			Hydro	PtG			Gas stor. cap.
	[GWh]	[GW]	Cycles	Cycles	[MW]	Charge	[GWh]	[GWh]
1	2.3	2.3	27	8	0	0%	0	653
2	8.9	4.4	111	40	0	0%	0	1 666
3	86.7	20.3	146	56	848	15%	815	3 074
4	241	50.0	109	202	1000	49%	2 661	2 584

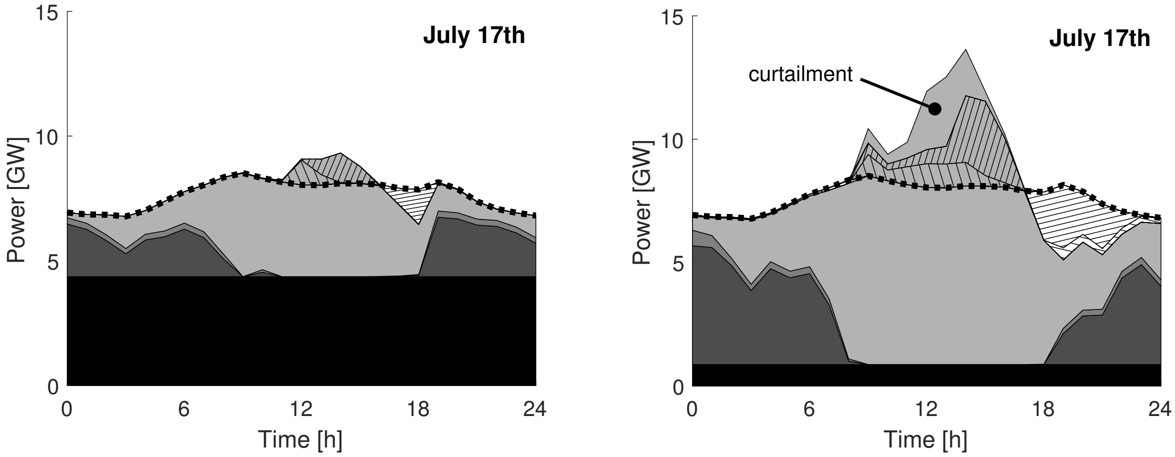
Table 6: Storage needs for 4 different scenarios. The gas storage is used as a buffer for both imported gas and PtG.

In the four scenarios, since WTs have a higher EROI than PV (11-12 compared to 7, respectively), the model leads to a faster increase of wind turbines compared to photovoltaic panels for an increasing share of RE (numerically illustrated in Table 5). It results in a merit order between technologies. Nevertheless, as shown in Scenario 2, both are increasing to provide an ideal mix and avoid curtailment due to the transmission line.
When the storage mix is composed of batteries and PHES, batteries are favoured due to their higher round trip efficiency (except for Scenario 4, that is explained below).

In the first scenario, there is negligible curtailment because nuclear provides the base load and CCGTs using imported gas are flexible enough to balance the supply-demand. 2.3 GWh of battery storage is required to absorb the excess of RE, for an overall 27 equivalent cycles a year. This solution is cheaper than building more RE and curtailing them, which is illustrated in figure 5(a).
In scenarios 1 and 2, the gross and net EROI are very close, the difference coming from the small capacity and the limited use of the battery storage. Due to a greater storage capacity and curtailment, this difference increases in scenarios 3 and 4. From a technical point of view, this result is the optimum. If the electricity price was taken into account, PHES and batteries might be more profitable and would be used more often. Also, the model is deterministic. With less anticipation, storage would be used more often for security of supply.
Figure 5(a) shows that when there is enough excess to charge both short-term storage types, PHES is charged first and discharged last because it has no self discharge compared to batteries.

In the second scenario, more storage is required with 8.9 GWh of batteries. Combined with hydro, the storage mix can absorb RE peaks and limit curtailment to 2.1% (see Table 5). Figure 5(b) shows a sunny summer day with excess RE production getting stored and curtailed. Because the model is deterministic, battery charge starts at the latest moment to minimise self discharge.
The storage is designed by two different constraints. First, excess of RE production constrains storage power input. During critical hours with high wind, high irradiation and low consumption, there is an excess of 5.6 GW between RE production and consumption which leads to a 4.4 GW of battery capacity plus 1.2 GW of PHES. Second, when the RE excess lasts for days, part of it is absorbed during the day and returned during night (see Figure 5(b)). The rest cannot be stored and is curtailed. This results from a trade-off between "paying" for less used extra storage capacity and curtailment.
In scenario 2, the ratio between WT and PV is higher compared to scenario 1, inducing a larger gross EROI. The net EROI is 4% lower than the gross EROI due to storage and curtailment. $CO_{2,eq}$ emissions are 34% higher than in the previous scenario (95.5% of the emissions come from gas), this is due to a higher share of gas in the production mix.

In the third scenario, battery storage reaches 86.7 GWh (see Table 6). Its power inlet is approximately equal to the PV installed capacity (30.6 GW) minus summer day consumption (11 GW) minus PHES storage (1.2 GW). In this scenario, storage is mostly used to shift summer solar excess production from day to night as illustrated in Figure 6(a). This storage combined to hydro is used for solar daily shaping. It absorbs solar peaks during summer days and provides power during summer nights (around 9 GW during a full night of 9 hours). More than 95% of the energy stored comes from RE. The number of battery equivalent cycles is close to that of scenario 2. It reflects the number of days PV energy is stored from day to night.
In this scenario, PtG is profitable for seasonal storage and summer PV peaks use. The optimal installed capacity is 848 MW and it reaches its minimum capacity factor of 15 %. As shown in Figure 6(a), the PtG production unit is at full load during summer days and even during some summer nights with very little load modulation. During days, PV produces enough energy for 4 different uses. First, it provides day consumption. Second, PV is stored in battery for the night consumption. Third, it supplies PtG units during the day to produce synthetic gas at full load. Fourth and



(a) Scenario 1. Summer day with hydro and battery charge and battery discharge.

(b) Scenario 2. Summer day with hydro and battery storage.

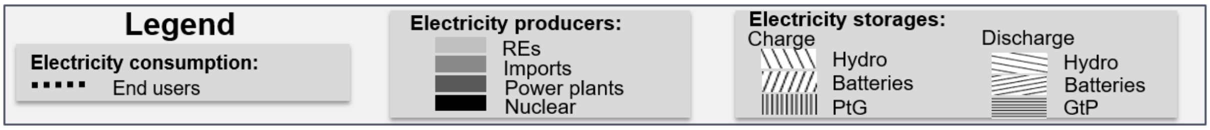


Figure 5: Power fluxes for a windy sunny summer day for the 1st (a) and the 2nd (b) scenarios. Consumption is the same and vary between 6.7 and 8.5 GW. Figure (b) shows that PHES is charged first and discharged last because it has no self discharge. In Figure (b), an excess of production cannot be absorbed and is curtailed.

last, PV is stored in battery to power the PtG units during the night. This overall system is energetically cheaper than increasing RE and thus curtailment or seasonal storage based on batteries.

Both net and gross EROI are lower compared to previous scenarios, with an increasing difference between them (13%) due to a higher use of storage and PtG.

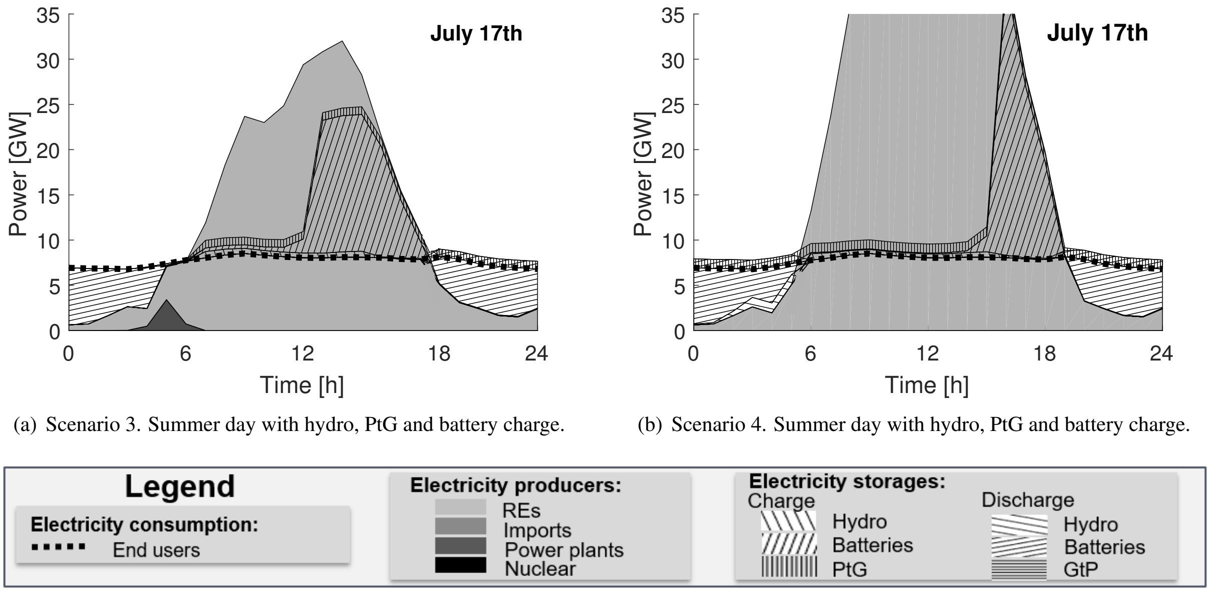
The $CO_{2,eq}$ emissions are lower than in scenarios 1 and 2 thanks to a lower share of gas. Gas is the predominant $CO_{2,eq}$ emitter (78%) followed by PV (14%), WT (4%) and batteries (4%).

In the fourth scenario, battery storage raises to 241 GWh with an installed power of 50 GW (see Table 6). The drivers are the same as in scenario 3 and are illustrated in Figure 6(b). The installed PV capacity is doubled, therefore the battery power (50 GW) and capacity (184 GWh) are doubled. An extra battery capacity (57 GWh) is required for longer term storage to support PtG which reaches its maximum size (1 GW) and has a capacity factor of 49%. This extra battery capacity is used a few times (less than 10 cycles) for long-term storage. This impacts negatively the overall number of cycles for battery which drops to 109 cycles. The PtG units produce around 4.4 TWh of synthetic gas used for critical moments as shown in figure 7(b).

Curtailment soars at 19% reflecting an heterogeneous distribution of RE over the year and the inability to absorb all the energy in the summer.

$CO_{2,eq}$ emissions decreased drastically compared to previous cases by nearly 60%. They are dominated by PV construction (3.2 Mt_{CO_2}) then batteries (1.0 Mt_{CO_2}) and finally WT (0.4 Mt_{CO_2}). These values are given with today LCA (assuming today energetic mix).

Two results were not expected. First, less than ten times during the year, electricity is stored at the same time than it is imported or produced with CCGTs, see Figures 7(a) and 7(b). This reflects a day with wind offshore at full load, hence saturating the transmission line. Therefore, the excess offshore electricity is stored and at the same time, mainland has not enough RE to be self sufficient and uses gas and imports. Upgrading the transmission line will decrease the curtailment but the total energy invested could be higher. This topic has been analysed and there is an optimum in terms of improvement of the transmission line and installation of storage capacities [28]. Depending on



(a) Scenario 3. Summer day with hydro, PtG and battery charge.

(b) Scenario 4. Summer day with hydro, PtG and battery charge.

Figure 6: Power fluxes for a sunny windy summer day for the 3rd (a) and 4th (b) scenarios. In both cases batteries are discharged during night to supply demand and sometimes PtG. With 100% RE, PtG is at full load during the whole summer.

the parameters, an optimum is reached before installing a transmission line able to transport the maximum power. Second, with a high residual gas production share such as in scenario 3, batteries are charged with electricity from CCGT and imports in order to provide enough power during nights. It happens in scenario 3 but is shown for an additional and even more critical case, see Figure 8. To prevent this aberration, extra CCGT capacities should be built in order to reduce the size of the storage and avoid electricity from CCGTs to be stored.

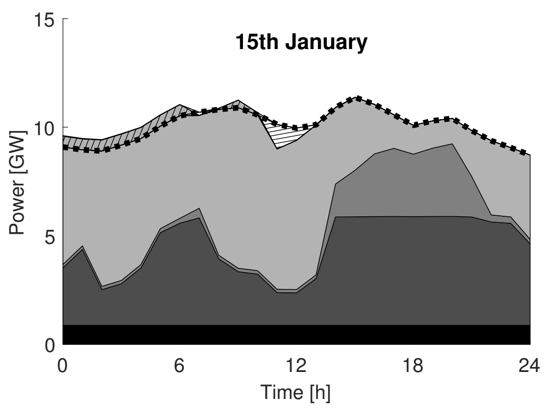
4.2. *Analysis of Belgium transition*

In this section, the Belgium transition with different shares of nuclear is analysed. Depending on policies, Belgium will increase the share of RE with a more or less spread nuclear phase out. The impact of RE transition on the storage is analysed with $CO_{2,eq}$ and EROI indicators.

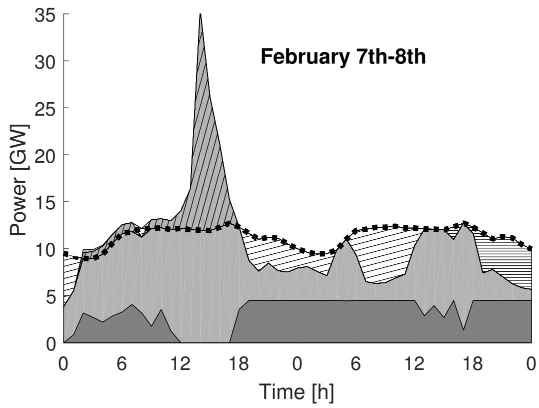
4.2.1. *Impact on EROI*

The net and gross EROI are illustrated in Figure 9 for different RE share. The gross EROI curve shows three distinct trends. First, between 15% to 20% of RE, it soars. Indeed, the gross EROI depends on the mix between WT and PV. It benefits from the high ratio between onshore WT and PV. The EROI creates a merit order strongly followed by the model. Second, between 20% and 40% of RE, WT are installed. Even if onshore WT is cheaper than offshore, WT are built in both cells. This is due to the complementary wind distribution in each cell. Third, above 40% of RE, the WT installed capacity reached its potential and only PV is installed, thus the EROI decreases. Figure 9(a) shows the gross EROI for different nuclear shares. The nuclear share does not affect the RE mix, this leads to overlap gross EROI curves.

The net EROI differs from the gross EROI due to curtailment, storage energy cost and storage energy losses. The net EROI trends are similar to gross EROI excepts for two points. It reaches its maximum for a lower share of RE between 30 and 40% depending on the nuclear share. Once the maximum is reached it declines twice as fast, see Figure 9(b). A higher share of nuclear increases the inflexible production which requires a higher storage capacity and curtailment. It slightly reduces the net EROI value by a maximum of 8%. The difference between the curves is



(a) Day where electricity is produced with CCGTs at the same time than being stored. From Scenario 3.



(b) Lack of supply in a 100% RE production system. From Scenario 3.

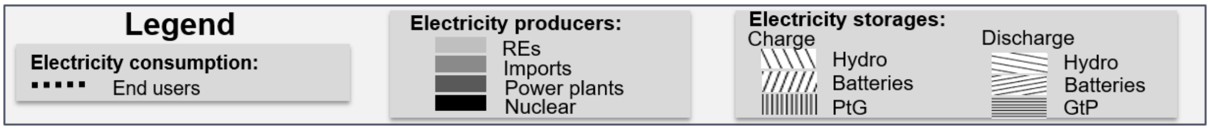


Figure 7: Power fluxes for two critical winter days. (a) is representative of transmission line saturation. Offshore wind farm is at full production, the transmission line is saturated and the excess is stored in offshore batteries (Capacity of 2 GWh) during 0 to 10 am. At 11 am, once the production decreases, transmission line stops to be saturated and offshore batteries start discharging. (b) illustrates the use of synthetic gas. It is used in CCGTs to provide enough power during the second day. During 3-12 am the first day, electricity is stored on the offshore wind farm at the same time than electricity is imported on the mainland. This come from the transmission line that is saturated.

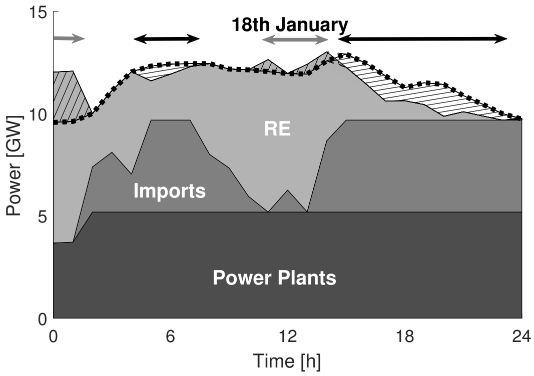
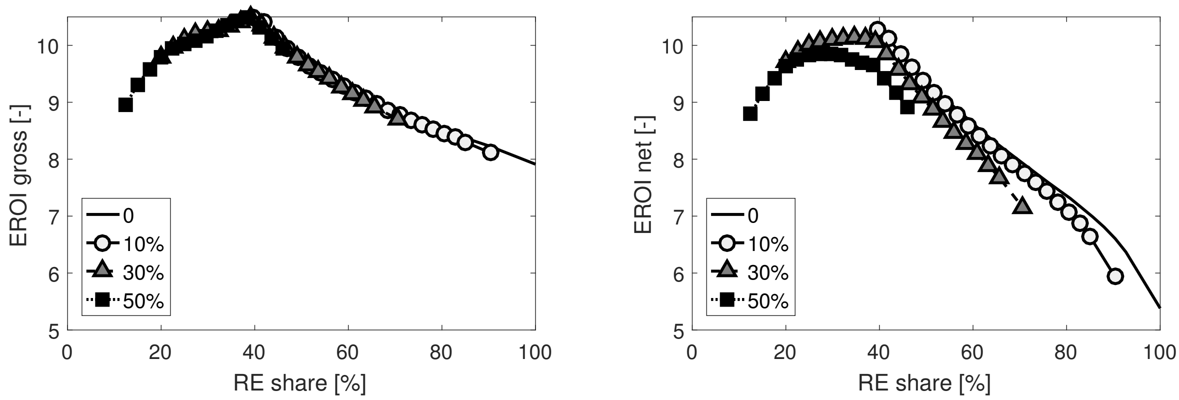


Figure 8: Additional case with 50% gas share in electricity production. During some critical period, electricity from CCGTs (grey arrows) is stored in batteries to supply power during nights (black arrows). Grey and white hatched areas represent charging and discharging batteries, respectively.

the cost of the extra storage capacity and curtailment. Nonetheless, the net EROI of a carbon free society based 50% on nuclear and 50% on RE compared to 100% RE are around 8.8 and 5.5 [-].



(a) (b)

Figure 9: Gross (a) and net (b) EROI variations in the energy transition for different RE production shares. Each curve represents a different nuclear production share (0, 10, 30, 50 %).

The impact of the energy losses on the EROI is illustrated in Figure 10 with a fixed production share of nuclear (30%). Losses are split in three categories, batteries, PtG and curtailment. Batteries have an energy cost and round trip efficiency generating energy losses. PtG is similar to batteries. Curtailment is a direct waste of energy.

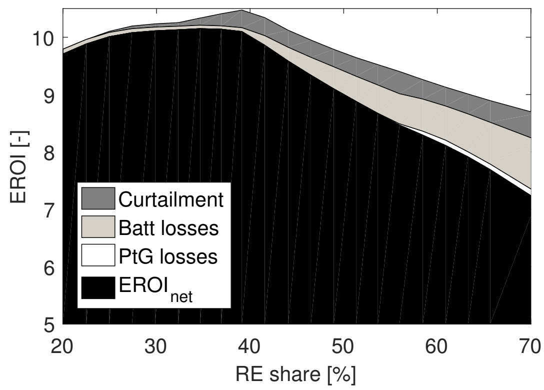


Figure 10: EROI loss distribution with a 30% nuclear production share. An increasing share of RE implies curtailment, more storage and losses, and PtG. The impact of storage cost and losses are predominant compare to PtG or curtailment.

First, curtailment increases until 40% RE share and it reaches a value of 3-4%. After, it remains constant and battery storage losses increase. At 60% of RE, PtG appears with a very low impact due to its lower yearly energy stored compared to batteries and PHES (see table 6).

4.2.2. Storage needs

Depending on the nuclear share, the storage size is linked to the RE share as shown in Figure 11. With a share higher than 30-40%, storage is required at large scale. Similar results have been obtained in a study performed for Belgium with a financial optimisation and focusing on battery storage only [26].

As it has been explained in Section 4, the battery storage design is driven by daily needs. It must be powerful enough to absorb high solar production. Its capacity is designed to supply energy during one night. Battery storage becomes

mandatory when the PV installed power overtakes the power consumed (around 10 GW).
Due to its unflexibility, nuclear requires storage at a lower RE share. Nevertheless, the required storage capacity is mainly driven by the RE share and not the inflexible share (RE and nuclear) as illustrated in Figure 11.
The required size of battery storage for Belgium with 80% RE is arount 100 GWh. To give an order of magnitude, one million of electric cars with 100 kWh batteries have an equivalent capacity of 100 GWh.

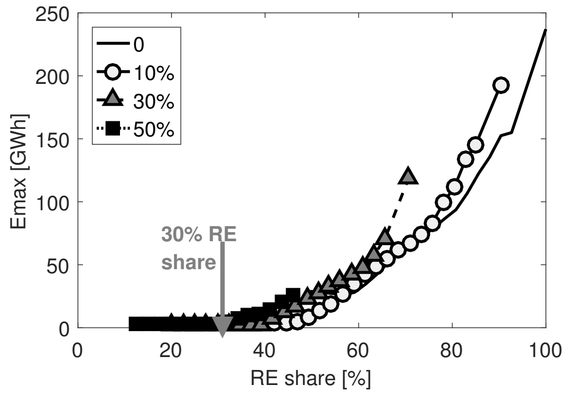


Figure 11: Required battery capacity depending on the RE production share. Each curve represents a different nuclear production share (0, 10, 30, 50 %). The grey arrow at 30% RE shows the point where batteries start to be massively needed.

Figure 12 shows the dependency between PtG and the inflexible production. Suppliers are composed of inflexible providers (RE and nuclear) and flexible ones (conventional power plants and imports). PtG becomes competitive when the flexible share (gas and imports) is lower than 30%. This trend is reduced to 15% if the nuclear share reaches 30%. Nuclear is a base load producer which decreases the required amount of RE production during the year and therefore the size of the backup storage required.

PtG becomes unavoidable for two reasons. First, with limited flexible production, a long-term storage is required. Batteries are too expensive to achieve long-term storing. Second, when batteries are full, it is cheaper to absorb large excess with PtG than curtailing the production.

4.2.3. Optimal curtailment

Curtailment is highly correlated to the RE share, as shown in Figure 13. Curtailment curves show four different trends depending on the RE share. First, below 20% RE share, curtailment is close to 0. Gas, import and storage can balance the power supply even with a 50% nuclear share. Second, between 30% and 40% of RE, curtailment increases.

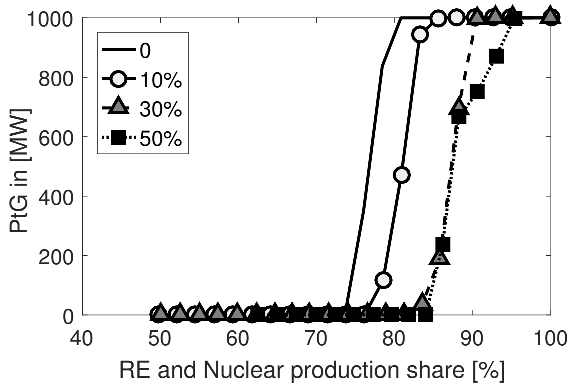


Figure 12: PtG installed power for different RE production shares. Each curve represents a different nuclear production share (0, 10, 30, 50 %).

Third, between 40 and 75% of RE, curtailment reaches a plateau at around 3.5%. This value is an optimum between installing more RE assets and curtail them or increase the storage capacity. Fourth, above 75% of RE, curtailment increases drastically and exceeds 10% reflecting a large amount of RE that cannot be absorbed by the system. Indeed, at 75% of RE, the installed PV capacity produces the same amount of energy per summer day than the consumption (including PtG) can absorb. Installing an extra capacity will be curtailed during these weeks and used only for the rest of the year, thus curtailment soars.

The impact of nuclear is between 1 and 3% of extra curtailment reflecting a smaller production flexibility.

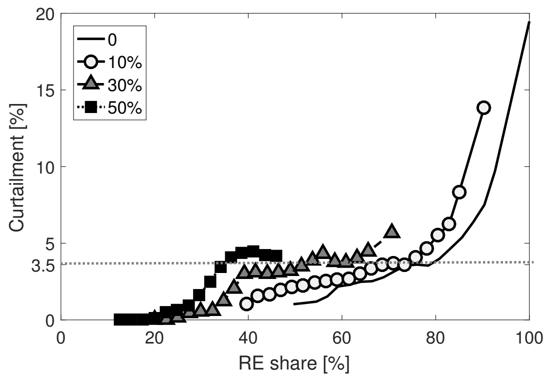


Figure 13: Curtailment for different RE production shares. Each curve represents a different nuclear production share (0, 10, 30, 50 %).

4.2.4. $CO_{2,eq}$ emissions

$CO_{2,eq}$ emissions related to CCGT production are one order of magnitude higher than those for the other productions (see Table 4). Hence, $CO_{2,eq}$ emissions and fossil fuel shares are proportional. Figure 14 shows the linear correlation between $CO_{2,eq}$ emissions and RE share for various nuclear shares. Belgium policies are planning a nuclear phase out for 2025 [43]. Nonetheless, the majority of the park may phase out in 2025 but one reactor (Doel 4) might remain until 2030. In Figure 14 an hypothetical energy transition is proposed in order to avoid $CO_{2,eq}$ emissions higher than in 2020 (13.9 Mt/year) for the electricity production. The milestones are:

1. **2020 :** 20% RE in 2020
2. **2025 :** 60% RE and 4.7 GW nuclear phase out
3. **2030 :** 70% RE and 1.2 GW nuclear phase out (no nuclear left)

After the nuclear phase out in 2025, Belgium plans to produce more electricity with gas power plants. Therefore the $CO_{2,eq}$ emissions will increase except if RE production share reaches 60% with a 10% nuclear share. Without nuclear, Belgium should reach a 70% RE share to recover the same $CO_{2,eq}$ emissions as in scenario 1 (20% RE).

5. Discussion

In this section, the impact of the assumptions that are electricity imports, PtG parameters and consumption profiles are analysed. Based on these analyses and on the results from the previous sections, trends will be extrapolated for other cases.

5.1. Sensitivity study

Import

Electricity import is a major assumption in this work. Figure 15 shows the influence of import (from France or The Netherlands) on the EROI losses for a constant RE assets equivalent to Scenario 3. The gas share is fixed at 8% of the consumption. The import share varies from 0% to 20% of the consumption compensated by the nuclear share varying from 20 to 0%, respectively. At a fixed RE production share, the gross EROI is nearly constant. Figure 15

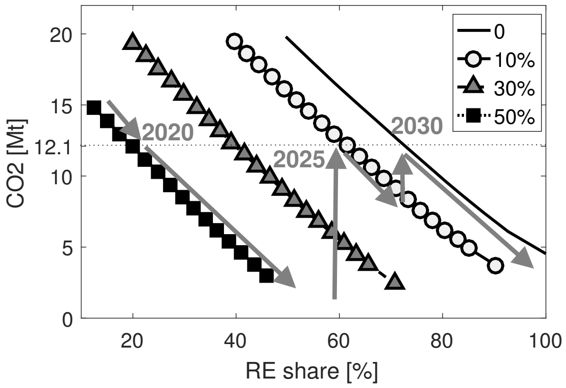


Figure 14: $CO_{2,eq}$ emissions for different RE production shares. Each curve represents a different nuclear production share (0, 10, 30, 50 %). A speculative scenario with a two-step nuclear phase out (2025 and 2030) is illustrated by grey arrows and grey dates. $CO_{2,eq}$ emissions are similar in 2020 and 2030.

shows a difference of 1.2% for the gross EROI between 0 and 20% of import share. Without import, there is more curtailment, therefore a larger RE capacity is required which decreases the overall gross EROI. Decreasing the import share increases the gap between gross and net EROI from 12 to 18%. It is equivalent to 0.35 point of net EROI per 10% import. The loss of flexibility is compensated by an increasing storage capacity and the use of curtailment.

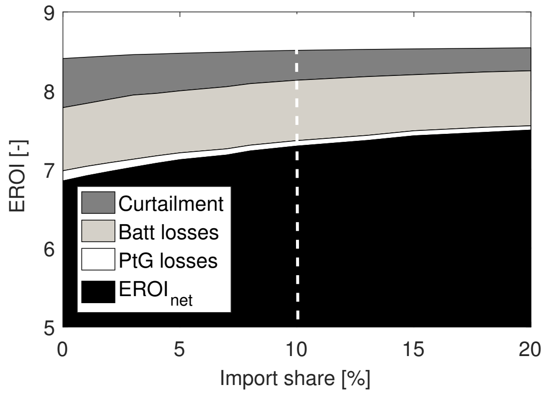


Figure 15: Impact of electricity import on the EROI losses. Imports vary between 0 to 20% of the consumption. RE and gas are fixed at 72% and 8% of consumption, respectively. Nuclear compensates the deficit of imports. The dotted white line is the reference scenario.

Power to gas

PtG behaviour has been analysed in Section 4.2.2. It has been highlighted that PtG becomes competitive for two different applications. The first is to provide enough flexibility in a low carbon society. The second is to absorb large excesses of RE when batteries are full (e.g. during a sunny summer). The first application is dominant and drives the optimal PtG capacity without a significant influence of cost, efficiency or maximal power capacity.

PtG is a new technology with only a few demonstration units. The four input parameters have been chosen quite arbitrarily for this study. These parameters with their reference values are an energy cost of 100 [MWh/MW], a minimum capacity factor of 15%, a maximum power capacity of 1000 [MW] and an electricity to gas efficiency of 63%.

The influence of these four parameters is described below. The model is not sensitive to the PtG cost. Indeed, the losses encountered during operation (36% efficiency for the round trip power to gas to power) are orders of magnitude larger than the cost to build the unit. The energy cost has to be a thousand times more expensive (100 [GWh/MW]) for the PtG to have an influence on the results. At this price, PtG becomes as costly as batteries and thus it is replaced by them.

Reducing the minimum capacity factor, PtG can be used to absorb RE excess during a longer period (the second application). For example, in a scenario with 60% RE and 0% nuclear, if the minimum capacity factor is set to 1% instead of 15% (as in the reference case), the curtailment decreases by 0.2% with PtG units of 600 [MW]. In that case, the additional amount of synthetic fuel produced is proportional to the amount of curtailment avoided.

The size of PtG units depends on the minimum capacity factor chosen. The optimization leads to a capacity factor always close to the threshold. Based on this value, the PtG capacity is adapted to reach the required amount of synthetic fuel for the long-term needs.

There is much less uncertainty on the efficiency of PtG. Nevertheless, its impact has been studied and a 5% variation has no effect on the installed capacity. A higher efficiency slightly increases the net EROI by reducing PtG losses and the extra RE assets needed to provide for these losses.

Consumption distribution and Demand Side Management (DSM)

DSM changes the consumption hourly or daily. So two other consumption curves have been analysed. First, a constant consumption curve throughout the year, second, a consumption shifted by a half day.
At a low share of RE as in scenario 1, the storage (batteries) remains the same in all cases because it is designed to absorb RE peaks. At a higher share of RE as in scenarios 2, 3 and 4, the battery capacity is driven by daily solar shift of production from day to night as illustrated in Figure 6 where the consumption seems flat compared to solar peaks.

Changes in the demand shape have a low impact on storage needs. Without a deterministic approach, storage would be used to face unforeseen events. Even more, DSM can partially replace storage and reduces the stress on the market. Moreover, it can locally avoid congestion and globally smooth peaks.

Case analysis

Belgium is densely populated compared to European countries and it will become 100% RE with difficulty. As shown previously in Figures 9 and 13, with more than 80% of RE, PV cannot be absorbed and is curtailed, thus the system EROI collapses. Four options exist to face this problem. The first is a technological improvement by increasing RE production or reducing its energy invested. The second is to allow a higher share of electricity import. The third is to keep 20% of nuclear share. The fourth is to reduce consumption.

5.2. General trends

Curtailment

Based on today technologies, curtailment reaches a plateau at around 3.5% even in a very low carbon society. This value is the result of a trade-off between the energy invested in RE assets, battery storage and PtG (including energy losses in storage). The plateau can be shifted. With a high wind potential, WT assets with curtailment are cheaper than batteries until the plateau reaches 7%. This value could be even higher with cheaper RE assets. For example, very cheap solar PV may be installed everywhere and used half of the time. The plateau can be lowered by increasing batteries round-trip efficiency or decreasing their energy cost.

Battery capacity

The required battery storage capacity should be determined by the most constraining case between a need of flexible capacity and a high share of PV. First, at low RE share, flexible capacity is the most critical in the sense that conventional power plants and electricity import capacity can be lower than the consumption. Second, with an increasing share of PV, its installed power capacity can produce more than consumption. Short-term storage is required for daily shaping
Therefore, for sunny countries, storage should become unavoidable when the installed solar capacity is higher than the summer consumption. For windy countries, because WT have a higher EROI, curtailment should be more profitable than batteries and should delay their deployment.

Power to gas

PtG is required to give flexibility with a gas production share lower than 25%. This value is lowered to 15% with a higher share of nuclear. The energy required during critical periods (lack of RE for days) cannot be supplied by batteries and must be provided by energy imported (gas and electricity) or synthetic gas. Thereby, with known gas and import shares, the amount of synthetic gas needed can be estimated.

6. Conclusion and future work

Increasing the RE share in the electricity system is challenging due to the inherent unpredictable production fluctuations. Energy management requires storage for transmission support, RE integration, distribution deferral and, at high RE shares, backup storage. A mix of storage with batteries, hydro and power to gas combined to curtailment and import can solve this problem but it reduces the net EROI of the electricity system.

The simulations based on possible scenarios for Belgium show that large scale storage becomes unavoidable with more than 35-40% RE production share.

At low RE share, the storage is designed to absorb RE peaks. The system requires an energy capacity of half an hour of the country consumption and a power output equivalent to a two-hour discharge. PHES and batteries are the best candidates. At higher RE share, the PV installed capacity becomes the main driver. The breaking point is when its installed power capacity is higher than the average consumption. In this case, daily solar shaping is required to store the day excess for the night consumption by means of large scale short-term storage. The optimal size of the storage regarding the EROI is designed to deliver full power during a whole night (country consumption multiplied by a summer night). Its power is designed to fully absorb solar energy peaks (reaching 30 GW with 80% of RE share). Even with an ideal solar-wind mix, a share of inflexible production (RE and nuclear) higher than 70% requires power to gas to balance consumption and production and answer renewable shortage. The ideal PtG unit would be a quick start unit with no need of modulation.

There is no urgent need for PtG for a safe electricity supply. The PtG sector may first develop to use cheap electricity to produce fuels used in other markets such as transportation.

The possible use of nuclear has been studied in the energy transition. It is not a competitor to RE integration. Its presence increases slightly the amount of required storage ($\approx$ 10%) and curtailment (between 1 to 3%). This comes from its inherent behaviour as base load. The RE share has to fit a lower consumption that does not require larger storage capacity than having the same share without base load. Nuclear delays the need for PtG to a later date because the gap between the demand and the supply is smaller.

Fossil fuels are responsible for 95-98% of $CO_{2,eq}$ emission, the rest is due to the production of photovoltaic panels then the batteries and the wind turbines.

An unexpected result is the amount of curtailment. With a RE share higher than 35%, curtailment reaches a plateau at around 3.5% reflecting a balance between battery storage, PtG and curtailment. Improving storage technologies reduces the value of the plateau. Decreasing RE energy cost increases the value of the plateau.

The consumption profile has a negligible impact on the storage needs. Demand side management will facilitate the integration of RE by covering some storage needs and hence reducing the storage size at low RE shares. Its impact will become marginal at high RE shares, when storage capacity is driven by PV assets. Batteries are mandatory for the daily solar shaping.

In a future work, we will increase the number of cells to be representative of a larger geographical area such as western Europe in order to reduce the impact of assumptions such as imports and study the benefit of RE complementarity between areas.

7. Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

8. Nomenclature

CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
DSM	Demand Side Management
EROI	Energy Return On (Energy) Investment
ESOI	Energy Stored On (Energy) Invested
HP	Heat Pump
LCA	Life Cycle Assessment
LCOE	Levelised Cost Of Energy
OCGT	Open Cycle Gas Turbine
PtG	Power to Gas
PHES	Pumped Hydro Energy Storage
PP	Power Plant
PV	Photovoltaic Panel
RE	Renewable Energy
RES	Renewable Energy Sources
TSO	Transmission System Operator
WT	Wind Turbines

Appendix A. Model structure

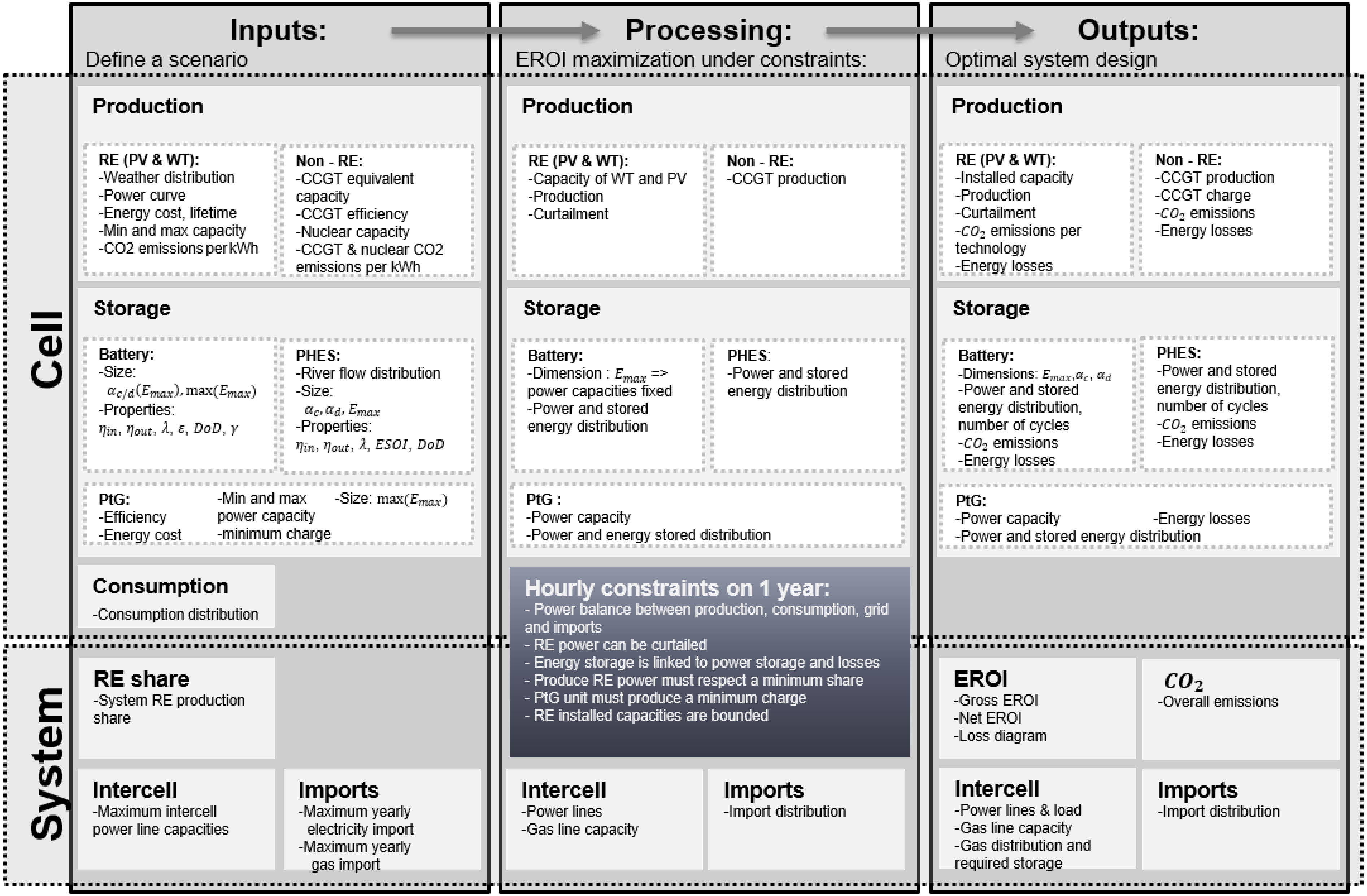


Figure A.16: Model structure. There are 3 steps: first the inputs, then the processing with several optimized variables and finally the outputs. For each step, some data concern each individual cell and others concern the whole system (all cells). The processing variables (middle grey box) are optimised by the solver to get the highest net EROI. Dark grey box summarises the system constraints

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