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Impact of storage and transmission capacity expansion on generation expansion planning for a 100% renewable electricity system in Portugal by 2040

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Abstract

This thesis examines the optimal investment approach in wind and photovoltaic (PV) capacity for Portugal's electric energy system, targeting 100% renewable generation by 2040, and analyzing the influence of planned transmission line and storage expansions. The integrated unit commitment and expansion decision optimization is formulated as a Mixed-Integer Linear Programming (MILP) model. Scenario analysis examines the impact of planned pump storage and transmission line pathways on generation expansion planning. For the resulting power plant park, the impact of battery storage optimization on the utilization of the electricity system is also analyzed. The results of this study show significant impacts of flexibility expansion pathways on generation expansion optimization. Pump storage and transmission line expansion within Portugal lead to increased PV expansion, which in turn reduces thermal production and CO_2 emissions. Transmission line expansion specifically enhances the utilization of geographical potentials by boosting PV expansion in these areas. Thus, this thesis provides cost-optimized investment approaches in wind and PV power plants for different scenarios of transmission line and pump storage expansion, facilitating a deeper comprehension of the influence of storage and transmission capacity on long-term generation expansion planning decisions.

Kurzfassung

Diese Arbeit untersucht den optimalen Investitionsansatz in Wind- und PV-Kapazitäten für das elektrische Energiesystem Portugals mit dem Ziel, bis 2040 eine 100% erneuerbare Stromerzeugung zu erreichen. Dabei wird der Einfluss geplanter Erweiterungen von Übertragungsleitungen und Speicherkapazitäten analysiert. Die integrierte Optimierung der Einsatzplanung und Erweiterungsentscheidungen wird als gemischt-ganzzahliges lineares Programmierungsmodell (MILP) formuliert. Die Szenarioanalyse untersucht den Einfluss geplanter Pumpspeicher- und Übertragungsleitungswege auf die Planung der Erzeugungserweiterung. Für das resultierende Kraftwerksportfolio wird auch die Auswirkung der Optimierung von Batteriespeichern auf die Nutzung des Stromsystems analysiert. Die Ergebnisse dieser Studie zeigen signifikante Auswirkungen der Flexibilitätserweiterung auf die Optimierung der Erzeugungserweiterung. Pumpspeicher- und Übertragungsleitungserweiterungen innerhalb Portugals führen zu einem erhöhten PV-Ausbau, was wiederum die thermische Produktion und die CO_2-Emissionen reduziert. Die Erweiterung der Übertragungsleitungen verbessert insbesondere die Nutzung geografischer Potenziale durch eine Förderung des PV-Ausbaus in diesen Gebieten. Diese Arbeit bietet somit kostenoptimierte Investitionsansätze in Wind- und PV-Kraftwerke für verschiedene Szenarien des Übertragungsleitungs- und Pumpspeicherkapazitätenausbaus zur Unterstützung bei der Entscheidungsfindung in der langfristigen Erzeugungserweiterungsplanung.

Contents

Abbreviations

CapEx capital expenditure
CCGT combined cycle gas turbine
DGEG Direção-Geral de Energia e Geologia
EDP Energias de Portugal
ENTSO-E European Network of Transmission System Operators for Electricity
EP expansion planning
ESP Spain
FIT Feed-in-Tariff
HU hydro unit
LCOE levelized costs of energy
MILP mixed-integer linear program
NECP National Energy and Climate Plan
PT Portugal
PV photovoltaic
REN Redes Energéticas Nacionais (national energy grid company)
RES renewable energy system
RMSA-E Relatório de Monitorização da Segurança de Abastecimento do Sistema Elétrico Nacional 2023-2040 (National Electricity Supply Security Monitoring Report)
RO resource optimization
TU thermal unit

1 Introduction

The climate crises and the decarbonization goals are putting more and more pressure on the energy transition to renewable energy. Therefore, in the next 10-20 years major energy infrastructure changes are needed. Looking at the production side this includes the strongly increasing construction and integration of renewable energy units, especially the volatile energy sources wind and solar. Since it hereby is about cost and time intensive investment decisions, expansion planning optimization tools play an important supportive role for an integration as cost, time and resource efficient as possible. Furthermore optimal generation expansion is interrelated with the amount of installed storage and transmission line capacity. Because it determines how volatile energy production can be temporally and spatially balanced. In order to plan a generation expansion pathway it is therefore important to consider the development of this parameters and understand how they impact optimal integration.

The primary objective of this work is to present cost-optimal investment strategies for wind and PV power plants within the electricity system of mainland Portugal (PT), with a specific focus on achieving 100% renewable power production by 2040. This objective is further explored by examining different scenarios of hydro pump storage and transmission line expansion to understand their influence on optimization outcomes. Additionally, the impact of cost-optimized battery storage expansion on the utilization of the resulting electricity system is analyzed.

The method applied for the generation expansion planning is an integrated unit commitment and investment decision optimization. The technical unit constraints in unit commitment are formulated as a linear program, whereas the investment decision optimization includes binary decision variables, making it a mixed-integer linear program (MILP). In the objective function, total costs are minimized while ensuring that load balance, technical limitations, and the 100% renewable energy system (RES) target are met. Additionally, the influence of storage and transmission line expansion is analyzed through a scenario analysis.

The work is organized as follows: Chapter 2 provides an overview of the state of the art in the topic area and outlines the original contributions of this work. Chapter 3 details the methodology used. Chapter 4 presents the data used for the case study. Chapter 5 showcases the results of the optimization and scenario analysis. Chapter 6 discusses and synthesizes the results. Finally, Chapter 7 offers conclusions and an outlook for future work.

2 State of the art

In this section, an overview of typically utilized mathematical methodologies for generation expansion problems and the importance of integrating short-term modeling into long-term expansion planning is provided to categorize the approach chosen for this thesis. Additionally, existing works that address the impact of storage and transmission line expansion on generation expansion planning or consider RES policies are presented. Furthermore, works focusing on electricity system planning in Portugal are reviewed. Finally, the progress beyond the presented works is outlined.

Generation expansion planning with a long planning horizon and multiple interdependencies with other sectors is a complex topic where numerous aspects may be considered. Various works address different facets of this issue. Aspects like interdependency with natural gas system, development of electric vehicle integration or supply of security in the future energy system are excluded at this point, since these aspects are not specifically addressed in this thesis. Further overview over works dealing with this topics is given by [1] and [2].

2.1 Mathematical model

Different approaches to describe the expansion planning problem in a mathematical model can be chosen. Methods for modelling the energy systems for expansion planning with high share of renewables can be divided in the 3 categories: optimization, equilibrium and other alternative models [3].

- In general **optimization models** can be classified as single- and multi-objective problems. Single objective model formulate all objectives in one cost function, including further aspects only in constraints, they can mainly be divided in cost minimizing or profit maximizing models. In multi-objective optimization multiple criteria like, total costs, environmental impact, reliability can be considered simultaneously making it possible to analyze trade off between alternative solution for different objectives [2].
  Different formulations of optimization models can be chosen in order to model the system in different degree of detail and complexity. In mixed-integer linear

programming only linear or linearized objective and constraint functions are describing the problem with partially discrete decision variables. It is commonly used to represent optimization problems. For example in [4] and **SHU2015** it is utilized for expansion planning problems. A bi-level optimization like in [5] is done by representing the optimization problem as two different problems built up on top or within each other. In non-linear programming at least one constraint or objective is a non-linear function. For example [6], [7] use it for expansion planning.

- **Equilibrium models** try to find a stable state for set of interacting mechanisms and can be divided in general and partial ones. It can additionally be combined with optimization, resulting for example in a stable energy system with minimized costs. This could also be seen as an optimization model, but they differentiate through representing the individual agents in order to model more realistic economic or intersectional interaction. In [8] it is used to model influence of emission trading on the coal dominated Polish power system or in [9] it is used to show scenarios for emission mitigation in Taiwan and analyze the current strategy. The method leads to simplified representation of technical system but is particularly suitable for modeling dependency to socio-economic parameters and model more realistic global economic interaction [3].
- **Alternative models** summarize modern portfolio theory, system dynamics, multi-criteria, econometric, cost-benefit analysis, life cycle assessment, simulations and probabilistic models, which are not already included in the descriptions above. This group of models characterize through a simplified representation of the technical energy model, but the advantage of easy utilization and combination with other models, for example more technically detailed technical models, and allows a higher flexibility to represent different aspects for example of RES expansion to sustainability and not a biased optimized solution. [3]

The review by [3] highlights that, despite their limited representation of broader economic or spatial structures, optimization models are predominantly used due to their focus on robust, detailed technical characteristics. Additional review papers, such as [10], which discusses aspects of renewable integration into energy system modeling, and [1] and [2], which cluster existing works based on their considered aspects, also emphasize the prominence of optimization models. Therefore, to maintain a focus on the technical representation of the electricity system, this in this study a MILP optimization program is utilized.

2.2 Consideration of short-term system characteristics

In the past, the energy system was dominated by well-predictable and slowly changing components. Therefore, the traditional planning model could calculate at a yearly temporal resolution level with average operation values [11]. However, with the increased share of volatile renewable energy sources, consideration of short-term operational constraints and flexibility resources has become increasingly important and should be included in expansion planning.
In some works, long-term capacity planning and operational planning are carried out in a linked but separate manner [12], [13]. However, to achieve an optimal solution, generation expansion planning has evolved from the traditional model approach to an integrated one. In the integrated planning model, short-term operational planning is incorporated into capacity expansion planning at an hourly or even finer basis [14].

In the following, insights gained in different works considering short-term characteristics are described. [15] finds that with looking at short term dynamics increased wind production influences operation schedule of dispatchable power plants, namely increased intermediate production compared to base production while peak production stays the same. [16] states that neglecting operational flexibility can lead to too little investment into flexible generation sources what can lead to curtailment of RES, insufficient reserve, and load shedding. [17] in their work compares the integrated model to the traditional one and shows that, it is important to consider operational constraints with increasing RES at planning state in order to not get sub optimal technical and financial solutions. [18] also analyzed the impact of considering unit commitment in generation expansion planning and also comes to the conclusion that neglect of short term flexibilities can lead to solutions that technically not meet demand, CO2 emission and RES targets of the optimization. [19] even states that consideration of short term flexibility lead to costs decrease in energy system planning. In general works which include short term dynamics show that a neglect can lead to a misjudgment of operation characteristics and costs of the power system. This can lead to financially and technically not optimal or even infeasible solutions [1]. Furthermore it has the advantage to additionally output an hourly system operation plan and flexibility strategy on top of system costs and capacity expansion plan and CO2 emissions [14]. Therefore in this thesis in the MILP short term unit commitment and long term expansions planning is modelled integrated.

2.3 Consideration of storage and transmission line expansion in generation expansion planning

Considering short-term characteristics, enables the more detailed consideration of flexibilities like storage and transmission line capacities for generation expansion planning which is increasingly important with increased share of volatile RES. A lot of works concentrate on analyzing the impact of solely storage or transmission line expansion.

For example [4] shows that additional storage expansion leads to noticeable changes in transmission and generation expansion investments. The impact of storage expansion planning on generation and transmission line expansion planning in this study is analyzed through co-optimization of the three components in a two-stage, stochastic MILP. It finds that co-optimization of storage capacity leads to significant investment cost decrease in generation and transmission capacity. This study only examines influence of storage expansion and not transmission line expansion and is tested on a 24 bus test system.

[20] looks at generation expansion planning together with transmission line expansion considering operations constraints for a high wind system and shows the importance of the co-optimization for decrease of curtailment of wind capacities and also points out the importance of consideration of operational constraints for the resulting technically feasible solution. It analyzes the advantage of modelling generation and transmission expansion planning together, and states, that high cost savings can be achieved compared to iteratively optimizing generation capacity end then transmission line capacity [20].

Combined transmission, storage and generation expansion shows that transmission line and storage expansion both facilitate integration of RES. [21] for this observation uses a multi-stage MILP model. It shows that battery storage optimization leads to decreased RES curtailment, power line congestion, emissions and planning costs. The model is applied to a test system.

2.4 Policy implications environmental concerns

Generation expansion planning problems developed from a solely cost optimization problem to a multidimensional planning problem in which environmental concerns like climate change mitigation and renewable share targets are considered. Therefor policies concerning this environmental concerns are integrated in the planning models [14]. Environmental concerns can be represented in the optimization model different ways in the objective function, in the constraints of the optimization problem. [1] describes the development from single-objective to multi-objective cost function, where in addition to the system cost minimization other objective functions are integrated. For example CO_2 emissions are minimized [22], or renewable share maximized. Here some works optimize in more detail for example a maximization of non-hydro production [23] or RES share during peak load [24]. Other works focus more on the tackling the impacts of increased volatile RES integration by minimizing curtailed energy [25], backup energy or transmission capacity [26] for integration of RES. Often works consider more then 2 objectives like [22] optimizes cost effectiveness, emissions and reliability together. Cost optimization still builds the basis for main works. Environmental impact is barely considered for solely optimizing the planning but mainly combined with cost minimization. On the other hand in a single objective optimization, environmental concerns can be represented in the cost function, giving a price to the resource which should be limited or increased. This is useful and commonly used in order to represent and evaluate possible financial policies. A lot of studies analyze impact and efficiency of policies for increasing renewable energy production, like Feed-in-Tariff (FIT) incentive, tradeable green certificates [27], [28] auctions and net metering [29], [30], renewable purchase obligation [31]. Others look on pricing and decreasing CO_2 emissions and non-renewable production with carbon taxes [30] and emission trade [32].

Defined political targets and regulations on the other hand can also be presented as constraints. For example for mandatory quotas of RES [33], [34], maximum CO_2 emissions [35], [36] or targets for efficiency increase for thermal power plants and energy saving on the demand side [37].

In a lot of studies both options are combined modelling a benchmark scenario with fixed regulation as constraint for analysis of effectively of financial policies. [27].
In this thesis in order to consider the specified 100% RES target a constraint for maximal CO_2 emissions is utilized.

2.5 Energy system planning: Portugal

In the past, different works have applied energy system planning on the electricity system in Portugal. [38] for example analyzes scenarios of RES penetration finding technically feasible unit commitment solutions for an energy system with high share of RES finds that wind expansion is more effective in terms of replacing thermal power plants, and points out the importance of the existing transmission line capacities and pump storage. As an outlook the study states possibilities to consider electrification and modelling of the electric network. [17] models the energy system planning with an integrated approach, analyzing the impacts of the consideration of short term characteristics. It shows that the integrated approach results in higher costs for RES expansion but does not include expansion of storage or transmission line capacities.

2.6 Own contribution

Based on the aforementioned research question, the progress beyond existing literature is presented as follows. An integrated generation expansion planning model formulated as a MILP with integer linear program unit commitment constraints is utilized. The optimization examines the impact of both storage and transmission line expansion separately and together on generation expansion planning. Rather than co-optimizing these elements, the model analyzes the impact of considering realistic scenarios for transmission and storage capacity through scenario analysis.

This model is applied to an electricity system based on the real-life system of Portugal. Previous works have primarily focused on Portuguese targets set until 2030 and have not considered the impacts of transmission line and storage expansion plans on generation expansion planning. This thesis, however, incorporates the policy goal of achieving 100% renewable generation by 2040. Portugal is divided into four regions, allowing for detailed analysis of main energy transmission within the country and regional effects on RES expansion, which are often neglected in other studies. Through modeling of transmission capacity to Spain (ESP), electricity trading with an external spot market is also considered in the transmission line expansion.

3 Methods

To tackle cost-optimal expansion planning, a MILP is employed to mathematically model and represent the energy system. The subsequent section delineates the considerations taken into account and the manner in which they are represented through constraint equations, as well as specifying the aspects that are excluded from the modeling. Furthermore, this section elaborates on the approach used to solve this mathematical representation and provides information on the configuration of the solver.

The utilized model is derived from an established unit commitment and expansion program developed by Siemens AG Austria[1]. It is noteworthy that modifications were exclusively made to the investment cost calculation for the purposes of this study.

3.1 Mathematical Model

The employed model comprises a resource optimization (RO), also known as unit commitment, serving as the medium-term planning and mathematical representation of the existing electricity system. Additionally, it incorporates an Expansion Planning (EP) component for long-term planning. The RO allocates required energy production to available generation resources within the planning horizon, typically spanning less than three years while minimizing costs. This optimization considers operational costs while addressing factors such as energy balance, fuel scheduling, reservoir management, and specific constraints on unit commitment. The RO is formulated as a linear optimization problem. In contrast, expansion planning (EP) introduces the opportunity to invest in new units to expand the power plant park. Leveraging binary decision variables, EP transforms the problem into a mixed-integer program, enabling strategic long-term planning decisions.

[1] `https://xcelerator.siemens.com/global/en/all-offerings/products/s/spectrum-power-7-ros.html`

3.1.1 Technical system representation

The system model is structured around distinct areas, each characterized by its designated load development over time. Transmission lines interconnect these individual areas, with specified maximal capacity. The line model incorporates an efficiency factor for active power transmission, accounting for power losses. Notably, the model exclusively takes into account active power, disregarding other parameters like reactive power, voltage, and frequency stability for the sake of simplicity and focus.

Within each area, the model specifies various generating units, allowing for the consideration of diverse technologies. The model accommodates:

- thermal units, encompassing nuclear, gas, co-generation, and fossil-fueled steam thermal units,
- hydro units,
- other renewable energy plants and
- storage units.

The **thermal units** in the model are characterized by several parameters, including maximal power output, efficiency factor, fuel type, fuel flow and storage specifications, maintenance and start-up costs, as well as emission factors.

The **hydro power plants** within the model comprise turbines or pump-turbines. These plants are defined by parameters such as maximum volumetric flow, minimum and maximum generated electric power, and efficiency factor. Additionally, each hydro power plant is associated with a particular reservoir situated in a specific valley, with specified inflow and drop height considerations.

Renewable units, such as wind and PV systems, are characterized by their maximum production profiles over time. In the context of expansion planning, renewables are predetermined with fixed profiles and associated investment costs to be considered as potential investments.

Storage plants are specified with a minimal and maximal energy content capacity and its charging and discharging efficiency and its maximal power transfer.

3.1.2 Objective and costs

This thesis classifies costs into two categories: investment costs (capital expenses (CapEx)), which are presented as annualized costs over the technology's lifespan, and operational expenses (OpEx). All costs are expressed as present values at the onset of the planning horizon, utilizing a discount rate of 4%. In cases where power plants already exist at the beginning of the time horizon, it is presumed that they are fully amortized, and only operational costs are factored into the analysis.

The objective function described by Equation 3.1 aggregates all pertinent costs while subtracting revenue from sales, with the aim of minimizing overall costs. The cost components considered encompass:

- Investment costs $\boldsymbol{C}^{Inv}$ associated with new expansions,
- Operational costs $\boldsymbol{C}^{Op,Maint}$, inclusive of fuel costs, maintenance expenses, and startup costs,
- Expenditures for electrical energy purchases from electricity market $\boldsymbol{C}^{P}$ and
- Deduction of profits from energy sales to electricity market $\boldsymbol{R}^{S}$.

$$C^{Total} = \boldsymbol{C}^{Inv} + \boldsymbol{C}^{Op,Maint} + \boldsymbol{C}^{P} - \boldsymbol{R}^{S} \rightarrow min \tag{3.1}$$

The operational and maintenance costs are determined using Equation 3.2. Specifically, for thermal units (TUs), the fuel costs for unit i and hour t are computed based on a price $p_{i,t}^{fuel}$ per unit of fuel volume consumed $\boldsymbol{Q}_{i,t}^{fuel}$, the maintenance costs are derived from a maintenance cost factor p_i^{maint} relative to the produced electric energy $\boldsymbol{P}_{i,t}$, and startup costs are calculated as startup cost factor $C_i^{startup}$ times number of startup event $n_i^{startup}$. In contrast, for hydro units (HUs) and Renewable Units, operational costs are assumed to be zero.

$$\boldsymbol{C}^{Op,Maint} = \sum_{i=1}^{n_{TU}} (\sum_{t=0}^{T_{Planning}} (p_{i,t}^{fuel} * \boldsymbol{Q}_{i,t}^{fuel} + p_i^{maint} * \boldsymbol{P}_{i,t}) + C_i^{startup} * n_{startup,i}) \tag{3.2}$$

The investment calculation (3.3), initially formulated as a lump sum at the expansion time step without discounting to a present value and with simple, non-compound interest rates, has been refined for this thesis. The investment costs $C_{k,t}^{Inv}$ of an investment option k at a specific moment t are now transformed into an equivalent annual cost over the investment's lifetime n using an interest rate j of 5%. These annualized costs are then aggregated until the end of the planning horizon $T_{Planning}$ as discounted present values, enhancing comparability of cash flows at different time steps. The chosen investment interest rate of 5% exceeds the discount rate d of 4%, accounting for higher interest rates associated with credit and investment risks.

$$\boldsymbol{C}^{Inv} = \sum_{t=0}^{T_{Planning}} \sum_{k=0}^{n_{Inv}} \frac{1}{(1+d)^t} * \frac{j*(j+1)^{T_k}}{(j+1)^{T_k}-1} * C_{k,t}^{Inv} * (\boldsymbol{Y}_{k,t}) \tag{3.3}$$

In the investment cost calculation, as expressed in Equation 3.3, a binary decision variable $\boldsymbol{Y}_{k,t}$ is introduced to model the expansion decision at a specific moment and for a designated maximum capacity. This inclusion transforms the problem into a mixed-integer linear problem.

$$\boldsymbol{C}^P = \sum_{t=0}^{T_{Planning}} p_t^M * \boldsymbol{P}_t^P \tag{3.4}$$

$$\boldsymbol{R}^S = \sum_{t=0}^{T_{Planning}} p_t^M * \boldsymbol{P}_t^S \tag{3.5}$$

As Equation 3.4 and 3.5 show, the costs $\boldsymbol{C}^P$ and revenue $\boldsymbol{R}^S$ associated with the energy exchanged with the electricity market result from the dynamic spot market prices p_t^M multiplied by the power sold $\boldsymbol{P}_t^S$ or purchased $\boldsymbol{P}_t^P$ at the given time step .

The costs for storage expansion $\boldsymbol{C}_{ES}$ are represented as in Equation 3.6, as a multiplication of a price $p_i^{ES,Cap}$ with the optimizable installed capacity $\boldsymbol{Cap}_i^{ES}$

$$\boldsymbol{C}_{ES} = \sum_{i=0}^{n_{ES}} p_i^{ES,Cap} * \boldsymbol{Cap}_i^{ES} \tag{3.6}$$

3.1.3 Constraints

The functionalities and interrelationships of system components are explicated through a set of constraints. The constraints required for this study can be succinctly categorized into Kirchhoff's first law for power balance in every node, Kirchhoff's second law governing potentials around a circuit, constraints delineating minimal and maximal operating ranges of units, limitations on the maximal transmission capacities of transmission lines, as well as constraints related to reservoir and expansion planning.

Load constraint

The primary fundamental constraint involves maintaining a balance in every node between the total electric load and production. The load encompasses the forecasted demand D_t, power pumped in hydro power units $\boldsymbol{P}_{it}^{HP}$, power sold to a market $\boldsymbol{P}_{it}^{S}$, and exported energy via transmission lines to another node $\boldsymbol{P}_{it}^{n_{TLex}}$. The total power production includes thermal production $\boldsymbol{P}_{it}^{TU}$, hydro turbining $\boldsymbol{P}_{it}^{HT}$, wind and PV production $\boldsymbol{P}_{it}^{W,PV}$, purchased power from an electricity market $\boldsymbol{P}_{it}^{P}$, and imported energy from another node $\boldsymbol{P}_{it}^{n_{TL_{im}}}$.

$$D_t + \sum_{i=1}^{n_{HP}} \boldsymbol{P}_{it}^{HP} + \sum_{i=1}^{n_M} \boldsymbol{P}_{it}^{S} + \sum_{i=1}^{n_{TLex}} \boldsymbol{P}_{it}^{n_{TLex}} = \sum_{i=1}^{n_{TU}} \boldsymbol{P}_{it}^{TU} + \sum_{i=1}^{n_{HT}} \boldsymbol{P}_{it}^{HT} + \sum_{i=1}^{n_{W,PV}} \boldsymbol{P}_{it}^{W,PV} + \sum_{i=1}^{n_M} \boldsymbol{P}_{it}^{P} + \sum_{i=1}^{n_{TL_{im}}} \boldsymbol{P}_{it}^{n_{TL_{im}}} \tag{3.7}$$

The commitment of individual resources is further specifically constrained.

thermal and hydro generation units operational constraints

The thermal system is subject to constraints that specify the maximum electric power production within a thermal block $P_i^{TU,max}$. Actual power production $\boldsymbol{P}_{it}^{TU}$ of the unit has to lie below this limit (3.8). The connection between electric power production and fuel consumption $\boldsymbol{Q}_{it}^{TU}$ is given, assuming constant efficiency η_i^{TU} (3.9). Additionally, limitations associated with fuel transport are taken into account (3.10).

$$0 \leq \boldsymbol{P}_{it}^{TU} \leq P_i^{TU,max} \tag{3.8}$$

$$\boldsymbol{P}_{it}^{TU} = \boldsymbol{Q}_{it}^{TU} * \eta_i^{TU} \tag{3.9}$$

$$0 \leq \boldsymbol{Q}_{it}^{TU} \leq Q_i^{trans,max} \tag{3.10}$$

In the hydro system, the commitment of the resource is primarily constrained by the continuous monitoring of reservoir levels $\boldsymbol{RL}_{it}$. The reservoir continuity equation 3.11 computes the change in reservoir level from one time step to the next, observing the volumetric flow turbined $\boldsymbol{Q}_{jt}^{HT}$ and pumped $\boldsymbol{Q}_{jt}^{HP}$ of hydro units that lead out of the reservoir $n_{HU_{out,i}}$ and into the reservoir $n_{HU_{in,i}}$.

$$\boldsymbol{RL}_{it} = \boldsymbol{RL}_{i,t-1} + \sum_{j=1}^{n_{HU_{out,i}}} (-\boldsymbol{Q}_{jt}^{HT} + \boldsymbol{Q}_{jt}^{HP}) + \sum_{j=1}^{n_{HU_{in_i}}} (\boldsymbol{Q}_{jt}^{HT} - \boldsymbol{Q}_{jt}^{HP}) \tag{3.11}$$

$$RL_{it}^{min} \leq \boldsymbol{RL}_{it} \leq RL_{it}^{max} \tag{3.12}$$

Equation 3.12 illustrates the limitation imposed on the reservoir level to ensure it stays within defined boundaries RL_{it}^{min} and RL_{it}^{max}. Additionally, specific levels for the reservoir at certain points in time can be designated, such as maintaining the same level at the same time each year. This approach prevents energy storage for periods longer than a year, facilitating the modeling of representative years separately. It is assumed that the hydro system operates with constant head and efficiency.

In the hydro system, both the pumping and turbining operations are further constrained by the maximum power limits in both directions. Equation 3.13 describes the relationship between the volumetric water flow rate $\boldsymbol{Q}_{it}^{T}$ and electric power $\boldsymbol{P}_{it}^{T}$, particularly in the context of the turbining direction. This relationship serves as the foundation for limiting volumetric power flow by the specified maximum power production $P_{it}^{T,max}$ (3.14). An analogous approach is applied for the pumping direction.

$$\boldsymbol{Q}_{it}^{T} * \Delta T * \rho * G * H * \eta_i^T = \boldsymbol{P}_{it}^{T} * \Delta T \tag{3.13}$$

$$0 \leq \boldsymbol{Q}_{it}^{T} \leq \frac{P_{it}^{T,max}}{\rho * G * H} \tag{3.14}$$

Wind and PV operational constraints

For wind and PV units, a power profile is defined, indicating the maximum producible power $P_{i,t}^{W,PV,max}$ based on the available natural resource. The actual production $\boldsymbol{P}_{i,t}^{W,PV}$ is constrained to occur below this variable limit (3.15).

$$0 \leq \boldsymbol{P}_{i,t}^{W,PV} \leq P_{i,t}^{W,PV,max} \tag{3.15}$$

Expansion planning constraints

In the context of expansion planning, the power plant models are subject to the following constraints:

$$\boldsymbol{Y}_{i,t-1} \leq \boldsymbol{Y}_{i,t} \tag{3.16}$$

$$P_{i,t}^{W,PV} \leq \boldsymbol{Y}_{i,t} * P_{i,t}^{W,PV,max} \tag{3.17}$$

$$\boldsymbol{P}_{i,t}^{W,PV} \leq P_{i,t}^{W,PV} \tag{3.18}$$

In the decision time grid from one time step to the next, the algorithm incorporates a decision variable to determine the execution of an investment $\boldsymbol{Y}_{i,t}$. Once executed, this decision variable cannot revert to zero in subsequent time steps (3.16). After execution, the unit can produce power $\boldsymbol{P}_{i,t}^{W,PV}$ like an existing unit limited to less than its maximal capacity $P_{i,t}^{W,PV,max}$.
The expansion decision variable and the optimization variable for the actual unit

commitment are segregated into two constraint equations (3.17, 3.18) by introducing an auxiliary variable $P_{i,t}^{W,PV}$. This auxiliary variable represents the maximal possible production profile but only after expansion, a measure taken to preserve linearity in the model.

Transmission line constraints

The energy exchange between different areas is facilitated through specified transmission lines, each with a defined maximum transmittable power $P_i^{TL,max}$. This constraint (3.19) ensures that the actual transmitted power $\boldsymbol{P}_{i,t}^{TL}$ at every time step does not exceed these established limits.

$$0 \leq \boldsymbol{P}_{i,t}^{TL} \leq P_i^{TL,max} \tag{3.19}$$

3.1.4 Electricity storage expansion optimization

$$C_{Total} = \boldsymbol{C}_{ES} + \boldsymbol{C}^{Op,Maint} + \boldsymbol{C}^{P} - \boldsymbol{R}^{S} \rightarrow min \tag{3.20}$$

For the case of battery storage optimization the objective function is structured differently. Due to limits of the model, not an optimization for PV and wind and storage is carried out together but with the resulting wind and PV expansion a storage optimization is carried out afterwards, with an objective function shown in Equation (3.20). The new cost term of storage expansion costs $\boldsymbol{C}_{ES}$ is included. In the storage optimization, the timing of the expansion is neglected, and the optimization is assumed in the beginning of the time horizon. For all time step the storage capacity is limited between defined minimum $E_i^{ES,min}$ and maximum $E_i^{ES,max}$ limits (3.21). And the installed capacity $\boldsymbol{Cap}_i^{ES}$ to which the capacity price of the unit is applied to then must be higher than the energy stored at each time step $E_{i,t}^{ES}$ (3.22). In the objective function this resulting costs are minimized.

$$E_i^{ES,min} \leq E_{i,t}^{ES} \leq E_i^{ES,max} \tag{3.21}$$

$$E_{i,t}^{ES} \leq \boldsymbol{Cap}_i^{ES} \tag{3.22}$$

3.2 Solver parameters

The optimization model is solved using XPRESS[2]. The MILP undergoes a five-step process, which includes presolving, solving the relaxed Linear Program (LP), heuristic, cutting, and the branch-and-bound method [39]. The MIP-GAP parameter is adjustable, allowing for control over the acceptable difference between the optimal linear solution and the best integer solution. A MIP-GAP below 5% is considered acceptable. Table 1 in Appendix 7 shows the utilized solver parameters in detail. The performance of the optimization calculation is highly contingent on the complexity of the problem, with the number of decision variables and constraints directly impacting the computational demands.

[2] https://www.fico.com/en/products/fico-xpress-optimization

4 Case study Portugal

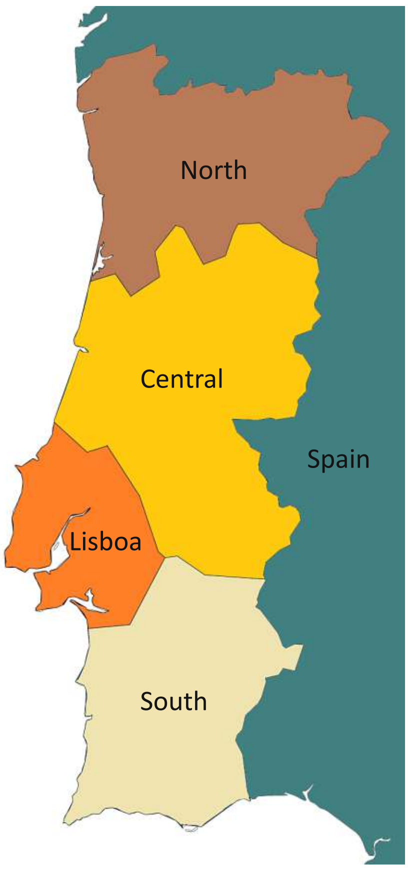


Figure 4.1: Area division. Adapted from [40]

In order to present cost optimized investment approaches in dependence of storage and transmission line scenarios into wind and PV for a realistic 100% renewable electricity system it is applied to mainland Portugal. The area of mainland Portugal is divided into areas in order to consider limitation of main transmission line capacities. Therefore the 4 areas North, Central, Lisboa and South are chosen as shown in Figure 4.1, based on [40]. The interconnection capacities between these areas and to Spain mainland are considered.

For the simulation 5 representative years out of the time horizon of 16 years from 2023-2040 are modelled. 2023 thereby is representing a reference year for the actual status. The four years 2025, 2030, 2035, and 2040 are chosen to represent 5-year intervals in the future. Each of these years is characterized by specified forecasted load and price developments, offering the opportunity for investment decisions to be made every fifth year. The smallest temporal resolution within these years is 1 hour. It is applied for variable RES production and load. For computationally handling of the unit commitment problem the decision grid for dispatchable power plants is 4 hours.

Further general information about the economic data utilized in this study is as follows: All costs in the optimization are represented as costs in the year 2023. Past values are converted using an inflation factor obtained from [41]. For future projections, a credit interest rate of 7% and a discounting rate of 5% are taken into account.

4.1 Initial state

The total electricity load consumed in Portugal mainland in 2022 was 48 400 GWh, with losses 52 700 GWh [42].

The currently installed generating capacities can be found at [43]. The total installed capacity at end of 2023 which is considered as the current situation is 20 615 MW. In Table 4.1 the composition of the installed capacity by production type from 2023 can be seen.

Unit type	Installed capacity in MW
Thermal	4585
Hydro	8200
Wind Onshore	5470
Photovoltaic	1810
Biomass	680
Wind Offshore	25
Total	20 615

Table 4.1: Power plant park capacities of different unit types

Table 4.1 shows that in 2023 75% of installed capacity was renewable generating capacity.

The next question pertains to the breakdown of energy generation by different types of generators. In 2023, the electrical energy mix comprised the components detailed in Table 4.2.

	Generation in GWh
Thermal	18 565
Hydro	8720
Wind	13 035
Solar	3480
Biomass	3200
Total generation	47 000
Hydro pumping	-2940
Export Import	9255
Losses	-4875
Total consumption	48 440

Table 4.2: Energy mix 2022 [42]

From this data, it is evident that 60.5% of the energy produced in Portugal and 58.6% of the total electricity consumed in Portugal were generated by renewable energy sources (RES).

4.2 Future targets

From this initial situation specific targets to address climate crises must be achieved.

2016 Portugal committed to the official long term general goal of carbon dioxide neutrality until 2050 [44]. As part of the European union they set main goals concerning Energy transition in the Regulation on the Governance of the Energy Union and Climate Action of the European Parliament and Council 2018 [45]. Targets of the European union for 2030 include: 32% renewable energy in gross final consumption, a 32.5% reduction in energy consumption, a 40% reduction in greenhouse gas (GHG) emissions compared to 1990 (or 30% compared to 2005), and a installed cross-national electricity interconnection capacity of 15% of the installed generating capacity [44].

Portugal outlines its goals and strategies for achieving them in the National Energy and Climate Plan (NECP) (2021-2030) [44]. The Relatório de Monitorização da Segurança de Abastecimento do Sistema Elétrico Nacional 2023-2040 (National Electricity Supply

Security Monitoring Report) (RMSA-E) [46] serves as Portugal's planning tool for the transition path towards these goals. It analyzes and forecasts developments of various parameters such as prices, load, and other relevant factors to inform decision-making and policy implementation.

The reduction of primary energy consumption by 32.5% compared to 2005, the target of energy dependency of maximal 65% and a reduction of green house gas emissions of 45-55% (2030), 75% (2040), 85.95% (2050) compared to 2005 are only indirectly relevant for this thesis with regards to the assumption of the load and interconnection development in [46]. The green house gas target was increased by Portugal from the European Union goal based on the findings of the IPCC special report on 1.5°C and Paris Agreement targets which finds that in the time period from now until 2030 the most significant decrease in GHG emissions is necessary. This leads in total to the target of renewable energy production percentage of cross final consumption of: 31%(2020), 34%(2022), 38%(2025), 41%(2027), 47%(2030) [44].

The goals directly pertinent to this thesis are those specifically targeted at the electricity sector. The share of RES in cross final production can be divided in the different sectors electricity, heating and cooling, and transport. For electricity, this concludes to targets of 60% (2020), 69%(2025), 80%(2030) renewable energy share [44]. A further directly relevant target for this thesis is the interconnection goal of 15% of the installed production capacity until 2030 [47].

In the NECP [44], generation expansion until 2030 is primarily anticipated in final stages of hydro power extension (+1300 MW), such as the Alto Tamega project, which was completed 2023, onshore wind farms (+3600 MW), and PV power (+7000 MW) due to a fall of technology costs and high regional potential. Offshore wind is rated with low potential compared to the aforementioned sources, with an increase of only 270 MW. Biomass is not considered very efficient for electricity production, and thermal concentrated solar power plants are also not seen as having high potential compared to photovoltaic power plants. Electricity storage requirements are expected to be mainly covered by hydroelectric pumping (+1300 MW), the expansion of batteries (+1000 MW), and hydrogen [44].

4.3 Load

Actual total energy consumption on mainland Portugal in the year 2023 was 50 700 GWh. Based on this historic data the load scenarios for the future are created. In the study RMSA-E 2022 of Redes Energéticas Nacionais (national energy grid company) (REN) and Direção-Geral de Energia e Geologia (DGEG) different forecast scenarios of the total electricity demand are calculated. The factors energy efficiency measures, electro-mobility, self demand and decentralization, hydrogen production and data centers and other major consumers are considered. This report presents, expected average growth rates of electricity consumption for different scenarios from the year 2023-2030 and from 2031-2040. In the ambitious scenario the electricity consumption is higher due to a faster increase of electrification and hydrogen production. For this thesis the high ambitious load scenario with annual increase rates of 2.2% until 2030 and 1% until 2040 is used. This assumption allows the expansion planning to find a resource portfolio that can cope with a high level of electrification.

Figure 4.2 shows the forecasted yearly load development in the future representative years together with the load development in the past.

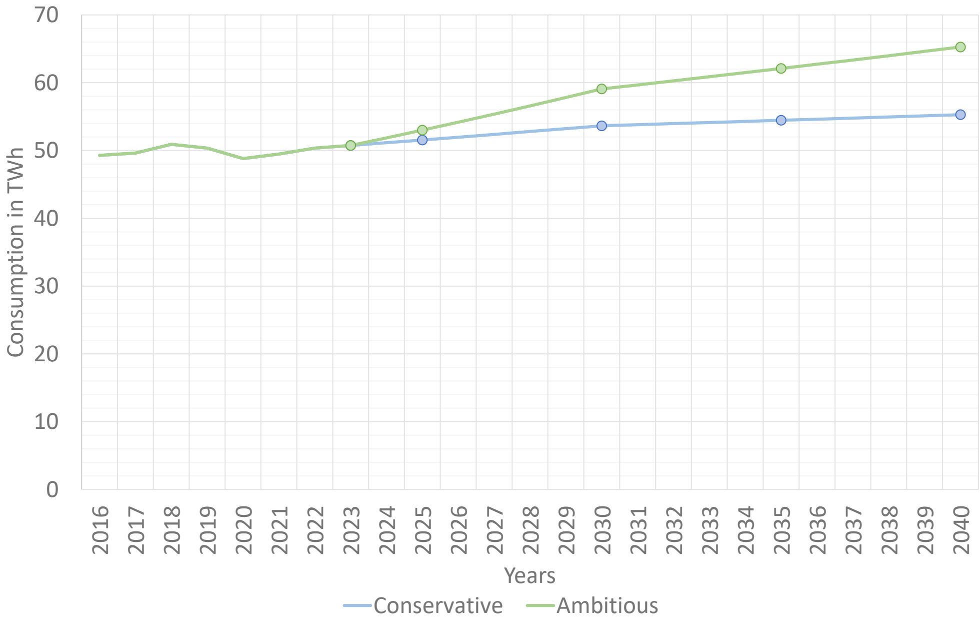


Figure 4.2: Yearly load development over time (ambitious and conservative scenario) [46]

For the hourly load profile, the initial profile from 2023 was scaled up with the increase rates of the report. No seasonal or daytime load shift or demand response over time is considered. The specific characterization of the profile for different weekdays is continuously taken into account.

4.4 Production units

The assumed power plant park, that exists 2023 to cover the Portuguese load is composed of thermal (gas, biomass, biogas), hydro, photovoltaic and wind power plants [43]. The detailed amount and allocation to areas is shown in Figure 4.3.

The distribution of installed capacity across different regions reveals interesting patterns. Lisboa, with the highest consumption, exhibits the lowest installed capacity, a common characteristic of urban regions. In this area, the generating capacity is primarily dominated by thermal gas production. In the North region, which holds the highest hydro generating potential, the installed capacity is predominantly hydro-powered, making it the area with the highest overall generating capacity. The North region also shares thermal gas and wind potential with the Central region. In the Central region, wind generating capacity occupies the major share, followed by gas and then hydro power. The South region, benefiting from the highest PV potential, has a concentrated and dominant PV capacity.

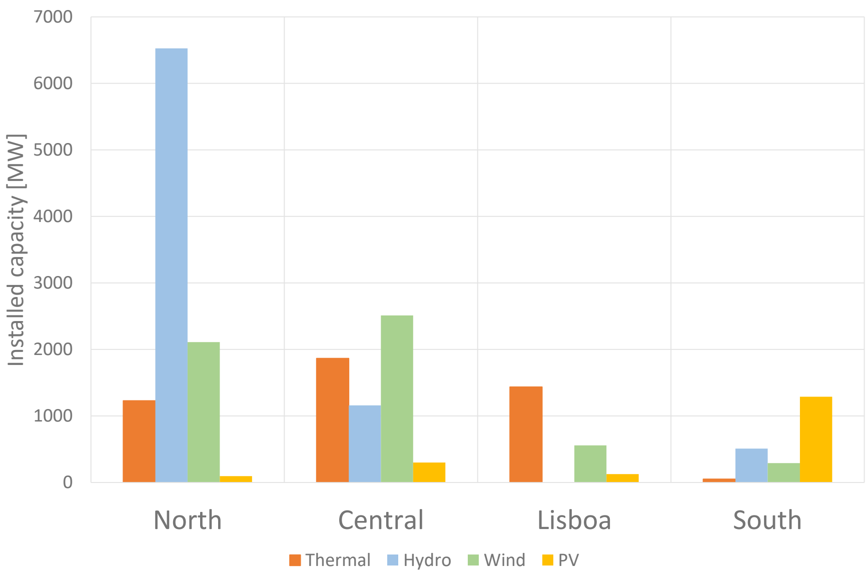


Figure 4.3: Initial installed capacity distribution over areas 2023

The considered characteristics and specific units considered in the study are described in the subsequent section.

4.4.1 Thermal power plants

Thermal generating units can be divided based on their fuel type. The fuel types mainly used are coal, natural gas, geothermal, biomass and biogas power plants. In Portugal the last coal power plant was shut down 2021 and therefore the greatest amount of thermal energy production currently is covered by gas power plants. Geothermal power plants are not used in Portugal mainland. Of the renewable thermal plants fueled by biomass and biogas biomass takes over the major portion.

Natural gas

The total installed capacity of gas power plants in Portugal is 4585 MW [43]. Table 4.3 shows the installed gas power plants for which specific data per generating unit was found. The missing capacity of 756 MW is divided between all areas in proportion to their consumption.

Area	Unit Name	capacity [MW]	commissioning date	expiring date
Central				
	Lares	826	2009	2040
	Pego C.C.	837	2010	2041
Lisboa				
	Ribatejo	1176	2004	2035
North				
	T.Outeiro C.C.	990	1998	2029
Sum		3829		

Table 4.3: Overview over natural gas power plants considered

For the life span of a thermal power plant 30 years are assumed [48]. Therefore the retirement of Outeiro power plant is assumed in 2029 like in RMSA-E 2022 REN DGEG.

The efficiency factor of natural gas power plants lies typically between 45-57%.[49] Combined cycle power plants reach an efficiency up to 60%. For Lares power plant

EDP gives an efficiency value of 57%. For the other power Plants an efficiency factor of 50% is assumed.

The gas price for the initial year is assumed as 40 €/MWh_{th} [50] and the assumption for the future representative years is overtaken from the scenario represented in [51] and can be seen in Figure 4.4.

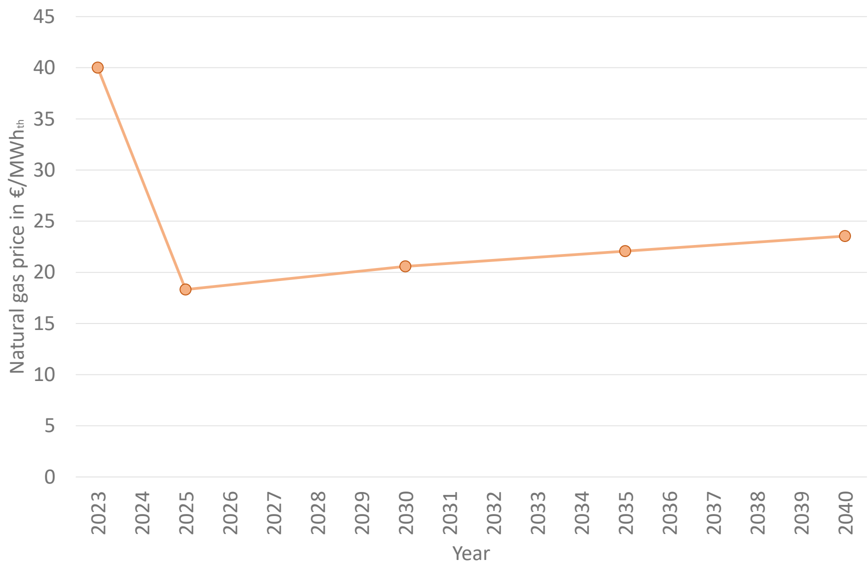


Figure 4.4: Gas price assumptions for the representative years [50] [51]

Renewable thermal power plants

The renewable thermal electricity is mainly produced by biomass in mainland Portugal with 5.7% of total load 2023 [43]. Biogas only made up 0.5% [46]. In this thesis only biomass is considered as relevant electricity production source.

Since it can be seen that biomass is used as a nearly constant base electricity production it is modeled as a fixed electricity contract with a constant capacity factor of 0.5 of the installed capacity which was the utilization factor in 2023. For the future the expected expansion in [44] is taken into consideration. The development over the years can be seen in Figure 4.5 For the fixed contract no production price is considered since it is not optimizable. For the division to the different areas data for biomass generating capacity was taken from [52] and [53].

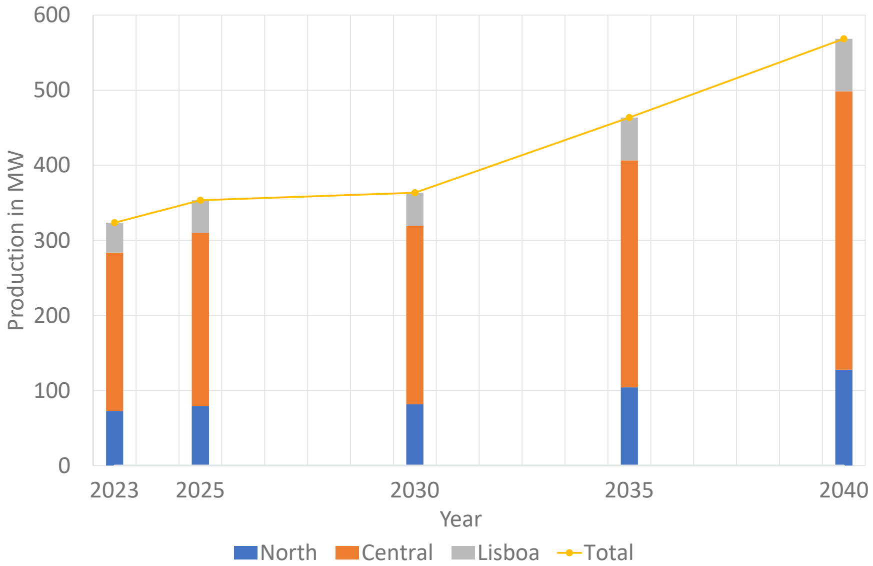


Figure 4.5: Biomass fixed constant production and distribution over areas for the representative years

4.4.2 Hydro power plants

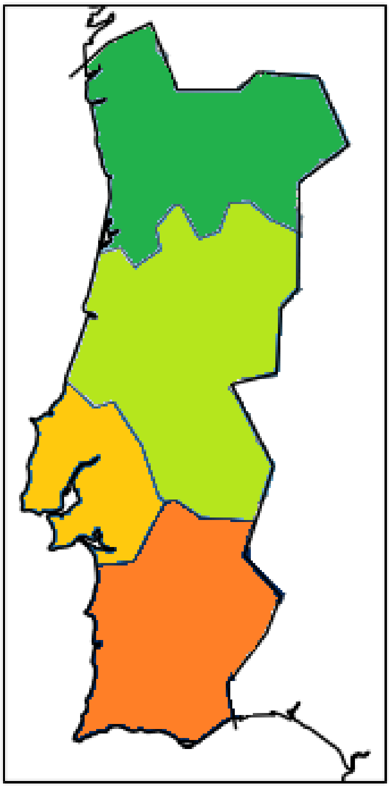
The total installed hydroelectric power capacity 2023 was 8196 MW according to European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency platform [43]. In Table 4.4 an overview over the installed capacity per generating units and their distribution over the areas is given [43] [54]. The production capacity for which no specific generating unit could be found of 325 MW is proportionally divided between all areas according to the installed capacity of the other hydro units.

The installed capacity is the constant maximum limit for electricity production optimization of the hydro power plant. A further integral limit is given by the amount of inflow to the upper reservoir. With a scenario generator from different historic time series one is picked by coincidence and taken as an inflow scenario for the different reservoirs. No specific further changes of inflow profiles due to climate change are considered.

Since the extension of the Alto Tamega power plant is already finished and the hydro power system in Portugal is already used to a high degree no further considerable expansion in hydro power is assumed in the future [46]. Furthermore, it is assumed that the hydro power plants will be maintained in any case, so their maintenance is not considered in the optimization, and no expiration of the hydro power plants is assumed. Efficiency factors for the units are derived from internal Energias de Portugal (EDP) data.

North	in MW
Gouvães	881
Venda Nova 3	780
Alto Lindoso	630
Foz Tua	253
Bemposta	240
Valeira	240
Picote II	234
Carrapatelo	201
Salamonde II	200
Picote	195
Bemposta II	191
Miranda II	189
Venda Nova 2	188
Pocinho	186
Miranda	180
Regua	180
Vidago	160
Vilarinho F.	144
Torrao	140
Baixo Sabor Mont	135
Crestuma	117
Daivoes	114
Venda Nova 1	90
Tabuaco/vilar	70
Alto Rabago	70
Canicada	64
Paradela	54
Salamonde	44
B Sabor J	30
Varosa	27
Touvedo	22
Ermal	12
Guilhofrei	5
PonEsperanca	3
Unknown	216
Sum	6483

Central	in MW
Aguieira	300
Castelo Bode	159
Fratel	132
Cabril	108
Belver	81
Ribeiradio	69
Bouca	44
Pracana	41
Caldeirao	40
Santa Luzia	29
Raiva	24
Vila Cova	23
Ponte Jugais	20
Desterro	13
LagComprida	13
LagVRossim	10
Ermida	7
Unknown	38
Sum	1151



South	in MW
Alqueva	480
Pedrogao	10
Unknown	17
Sum	507

Total	8142 MW

Table 4.4: Hydro power plant capacities for each area

4.4.3 Wind

The total installed wind capacity in Portugal mainland is 5358 MW which represents 26% of total installed capacity. The main part is produced in onshore farms only 25 MW of offshore power plant capacity is installed in area North. The distribution of the onshore wind capacity over the areas can be seen in Table 4.5 [55].

Area	Installed capacity [MW]	$kWh/kWh_{profile}$
North	2110	1.00
Central	2512	1.00
Lisboa	557	0.95
South	290	0.90
Total	5469	

Table 4.5: Wind capacity and power output factor per region

The wind power output per installed capacity differs per region due to different geographical location and terrain characteristics. In Figure 4.6 a map of wind power density in Portugal overtaken from [56] can be seen. For whole Portugal mainland the mean power density at 10% windiest region is 508 W/m^2 [56]. The 10% windiest region is taken as reference since it is not always possible to build the power plants at the windiest location but it is still attempted to realise them at preferably windiest places. Therefor the 10% windiest areas are seen as realistic average values for an area. The mean wind power density of whole Portugal was taken as the reference power density with which the hourly wind profile for whole Portugal is related. This base hourly generating profile for the whole country was taken from [43] from year 2022. For the individual areas also the mean power density at the 10% windiest region is taken and the wind profile is scaled proportionally to this factor. The resulting wind power output factors considered for each area can be seen in 4.5.

Besides onshore wind farms with its geographical location Portugal has the possibility of using offshore wind farms. Until 2024 a 25 MW power plant is installed in area North for which the generation profile is overtaken from [43]. For further expansion offshore wind power potential at the Atlantic is considerable. But the steep coast leads rapidly to great depths near to the coast, which makes realisation mainly possible with more expensive floating offshore wind farms.

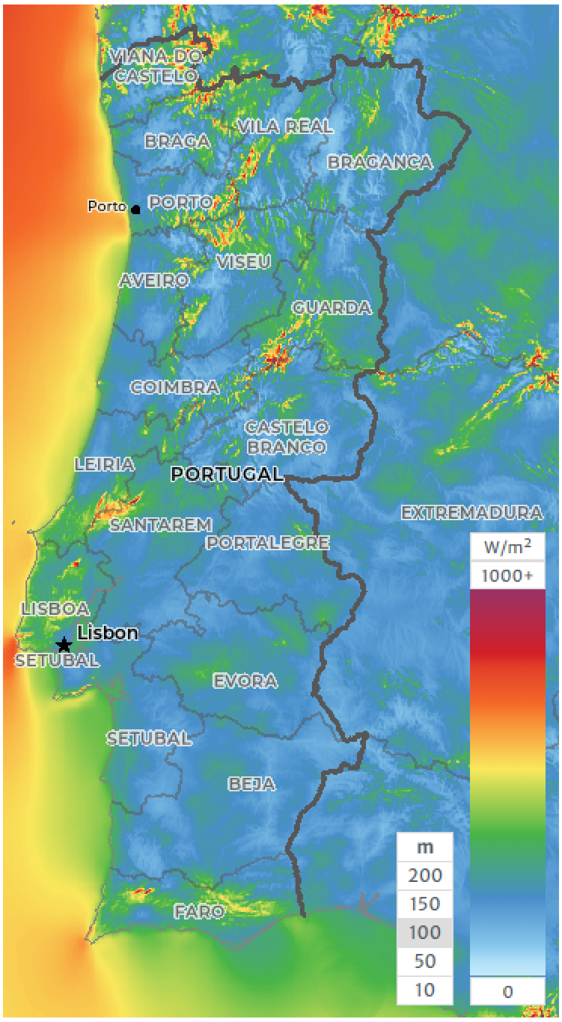


Figure 4.6: Mean wind power density in W/m^2 [56]

4.4.4 Photovoltaic

The distribution of the total installed photovoltaic capacity of 1811 MW over the areas is reconstructed from data of [57] and can be seen in Table 4.6.

Area	Installed capacity [MW]	kWh/kWp/day
North	96	3.9
Central	300	4.3
Lisboa	125	4.5
South	1288	4.6
Total	1811	

Table 4.6: Photovoltaic capacity and power output factor per region

For photovoltaic power plants a varying generating profile over time is assumed. For this the base year 2022 has been taken from [43] as a general production profile of the whole country and overtaken for the following years, like for the wind profile. Also a varying photovoltaic power output per installed capacity was considered for the different areas due to different solar irradiation at the different geographical locations. Figure 4.7 shows a map of realistic PV output over the area of Portugal [58]. The resulting extracted factors per are in this study is shown in Table 4.6. The total Portuguese PV profile has been scaled down to the generating kWp capacity totally installed in whole Portugal. This profile is then scaled up with the installed capacity per area and the capacity factor of the area.

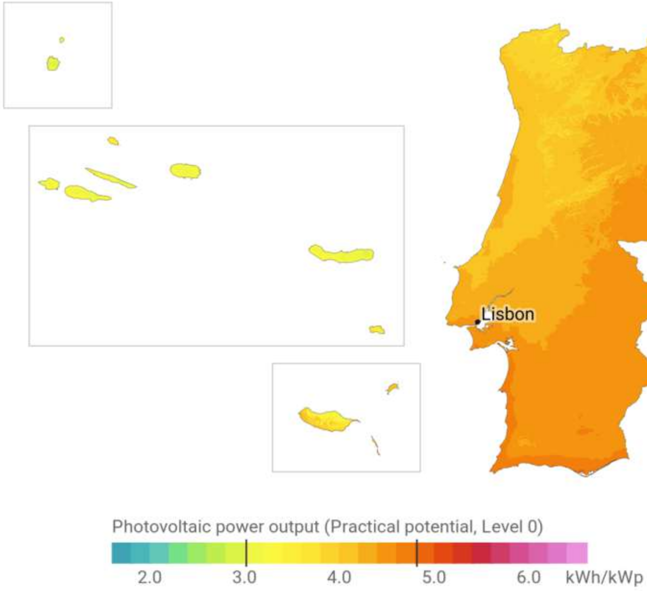


Figure 4.7: Realistic PV output in $kWh/kWp/day$ [57]

4.5 Transmission lines

Between the modelled areas transmission lines specify the limitation for exchangeable power. The transmission capacity can be limited by different factors. There is the thermal capacity limit due to losses in the power line preventing overheating or sinking of the power lines. Especially for longer lines (>100km) the limits of voltage drop, phase angle for system stability, get more relevant. This limits differ from time to time depending on the load and generation in the system. This leads to a capacity profile which is available for commercial exchange. This capacity can also differ for the direction of the power flow.

The transmission lines can be divided in cross-national lines between Portugal and Spain and lines within Portugal.

4.5.1 Cross-national lines

The total average actual interconnection capacity from Portugal to Spain is 3004 MW and 3745 MW from Spain to Portugal. Table 4.7 shows the list of specific interconnections and their thermal capacity considered [46].

	PT	ES	Capacity in MW	%
Central				14
	Falagueira	Cedillo	1386	14
North				58
	Lagoaça	Aldeadávila 1	1587	16
	Pocinho	Aldeadávila 1	405	4
	Pocinho	Aldeadávila 2	405	4
	Pocinho	Saucelle	395	4
	Alto Lindos	Kartelle 1	1525	15
	Alto Lindoso	Cartelle 2	1525	15
South				28
	Alqueva	Brovales	1333	14
	Tavira	Guzman	1386	14
Total			9947	100

Table 4.7: Transmission line capacities Portugal - Spain [44]

The total average interconnection capacity in both direction is proportionally divided onto the different areas by the percentage of the thermal capacity. The transmission capacities considered for each area to Spain and back are presented in Table 4.8 and an overview with an geographical classification is given in 4.8.

Area	Percentage	Import in MW	Export in MW
North	58	2200	1764
Central	14	521	418
South	28	1023	821
Total	100	3745	3004

Table 4.8: Actual transmission capacity in MW between the areas North, Central and South to Spain

The transmission efficiency was assumed as 90% because in the model a less dependent Portuguese electricity market from Spain is modeled, therefor imports and exports are less beneficial due to high transmission losses.

4.5.2 Lines within Portugal

The internal transmission capacities between the areas within Portugal are overtaken from [40] and assumed to be symmetric in both directions. The capacity of the transmission lines within Portugal can be seen in Figure 4.8. For the interconnections within Portugal an transmission efficiency of 98% is considered.

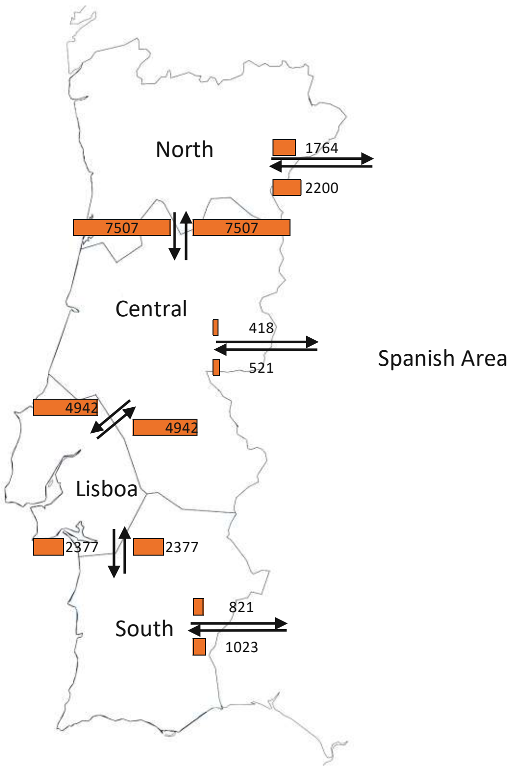


Figure 4.8: Maximal capacity of transmission lines between areas

Figure 4.8 gives a geographical overview over all considered transmission lines and their capacity.

4.6 Electricity market price

As an external electricity spot market to which power can be sold and from which it can be purchased the Iberian Spot Market in Spain is modelled. The maximum power that can be transferred is limited by the transmission lines. In order to optimize the amount of energy sold or purchased for this market a price forecast is provided. The hourly price profile for the past year 2023 is obtained from REN [59]. Future development assumptions are sourced from [51], which provides an hourly forecasted electricity spot market price profile for Portugal for 2030 and 2050 across different scenarios. For this thesis, data from the scenario envisioning a more flexible and decentralized energy market in Spain is adopted. The total electricity market prices for the representative years 2025, 2035, and 2040 are assumed to follow a linear transition from 2023 to 2030 and 2050.

4.7 Investment opportunities

In order to know in which magnitude expansion possibilities have to be considered one can orient on existing assumptions for the future. The maximal power load point increase assumed in this study from 2022 to 2040 is 2682 MW from 8552 to 11 180 MW in 2040. The DGEG report expects an increase from 2022-2040 of nearly 20400MW PV, nearly 10 000 MW wind onshore, 2000 MW wind offshore, nearly 500 MW CSP, 400 MW biomass and 100 MW bio gas [46]. In this thesis only the technologies with an assumed potential of more than 1 GW namely PV, onshore and offshore wind power are considered.

In [60] results from different studies about costs for photovoltaic and wind power plants are summarized and also future assumptions until 2050 are presented. Figure 4.9 shows the assumed development of CapEx for the different expandable technology types. The prices for 2023, 2030 and 2050 are overtaken from [60]. The price development for the representative years in between is represented by polynomial regression.

As the maximum geographical onshore expansion potential per area, the values presented in Table 4.9 are considered, sourced from [40]. For offshore wind farms, Portugal's potential for expansion is concentrated along the coastal areas of the North and Central regions [61]. In these areas, expansion options are provided without a specific maximum potential being defined.

	PV in GW	Wind in GW
North	13	39
Central	14	64
Lisboa	7	16
South	11	42
Total	45	162

Table 4.9: Maximum geographical onshore wind and PV expansion potential

For all expansion technologies per areas and representative year the expansion decision resolution is 500 MW.

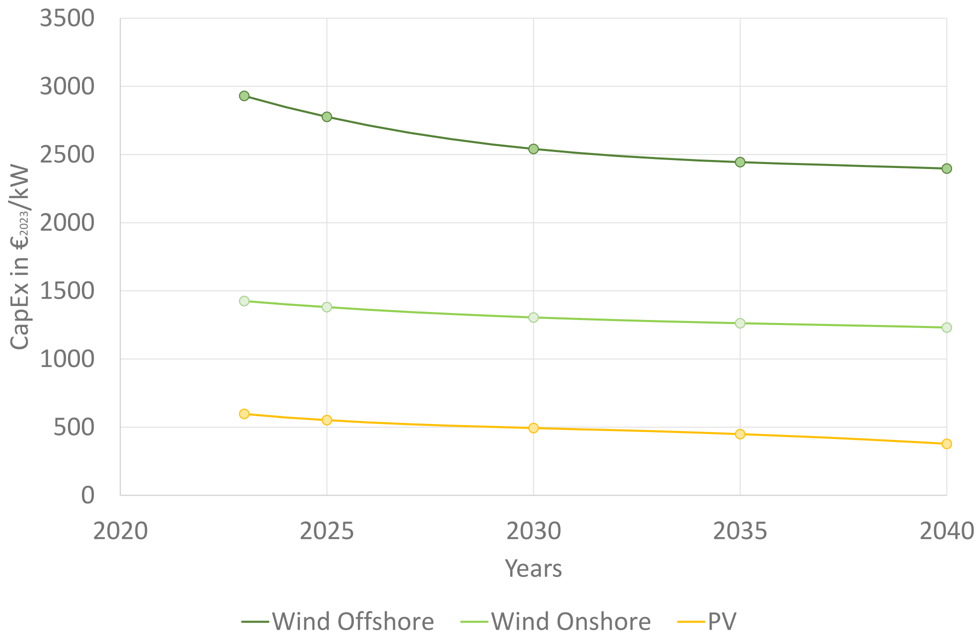


Figure 4.9: CapEx for different expansion options over the planning horizon in $€_{2023}/kW$ [60]

For the investment optimization of wind and PV a scenario analysis on storage and transmission line expansion is carries out. The characteristics and details of these expansions are described in detail in the respective scenario description in the results chapter.

5 Results

In the subsequent section, the cost-optimal investment approach for wind and PV plants, derived from the previously introduced model and data, is detailed. Results are presented for the following scenarios: first for the base scenario with the current electricity system followed by scenarios with storage and transmission line expansion. The results are presented, structured in the following aspects:

- Investment Decisions Overview: Presentation of investment decisions, detailing the capacity (in MW) and timing for each area and unit type (wind and PV).
- Installed Capacity and Energy Mix Analysis: Overview of the resulting total installed capacity and energy mix over the years for Portugal as a whole and individual areas, including import and export dynamics.
- Energy Flow Development between Areas: Analysis of the energy flow development between different areas, highlighting the inter-area exchange patterns.
- Cost Distribution Overview: Presentation of the cost distribution, including investment costs, operational costs, purchase costs, and sale revenue.

This structured approach allows for a comprehensive analysis of the model results, capturing both the macroscopic and geographical aspects of the energy system dynamics.

5.1 Base case

The initial presentation focuses on the expansion decisions obtained from the optimization process. Expansion options in PV, onshore wind, and offshore wind plants are detailed. Notably, the optimization did not indicate offshore wind expansion. Therefore, only expansion in PV and onshore wind plants is presented in Figure 5.1. It provides a comprehensive overview of the expansion decisions, revealing the temporal and spatial distribution and capacity contributions. The table illustrates that major investments and expansions are concentrated in 2025, with a total addition of 9500 MW capacity, predominantly in wind (7000 MW) compared to PV (2500 MW). In the subsequent 5 year periods until 2040, additional capacity installed per period is maximal 3000 MW , with PV expansion dominating during this period.

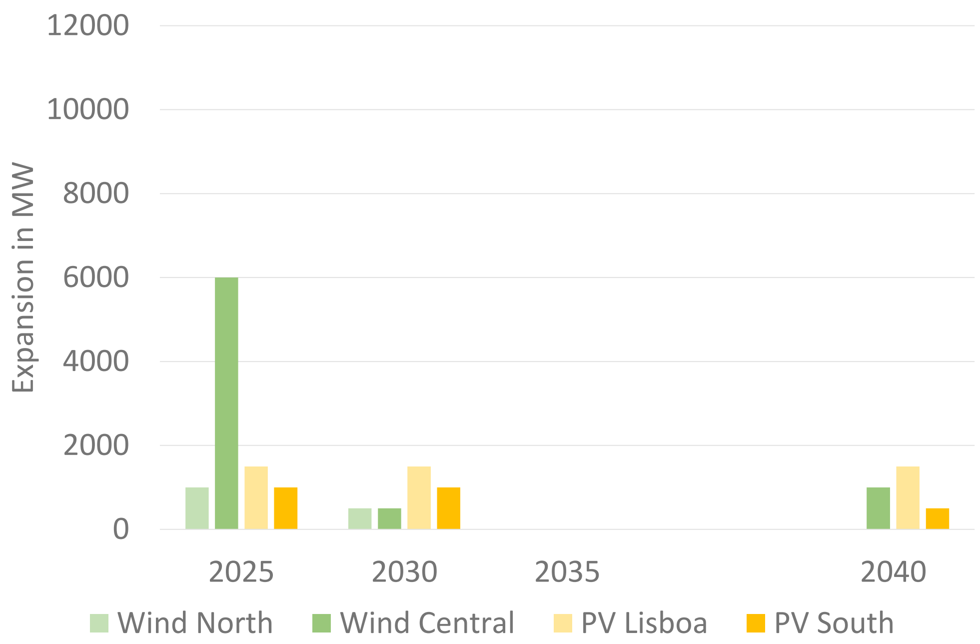


Figure 5.1: Expansion decisions of PV and wind onshore in MW for each geographical region and expansion year (2025, 2030, 2035, 2040)

Additionally, it is evident that PV is exclusively installed in the Lisboa and South areas, where geographical conditions are more favorable. Conversely, wind expansion is concentrated in the North and Central areas, where the wind power density is higher compared to the other regions. The diverse generating potentials considered for these specific regions are detailed in the case study.

For the timing of investments, learning curves are taken into account to anticipate the future development of prices for expandable technologies. It becomes apparent that investing in new power plants at a later time could result in lower costs. However, the significant wind investments made early on suggest that the learning curves of wind technologies have already reached a point where they are economically advantageous compared to gas power plants or the spot market in Spain for a high amount of wind penetration. Also PV is profitable already to invest in 2025 but the investments are more distributed over the time, showing that the learning rate here has a higher influence.

5.1.1 Yearly generating capacity distribution in whole Portugal

The resulting composition of the installed capacity in each representative year for whole Portugal is presented in Figure 5.2.

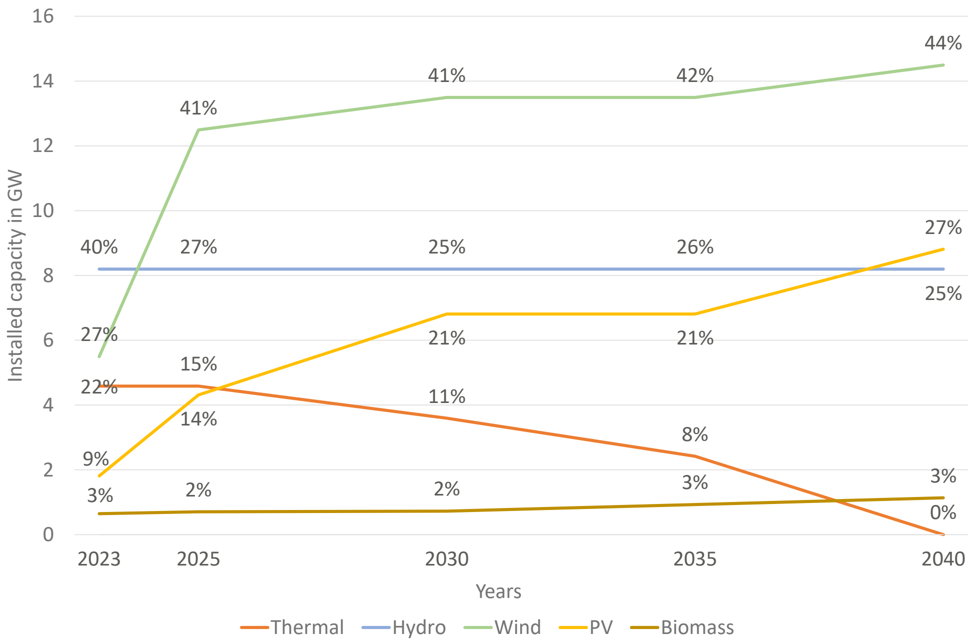


Figure 5.2: Installed capacities of generating units in GW and percentage over the planning horizon

The existing power plant park, totaling 20 700 MW in 2023, expands significantly to 30 300 MW in 2025, marking a remarkable increase of nearly 50%. By 2025, 85% of the installed capacity is attributed to RES. Wind and PV capacities more than double, experiencing growth rates of 227% and 238%, respectively, compared to the 2023 installed capacity. This shift transforms the electricity system from being dominated by hydro power in 2023 to one dominated by wind power, with PV capacity reaching a similar level as thermal gas power plants.

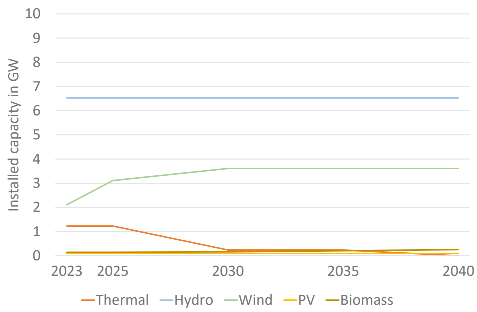
In the subsequent years, additional wind and PV investments are made in 2030, while thermal gas capacity decreases due to the expiration of units. This results in a renewable percentage of 89% of the total generating capacity. By 2035, no further wind expansion occurs, but an additional thermal gas power plant expires, reducing thermal gas capacity to only 8% of the installed capacity.

In 2040, additional 2000 MW of PV capacity is installed, and as specified, no thermal gas capacity is available anymore. With this expansion, PV capacity surpasses hydro production capacity. Together, wind and PV potentials make up 70% of the installed capacity, while the remaining base load power plants, hydro, and biomass power plants represent 30% of the total installed production capacity.

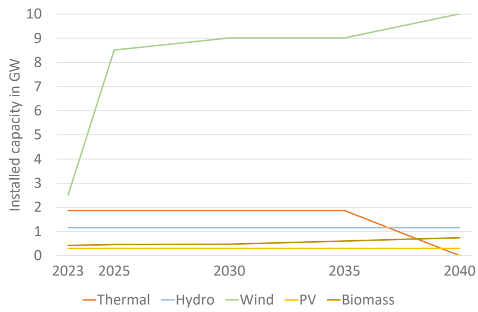
5.1.2 Yearly generating capacity distribution in areas

In order to understand the whole energy system and its influence to the expansion decision a detailed look into the electricity system of the separate geographical areas is made.

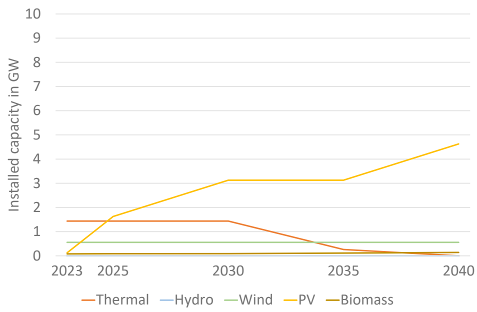
Based on the initial power plant park described in the case study the development of the installed capacity over time in each area is shown in Figure 5.3 and analysed in the following section.



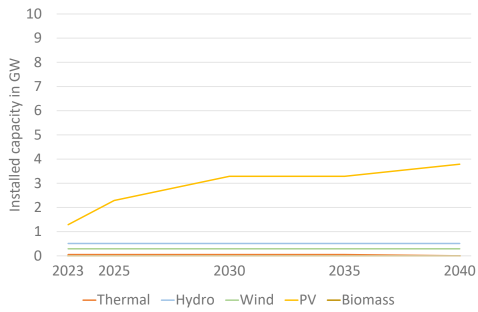
(a) North



(b) Central



(c) Lisboa



(d) South

Figure 5.3: Development of installed capacity per production type over the planning horizon for each area

With the expansion decisions, the composition of power plant parks in individual areas evolves, resulting in changes to their characteristics.

- **Wind Expansion:** The major part of wind expansion occurs in the Central region, where wind production capacity increases significantly, reaching 10 000 MW by 2040. This marks a 3.79-fold increase compared to 2023, making wind power the predominant unit type in Central by a considerable margin. A minor part of wind power expansion takes place in the North, where hydro power remains the major production potential. Notably, major gas power production expires in the North until 2030, while in the Central region, it expires in the 5-year period leading up to 2040.

- **PV Expansion:** Similar to wind expansion, PV expansion is concentrated in one region, namely Lisboa. In 2025, the PV potential increases to the extend that it shares the main production capacity with gas power production. By 2030, PV capacity in Lisboa further increases, becoming the primary production capacity. This trend intensifies as the main gas production potential expires until 2035, and with significant increases in PV capacity observed by 2040. Overall, the power plant park in Lisboa transitions from being gas power-dominated to strongly PV-dominated. Also in the already PV-dominated region South, significant PV expansion occurs in 2025, 2030 and 2040 reaching an installed capacity of 3800 MW.

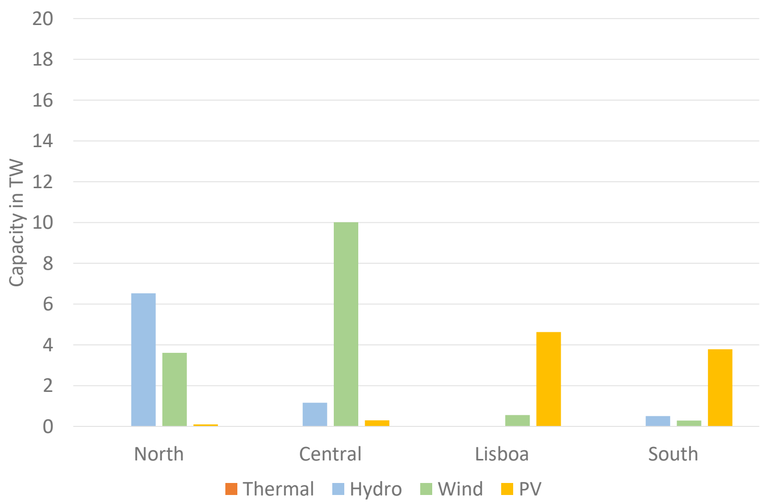


Figure 5.4: Installed capacity per production type per area in 2040

In total the power plant park in Portugal 2040 is distributed across the areas as shown in Figure 5.4.

5.1.3 Yearly energy mix in total Portugal

The resulting energy mix produced with the installed capacity and its development over the years is depicted in Figure 5.5.

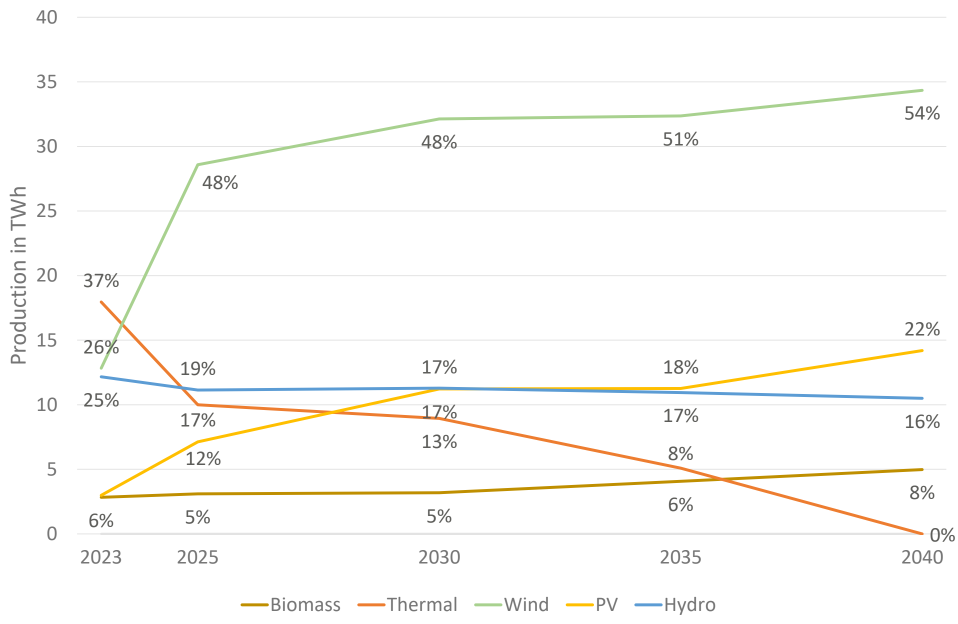


Figure 5.5: Yearly energy mix development in Portugal over the planning horizon

In 2025, the previously dominant energy production by gas power plants decreases to 17% of the total energy production, supplemented by a significant increase in wind and PV production. Renewable sources contribute to 83% of the electricity generation. The distribution of energy among renewable sources is influenced by the characteristics of the unit types:

- Wind power plants, with their high full load hours compared to PV, contribute a higher percentage of energy production than their percentage of installed capacity. They represent 48% of the total energy production with 41% of installed capacity.
- Conversely, PV energy production represents a smaller portion of the total produced energy than its share of installed capacity. PV represents 12% of the total energy production with 14% of the installed capacity.

- The total hydro production comprises hydro production minus hydro pumping for storage. Turbining this stored energy is not considered as production in this figure, as the production of hydro power plants also falls below their percentage of installed capacity. Due to the increased fluctuating electricity production of wind and PV, hydro power plants are increasingly utilized for storage and less for additional generation, resulting in a minor decrease in hydro production over the whole period.

In 2030 PV production equals the production by hydro power with 17 % of the production and wind production further increases. In 2040 76% of the electricity is produced by wind and PV and the remaining 24 % are produced by hydro power and biomass.

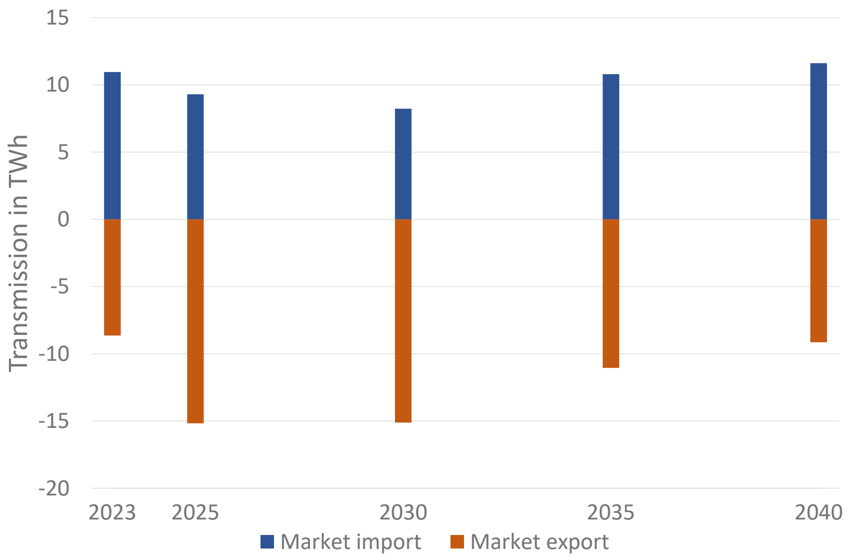


Figure 5.6: Yearly import-export balance between Portugal and Spain

Furthermore, the increase in PV and wind capacity leads to a notable rise in exported energy to the Spanish spot market. Conversely, less energy is imported from Spain. The increase of export thereby exceeds the decrease of import. This trend suggests that with the additional PV and wind generating capacities in Portugal, it becomes more favorable to produce electrical energy domestically than to import it. Moreover, in many cases, it is even advantageous to produce additional electric energy for export to Spain. This development implies that, based on the assumed spot market price scenario for Spain, the transition to RES in Portugal is progressing at a faster pace than in Spain. Consequently, pursuing a transition to RES as swiftly as possible in Portugal, potentially outpacing Spain, could prove profitable by enabling energy export and sales.

In the years 2035 and 2040, the export to Spain decreases. This could be attributed to the significant decrease in gas power production potential during this time period, resulting in a greater need for produced energy within Portugal itself. Additionally, the assumed spot market price decreases, leading to fewer time periods where selling energy to Spain is advantageous. As the share of volatile RES increases in 2035 and 2040, the import also rises, slightly surpassing the level observed in 2023 in 2040.

5.1.4 Yearly energy mix in areas

Transitioning from the analysis of the total energy mix, the distribution to the different areas and their imports and exports are examined.

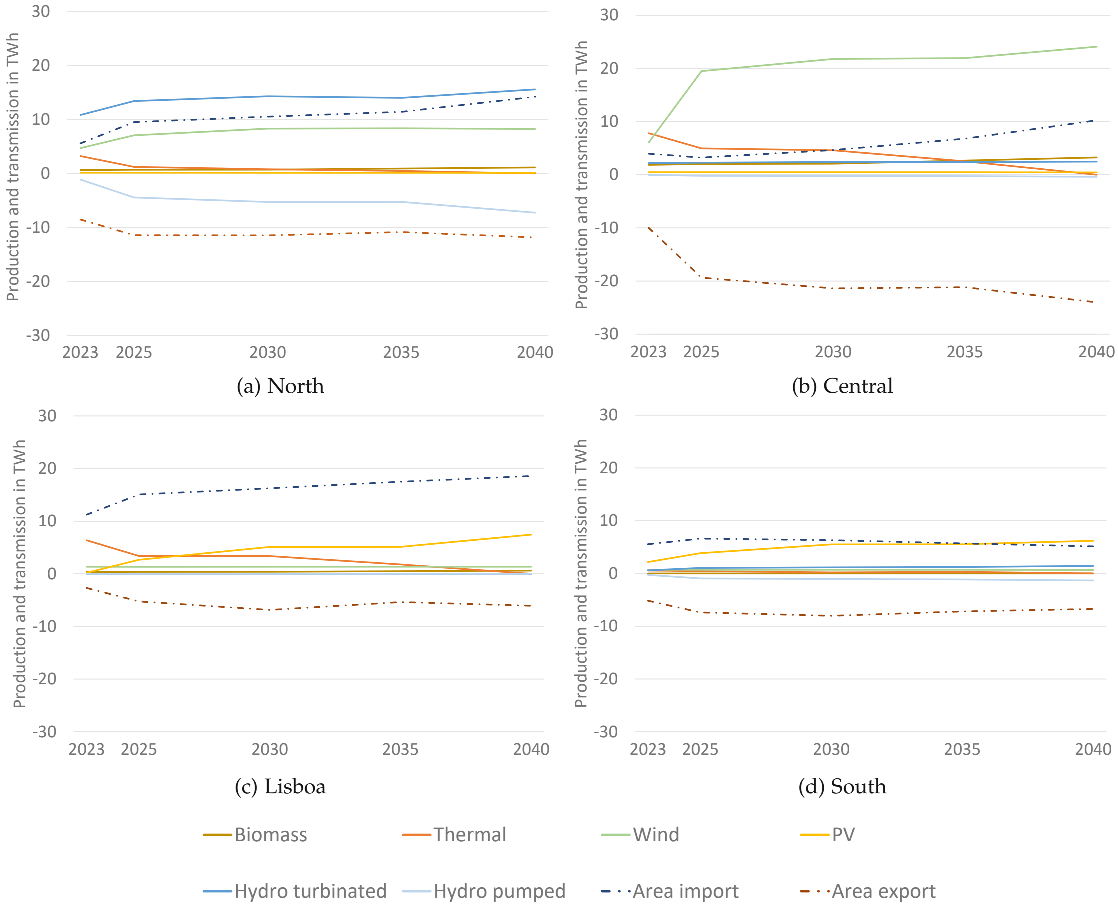


Figure 5.7: Yearly energy mix development for each area over the representative years

Looking at the import-export balance in Figure 5.7, it becomes apparent that over the entire period, North and South are nearly balanced areas, while Central is primarily an exporting area and Lisboa is mainly an importing area. When high renewable expansion occurs, export of the area increases and in areas with gas power production this productions significantly decreases. This trend is noticeable in all areas during the transition from 2023 to 2025. In instances where gas power plants expire without a significant increase in RES in the area, compensation occurs through increased import, as seen in Central from 2035 to 2040. Also before expiring of the gas power plant gas power production decreases and is replaced by imports. Furthermore, the utilization of hydro power plants for storing energy increases significantly with the rise of volatile RES, as best seen from the increase in pumped energy in Figure 5.7a.

In order to understand better the interaction between the individual areas, the transmission lines in between and the transmitted power is further analyzed.

5.1.5 Energy flow over transmission lines

Due to the unequally distributed expansion, a change in the total electricity system can be expected, particularly in the utilization of transmission lines. In the following section the energy transmission flow between the areas is analysed. This analysis is crucial for recognizing changes in the amount of energy flow, identifying potential bottlenecks in transmission lines, and understanding how these factors may influence the results of the investment approach. Specifically, we aim to determine whether transmission lines reach their capacity limits and assess how this impacts the overall energy distribution pattern.

The yearly energy flow and its development over time caused by the expansion can be seen in Figure 5.8.

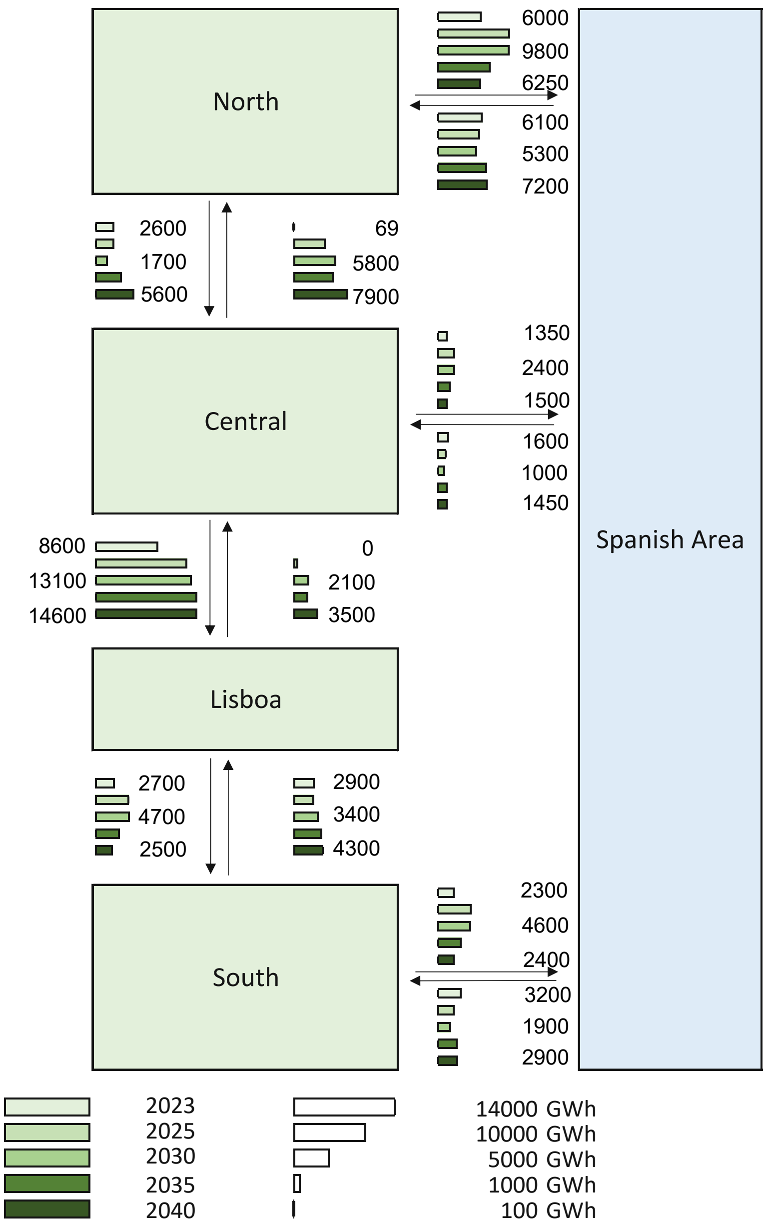


Figure 5.8: Development of area exchange in GWh over the years

In 2023, the primary energy flows are observed from the northern regions towards the southern regions, specifically from North to Central to Lisboa. This flow pattern

is attributed to the presence of a large number of hydro and gas power plants in the northern regions, coupled with high consumption and low production in the area of Lisboa. Conversely, minimal energy flow is observed in the reverse direction, from Lisboa to Central to North.
Between Lisboa and South, a similar amount of energy is transferred in both directions. This equilibrium can be explained by the dominance of volatile PV power generation in the South. A more comprehensive understanding of these energy flows can be obtained through the analysis of average hourly day profiles.
Energy exchange with Spain occurs in all areas where it is possible. The North region boasts the highest transmission capacity installed, facilitating significant energy exchange with Spain, primarily due to the presence of a large number of installed hydro power plants.

With the expansion of wind and PV power plants in the energy system by 2025, a significant portion of renewable expansion is realized in Central and Lisboa, compared to smaller expansions in South and North. Consequently, the transmitted energy from Central to North and from Lisboa to South experiences a notable increase, while the opposite direction witnesses a decrease. Additionally, there is a significant increase in the amount of transmitted energy from Central to Lisboa and a slight increase in the opposite direction. Transmission at this link increases in both directions, as it serves as the link between the northern wind-producing and southern PV-producing areas, facilitating the balancing of temporally different energy generation patterns. As for the transmission lines to Spain, the trend observed in Figure 5.6 is evident across all lines. In 2025, the export for all lines increases while imports decrease.

By 2030, PV investments happen in Lisboa and South, with minor wind expansions in Central and North. Consequently, the transmitted energy from Lisboa to Central to North increases. Furthermore the major gas power production expires in North which is another reason for the higher imports from and lower exports to Central. However, exports to Spain decrease due to developments in the spot market price.

In 2035, no further expansion of wind and PV was planned but the gas power plant in Lisboa expires, resulting in less energy exported to South and Central and more energy imported from these regions. Central's imports from the North also increase in 2035.

By 2040, assuming zero electricity production from gas power plants, the main part still accessible in the Central region abolishes. In Central also 1000 MW wind is additionally installed. Resulting in an increased exchange between the areas North and Central. Additionally, there is further expansion in PV in Lisboa and South. Consequently, transmission from Lisboa to Central also increases.

The overall energy flow shifts from a production-centered North and consumption-centered South to a wind- and hydro-dominated North and PV-dominated South, thereby transitioning the unidirectional power flow to a bidirectional one. It can be concluded that replacing a gas-supported electricity system with 100% RES necessitates increased flexibility in utilizing transmission lines or storage, resulting in a total energy transmitted of 38 484 GWh in 2040 compared to 16 789 GWh 2023. For a more detailed analysis, the temporal characteristics of power flows are further analyzed in the subsequent sections.

In order to determine if a power line is fully utilized and reaches its limit, the yearly maximal peak utilization of the different lines is presented in Figure 5.9. The total available transmission capacity of the individual lines can be seen in the case study in Figure 4.8. The cross-border transmission lines to Spain, even without expansion, reach their limits due to strongly fluctuating imports and exports aimed at economically utilizing fluctuating spot market prices. Therefore, Figure 5.9 only shows the peak transmitted power for the lines within Portugal, as the maximal transmitted power for the cross-border lines is consistently at their maximum transmittable power every year.

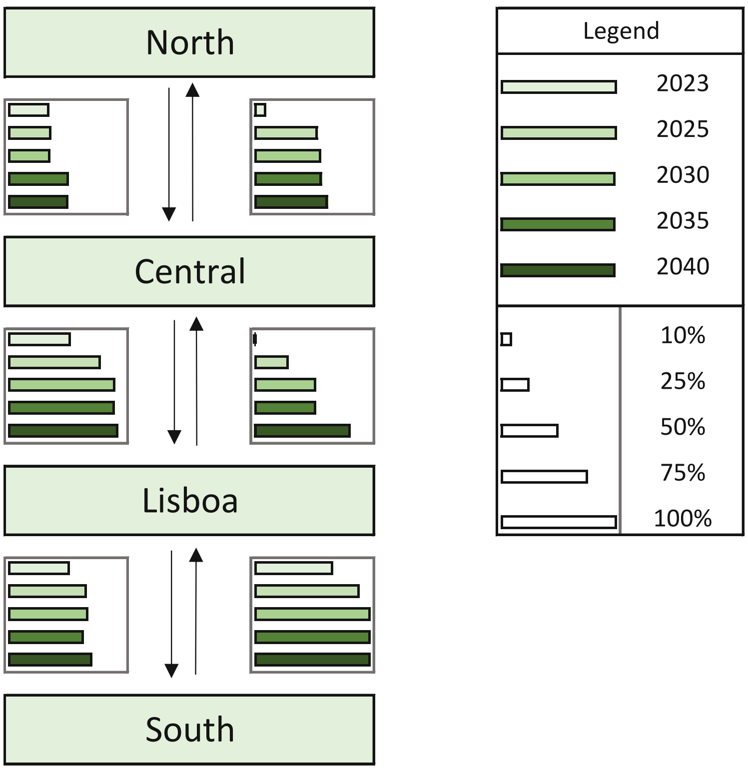


Figure 5.9: Maximal transmitted power as a percentage of transmittable capacity for each power line within Portugal per representative year

Looking at the transmission direction from South to North, it can be seen that the line from South to Lisboa as the only line reaches their limit from 2030 on. After the maximum transmitted power increases from already 68% of the transmittable power 2023. The limit is reached in 2030 95h, 2035 110h and 2040 62h. In the other lines from Lisboa to Central and from Central to North in 2023 the maximal transmitted power is nearly zero. The northern regions have enough base power plants and Lisboa needs their PV production themselves. The significant expansion of PV plants in the South (South and Lisboa) leads to an increased power transmission to the North already 2025. In 2040 due to the expiring of the gas power plant then the maximal transmitted power from Lisboa to Central significantly increases again, but no limits are reached.

In the other direction hydro and wind power production is transmitted to the southern regions, at times of low PV production and high load. In all lines the maximal transmitted power increases over time, especially for the line from Central to Lisboa after 2030 but also here with a maximum of 96% of the transmittable capacity no limit is reached.

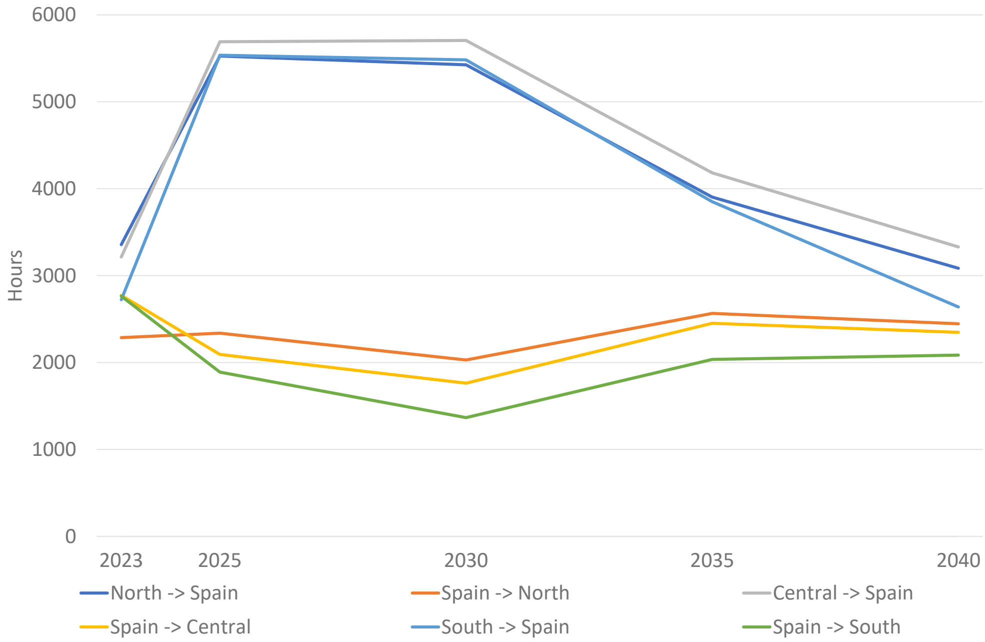


Figure 5.10: Congestion hours of power lines to Spain

In Figure 5.10 the hours of limitation per year for each transnational power line and direction in shown. It can be seen that the expansion of wind and PV and the with this increased price difference to the spot market lead to an increase of power lines utilization which goes back again until 2040.

5.1.6 Hourly day profile

In the previous part the yearly balances of the yearly energy system was described, but no information about the temporal profile was given. With 100% renewable electricity production the question arises how the highly fluctuating energy generation is balanced to fit the load. Therefor resulting hourly representative day profiles for the final power plant park in 2040 for a month in summer (week 25-28) and winter (week 2-5) are analyzed. In this section on four selected Figures the seasonal and diurnal changes in the areas are described. Further summer and winter profiles for each area for 2023 and 2040 are presented in Figure 1-4 in Appendix A.

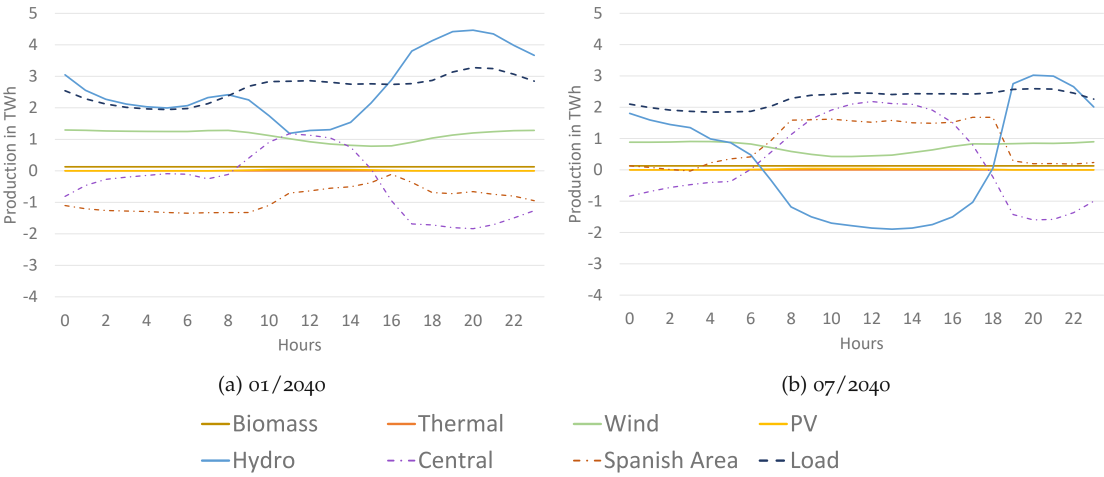


Figure 5.11: Representative day profile for one month in winter and summer in North

In Figure 5.11, the high hydro and wind production in the North area can be observed, whereas due to no expansion, the PV production is nearly zero.

For seasonal difference can be observed that hydro production in winter is significantly higher than in summer. Also the spot market price changes with the season significantly. In winter the average price is higher than in summer. This can be seen especially in North region. Due to high hydro production and high spot market prices in winter energy is mainly exported to Spain, especially during the nights. The exported energy decreases at time periods when spot market price is lower, hydro production is saved for other time periods and wind production is also slightly lower, like in North during the hours 11-17. Further more the hydro power in North balances the volatile energy production coming from Central. Wind production is mainly constant, but the high amount of PV production during the day is transmitted over Central to North and stored there in hydro power plants. The energy is then released during the night and the overshoot is transmitted back to Central.

In summer average spot market price is lower and therefor energy is not exported to Spain. Energy import from Spain varies from nearly zero during the night to higher import during the day. The hydro production decreases so far that in during the day hydro power is not only producing less but pumping significantly surpasses production and only during the night hydro production is positive 5.11. Hydro pumping also increases due to higher PV production during the day which is imported from Central. In Central one can clearly see the role as the interface between north and south. As the exchange with Lisboa is balanced with the exchange to North 5.12.

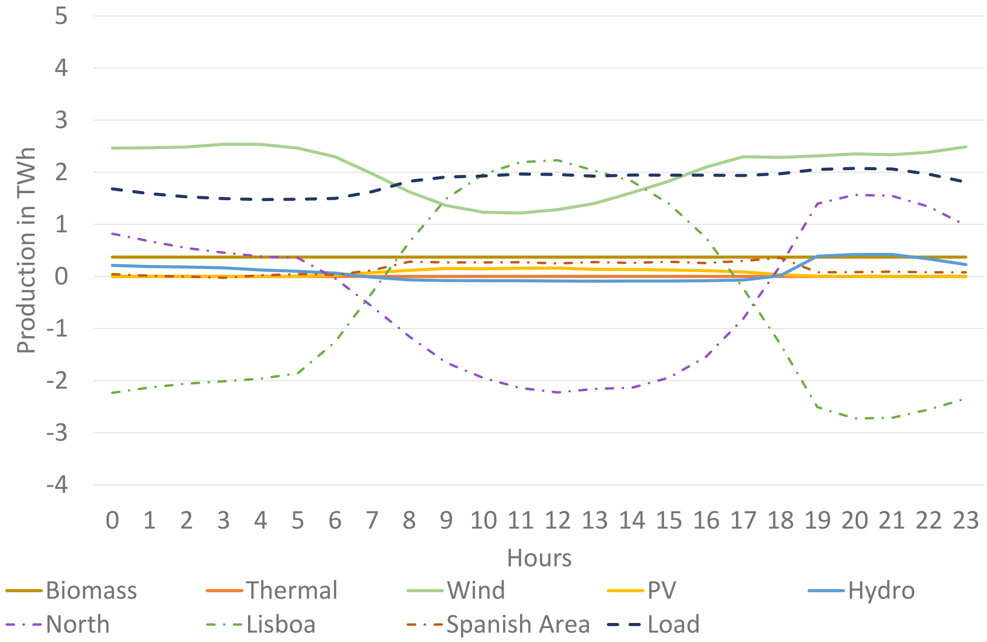


Figure 5.12: Representative day profile for 07/2040 in Central

The energy coming from the hydro power plants in North together with high wind production in Central is further transmitted to Lisboa during the nights. In summer during the day the PV produced energy is imported to Central from Lisboa.

In Figure 5.13 on the other hand can be seen that in winter only minimal amount of energy can be transferred from Lisboa to Central, but during the peak hours during the day Lisboa still covers their load with energy produced in Lisboa and from South. During the night then the overshooting energy of production and import from Central is transmitted to South. The load in South during the nights is covered by import from Lisboa from the North and minor parts of hydro, wind and biomass production to such a degree that it can be additionally exported to Spain during many hours when it is economically favourable depending on the the spot market price.

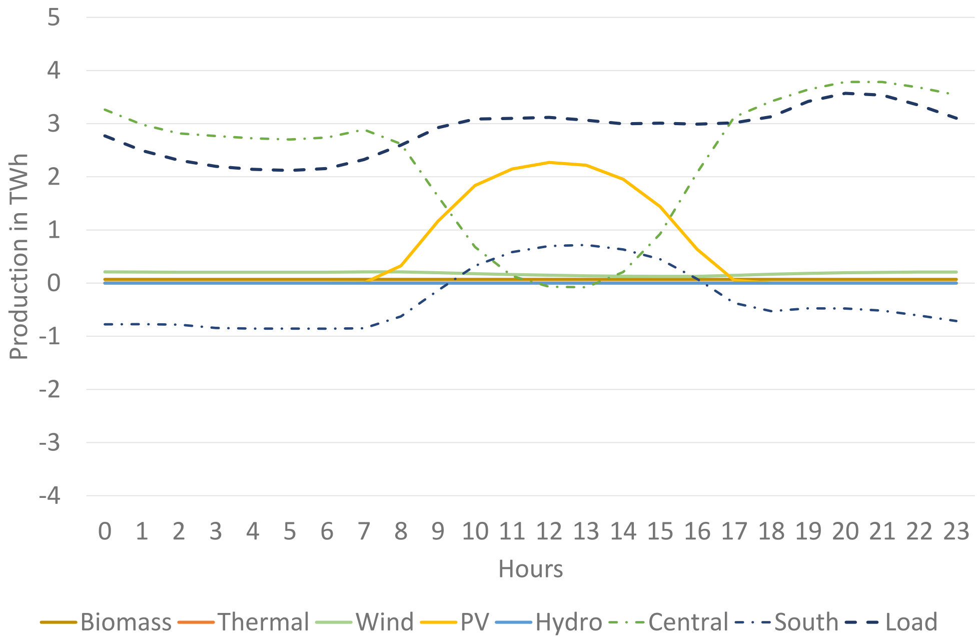


Figure 5.13: Representative day profile for 01/2040 in Lisboa

In summary it can be said that during the night energy is mainly transmitted from North to South, produced mainly from hydro and wind power in the North and Central. In winter from the in general higher hydro production and in summer from the stored energy in hydro plants. In summer during the day PV production in the southern regions is so high that it is transmitted to North and the hydro power plants are highly used for pumping. In winter during the day the PV production decreases so far, that the southern region can produce their own energy in the peak hours but only transmit a minor amount of energy to Central. The energy produced in Central during the day is transmitted to North in order to store it for the night.
The connection to Spain in winter is mainly used for exports and in summer for imports due to higher spot market price in winter.
For the hourly capacity market in Portugal this shows that with the assumed transmission line capacities and pump storage capacities the volatile renewable production can be balanced. Not considering short term balance and system security.

5.1.7 Economic analysis

The optimized investment approach yields significant economic benefits primarily by reducing reliance on thermal power generation and external imports, and enabling increased export potential through renewable energy sources. In this section the economic aspects of the investment approach are analyzed and its potential is assessed by comparing it with alternative scenarios. The cost savings and revenue generation achieved through the optimized investment approach are evaluated compared to the alternative scenario, of maintaining the existing power plant park. On the other hand costs of achieving the goal of zero CO_2 emissions 2040 compared to a scenario without this specified target are discussed. Further the required CO_2 price in order to reach the target only through economical optimization is given.

In the base case scenario, the total costs over the 5 representative years amount to €396 million. These costs are broken down as can be seen in Table 5.6.

Cost types	Scenarios base case in € million	business-as-usual in € million	no RES target in € million
Investment	2860	0	2770
Thermal production	3380	7800	3450
Market Purchase	1300	1800	1270
Market Revenue	- 7000	- 6800	- 7150
Total	540	2800	340

Table 5.1: Cost structure comparison of different scenarios

To analyze the effectiveness of the investment scenario, it is compared to a business-as-usual scenario where the power plant park is maintained as in the initial situation of 2023, with no investments in renewable units. In this scenario, the option of extending the lifetime of combined cycle gas turbine (CCGT) plants is modeled with a levelized costs of energy (LCOE) of new CCGT power plants in the EU, resulting in €115/MWh after the expected expiration date [62]. The expiration date for all CCGT plants is set at the latest by 2040, whereas in the base case, it was assumed that they are forced to expire.

Providing the electricity with the power plant park maintained as in 2023 leads to an increase in total costs of €2260 million over the whole period compared to the base case. The costs compose of the different parts as given in Table 5.6.
It can be seen that the costs for gas power production significantly increase, the costs

for market purchase also increase and the revenue from imports decreases compared to the base case.

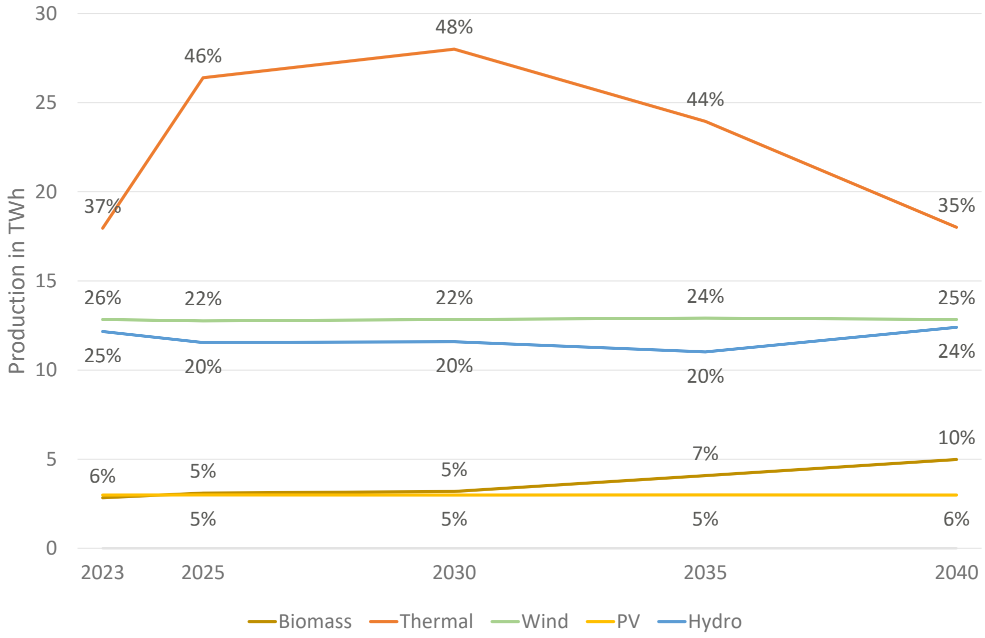


Figure 5.14: Energy mix development over the planning horizon for business-as-usual scenario without wind and PV expansion

Analyzing the energy balance, it becomes evident that thermal gas power production experiences a significant increase, totaling 74 TWh. Conversely, without expansion, the combined production of wind and PV power is 111 TWh smaller than in the base case. Hydro production, on the other hand, sees an overall increase of 36 TWh. Additionally, there is a notable increase in imports from Spain, totaling 26 TWh, while exports decrease by 8 TWh. These shifts underscore the substantial impact of renewable energy expansion on the energy landscape, with renewable sources playing a pivotal role in offsetting the reliance on thermal gas power and facilitating greater energy independence.

For the temporal development of the energy mix in the this case in Figure 5.14, two distinct effects can be observed. Firstly, there is a significant increase in gas production until 2030. This surge can be attributed to the projected substantial decrease in gas fuel prices and increase in electricity demand. In comparison in the base case thermal production significantly decreases.
However, starting from 2030, gas begins to decline until 2040. This downward trend can be attributed to several factors: the decreasing spot market price in Spain, resulting

from the transition towards RES in the Spanish' power plant park. Additionally, the increasing costs associated with rehabilitating gas power plants contribute to the decrease in gas power production.
The evolving dynamics of energy exchange between Portugal and Spain, characterized by a shift towards high energy imports from Spain, are evident in Figure 5.15. These observations underscore the economic competitiveness of a power plant park with a high renewable share compared to one reliant on conventional energy sources, as demonstrated by the scenario resembling the power plant park's composition in 2023. Looking at the CO_2 emissions, in this scenario in total 6 million t CO_2 more are emitted than in the scenario of the base case. And in year 2040 same emissions like in 2023, 6.48 million t, would be emitted.

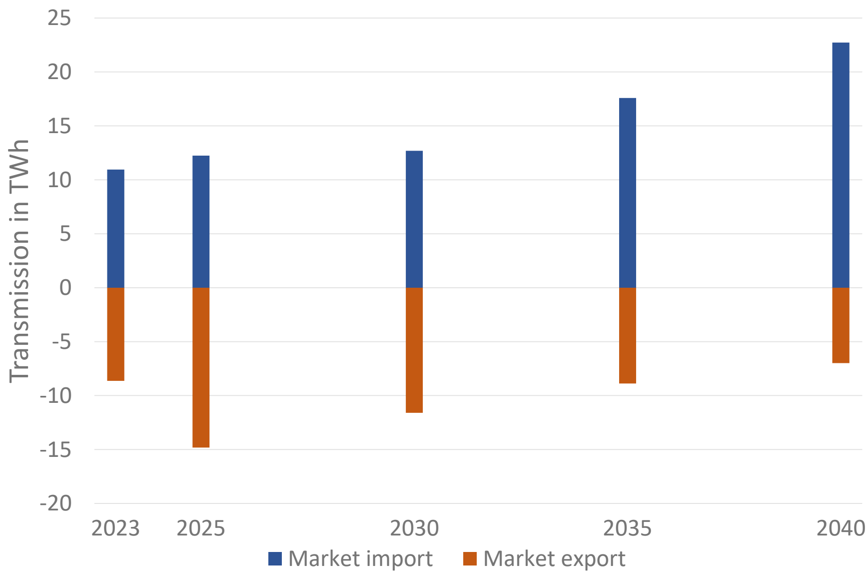


Figure 5.15: Import export development over the years without expansion

With the scenario without RES target it is analysed what the cost optimal investment approach would be without further policies and which degree of renewable penetration would be reached then as the most economic path. In this scenario no further CO_2 prices are considered, since these are also considered as policies. Also here LCOE of 115 €/MWh are considered for the expired gas power plants.

Without the goal of zero electricity production by gas in 2040 the investment in 2040 decreases for wind by 1000 MW and for PV by 500 MW compared to the scenario with the goal of 100 % RES in 2040. It leads to total costs of 340 million €. The structure of the costs can be seen in Table 5.6. The base case exceeds the most economical approach by 200 million € in order to fulfill the policy goal.

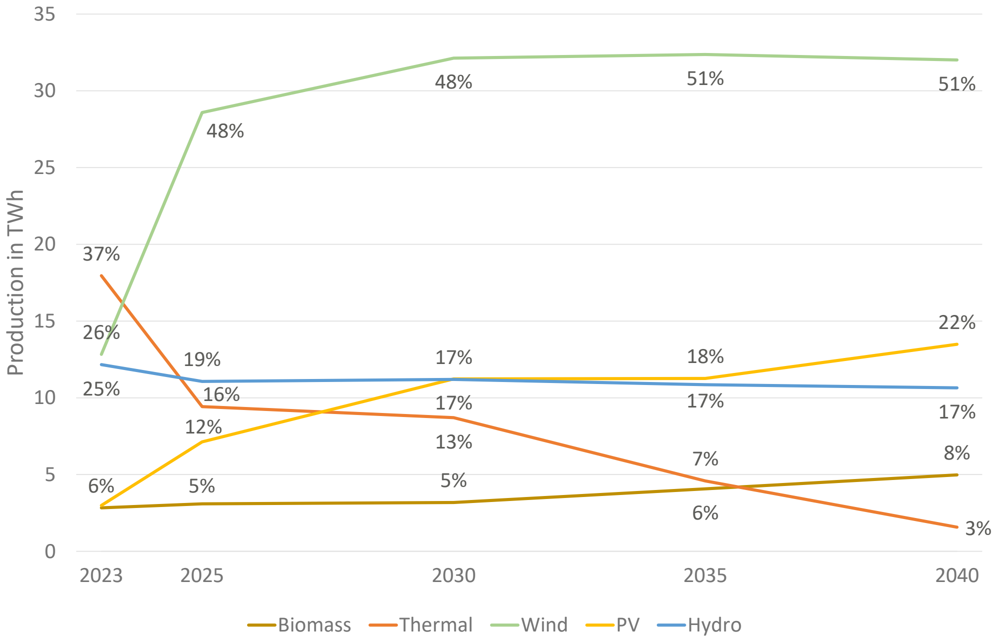


Figure 5.16: Energy mix development with expansion without RES target 2040

In Figure 5.14 it can be seen that the main difference in energy production compared to the base case occurs in 2040. Wind power production is not increased leading to a remaining part of power production of 2.6 % associated with thermal power plants. This illustrates that considering a 1h active power balance a replacement of gas power plants up to an 97.4% renewable share is in general the most economic scenario. Only for the replacement of the last 2.6% further policies are necessary. Without any policy the remaining 2.6% production of 1148 GWh from gas power plants lead to emissions of 413 000 t CO_2 in 2040. This emissions would be the remaining part of CO_2 emission from the electricity system in 2040. The CO_2 emission development over the years for the different scenarios can be seen in Figure 5.17 In order to fulfill a zero CO_2 emission target the limitation of production by gas power plants could be transformed into a CO_2 pricing. The shadow price of the optimization of CO_2 in order to reach zero emissions is 1.069€/kg.

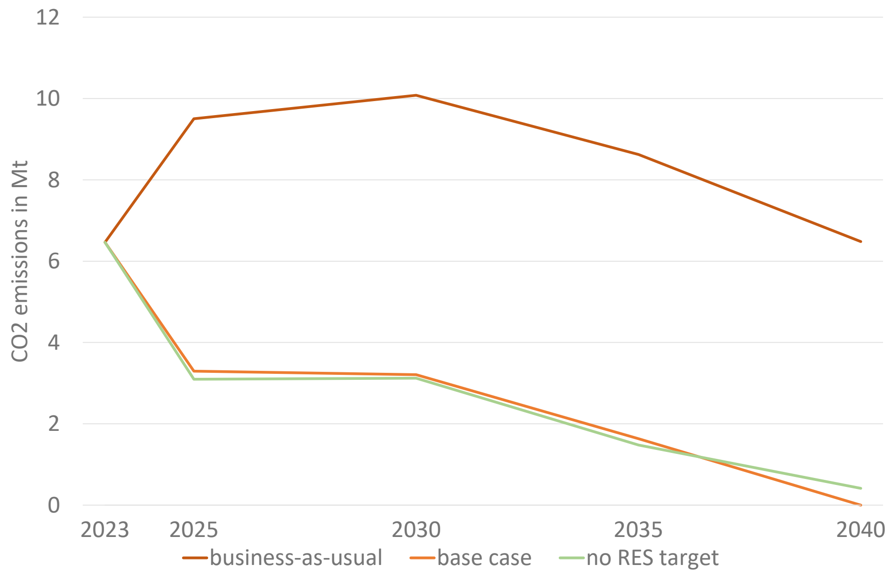


Figure 5.17: CO_2 emission development of different scenarios over the planning horizon

5.2 Storage and transmission line expansion scenarios

Coming from the base case, in the following section storage and transmission line expansion should be taken into consideration. In the subsequent section the influence of storage and transmission line expansion on the wind and PV investment approach is described. The impact is analyzed by scenarios of planned pump storage and transmission line expansion of Portugal. On top of that an optimization of additional battery storage expansion is carried out. Here the influence of increased battery storage capacity on the fixed power plant park is analyzed.
First the characteristics and development of the scenarios is described. And then the results with a focus on installed wind and PV capacity, energy mix, CO_2 emissions and cost development and power line utilization are presented in a quantitative and qualitative way.

5.2.1 Scenario description

For the scenario analysis scenarios with expanded transmission line and pump storage capacity are modeled. Scenario development orients on official plans in Portugal. It is important to notice that no optimization of pump and transmission line capacity is carried out. The expansion of pump and transmission line capacity is predetermined by various factors such as grid stability, security of supply, and reserve market, which are not accounted for in this study. Therefore, the expansion is assumed to be fixed and no costs or economic recommendations for feasibility of the expansion are given.

The hydro pump storage expansion scenario: The scenarios are oriented on the assumptions of [44] with a forecasted expansion of pump capacity of 1000 MW in 2025 and 300 MW in 2030 is implemented to the model. The expansion is divided on the areas with 1050 MW in North, 180 MW in Central and 120 MW in South. It is important to notice that, since the expansion of pump capacity is assumed as fix, no costs for retrofitting of the hydro power plants for pumping is assumed. The resulting total costs do no include costs for the conversion to pump-turbines.

For the power line expansion scenario: The two different scenarios of expansion in Portugal and additionally to Spain are considered separately. The scenarios are oriented on the expansion plans of REN [63]. Therefor, it is assumed that the already modelled power lines within Portugal between South and Lisboa, Lisboa and Central and Central and North and to Spain the ones from North and South are expanded. For the analysis the lines which are planned to be expanded are expanded by a capacity of 1500 MW. Also here the expansion is assumed as fixed and no costs are considered in the optimization. But for the retrospective comparison of cost savings to installation costs the power line expansion is assumed as a reference lines of 400 kV single-circuit overhead lines with an average length of 150 km and an additional expansion of two substations as these are the predominantly characteristics in the noted planned projects in [64]. With this the expansion costs of €70 million for the reference line and €10 million for per substations are taken from [65].

Tr Line \ Storage	-	pump exp	battery opt
-	base	pump	st. opt
in Portugal	PT base	PT pump	PT st. opt
to Spain + in Portugal	PT+ESP base	PT+ESP pump	PT+ESP st. opt

Table 5.2: Overview over storage and transmission line expansion scenarios

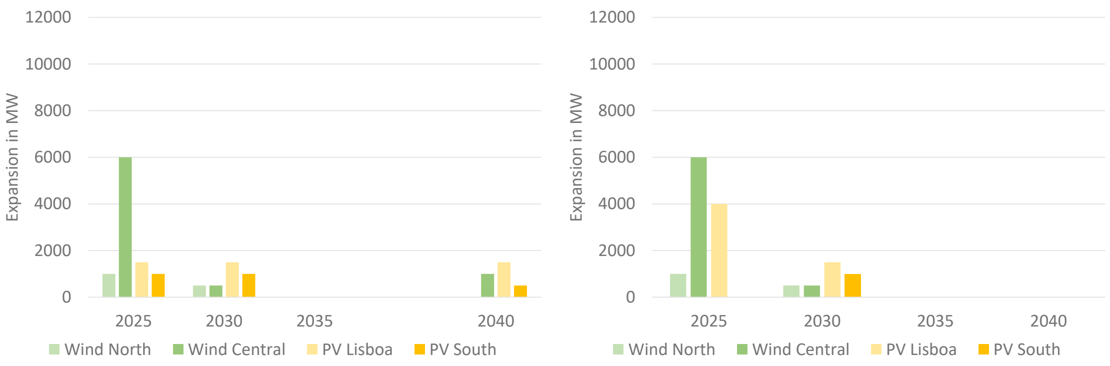
On top of the planned storage and transmission line expansion scenarios an additional separate battery storage capacity optimization is carried out overtaking the power plant park from the pump expansion scenarios as fixed. Due to complexity and time limitations no closed solution of the storage optimization with wind and PV expansion optimization is carried out. The characteristics of the battery storage is set as following. The battery is modelled as a 1h storage, with 100% efficiency to cushion peak power in the system. The assumed total costs are overtaken from 4h battery as 150 000 €/MWh [65], where only 30% have to be covered by the capacity market, since it is assumed that only 30% of the revenue of a battery storage system are earned by the capacity market [66]. This leads to costs of 45 000 €/MWh.

Transmission capacity and battery capacity are often interrelated. Therefore, the effects of both transmission line and battery storage expansions are analyzed together to understand how these capacities influence each other. An overview of the scenarios to be analizyed is provided in Table 5.2.

5.2.2 Base case with storage expansion

This section explores the effects of the scenarios without transmission line expansion involving pump capacity expansion and battery storage optimization on the modelled electricity system.

Wind, PV and storage expansion



(a) Without storage expansion

(b) With pump storage capacity expansion

Figure 5.18: Expanded capacity in wind and PV per year and area in MW for different storage expansion scenarios

In the base case in total 16 000 MW are expanded, 9000 MW wind and 7000 MW PV. Resulting in 32 000 MWa wind (5500 MWa North, 26 500 MWa Central) and 19 500 MWa PV (12 000 MWa Lisboa, 7500 MWa South) over time.

The expansion of pump capacity, compared to the base case without storage expansion, brings about significant changes in the optimized investment approach for wind and PV production capacity. In total 14 500 MW (-1500 MW) are expanded, 8000 MW (-1000 MW) wind and 6500 MW (-500 MW) PV. Wind expansion just decreases by the 1000 MW expansion 2040, but for PV there is a notable temporal shift from 3000 MW 2040 to 1500 MW expansion 2025. This results in increased available capacity over time of 23 500 MWa (+4000 MWa) for PV production while maximum installed capacity for the 100% renewable power system 2040 decreases.

Also a spatial shift occurs in PV expansion, which is expressed in a deferral of 1000 MW from South to Lisboa. Wind expansion decreases by 1000 MW in Central.

For the power plant park of the pump storage expansion the optimization outcomes for battery storage capacity indicate an optimized battery storage capacity of 790 MWh in the South region.

Energy production

	Scenarios		
Production in TWh	base	pump	battery optimization
Thermal	42.0	35.0	33.8
Wind	140.3	138.1	139.0
PV	46.8	53.5	53.4
Hydro generation	85.2	93.1	92.8
Hydro pumping	-29.2	-39.1	-38.7
Import	45.8	49.5	49.8
Export	-65.7	-64.9	-64.9
Losses	-2.9	-3.1	-3.0
Total	280	280	280

Table 5.3: Total energy production per technology type in TWh for different storage expansion scenarios

Compared to the base case with expansion of pumping PV production increases by 2.3 % of the total production. Also market imports from Spain increase by 1.4% of total production, while export slightly decreases by 0.2%. 3.4% more energy is pumped while only 2.7% more are turbined, showing that hydro power plants are increasingly used for creating flexibility through storage and less for own production. Despite same amount of installed capacity wind production also slightly decreases by 0.7% of total production. With all this changes. it is possible to decrease thermal production by 2.4%

of total production and with this reduce total CO_2 emissions by 2.5 Mt (16.6%) to 12.6 Mt.

With additional storage expansion due to higher storage capacity with the same amount of installed wind and PV, wind production increases by 0.3%, while PV production stays the same. Market import also increase by 0.1% of the total energy load replacing the -0.4% decrease of thermal production compared to the case without storage optimization. In this case the energy stored in hydro power plants decreases by 0.1% of total load.

Composition of total costs

In this scenario the economic influence of the expansion of storage capacity on the system considering capacity market level is described.

Cost types	Scenarios base in € million	 pump in € million	 battery optimization in € million
Investment	2860	2880	2880
Thermal production	3380	3070	3013
Market Purchase	1294	1297	1292
Market Revenue	- 6994	- 6988	- 7000
Storage exp			36
Total	538	260	222

Table 5.4: Cost structure comparison of the different storage expansion scenarios in base case

In the pump expansion scenario, costs decrease substantially by €278 million, from €538 million to €260 million, excluding costs for conversion. This implies that from the perspective of the capacity market, an investment would be considered profitable if the costs for the investment fall below €214 000 per MW.
Moreover, earlier but less PV and wind expansion results in increased investment costs due to a higher percentage of power plant life time in the planning horizon. This increase is outweighed by the cost decrease of thermal production, facilitated by the replacement with PV production along with higher energy import from Spain and higher hydro pump storage flexibility but less own hydro production. Here it is important to note the increased amount of imported energy, despite nearly consistent costs for market purchase. This could be attributed to the higher flexibility afforded by more pump storage capacity, enabling more energy import during times of low energy prices to be stored for periods of higher demand.

The additional storage optimization results in decreased total costs of €222 million. The costs for the storage expansion amount to €36 million, leading to cost savings of 326 000 €/MWh storage expansion. Due to higher wind production and market imports together with storage capacity costs for thermal production decrease. Again it is important to notice that with battery storage optimization energy purchased from Spain increases while the induced costs even decrease. Which indicated that a higher amount of energy can be exported at times of lower costs on the spot market due to higher storage capacities.

Power line utilization

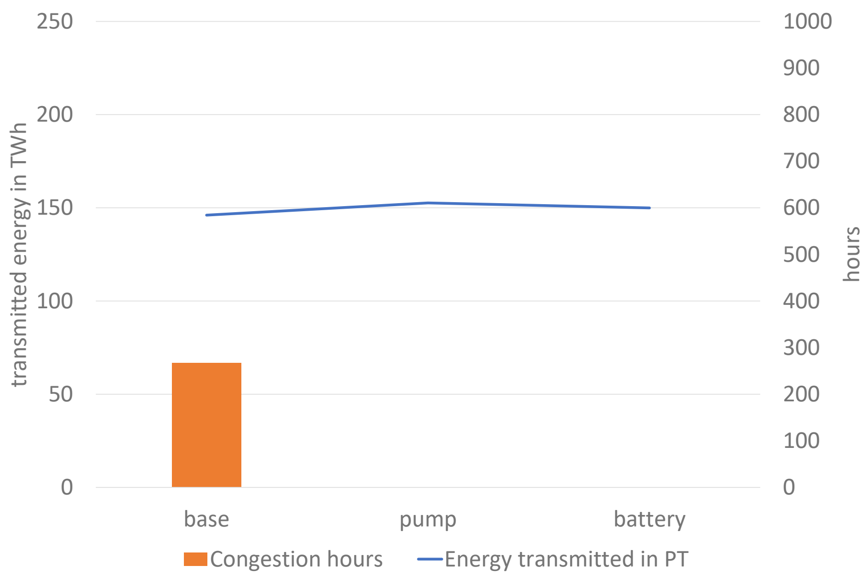


Figure 5.19: Total energy transmitted and congestion hours within Portugal

The adjustments made in wind and PV expansion have notable implications for the utilization of transmission lines. Especially the higher PV expansion in Lisboa following the pump capacity expansion, coupled with the enhanced capacity to balance temporal differences between production and consumption show influence. Total transmitted power in Portugal increases by 2.5% to 152 TWh, compared to 146 TWh in the base case. Only the energy transmitted from Central and South to Lisboa decreases. A similar situation is given for the peak power line utilization with PV expansion occurring earlier, in 2025 rather than 2040, the power lines are utilized more extensively sooner but with reduced maximum power overall. Power line utilization away from Lisboa increases, while power transmission to Lisboa decreases, primarily due to the shift of higher concentration of PV expansion to that area. This leads to the fact that the power line from South to Lisboa is not limited anymore and with this no power line is limited any more, so congestion hours within Portugal decrease from 276 to zero. Figure 5.19 gives an overview over total energy transmitted and congestion hours within Portugal for the different scenarios.

With storage optimization, the total energy transmitted across all lines in Portugal decreases by 1.7% to 150 TWh. Additionally, the maximum power line utilization slightly decreases, except for the line between Lisboa and the South, where peak utilization in both directions increases. This indicates that the battery storage in the

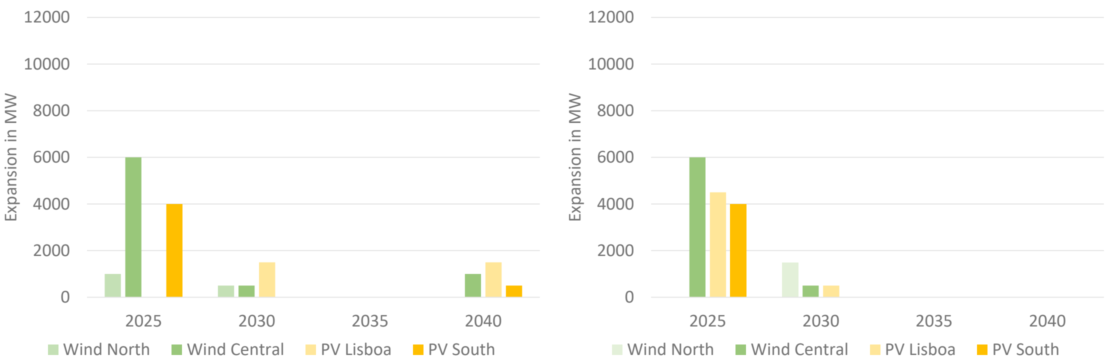
South is utilized to manage peak production and consumption. Despite these changes, power line congestion hours remain at zero.

The import from Spain increases at all interconnection with increasing storage capacity regardless of rather pump of battery.

5.2.3 Transmission line expansion in Portugal with storage expansion

In this scenario, the impact of expanding transmission lines in Portugal as planned in the NECP [44] alone and in combination with the storage expansion scenarios are examined.

Wind, PV and storage expansion



(a) Without storage expanison

(b) With pump storage capacity expansion

Figure 5.20: Expanded capacity in wind and PV per year and area in MW in different storage expansion scenarios, with transmission line expansion in Portugal

The base case with transmission line expansion results in 16 500 MW expansion, 9000 MW wind, 7500 MW PV, +500 MW compared to the base case without power line expansion. So the transmission line expansion within Portugal only influences PV expansion, wind expansion stays exactly the same. A minor temporal shift increases PV available capacity over time to 22 500 MWa (+3000 MWa), wind stays the same as in the base case with 32 000 MWa.
Instead of 1500 MW in Lisboa 2025 and 1000 MW in South 2030, 3000 MW of PV are expanded in South. This leads to an available capacity over time of 6000 MWa (-6000 MWa) in Lisboa and 16 500 MWa (+9000 MWa) in South compared to the base case without power line expansion. This highlights that the transmission line from South to Lisboa is previously a limiting factor for PV expansion in South. With increased transmission line

capacity, the higher PV generation potential in the southern region is more effectively utilized.

With the additional expansion of pumping capacity in hydro power plants, 8000 MW (-1000 MW) wind and 9000 MW (+1500 MW) PV, in total 17 000 MW are expanded, compared to the previous scenario with power line expansion in Portugal. Here PV expansion in South slightly decrease back by 500 MW in 2040, while in Lisboa in 2025 4500 MW more PV is installed instead of 1000 MW 2030 and 1500 MW in 2040. Leading to a highly increased available PV capacity over time of 35 500 MWa (+13 000 MWa). Available wind over the whole planning period decrease by 30 000 MWa (-2000 MWa) compared to the case without pump expansion.

Compared to the scenario with pump expansion without power line expansion, there is an additional 2500 MW of PV expansion, while the amount of wind expansion remains the same. Thus, also with pump expansion transmission line expansion within Portugal mainly influences PV expansion. The expansion of power lines in Portugal, combined with expanded pump capacity, leads to a higher increased of PV expansion compared to the scenarios without pump capacity expansion.

With the resulting higher expansion of PV production, transmission line expansion leads to a higher level of storage expansion, amounting to 3425 MWh in the South.

Energy production

With power line expansion within Portugal, compared to the base case, PV production increases by 1.7% of total energy load. This increased energy production decreases imports from Spain by 0.7%, hydro generation by 0.11%, thermal production by 0.68% and increases exports to Spain by 0.14% of the total production. This results in a decrease in CO_2 emissions by 4.77%, reducing the total emissions to 14.39 Mt from the base case.

With significantly increased PV capacity in the scenario with pump expansion also energy produced by PV increases by 7.2% of total load. Wind on the other side in accordance to the installed capacity decreases by 1.6%. Hydro production decreases by 0.9% while pumped energy increases by 4.6%. Imports from Spain decrease by 1% and exports increase by 0.5% of the total load. Thermal production also decreases by 3% leading to a CO_2 decrease of 26.2% compared to the base case.

Storage optimization, while maintaining the same power plant park configuration, results in an increased energy production from wind by 0.5% and from PV by 0.1% of the total load. Furthermore 0.5% more energy is imported, which results in decreased thermal production of 0.9%.This decreases emissions compared to the base case by

Cost types	Scenarios base in € million	 pump in € million	 battery optimization in € million
Thermal	40.0	31.0	28.3
Wind	140.2	135.5	136.5
PV	51.9	73.2	73.5
Hydro generation	86.5	97.2	96.3
Hydro pumping	-30.8	-44.2	-43.2
Import	43.9	41.3	42.7
Export	-66.2	-67.9	-68.3
Losses	-3.3	-3.8	-3.7
Total	280	280	280

Table 5.5: Total energy production per technology type in TWh for different storage expansion scenarios

32.6%. Also with transmission line expansion in Portugal, battery storage expansion leads to decreased amount of energy stored in pump storage (-0.4%).

Composition of total costs

The total costs compared to the base case without considering costs for transmission line expansion decrease by €27 million, €9 million per line. Which stands in no relation to the costs for the transmission line expansion of €90 million. This suggests that solely considering the capacity market, the expansion of power lines solely within Portugal would not be economically favorable. Nevertheless, other factors such as grid stability and reserve market considerations may still necessitate the expansion of these lines. The costs decrease due to increased PV production replacing thermal production and energy imports and increasing exports to Spain.

When pumping capacity is expanded while transmission lines within Portugal are expanded costs decrease by €309 million to €202 million. This would mean 237 000 €/MW savings per pump capacity expansion. From the other perspective transmission line expansion saves €58 million, divided onto the 3 expanded lines, this would mean €19.3 million saving per power line. The investment costs increase due to higher and earlier PV investment but are exceeded by the decreased thermal production and import costs. The cost savings of pump expansion are higher together with transmission line expansion because the two expansions support each other with enabling increased PV production which is stored in northern pump power plants.

Cost types	Scenarios base in € million	pump in € million	battery optimization in € million
Investment	2929	3150	3150
Thermal production	3291	2886	2770
Market Purchase	1280	1222	1208
Market Revenue	-6990	-7058	-7134
Storage exp			154
Total	511	202	145

Table 5.6: Cost structure comparison of the different storage expansion scenarios with transmission line expansion in Portugal

With battery storage optimization the total costs are €146 million. Compared to the previous scenario with power lines and pump expansion costs decrease by 56 € million. The costs decrease due to thermal production replaced by more imports, wind and PV production. With expanded power lines within Portugal more costs can be saved through battery expansion compared to the scenario where the power lines in Portugal are not expanded. Because also here the expansion of storage and transmission line support each other economically. More peak wind power produced in the North can be transmitted to the South and stored there. From the other perspective compared to the case with battery storage optimization without transmission line expansion costs decrease by 76 € million, 25.3 € million per line. Also here can be seen that the expansion of power lines with additional storage optimization has more financial effect than without.

Power line utilization

In the case of transmission line expansion without pump expansion in general the peak utilization decreases and the power lines are relieved except the power line from South to Lisboa is already limited from 2025 on, because of the additionally installed capacity of 3000 MW of PV production in South in 2025 compared to the base case. In this scenario the power line between North and Central and Central and Lisboa would not have to be expanded since the initial limit is not reached. Except for the line from Lisboa to South total energy transmission increases at all lines, especially for all lines from South to North. Energy transmission during the whole period in Portugal increases by 11.7% to 163 TWh compared to the base case without transmission line expansion in Portugal.

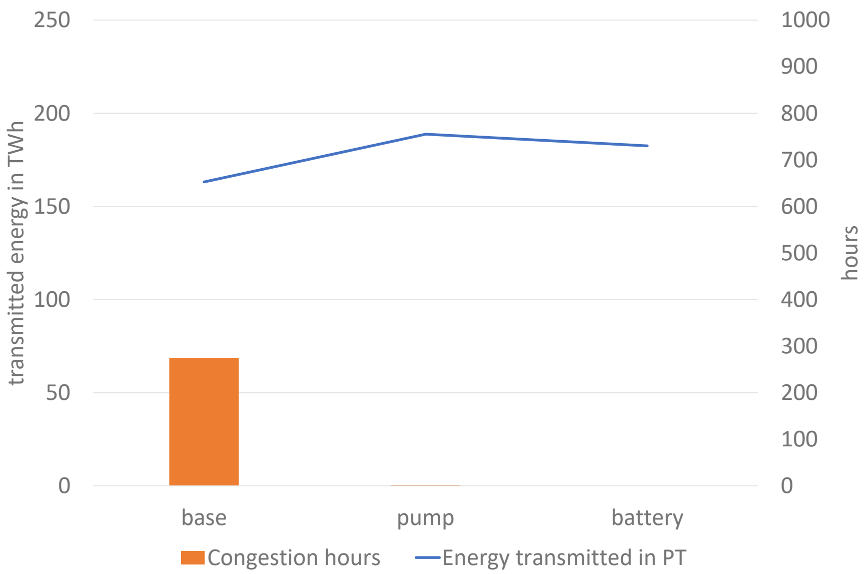


Figure 5.21: Total energy transmitted and congestion hour within Portugal

With pump expansion and the additional and earlier PV expansion in Lisboa peak utilization of the all power lines increases, except the power line from South to Lisboa. This line is relieved and only reaches their limit in 2040. In this scenario also the power line from Lisboa to Central surpasses their initial limit and therefore is necessary to be expanded. Also the total transmitted energy increases for the lines from Lisboa to North, transmitting the PV produced energy in Lisboa to the pump storage plants in the North. Only the energy transmitted between Lisboa and South and from Central to Lisboa decreases. In total with pump expansion transmitted energy increases by 15.7% to 188 TWh.

With battery storage optimization total energy transmitted during the whole period in Portugal decreases by 3.3% to 182 TWh. Storage capacities are expanded in South, decreasing dependency for storing energy on the northern areas. For this reason less energy is transmitted from South to North but increased energy is transmitted from North to Central. In general South's imported energy from all areas decrease and export to Spain increases. This shows that with storage optimization South can produce more energy from PV power plants for themselves and can even export more to Spain. The situation is different for maximum power line utilization. It can be seen that maximum power line utilization increases in the direction to the areas where battery storage is expanded (Lisboa+South). This shows that battery storage is used to store peak production from other areas while not importing more energy. The peak utilization of the power line from South to Lisboa decreases and with this is not limited any more.

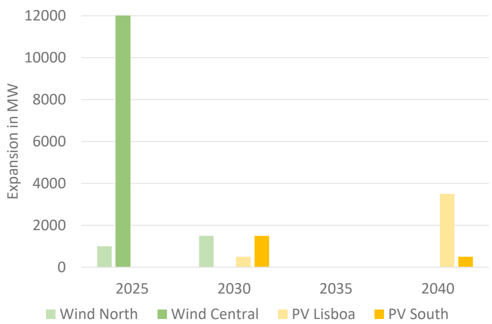
Probably because South and Lisboa both have more battery storage available to balance peak power. The peak transmission from and to North decreases.

5.2.4 Transmission line expansion in Portugal and to Spain with storage expansion

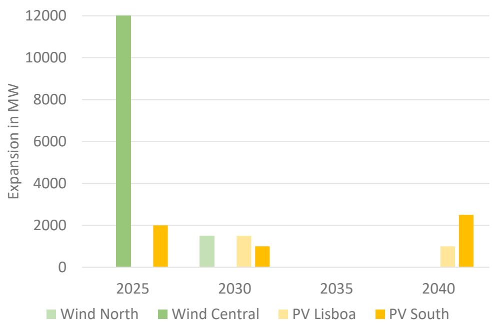
In this scenario in addition to the storage expansion and transmission line expansion within Portugal the lines to Spain are also expanded. As planned right now by RES [63] the power lines from South and North are expanded which fulfills the EU target of installing 15% of the installed capacity as interconnection to another country.

For this scenario has to be clarified that no interrelation with the spot market and no maximum export limits are defined besides transmission line limits. For a more detailed approach the influence of the interconnection of the energy exports to Spain and the Spanish spot market price should be considered.

Wind, PV and storage expansion



(a) Without storage expansion



(b) With pump storage capacity expansion

Figure 5.22: Expanded capacity in wind and PV per year and area in MW in different storage expansion scenarios, with transmission line expansion in Portugal and to Spain

Compared to only expanding the lines within Portugal, with power line expansion to Spain, 14 500 MW (+5500 MW) wind and 6000 MW (-1500 MW) PV, in total 20 500 MW (+4000 MW), are expanded. Wind expansion increases strongly by 4500 MW in Central and 1000 MW in North while PV expansion decreases in South by 2500 MW and increases in Lisboa by 1000 MW but only 2040. Due to temporal shifts available expanded wind capacity over the period increases even stronger to 56 500 MWa (+24 500 MWa) and for PV decreases to 10 000 MWa (-12 500 MWa), compared to the case with power line expansion in Portugal.

Splitting the transmission line expansion up to the one to Spain and the one within Portugal, it can be seen that transmission line expansion to Spain lead to an egual amount of 20 500 MW RES expansion, with a slightly higher proportion of wind capacity (15 000 MW wind, 5500 MW PV) and it is interesting to notice that wind expansion is also carried out in the southern regions with less geographic potential. Together with expansion of the power lines in Portugal expansion shifts to increased PV capacity of 6000 MW while wind capacity decreases to 14 500 MW and wind is again only expanded in the norther regions.

With expansion of pumping with 21 500 MW (+1000 MW), 13 500 MW (-1000 MW) wind and 8000 MW (+2000 MW) PV are expanded, compared to the previous case without pump expansion. 1000 MW (-4000 MWa) less wind in North and 1500 MW less but earlier (+500 MWa) PV in Lisboa and 3500 MW (+8500 MWa) more PV in South are expanded, compared to the case without pump expansion. So with pump expansion PV expansion significantly increases.

With power line expansion to Spain, and the resulting increased PV and wind expansion also an higher amount of storage is expanded, with 8840 MWh in South and 700 MWh in Lisboa.

Energy production

The changes in the energy mix described below are expressed as a percentage of the total load.

With power line expansion to Spain, export to Spain increases sharply by 17% while import also increases by 3.2% compared to the base scenario wit transmission line expansion within Portugal. Like the increased expansion in wind and PV indicates, wind production highly increases by 20% and PV production decreases by 7% of total load. Also thermal production increases by 4% and hydro production decreases by 0.6% while pumping increases by 2.4%. Transmission line expansion to Spain with the increased thermal production leads with 18.5 Mt CO_2 to an increase of 28.7% compared to the case with transmission line expansion only in Portugal, or an increase of 22.6% compared to base case.

With pump expansion compared to the previous case wind production decreases by 3.3% and PV production increases by 5%. Thermal production also decreases by 1.1% which is still a higher thermal production than in all cases without transmission line expansion to Spain. Pumped energy increases by 4.4% while total production decreases by 1%. Export to the Spanish spot market increase by 6% while import also slightly increase by 3%. Thermal production leads to 17.4 Mt CO_2 which means a 6.2% decrease

Cost types	Scenarios base in € million	 pump in € million	 battery optimization in € million
Thermal	51.5	48.2	43.8
Wind	199.7	189.7	190.9
PV	30.9	46.0	46.3
Hydro generation	91.8	102.4	100.0
Hydro pumping	-37.9	-51.1	-48.2
Import	52.5	54.2	59.7
Export	-121.8	-122.8	-124.9
Losses	-4.1	-4.4	-4.2
Total	280	280	280

Table 5.7: Total energy production per technology type in TWh for different storage expansion scenarios

compared to the previous scenario due to pump expansion, or a increase from base case of 14.9%.

With the same power plant park optimized storage expansion leads to 4% more wind, 1% more PV energy production, 2% more import and 1% more export to Spain with 1.5% less thermal production of total load. With increased battery storage capacity in the southern regions utilization of the hydro power plants for pumping decrease by 1% while generation increases by 0.2%. With thermal production CO_2 emissions decrease by 9.2% from the case without storage optimization but are still higher than the emissions in the base case by 4.3%.

So with transmission capacity expansion to Spain thermal production and CO_2 emissions increase for higher exports to Spain.

Composition of total costs

The expansion of the power lines to Spain and its optimized power plant park leads to cost savings or revenue increase of €2962 million compared to the power line expansion only within Portugal. For the 2 additional expanded lines this means €1481 million per line. Which means 20 times the costs of the expansion of the line is saved in total. Compared to the expansion of the lines to Spain the lines within Portugal additionally save €75 million. Divided on the two lines €25 million per line is still beneath the power line costs of €80 million. Therefor, also other arguments like reserve market or grid stability would be necessary to make the expansion of the lines favourable but together

Cost types	Scenarios base in € million	 pump in € million	 battery optimization in € million
Investment	4278	4239	5239
Thermal production	3792	3647	3453
Market Purchase	1308	1284	1278
Market Revenue	- 11 830	- 12 002	- 12 355
Storage exp			421
Total	- 2451	- 2831	- 2963

Table 5.8: Cost structure comparison of the different storage expansion scenarios with transmission line expansion to Spain and in Portugal

with the expansions to Spain they are more favourable then in the scenario without transmission line expansion to Spain and without pump expansion.

The high decrease in costs comes from the higher capacity to sell energy to the spot market in Spain. Investment costs for the additional wind capacity increase from 2929 to €4278 million, enable increased wind production. Also thermal production costs increase due to higher production and energy purchase costs for energy imported from Spain increase but the revenue of the sold energy increases by €4842 million to €11 830 million. And with increased utilization of pumping of hydro power plants prices can be additionally shifted.

With pumping capacity expanded additionally €397 million are saved, 305 000 €/MW. Mainly through less expansion investments and thermal production, also there is slightly more revenue achieved through export to Spain. The additional line expansion to Spain here saves €3034 million compared to the scenario with pump expansion and power lines expanded only in Portugal. So with pump expansion even more costs are saved through expansion of the power lines to Spain then without pump expansion. The power line expansion within Portugal under this circumstances save €236 million.

The battery optimization results in €421 million investment costs in storage capacity. With the same power plant park more wind and PV energy production, more import and export to Spain, less thermal production and a cost decrease of €131 million is achieved. From the other perspective the power line expansion to Spain already considering battery storage optimization leads to cost savings of €3109 million.

The increased flexibility of storing energy with pump and battery storage expansion makes it possible to increasingly use cheap power production like wind and PV and store it for later consumption. This also allows for an increased amount of energy to be purchased from the Spanish spot market during times of low electricity prices.

Consequently, with increased imports of energy from Spain, the total costs for energy purchases decrease.

Power line utilization

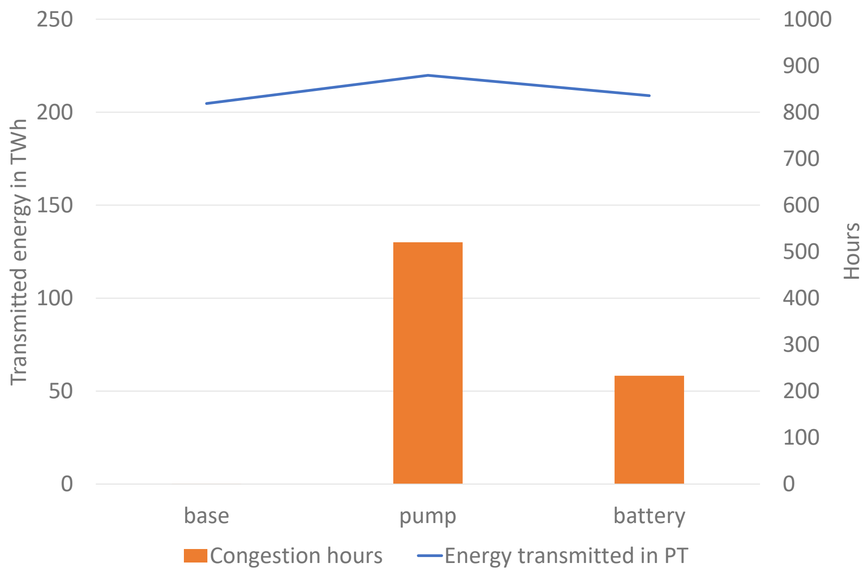


Figure 5.23: Total energy transmitted and congestion hours within Portugal

With power line expansion to Spain energy transmission in Portugal over the whole period increases by 25% compared to the case with transmission line expansion to Portugal, resulting in 204 TWh. The power lines from the areas where PV and wind expansion increased (Central, Lisbao) to the areas where transmission capacity to Spain increased (North, South) are increasingly used compared to the scenario where only power lines in Portugal are expanded. This effect is the same for peak utilization and total transmitted energy of the power lines. So the power lines from Central to North and from Central to Lisboa and from Lisboa to South transmit increased amount of energy while the amount in the opposite direction decreases. The maximum transmitted power from Central to Lisboa increases so far that the limit is reached from 2035 on while the maximum transmission from South to Lisboa decreases so far that the line no longer reaches their limit. Concerning the interconnection with Spain the transmission at the power lines from North and South to Spain increase strongly due to the higher capacity while the imports only increase slightly. For the Central region export to Spain also slightly increases and import even decreases.

With pump expansion total energy transmitted within Portugal increases by 7.3%

compared to without pump expansion to 220 TWh. More PV is installed earlier in South and Lisboa therefore energy transmission from Central to Lisboa to South decreases. South in general with the expanded pump and PV production capacity decreases their imports from Lisboa as well as Spain while the exports significantly increase. North and Central increasingly import and decreasingly export to Spain and Lisboa with the installed pump power in the North. So the pump expansion in the North leads to increased imports using hydro power plants increasingly for pumping to store cheap energy from Spain and Lisboa replacing thermal production and 1000 MW wind expansion. In the South pump expansion lead to additional PV expansion replacing imports and increasing exports to Lisboa and Spain. For the peak line utilization this means that the power lines from South to North are increasingly used and the one from South to Lisboa is limited. Interesting to notice is that maximum utilization from Lisboa to South also slightly increases while total transmitted energy decreases. This shows that pump storage is used to store peak power from Lisboa.

With battery storage expansion which is only carried out in South and Lisboa total energy transmitted within Portugal decreases by 8% to 202 TWh. Energy transmission in all power lines decrease especially between South and Lisboa. Therefor, the energy transmission from North to South increases especially from Central to Lisboa. Peak line utilization on the other hand increases for the power lines from Lisbao to Central and South and from North to Central. The power line from Lisboa to South is additionally limited and the power line from Central to Lisboa is already limited from 2025 on. The power line from South to Lisboa is limited like in the scenario without battery storage optimization. This again shows that increased short term battery storage optimization, decreases energy transmitted but increases peak power transmission over power lines.

In Figure 5.24 a representation is given how increased storage expansion in South lead to limitation of the power line between Central and Lisboa. With the same power plant park as with pump expansion more wind, PV and hydro power is produced over the whole time period. At peak wind and hydro production in the North and Central more energy is transmitted to Lisboa and further to South where storage is installed. With this increased energy transmissed for storage in the battery storage system the power line from Lisboa to South is limited at 04/01/2040 in the morning.

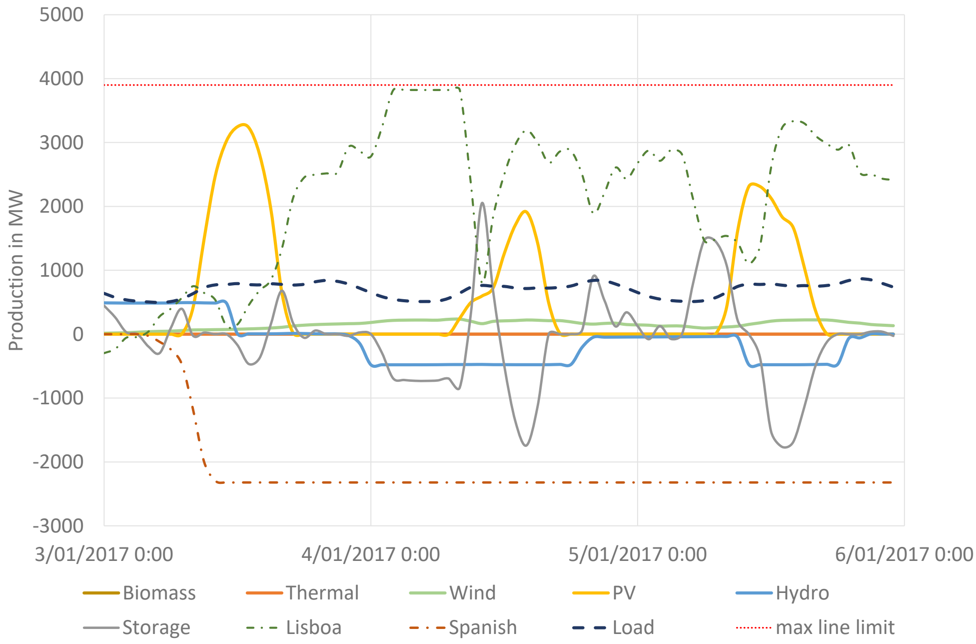


Figure 5.24: Energy production profile per technology type in region South for 03/01/2040 - 05/01/2040, representing influence of battery storage capacity for the peak power line utilization to Lisboa

Potential of additional power line expansion

As described, after power line expansion in Portugal the lines between South Lisbao and Central are limited, due to PV expansions. This arises the question of the potential of increased expansion beyond 1500 MW per power line.

Modelled further line expansion of again 1500 MW from South to Lisboa and Central and from Lisbao to Central lead to only minor cost savings and changes in the investment approach. They do not increase the amount of investment in PV capacity, but decrease it by 500 MW and shift 500 MW from Lisboa to South. But they lead to a relieve of peak transmission for the power lines from South to Lisboa and from Central to Lisboa.

Furthermore the question arises how a power line expansion from Central to Spain would influence the electricity system. With additionally installing a 1500 MW power line from Central to Spain more wind in Central and less PV, shifted more to Lisboa, is expanded. The costs decrease additionally by €1300 million because revenue increases by around €2000 million. Also with expansion of the power line from Central to Spain the power line from Central to Lisboa is limited, due to the high amount of installed wind power. The scenarios with transmission line expansion to Spain can only be seen as trends, which can be applied for small changes on transmission capacity. It can not be applied for major changes, since no interrelation with the spot market in Spain is considered.

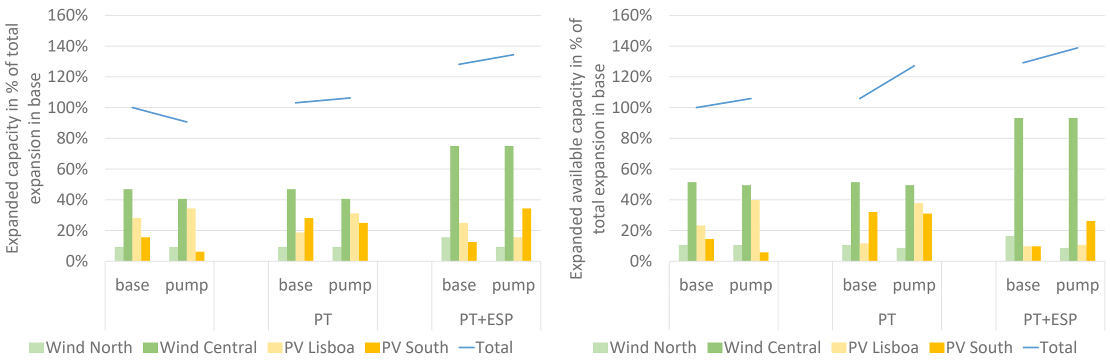
6 Discussion and synthesis of results

In the following section the obtained results are summarized and discussed, concentrating on the parameters of total installed capacity of wind and PV expansion, energy production by technology type, CO_2 emissions, energy transmission and congestion of power lines and origin of cost saving in a quantitative and qualitative way. The technical influence on the energy system and cost saving possibilities are described. No advise for investment in pump or transmission line capacity is given.

The following general trends can be observed for generation expansion planning for wind and PV in Portugal regardless of storage and transmission line expansion. No offshore wind power plants are expanded. Onshore wind and PV power plants are solely expanded in geographically advantageous areas — PV in the southern regions of Lisboa and South, and wind in the northern regions of Central and North. The amount of expansion in wind and PV is nearly balanced with a mostly dominant role of wind. Wind is predominantly expanded in the region, where significantly less hydro power is installed. Main expansions are carried out in the first five-year period, indicating that learning curve and RES target are only relevant for a high share of RES. Even in a scenario without explicit RES target, a high share of RES by 2040 is achieved. Transitioning to renewable electricity production with investments in wind and PV power plants presents significant potential for total cost savings compared to continuing electricity generation with the current power plant park.

6.1 Synthesis of quantitative results

The **pump expansion** scenarios highlight the impact of expanded pump capacity on PV and wind expansion. In Figure 6.1, the influence of power line and pump storage capacity expansion on the expansion decisions for wind and PV capacity is illustrated. Further an overview over the difference in total expanded capacity in MW and expanded available capacity over the period in MWa of wind and PV is given. For pump expansion without power line expansion it shows that a reduction in overall expansion of wind and PV occurs but a shift towards earlier expansion increases available capacity over time 6.1b while with power line expansions total installed RES expansion increases 6.1a. In general with pump storage expansion total expanded



(a) expanded capacity in MW

(b) available expanded capacity over time in MWa

Figure 6.1: Total expanded wind and PV capacity and capacity over time per area for pump storage and transmission line expansion scenarios

capacity of PV power plants increases while wind expansion decreases, this trend also can be seen by the amount of energy produced by technology in Figure 6.2. Even more PV is expanded due to pump capacity expansion when power lines in Portugal are expanded.

Pump expansion and increased PV production leads to increased energy transmitted within Portugal. This can be explained with the different location of the increased PV capacity in Lisboa and South to increased pump capacity in South and North. The development has to be differentiated for the peak utilization of the power lines. Without transmission line expansion to Spain pump expansion shifts PV expansion from South to Lisboa, with this congestion of power lines decrease to zero due to relieve of the power line to Lisboa. With transmission lines expanded to Spain, pump expansion only increases PV expansion in South, where interconnection to Spain is given. With this congestion hours of power lines within Portugal increase.

With pump storage expansion total costs decrease, mainly through replacement of thermal production and together with power line expansion also because of decreased purchase costs and increased sales revenue. Figure 6.3 shows the amount of cost savings in percentage of total costs of the base case and the change of the individual cost parts. With reduction of thermal production CO_2 emissions over the whole period decrease. The effect and utilization of pump storage capacities increases with the expansion of power lines. Therefor total cost savings which are reached with pump expansion increase from 213 000 €/MW pump capacity expansion without power line expansion to 273 000 €/MW with expansion in Portugal and 305 000 €/MW with expansion to Spain.

Battery storage optimization is conducted on top of the fixed optimized power plant park after pump expansion, with RES expansion fixed. Figure 6.2 demonstrates that

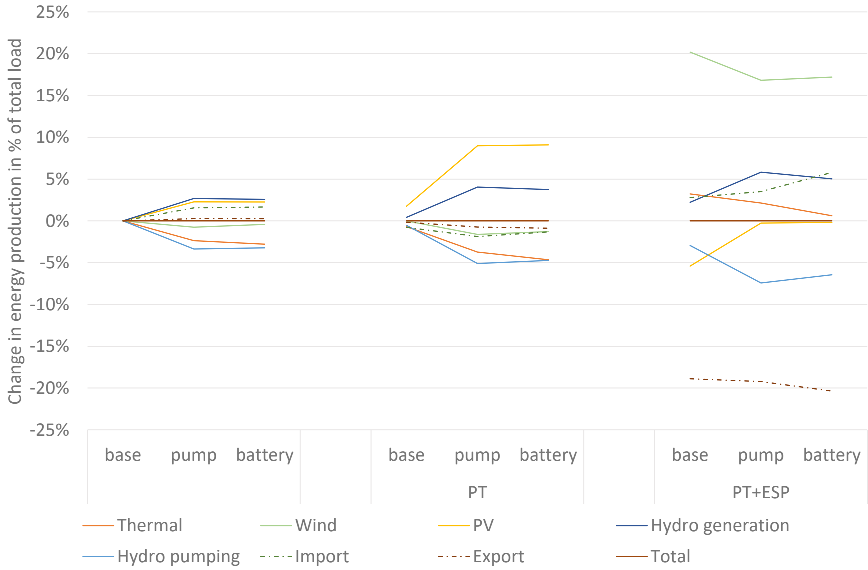


Figure 6.2: Difference in energy mix compared to the base case, expressed in percentage of total consumption, for storage and transmission line expansion scenarios

energy production from the expanded wind and PV power plants slightly increases with battery storage expansion. This indicates that the installed capacity of wind and PV power plants can be utilized more efficiently with the expansion of battery storage. Moreover, it is observed that pump storage utilization decreases with additional battery storage capacity, as does the energy transmitted within Portugal. This suggests that battery expansion alleviates the need for other flexibility facilitators. Additionally, thermal production and, consequently, CO_2 emissions further decrease with battery storage expansion. Along with increased revenue from exports, costs further decrease, as shown in Figure 6.3. Notably, battery storage optimization enables the purchase and storage of more energy from the Spanish spot market during periods of low electricity prices, resulting in reduced or unchanged total purchase costs. This effect is particularly evident with increased transmission line capacity to Spain.

The optimized amount of battery storage expansion significantly increases with power line expansion in Portugal and especially to Spain. Battery storage expansion grows due to increased PV expansion when power lines in Portugal are expanded, and because of the higher economic potential of battery capacity with greater interconnection capacity to the Spanish spot market. Total cost savings, excluding storage costs, increase from €74 million to €553 million with power line expansion in Portugal and Spain due to higher storage expansion. However, cost savings per MW of battery storage decrease from 90 000 €/MW to 60 000 €/MW with power line expansion in Portugal and Spain. This indicates that while increased wind and PV expansion due to power line expansion

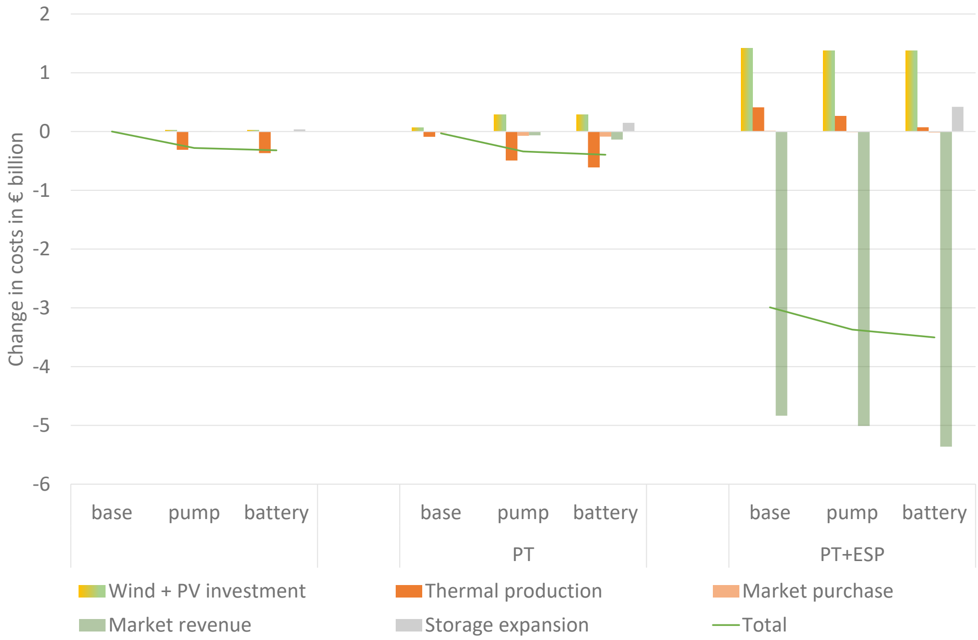


Figure 6.3: Difference in total costs and individual cost components compared to the base case in € billion for storage and transmission line expansion scenarios

enhances the potential and utilization of storage expansion, it reduces the cost savings per MW of storage capacity.
Battery storage is primarily used to balance peak power, as evidenced by the overall decrease in energy transmission within Portugal while peak power utilization of lines to areas with battery storage increases. In particular, in the scenario with power line expansion to Spain, the resulting high wind expansion in Central limits additional power lines to the South. However, congestion hours are lower than without battery expansion.

Power line expansion within Portugal, increases expansion of PV capacity, and shifts it to South, making possible to increasingly use the higher geographical potential there. Together with pump expansion more RES are expanded than without, and especially the availability over the time period increases due to earlier investment (Figure 6.1b). The increased PV energy production with power line expansion in Portugal can be seen in Figure 6.2. Furthermore it can be seen, that power line expansion within Portugal leads to an increased utilization of pump storage power plants and increased exports to Spain while thermal production and imports from Spain are decreased. With this costs and CO_2 emissions decrease. The cost savings through power line expansion within Portugal increase with storage capacity expansion from 27 to 76 € million with battery storage optimization showing that power line and storage expansion support each other in the way of utilization and effect. This would mean 25 € million cost savings per 1500 MW line expansion. Total energy transmitted within Portugal increases, due to increased capacity. With increased PV expansion in South the peak utilization of the power line from South to Lisboa increases with slightly increased congestion hours in base case. With pump expansion amount of congestion decreases to only 2h and with battery expansion the power line from South to Lisboa does not reach their limit anymore. Furthermore the power line expansion leads to a higher battery storage expansion because the increased PV capacity increases their potential of utilization in Lisboa and South.

The resulting investment approach without increased interconnection to the external Spanish power system indicates investment in 9000 MW PV and 8000 MW wind resulting in total installed capacity of 10 000 MW PV and 13 000 MW wind and an expansion of 3280 MW battery storage. This investment approach can be evaluated with the forecasted PV and wind expansion with current policies and measures in Portugal in [44] of 13 200 MW PV and 9000 MW wind capacity in 2030. The shift to increased wind expansion and minor PV expansion can be explained due to a central-planner based cost optimization without considering revenue generation at the Portuguese spot market which could make increased investment in PV capacity favourable for individual generating parties.

The expansion of **transmission lines to Spain** strongly changes the investment approach with a sharp increase in wind expansion in Central and also slightly in North, while PV expansion in general decreases. With power line expansion to Spain utilization of hydro pump storage further increases. Energy exported and sold sharply increases, leading to strongly increased revenue, while energy purchased from the spot market also increases while total purchase costs stay constant, showing that more energy is purchased for a lower price. With increased export to Spain thermal production and with this CO_2 emissions increase.
This together leads to high cost savings which increase with additional battery storage expansion to €1500 million per power line expansion compared to the case with battery expansion and transmission line expansion only in Portugal. With only considering power line expansion from North and South to Spain, the energy transmitted over the power lines withing Portugal increases and especially the ones from Central are increasingly utilized.
The expansion of the line from Central to Spain in this model would lead to significant additional revenue due to increased market purchase additional wind installations and less expansion of PV shifted more to Lisboa. This would lead to lower congestion of power lines within Portugal. Also the further expansion of power lines between South, Lisbao and Central would lead to a relieve of the power lines but only with minor cost saving. In order to analyze the influence of individual lines to Spain an own

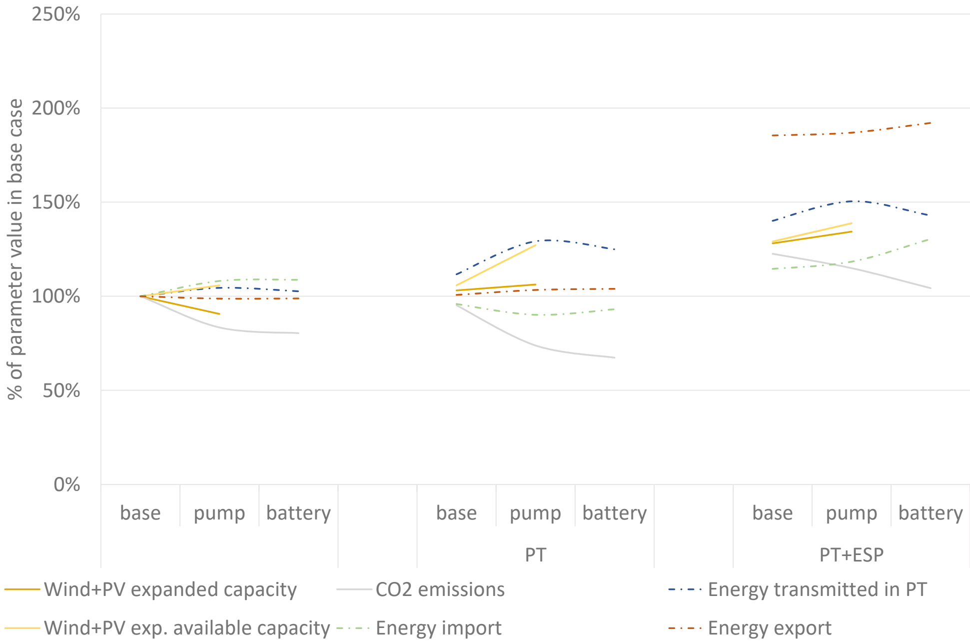


Figure 6.4: Comparison of different parameters, expressed in percentage of the value in base case, for storage and transmission line expansion scenarios

optimization has to be carried out and the influence of high amount of exported energy to the Spanish spot market should be taken into consideration.

For the additional expansion of power lines to Spain it could be shown that it leads to a sharp increase of wind expansion in order to increasingly export the energy. The trends observed in this scenario are only applicable for small changes since high production and export of wind power would influence the spot market price which was assumed predefined for this thesis.

6.2 Synthesis of qualitative results

As can be seen in Table 6.1 the expansion of hydro pump storage capacity leads to increased PV expansion. which in turn reduces thermal production, CO_2 emissions, and costs. Energy transmitted in Portugal increases while hours of congestion decrease. Also transmission line expansion in Portugal leads to increased PV expansion, especially in the region South where geographical potential can be increasingly used. Power line expansion increases utilization of installed pump storage capacities. Together this again decreases thermal production, CO_2 emissions and dependency of imports from Spain.

	pump	battery	PT	ESP
Wind expansion	-			++
Wind production	-	+		++
PV expansion	+		+	-
PV production	+	+	+	-
Thermal production	-	-	-	+
Pump energy	+	-	+	+
Energy transmitted PT	+	-	+	+
Hours of congestion	-	-		+
Export				+ +
Import			-	+
Costs	-	-	(-)	–

Table 6.1: Qualitative impacts of storage and transmission line expansion

Transmission line expansion to Spain leads to strongly increased wind expansion in Central. With sharply increased export to Spain high revenues are achieved for this also thermal production and CO_2 emissions increase but also congestion hours in Portugal strongly increase. The battery storage optimization increases utilization of wind and PV capacity and reduces pump storage, power line utilization and thermal production.

7 Conclusion

In this thesis, the influence of planned transmission line and pump storage expansion on the cost-optimal investment approach of wind and PV power plants for a 100% renewable electricity system is analyzed. The utilization of a MILP for cost-optimal generation expansion planning of wind and PV across various storage and transmission line expansion scenarios is proposed. Significant changes in the amount, timing, and location of wind and PV expansion were observed, underscoring the importance of considering planned developments in transmission and storage expansion for generation planning. On top of this, the impact of cost-optimized investments in additional battery storage capacity on the utilization of the resulting electricity system is examined. In both cases with the applied methodology notable changes in PV and wind utilization, energy mix, cost structure, CO_2 emissions and power line utilization could be shown.

For the generation expansion planning in Portugal from the point of view of a capacity market-based central planner, offshore wind farms are not considered profitable and are therefore not expanded. The varying geographical potential of different areas in Portugal plays a significant role, resulting in PV expansion being concentrated in the southern regions and wind expansion in the northern regions. Onshore wind and PV power plants are currently very profitable, leading to substantial early expansions.
The scenario analysis of storage and transmission line expansions reveals several key findings. Flexibility expansion within an electricity system, in the form of storage and transmission lines, enables increased PV expansion, which in turn reduces thermal production, CO_2 emissions, and costs. Transmission line expansion specifically enhances the utilization of geographical potentials by boosting PV expansion in these areas.
Pump storage and transmission line capacities are interrelated since the location of hydro pump storage is predefined and cannot be ideally chosen. Therefore, increased transmission capacity enhances pump storage utilization. Pump storage expansion also increases transmitted energy, but congestion hours on the power lines decrease.
Battery storage optimization further increases the utilization factor of wind and PV power plants. With a consistent power plant park, it alleviates the load on other flexibilities, thereby decreasing pump storage utilization and the amount of energy transmitted. As short-term storage, it solely increases peak power transmission around the areas where battery storage is installed.
Transmission line expansion within Portugal reduces dependency on the Spanish spot

market by decreasing imports. On the other hand, the expansion of transmission lines to Spain significantly increases the dependency on the Spanish spot market. This results in higher wind expansion and thermal power production to boost revenue from exports to the Spanish spot market. Consequently, power line utilization within Portugal increases, leading to more congestion hours.

The specific resulting expansion decisions strongly depend on the geographical conditions in the observed area but the above described trends in the impact of expansion of power lines and pump storage capacities are expected to apply to other systems as well. For application of this trends to another system the structure and degree of utilization of the existing electricity system should be taken into consideration. The impact of expansion to an external electricity system of course strongly depends on the assumed development of the spot market price there.

In general, the used MILP model is applicable for arbitrary electricity systems. It has been shown to be useful to research cost optimal expansion in renewable energy sources and analyze the influence of transmission and storage expansion pathways by scenario analysis. The resulting expansion approach for the scenario, which includes plans for storage and transmission line expansion in Portugal, can be evaluated against the forecasted expansion in the NECP. The optimization leads to a very similar total expanded capacity, only with a shift in proportion from PV to wind capacity. This shift can be explained by the optimization being done from the perspective of a central planner.

For computational feasibility in this work multiple constraints apply, highlighting possible further research areas. It is important to note that results for impacts of transmission line expansion to Spain in this work are only applicable for small changes since no interrelation of the exported power and the spot market price is considered. For a more detailed analysis this interrelation should be represented in the model. Furthermore, for the 100% renewable electricity system in future works exact unit commitment and reserve constraints may be considered, as well as security of the system. If not planned scenarios should be compared, for a holistic investment approach into generating unit, storage and transmission line capacities a co-optimization model for all 3 components should be carried out. Further interesting questions that could be analyzed based on this work are the influence of environmental change due to climate change, or the impact of demand side management mechanisms. In general, a holistic approach to generation expansion planning should go beyond technical feasibility. It should, for example, also consider the sustainably available resources and space necessary for the energy transition.

Nomenclature

Binary Variables

Y Binary decision variable for investment at each time step

Index

$^{min}, ^{max}$ minimum/maximum of limited variable

$HU_{out,i}$,$HU_{in,i}$ Hydro units that take water from/spill to reservoir i

ES Energy storage unit

HP Hydro pumping unit

HT Hydro turbining unit

Inv Investment

M electricity market

Op,Maint Operational and maintenance

P Purchase

S Sales

t time step

TL, TL_{ex} TL_{im} transmission line/in import/export direction

trans transport

TU Thermal unit

W,PV wind and PV units

Parameters

ΔT arbitrary time period

η efficiency factor

$n_{...}$ number of ...

T_k lifetime of unit k

$T_{Planning}$ modelled time horizon

j, d interest rate, discount rate

p price in €/unit

Variables

Cap installed total capacity of storage in MWh

C Costs in €

E Energy produced or consumed

P Power produced or consumed at time step

Q water or fuel consumption per time step in m^3 or MWhg

R Revenue in €

RL Reservoir level

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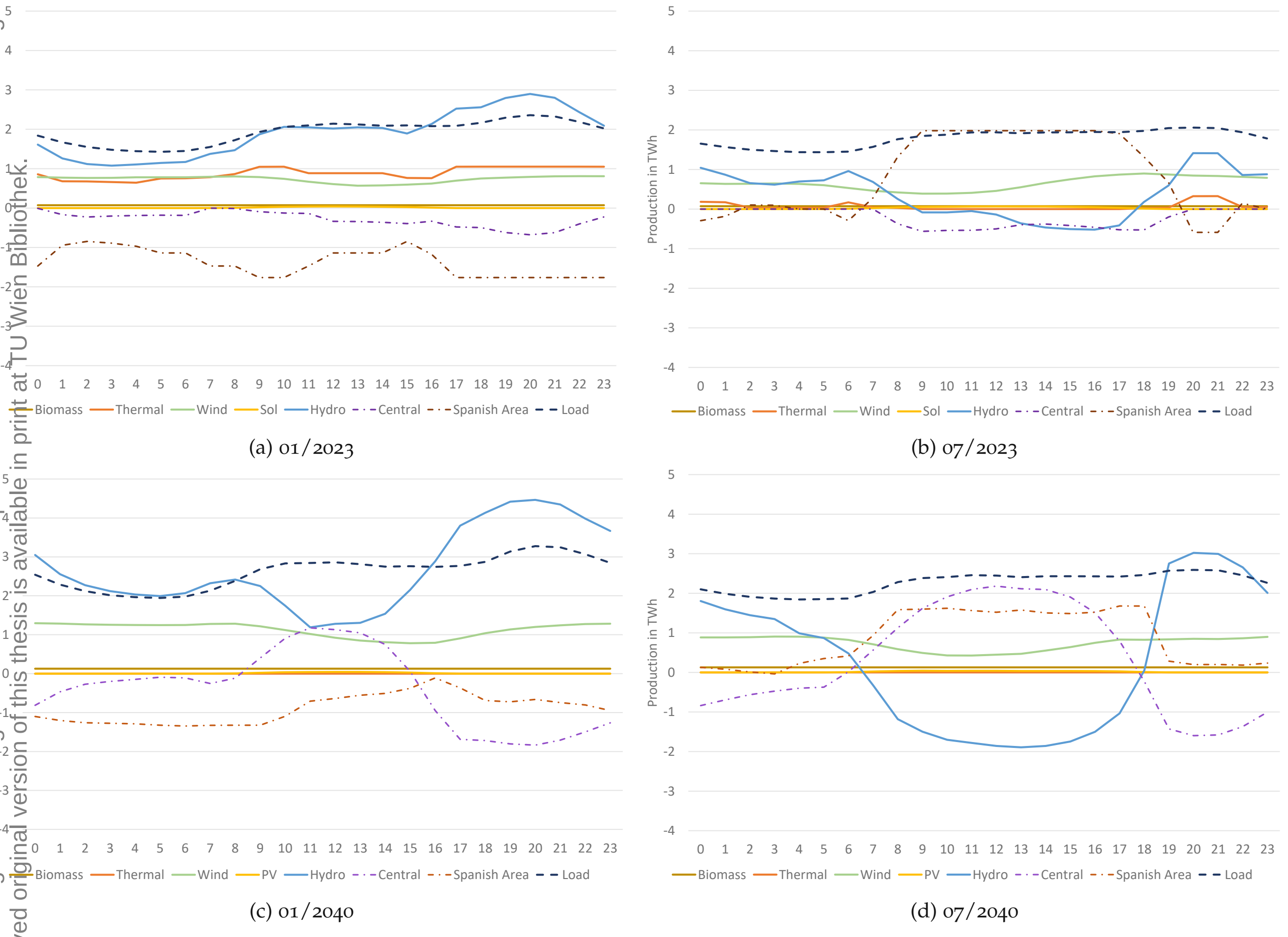
Appendix

Appendix A. Hourly representative day profiles



(a) 01/2023

(b) 07/2023

(c) 01/2040

(d) 07/2040

Figure 1: Representative day profile for one month in winter and summer of initial year 2023 and final year 2040 for region North

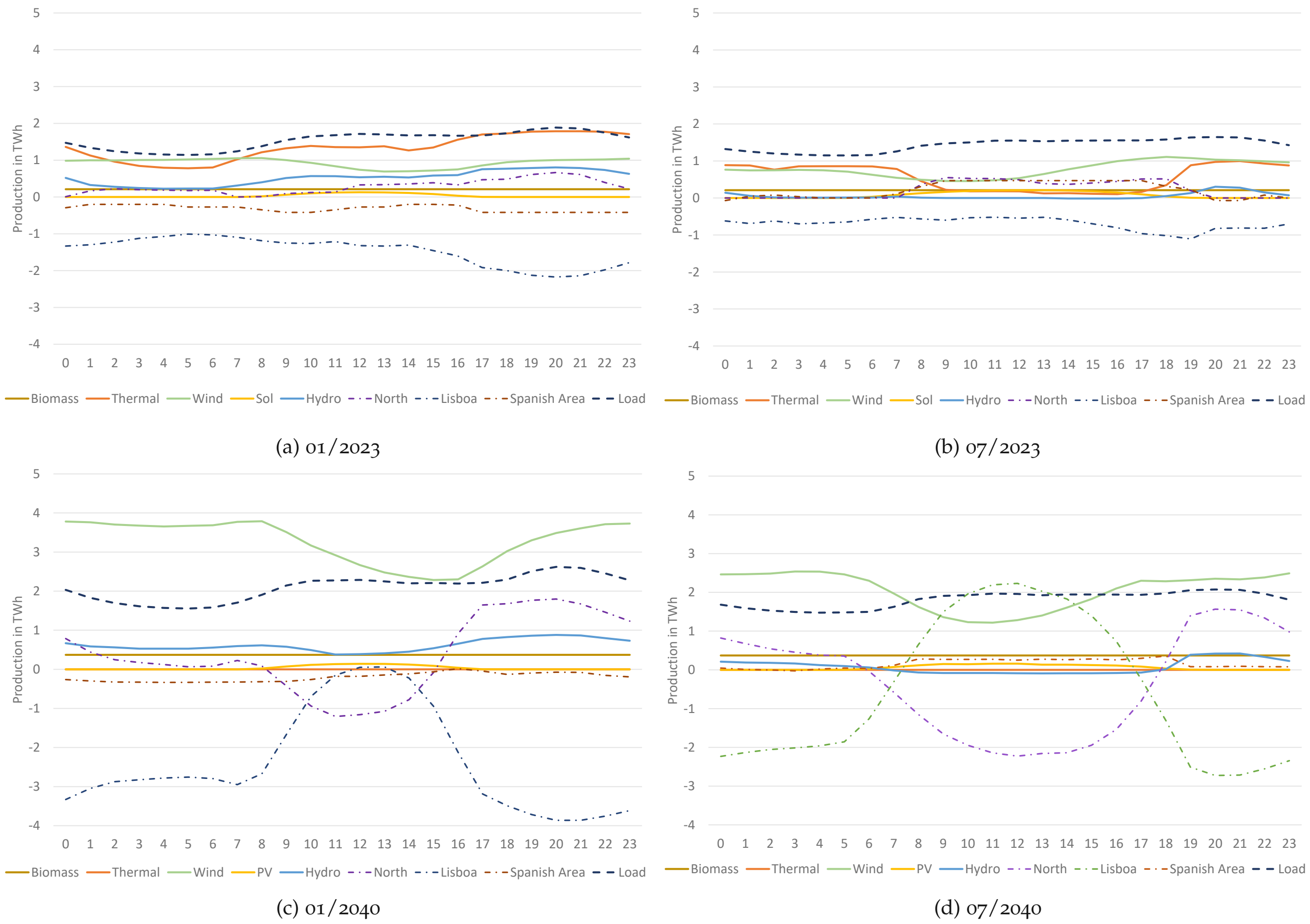
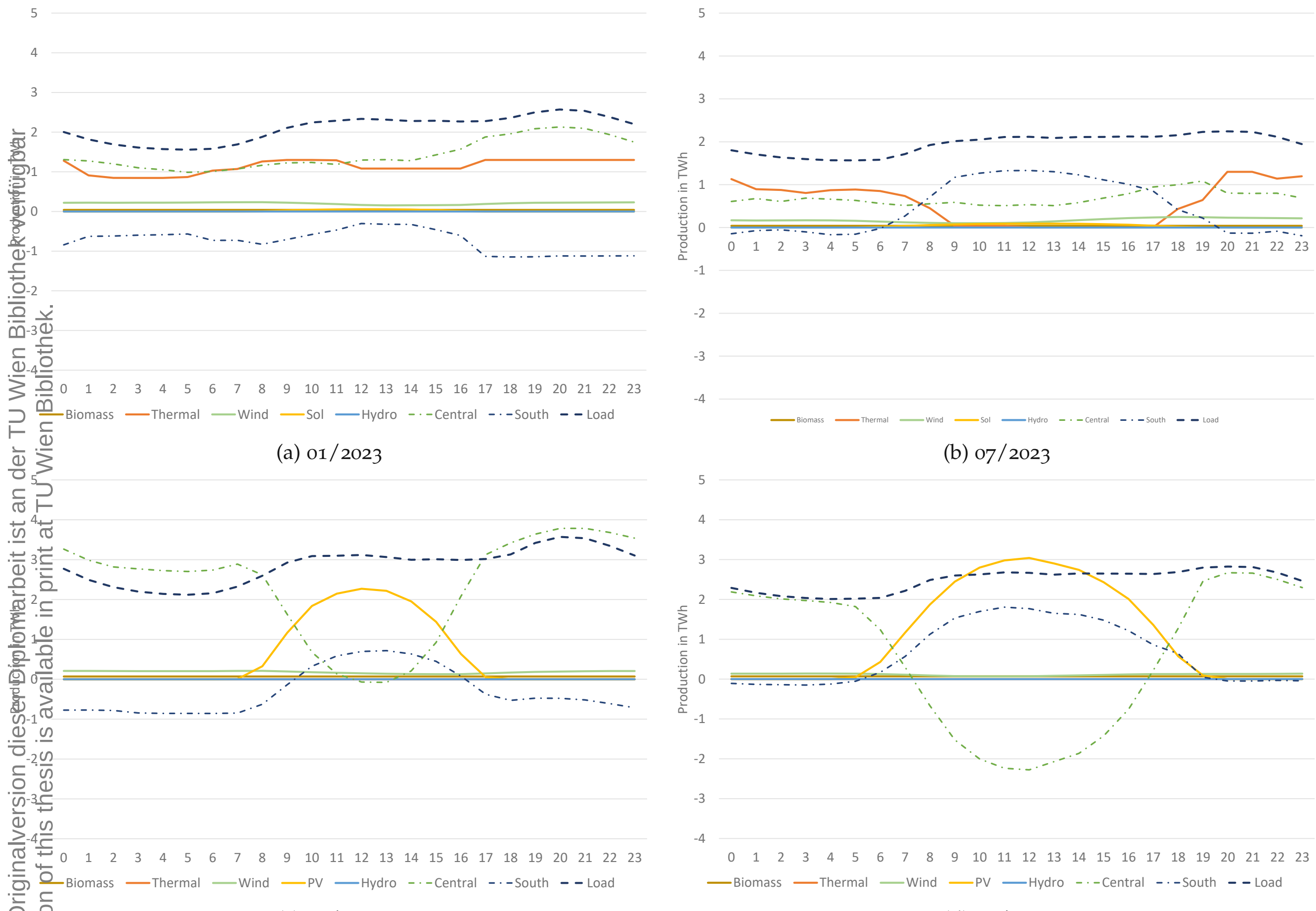


Figure 2: Representative day profile for one month in winter and summer of initial year 2023 and final year 2040 for region Central



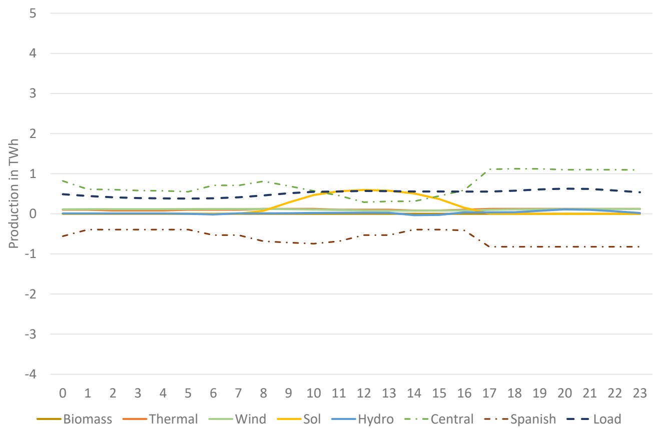
(a) 01/2023

(b) 07/2023

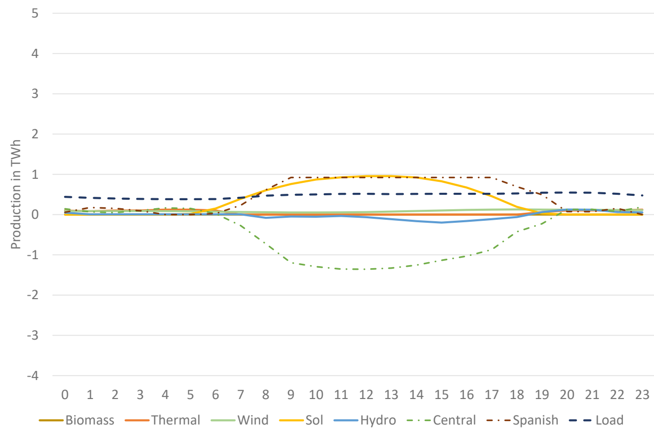
(c) 01/2040

(d) 07/2040

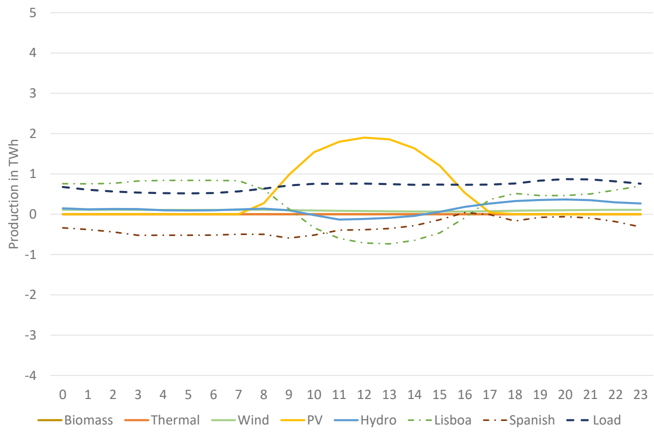
Figure 3: Representative day profile for one month in winter and summer of initial year 2023 and final year 2040 for region Lisboa



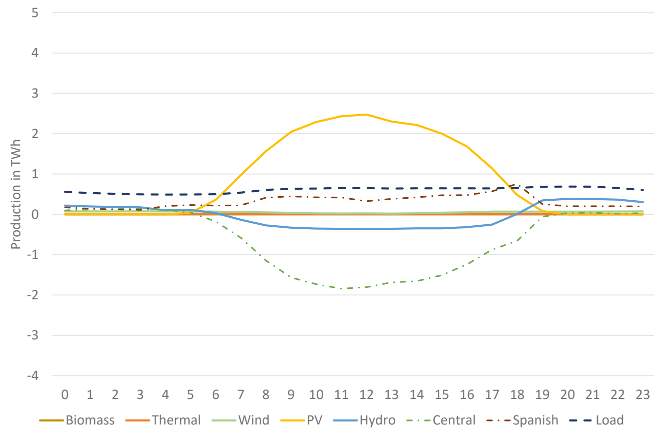
(a) 01/2023



(b) 07/2023



(c) 01/2040



(d) 07/2040

Figure 4: Representative day profile for one month in winter and summer of initial year 2023 and final year 2040 for region South

Appendix B. XPRESS solver parameters

General		
	Default Algorithm	Newton Barrier
	Deterministic	On
	Feasibility Tolerance	-1 (default)
	Threads	based on hardw. config.
Preprocessing		
	Presolve	Normal Presolve
	Crash	-1 (default)
Root Relaxation		
	Start Algorithm	Primal & Dual & Barrier
	LP Threads	based on hardw. config.
	Barrier Threads	4
	Dual Simplex Pricing Method	Automatic
Cutting and Heuristic		
	Cut Strategy	Automatic
	Cover Cuts	-1 (default)
	Nr. of Iterations	-1 (default)
	Heuristic Strategy	Automatic
	Heuristic Treads	-1 (default)
	Heuristic Search Effort	-1 (default)
Branch and Bound		
	MIP Gap	0.05
	Node Selection	Local first then depth
	Strong Branching	Disable
	Sub Algorithm	Automatic
	MIP Threads	4
	MIP Presolve	-1 (default)
	MIP Tolerance	-1 (default)
End Algorithm		
	End Algorithm	Newton Barrier

Table 1: XPRESS solver parameters