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A Multi-Objective Approach to the Prospective Development of the European Power System by 2050

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Abstract

This paper reports the recent work carried out to engage both the environmental impact and the economic indicators on the prioritisation of dispatchable technologies in the European energy mix up to 2050. Those two contradictory indicators are incorporated in a multi-criteria optimisation leading to iterations of two scenarios: business as usual and 2 °C climate policy. The results present the evolution of the climate change emission versus the operational costs of the power system up to 2050. The yearly electricity mix evaluations allow assessing the long-term development of the European energy system, where a focus is done on variable renewable energy production. It is shown that policy-only solutions, associated with a traditional cost-oriented optimisation, have a limited impact on helping the power sector to

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reach emission levels targets. Integrating the objective of reducing emissions to the management of power plants would reduce the absolute and cumulative carbon dioxide equivalent emissions. The counterpart is that the system electricity price tends to increase faster thus implying increased social costs.

Keywords: Multi-objective optimisation, Power system modelling, POLES, EUTGRID, 2050 target, Environmental impact

1. Introduction

The recent increase in earth temperature level, known as the global warming, correlates with anthropogenic activities [1]. As this phenomenon takes more importance, the global impacts are already perceivable. As a response, most of the world leaders jointly agreed on a limitation of the temperature rise by 2°C by the end of the century, by signing and further ratifying the Paris agreement [2]. In this context, all energy sectors must put efforts in reducing their impact on the increase of carbon dioxide equivalent (CO_{2-eq}) concentration in the atmosphere. The power system will need as well to drastically reduce its impact on the CO_{2-eq} emissions. In Europe, it is expected that the power sector reduces its emission by 80% by 2050 [3] in order to cope with the Paris agreement. This drastic reduction in emissions should push for changes in infrastructure, behaviour of consumers, energy business models, and institutions/governance [4]. Changes in the infrastructure implies adapting the power system as well as increasing the penetration of clean technologies in the energy market. In Europe, yearly investments of 183 b\$ to 302 b\$ in clean technology solutions was evaluated to reach the climate policy or 1.5 °C target [5].

As defined in the European regulation, clean technologies are based on renewable energy sources [6]. An important share of electricity production could come from variable renewable energy sources (VRES) that include wind and solar power technologies. As their name suggests, the production of electricity from VRES technologies is fluctuating and therefore naturally limits their penetration in current power systems. To overcome that issue, measures were identified by Cochran et al. [7] that aggregate a set of engineering and economic solutions. These measures focus on the network, the flexible generation of power, the storage technologies, the controllable loads, the system operation, and the electricity markets. The network transformation measures integrate adaptation of the power network to accept more VRES, which includes grid reinforcement and expansion. The load flexibility is also emphasised by increasing the interaction with the traditional dispatchable technologies, such as coal, gas or oil-based power plants, but also including others such as nuclear power-plants [8]. Uneconomical but widely used solution is the curtailment of the VRES power production [9]. The integration of storage systems throughout the network may be a solution to overcome the curtailment issue. The modification of the technology landscape by 2050, with the inclusion for instance of electric vehicles, will also impact the load profiles that is expected to see more frequent and higher peaks than in today's reference scenario [10]. Other aspect affecting the future demand side is the electrification of more sectors and how these will impact the network [11].

All these measures can be related to the super-grid or smart-grid evolution. The super-grid is a network evolution where the interconnections

between regions represent the core of the power system [12], along with the balancing technologies and the alteration of the demand patterns. On the opposite, Blarke and Jenkins [12] state that the smart-grid is built on the interactions between small scale production, storage and load shifting. While the super-grid and smart-grid paradigms may hinder each other’s development, their interactions shall, in the end, merge to form of a “super-smart-grid”.

1.1. Energy system models

Energy system models (ESM) are commonly used when planning long-term power system infrastructure needs. These models allow finding the optimal solution of an energy system and its infrastructure. These optimisation models allow to picture a probable future. One of the most popular is the TIMES model which was developed within the International Energy Agency framework and documented by Loulou et al. [13]. The TIMES model uses economic projection and technology road-maps as inputs. Other ESM, classified as simulation models, provide trajectories based on economic projections and other endogenous inputs related to, for example, population growth or fossil fuel usage, for a given time-step (yearly, 5-years, etc.). The TIMES model was further used by the Joint Research Center to better represent the future of the European power system [14]. There is already a profusion of such ESM [15], the most known being the Prospective Outlook for Long-term Energy Systems (POLES) or the Price-Induced Market Equilibrium System (PRIMES) models. Ultimately, the next iteration of ESM will be combining the optimisation energy system model with the simulation-based model on macroeconomic growth [16].

While the previous ESM are mainly used to optimise an energy sys-

tem using the least-cost path under technical constraints, the deployment of multi-objective tools within these ESM becomes more prevalent. Applications focused on local energy planning combining the freely available ESM EnergyPlan [17] and multi-objective evolutionary algorithm resulted in an energy balanced system with 100% penetration of VRES [18]. The model considered the annual system costs and the CO_{2-eq} emissions related to the combustion plants to be minimised. Other multi-objective optimisations considered the combination of power transmission losses and emissions reduction [19], further corrected by Ahmadi and Ahmadi [20] that considered the social welfare combined to emission reduction and maximisation of renewable production [21]. These multi-objective optimisations considered either the short-term planning of local networks or provided a snapshot of the future state of a network but lacked the interaction between long-term economic modelling and ESM for network management and planning. Finally the representation of the VRES variable production in long-term ESM needed to be revised [22].

1.2. Objectives of the present work

The main goal of this study is to evaluate the energy, environmental, economic and infrastructure impacts that combined economic and environmental objectives have on the evolution of the power system infrastructures when prioritising the use of dispatchable technologies as a primary flexibility measure for integrating VRES. The multi-objective optimisation must follow different policy scenarios that influence the future energy system and integrate future economic projection and their associated constraints.

The paper is organised as follow. First, the backbone models are detailed.

Then, the integration of the multi-objective method within the existing models is described. Finally, results are reviewed, to assess the robustness of the multi-objective model, and the impact of a multi-objective optimisation on the development steps of the power system towards 2050.

2. Coupled models

The proposed implementation of the multi-objective optimisation of the power system relies on two main models, namely the Prospective Outlook for Long-term Energy Systems (POLES) [23, 24], and the European Transmission Grid Investment and Dispatch (EUTGRID), a model developed by Allard et al. [25] and finalised in a thesis in the Grenoble Electrical Engineering Laboratory (G2ELab) [26]. EUTGRID is an extension of the European Unit Commitment And Dispatch (EUCAD) developed by Després et al. [27].

2.1. *Combining long term energy prospect with power simulation*

The POLES model is a worldwide economic model that seeks for the long-term energy balance of sector-defined supply and demand. It is currently jointly developed by the Joint Research Centre (JRC), the Sustainable Development and Energy Economics laboratory from the University of Grenoble (GAEL) [28], and the consulting company Enerdata. In this research, the Gael version of POLES is used. The integration of the POLES and EUTGRID models is done through a soft link, where each iteration occurs yearly and models feed each other to present a balanced power system. The implementation is presented in [Figure 1](#). For the optimisation, the

GAMS platform is used².

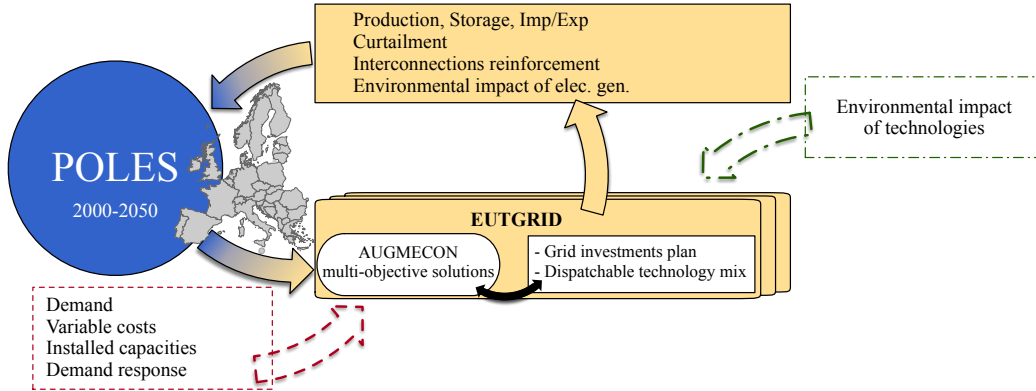


Figure 1: Structure of the used model, combining simulation and optimisation techniques for the prospective planning of the European power system towards 2050.

POLES is a simulation model providing the trajectory of the European electric system based on a recursive model which is influenced by endogenous factors such as economic projections by country, population variations, carbon constraints, known resources, policies, and technologies [24]. EUTGRID is an optimisation model able to provide an optimal solution to a complex problem that is the European representation of the transmission system with an hourly resolution (optimal power flow). For each year, POLES computes the energy mix for electricity production and feeds EUTGRID with variables such as electricity costs, demand-response rates and electricity demand by country. The EUTGRID model then builds the European power grid and estimates the investments needed by the transmission power system, based on the production of VRES, the availability of dispatchable technologies such as gas, coal, nuclear, biomass, oil, geothermal, or storage, and the congestion

²<https://www.gams.com/>, accessed in September 2019

of the transmission lines [29].

2.2. The power system model

The EUTGRID model is used to simulate the operation of the grid on a 24-hour basis. Initially, the target was to find the optimum operation of the system aiming at minimising the total cost, by respecting constraints, such as the supply-demand equilibrium, the maximum thermal line capacities, the ramping capabilities, and the range of generation capacities of each production technology. The EUTGRID model considers 87 clusters within Europe based on the 96 regional division set in the ‘e-Highway 2050’ European project [30] (presented in Figure 2b). The dismissed clusters were the Baltic countries as well as the Balkan countries (lack of data and minimal impact on the results). In addition, the transmission network was modelled to integrate both the high voltage AC (HVAC) and the high voltage DC (HVDC) lines as illustrated in Figure 2a.

The technical parameters of the connections between nodes are derived from the real grid. It is worth noting that only neighbouring clusters are connected, with unique connections. The method used to cluster the grid is based on technical criteria, resulting in around 100 clusters. It is considered as a good trade-off between accuracy and complexity (the initial representation of the European grid contained no less than 1000 nodes).

As established, wind and solar production varies at multiple time scales in addition to the geographical horizon. Patterns can be observed on seasonal, weekly, and hourly scales. A clustering method, introduced by Nahmmacher et al. [31], was used to consider that fact in the presented work. The logic of the algorithm is to group in clusters days with the closest wind or solar pro-

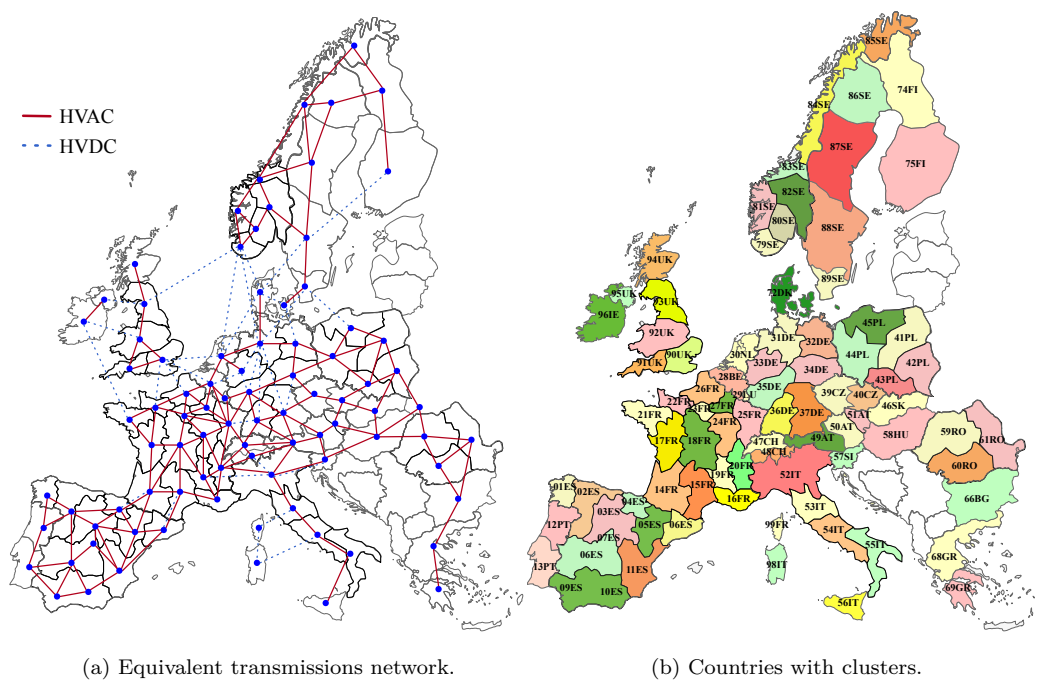


Figure 2: Corresponding countries and clusters of the transmission network as modelled in EUTGRID, adapted from [30].

duction, forming a predefined number of categories, in our case six per season (summer and winter) [32]. The representative day of the cluster (namely the “centroid”) is the one with the minimum distance with all the other days of its cluster. Those 12 typical days’ production profiles of VRES are used in the EUTGRID model. According to the size of each cluster the required coefficients are set, defining the possibility to have such a day during each year of the simulation [32].

During the coupling of POLES and EUTGRID, some modelling hypothesis are considered for the operation of the grid. Nuclear and hydro power are considered as “must-run” technologies and are characterised by their yearly load factor and a default production profile. Their profiles can be adapted to the total load profile e.g. forced outages for nuclear maintenance and include some flexibility to accommodate for the high penetration of VRES. Pumped hydro and storage facilities add flexibility, storing when the VRES production is high and producing when the VRES production is low. The production curtailment is allowed in the case of a combined oversupply of solar, wind, hydro, marine and nuclear power. V2G is an integral part of the prospective technologies while the power-to-heat technology is represented not as a flexibility measure but in the demand curve. There is a simple representation of low-temperature district heating in the POLES and EUTGRID coupled models, but it is insignificant at the transmission level scale (which is the scope of this study). A focus at the distribution grid level would better illustrate the benefits from this modelling capability. Note that all the modelling hypothesis are detailed in their original publications for EUCAD [32] and EUTGRID [26].

2.3. Prospective environmental impact

Currently, prospective models account only for the six main gases listed in the Kyoto protocol to assess the global warming impact of their models whether it is in POLES [24] or PRIMES [33]. Furthermore, these models only consider emissions related to the combustion process of the electricity production. Therefore, there is a misrepresentation of the environmental impact from the proposed projection of the electricity mix. It also may lead to biased decisions on which technology to give preference to. The EUTGRID model considers current technologies but also prospective technologies when planning the future energy mix and production mix.

In order to integrate the environmental impact in the decision-making process, environmental indicators based on life cycle assessment (LCA) studies were integrated for all technologies. The database relies on a combination of existing LCA based on EcoInvent 3.X³, the New Energy Externalities Development for Sustainability (NEEDS) database [34], and the literature. This database was first created by Louis et al. [35] to evaluate the power system development based on an environmental merit order. The life cycle inventories are further characterised using the ReCiPe2008 method [36]. As illustrated in Figure 1, the environmental database directly feeds EUTGRID during the decision phase of the model and is used as an input for the multi-objective optimisation.

³<https://www.ecoinvent.org/>, accessed in September 2019

3. Multi-objective optimisation

Each year, the POLES model evaluates the energy demand, the variable cost of electricity, the installed capacity and the demand-response potential in the network. In parallel, the environmental impact of each technology is provided for each main regions using an LCA approach. The EUTGRID module looks for the solutions of the multi-objective problem and provides the payoff tables for prioritising dispatchable technologies. Infrastructure investments are further decided depending on the curtailment level of each transmission line and feed back POLES. The following section details the two main objectives and the methods used for implementing the multi-objective optimisation.

3.1. Objectives functions

Two objectives are simultaneously considered to optimise the planning of the power system. The first objective function, expressed in (1), relates to the system costs and has been defined as part of the EUCAD model in [27].

$$\min C_{tot} = \sum_{k=1}^K \sum_{t=1}^{24} \left(C_{nde}(k) \times P_{nde}(k, t) + \sum_{j=1}^{T_d} \left(C_{dt}^{var}(k, j) \times P_{dt}(k, j, t) + C_{dt}^{rmp}(k, j) \times r_{dt}^2(k, j, t) \right) \right) \quad (1)$$

where C_{tot} is the total cost of the system (k\$); K is the number of clusters used in EUTGRID (87 in this paper); t is the hour of the day; C_{nde} is the cost of non-distributed energy (k\$/GWh); P_{nde} is the non-distributed power (GW); T_d is the number of dispatchable technologies available in POLES and

EUTGRID; C_{dt}^{var} is the variable cost of dispatchable technologies (k\$/GWh); P is the power produced for each dispatchable technology by cluster (GW); C_{dt}^{rmp} is the ramping cost of dispatchable technologies (\$/MW²) and r_{dt} is the ramping rate of dispatchable technologies, the rate at which they can change their output at time t (GW).

The variable cost, C_{dt}^{var} , integrates all costs for each technology, including fuel cost, variable O&M costs, subsidies or taxes on power output or fuel input (including a potential carbon value), and CCS technologies including CO₂ transport and storage costs [24]. The variable cost is calculated within the POLES model and its value updated every year. The variable is further inherited by EUTGRID to optimise the total cost of the system C_{tot} .

The second objective function aims at minimising the total emissions at the European level. The expression of the objective function follows a least-emission optimisation model by Louis et al. [35], as summarised in (2).

$$\min E_{tot}^i = \sum_{\substack{j=1,\dots,T_d \\ c=1,\dots,C \\ k=1,\dots,K \\ t=1,\dots,24}} F_i(k, j, c) \times P(k, j, c, t) \quad (2)$$

where E_{tot}^i is the total emission of an indicator i listed in the ReCiPe2008 version of the characterisation method of emissions [36]; F_i is the emission factor of the selected indicator i , for each cluster k , within each country c and technology j (/GWh); P is the power produced within each cluster k for all technologies j in each country c (GW).

Emissions may account any types of emissions listed in the ReCiPe2008 endpoint method but only one indicator can be considered at a time in the multi-objective optimisation problem, the reason being purely compu-

tational. In this research, only the greenhouse gas emission levels are considered although land use, land use change and forestry (LULUCF) could be set as another objective in another scenario if desired

The optimisation problem is defined under a set of constraints, such as the load flow for balancing the power system, the demand as simulated in POLES, the maximum line capacities, the ramping capabilities, and the maximum power output of the power plants among others. All the constraints are detailed in their original publications EUCAD [32] and EUTGRID [37].

3.2. The augmented ε -constraints

The presented objectives are combined in a multi-objective algorithm aiming at proposing a set of optimal solutions in the form of a Pareto front. In case there is a single objective function in a mathematical problem, the optimal solution is unique if existing. However, in case of multiple contradictory objectives, no single optimal solution exists that simultaneously optimises all objective functions. The Pareto optimal solutions are the ones that cannot be improved for one objective function without deteriorating at least one of the others.

The the augmented ε -constraints, also known as AUGMECON, has been developed in GAMS [38] and adapted to the EUTGRID model to perform the multi-objective optimisation of the European power system on a long-term perspective. The results of the modified EUTGRID model are a set of optimal solutions, the number of which depends on the number of selected grid points. As described in the previous section, because of the coupling of EUTGRID with POLES, upon the completion of the simulation of EUTGRID for each year, the user must decide regarding the solution that POLES will consider,

for the decisions to be taken for the next year. In this work the chosen solution is a compromise of the two considered objectives for each iteration. Moreover, except for the objectives to be optimised, the user also must select the number of intervals for the AUGMECON method, to split the range of each objective function in equal parts. In this set of simulations, 10 steps lead to 11 grid points, which is also the maximum number of Pareto optimal solutions provided by the EUTGRID model.

3.3. Scenarios and hypothesis

The multi-objective optimisation combined with a link to the macro-economic model POLES, in a looped implementation, results in the establishment of the European pathways to reach either the business as usual (BAU) or the climate policy goals (2°C climate policy scenario, denominated as CP hereafter). To assess the scenarios, the results are reviewed for a specific year as well as the evolution of the multi-objective alternatives throughout the modelled period. Further, the impacts on the infrastructure of the power system and their related economic or environmental objective is reviewed. All supporting raw data are available in data repository [39].

In both scenarios, the storage facilities are not presented, as they are modelled with a state of charge being identical at the beginning and at the end of each day. As a result, they only serve as “load displacement” facilities within the day, and their operation is not of great importance for the current study.

4. Results and discussion

Multiple optimisation scenarios were simulated to minimise the two defined contradictory objectives. In the next subsection, the results refer to only the year 2013, simulated in EUTGRID. Those results serve as a validation of the multi-objective optimisation algorithm as there are actual data up to that year.

4.1. Yearly optimisation scenarios

As introduced in [subsection 2.2](#), each year is split into 12 representative days of the power network state, 6 days for the summer period and 6 for the winter period. Each day is further detailed at an hourly time step. The ε -constraint algorithm finds 10 possible solutions, for each simulated representative day (12 in total), that are plotted in [Figure 3a](#). Each day is given a weight w_d representative of their occurrence during the period they are defined for and are finally summed up to build the Pareto front of the entire year as expressed in [\(3\)](#).

$$P_r^{year} = \sum_{d=1}^{12} w_d \times P_r^{day}; \text{ where } \sum_{d=1}^{12} w_d = 1 \quad (3)$$

In [Figure 3b](#), all the curves of the different days are summed using their corresponding weights, resulting in a single curve, which refers to the yearly values.

As a first obvious validation of the implemented method, the first possible solution (max emissions – min cost) matches the corresponding values of the single-objective optimisation of the cost. Accordingly, the last solution (min

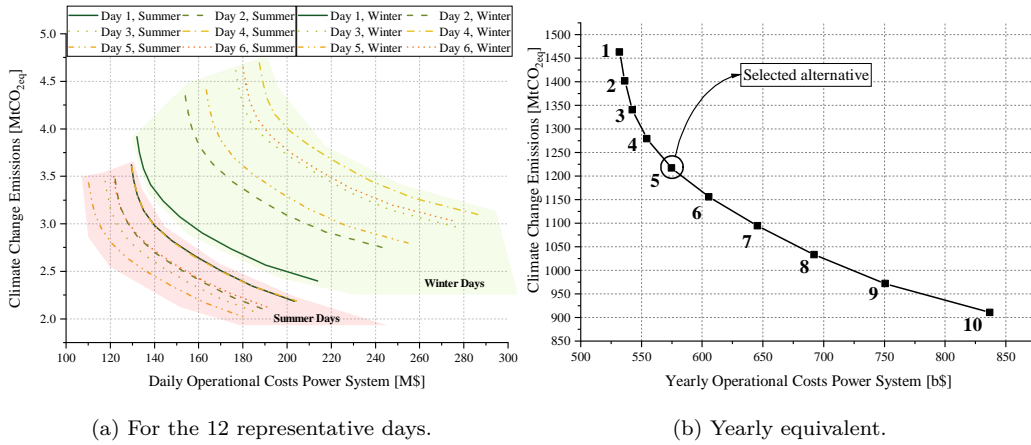


Figure 3: Pareto fronts representation for the year 2013.

emissions – max cost) would be obtained if only the climate change emissions were considered.

Two sets of Pareto front can be identified for the winter and summer seasons. Winter days present more variety of profiles compared to summer days. This behaviour is coherent with the variation of power production and temperature as used in generation forecast techniques [40]. These 12 representative days were further aggregated to form a single Pareto front for the studied year and is represented in Figure 3b. The yearly equivalent solutions represents the different combinations of dispatchable technologies usages for achieving the lowest emissions and system costs. To find the best compromise between all Pareto optimum points, the climate emission data and the total costs variable were normalised following their normal distribution. The best compromise is the solution obtained while having the same weight on both objectives for all years. The fifth point has been found to be the closest optimal point to that compromise, and is highlighted in

[Figure 3b](#). The compromise solution is used as an illustrative support, with a specific energy mix that is discussed in the next section.

4.2. Long-term multi-objective optimal scenario

Once a solution is selected (in our case the closest to an equal consideration of both objectives), it is used by EUTGRID and fed back to POLES to simulate the energy mix of the upcoming year. Therefore, the choice of the solution has an indirect effect on the proposed alternative for the following years. The set of Pareto fronts for the BAU and the CP scenario are presented in [Figure 4](#).

At first, two clear tendencies appear: the BAU scenario see its set of Pareto fronts increase in emissions and systems costs overall, while the CP scenario see its set of Pareto fronts decrease in emissions but increasing to a similar level regarding the system costs.

Furthermore, the energy mix for electricity production are extracted for each of the alternatives. The main shift of technology occurs between coal and gas, as illustrated in [Figure 5](#). Note that in the simulations, the VRES production is consumed as much as possible (hence its constant value in the four selected years). To that effect, dispatchable technologies are optimised along with curtailment.

The least-cost alternative prefers higher production from coal-based technology while the least-emission alternative prefers the gas-based technology. The compromise alternative is thus within these boundaries. This tendency seems to fade over time as no clear distinction can be made for the year 2040 and 2050. By 2050, only two types of technology using coal would be still running: the integrated coal gasification with combined cycle and CCS, and

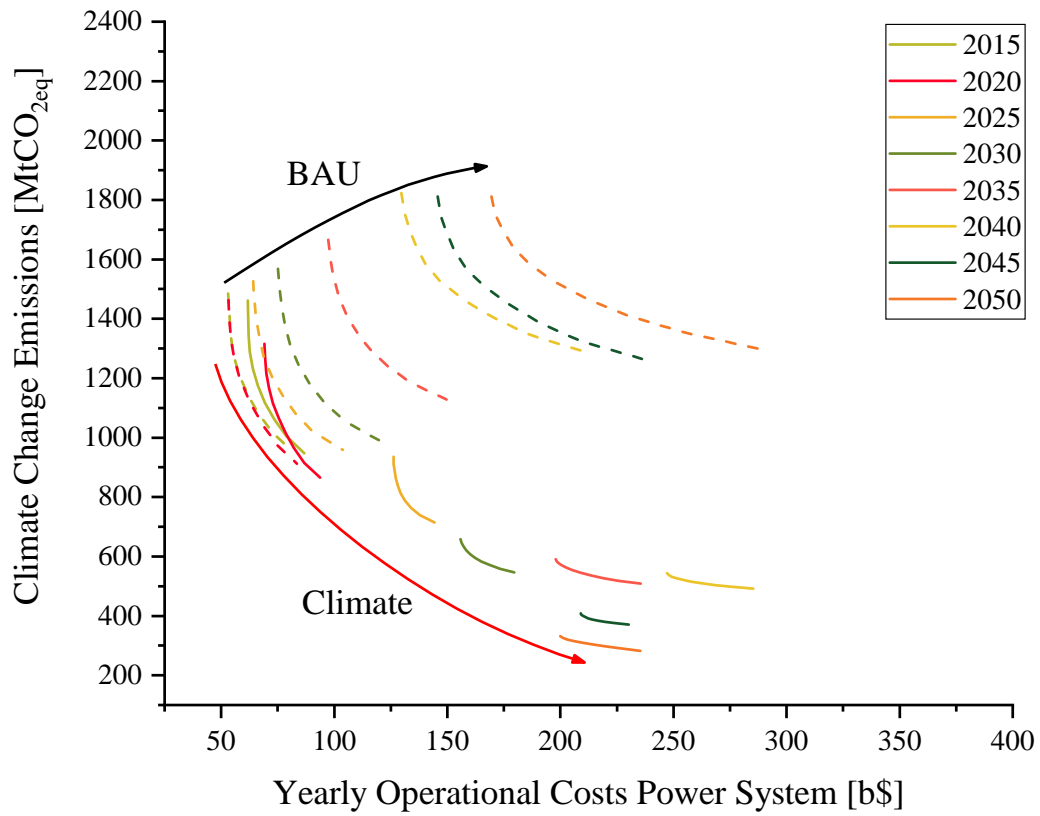


Figure 4: Evolution of the equivalent yearly Pareto fronts for the 2015–2050 period, using the BAU and the CP scenario.

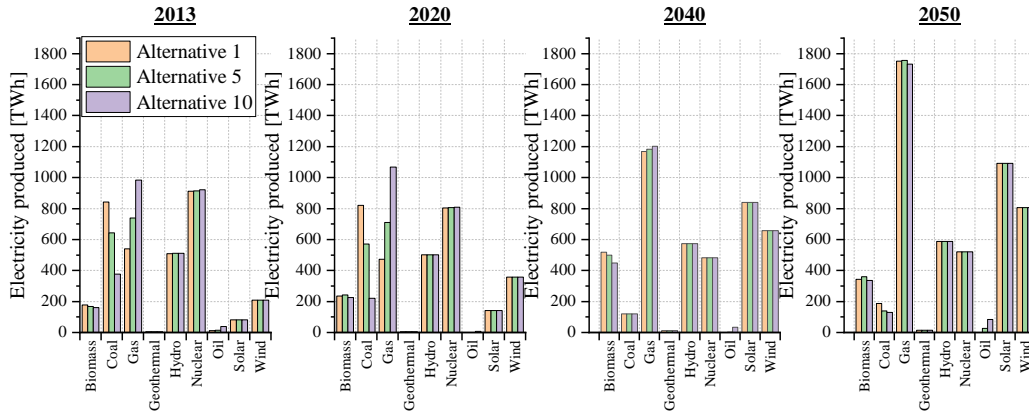


Figure 5: Yearly electricity production mix for 3 alternatives (1, 5, and 10 as presented in Figure 3b) in 2013, 2020, 2040, and 2050 under the CP scenario.

the pressurised coal supercritical with CCS. Both technologies are considered prospective and shall enter widely the commercial market by the year 2025. UK and Poland would be leading this market and similar findings were reported by Sithole et al. [41], while the environmental impact of different UK scenario including the phase out of coal power plant by gas turbines was found to be crucial for the UK national target [42]. This is an important challenge for central European countries that relies heavily on coal-fired power plants [43]. Biomass-based technologies are usually not preferred in the least-emission alternatives as the system boundary was set to the production of electricity thus disregarding the re-absorption of carbon. The production of VRES cannot be dispatched. This means that their production cannot be adjusted, and the only possible action is to reduce or curtail it, in case the grid cannot cope with it, which in all cases is not preferable. Therefore, their production is always constant for all possible solutions of the Pareto front.

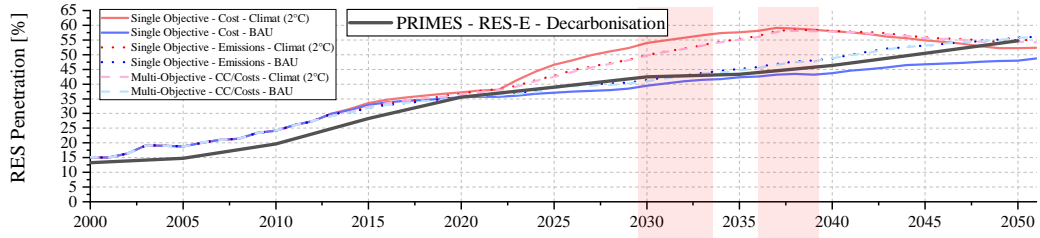
4.3. Long-term system development

The long-term impacts on the power system may be regarded under the economic and the environmental changes that the different policies and strategies are leading. Firstly, the penetration of VRES and their impacts is detailed. Secondly, the impact on the investment needs for supporting and strengthening the transmission power system will be evaluated. Those impacts are directly connected to the system costs and thus will need to be observed. Finally, the long-term climate change related emissions is stated under the frame of the multi-objective model.

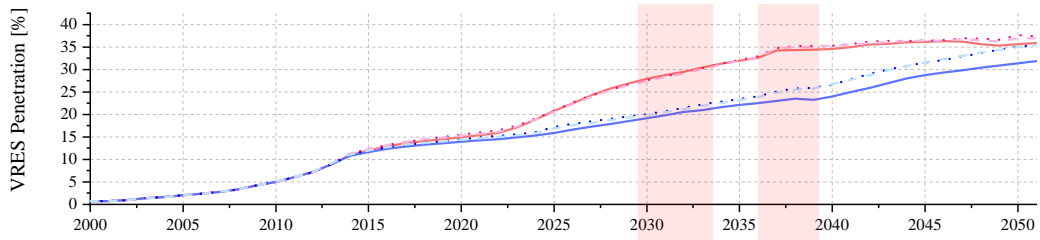
4.3.1. Variable renewable energy sources

The increase of renewable energy sources (RES) and especially VRES is critical for achieving the decarbonisation target envisioned for 2050. In the framework of the EUTGRID model, it is possible to measure the penetration of electricity produced from RES and VRES based on the energy mix simulated in POLES. The market penetration of these technologies is depicted in [Figure 6](#).

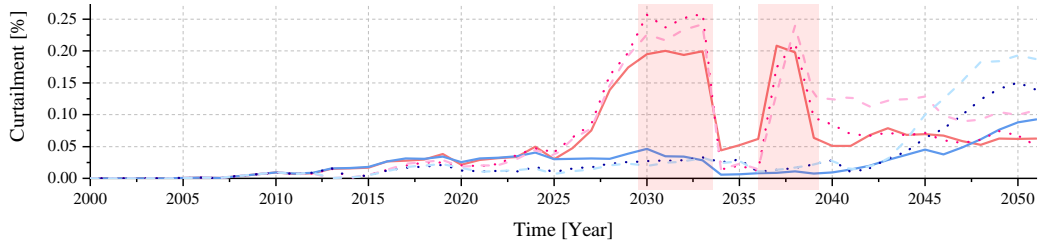
By 2050, the RES market reaches in all scenario a maximum of 56 % of the total production except in the case of the cost optimisation that sees a lower RES penetration (48 % for the BAU scenario and 53 % for the CP scenario). This trend is coherent with the findings from the PRIMES model as depicted in [Figure 6a](#). A similar trend can be seen for electricity produced from VRES. The electricity production from VRES attains a level of 35–37 % of the total electricity production in all scenarios and optimisations except for the cost optimisation in the BAU scenario. In the latter, the VRES production reaches only 31 % by 2050. The main difference between the two



(a) Renewable energy.



(b) Variable energy sources.



(c) Curtailment rate.

Figure 6: Pan-European renewable and variable energy penetration rate, as a fraction of the total electricity produced, with the corresponding curtailment rate from 2000 to 2050.

scenarios is that VRES penetration increases twice as fast for the CP scenario with a rate of 1.2%/year than for the BAU scenario (0.6%/year on average). The multi-objective optimisation follows a similar behaviour than the one based on the climate change related emissions.

Curtailment is an important indicator to evaluate if some production from VRES has been avoided to protect the stable operation of network but also to know if the VRES production was used in the most efficient way. [Figure 6c](#) illustrates the temporal variation of the curtailment level at the European scale. Two main peaks of curtailment period are identified when the CP scenario is considered: 2029–2033 and 2036–2038. The multi-objective optimisation demonstrates higher levels of curtailment than with the cost optimisation alone but lower than with the environmental optimisation. At the European scale, the curtailment is limited to a very low level of 0.26%/year (note that it is a European average). For information, the maximum peak of 39%/year of curtailed production is reached in a cluster (16FR) known for its critical infrastructure [44] (See [Figure 2b](#) for the clusters' representation) and has been subject to numerous projects to improve its reliability, the latest being the FlexGrid project piloted by the PACA region to increase flexibility.

4.3.2. Impacts on the infrastructures of the power system

Changes in the infrastructure of the transmission line is critical as the EUTGRID model is based on an optimisation of the pan-European power system through power balancing in the transmission network, considered as a super-grid. Investments are done either to reinforce the existing power lines or to build new HVAC/HVDC lines. In turns, the adjustment of the

power network will be considered as an increase of the capacity of the power lines. Investments for the various scenario are illustrated in [Figure 7](#), see also [MovieS1](#) for an interactive presentation of the investments and the physical infrastructure development for the period 2000–2050. Investments plan for the system cost optimisation are already reported in another study and validated against the ENTSOE-E projections on grid investment needs [25]. For the period 2010–2030, the investment plan has already been defined by ENTSOE-E and therefore EUTGRID does not create more investments and line reinforcements (grey area in [Figure 7](#)). For the period 2030–2050, the investments plan based on the identified congested line and reinforcement needs are then further implemented.

First, the main difference between the CP and the BAU scenarios is the need for larger investments. On average, the system cost optimisation sees an increase of +18% in its investments, the climate change emissions optimisation +43%, and the multi-objective optimisation +55%. The main investment occurs in 2033 in every optimisation cases with a high HVDC installed capacity of about 46 GW, and smaller investments on HVAC line with 20 GW, 26 GW, and 22 GW installed capacity for the previously mentioned optimisation respectively. It can be hypothesised that this large investment need in infrastructure comes after the sudden peak of curtailed VRES production as it is illustrated in [Figure 6](#). In both scenarios, the cost optimisation has the highest investments on the infrastructure. For the period 2010–2050, the cost optimisation invested \$318 billion (\$180 billion for 2010–2030 and \$138 billion for 2030–2050) in the BAU scenario and \$374 billion (\$180 billion for 2010–2030 and \$194 billion for 2030–2050) in the CP scenario. In that

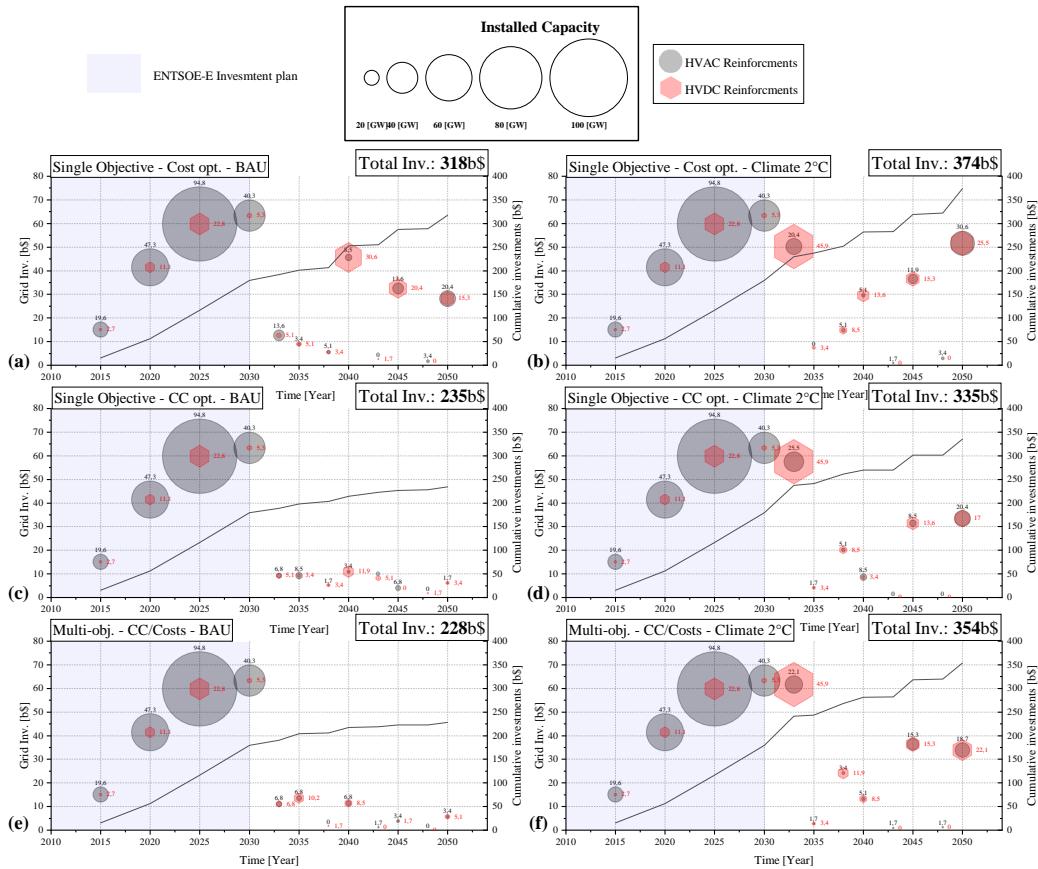


Figure 7: Pan-European transmission network investments under BAU policy (left) and climate 2°C (right) policy projections. Operational cost objective (top), environmental impact objective (middle), and multi-objective optimisation (bottom) are presented (See also [MovieS1](#)).

case, the environmental optimisation has the lowest investments in the infrastructure while the multi-objective is in-between. The multi-objective optimisation presents more investments in the HVAC infrastructure in 2045 and HVDC in 2050 than the emission optimisation. However, in the case of the BAU scenario, the multi-objective optimisation presents the lowest investments although close from the emission optimisation. Overall, the multi-objective optimisation has -28% of investments compared to the cost optimisation in the BAU scenario, and -5% in the CP scenario.

As detailed in Allard et al. [37], the EUTGRID model does not consider cancellations, delays or rescheduling of investments, which in turn can under-evaluate those investments needs as projected in the model. Nevertheless, the investment mechanism is consistent with findings from ENTSOE-E when putting aside temporal delays happening in any construction projects. Moreover, electricity production and management technology investments will need to be considered and are evaluated by POLES to range between 198 b\$/year to 249\$/year for the period 2015–2050 for different policy scenario [5].

4.3.3. System costs

The scenario that limits most of the system costs is the single objective cost optimisation under BAU scenario. The second most economical alternative is the single objective system cost optimisation under the CP scenario. This outcome was expected as the BAU scenario is the one that presents the least changes in technology. The evolution of the system costs follows two main patterns and is presented in [Figure 8](#).

All trajectories based on the BAU scenario see the price of the system

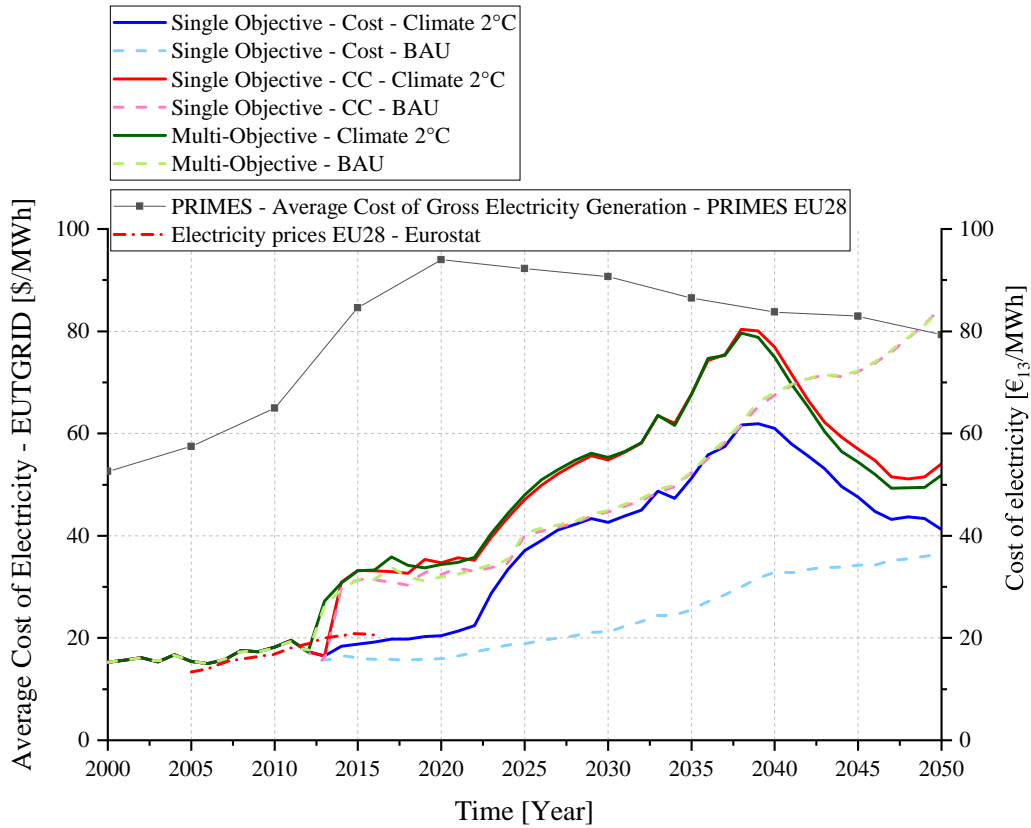


Figure 8: Evolution of the pan-European system costs through the period 2000–2050. On the right axis are the Eurostat and PRIMEs data, on the left axis are the EUTGRID results.

constantly rise throughout the period 2000–2050. The optimisation under the CP scenario presents a greater increase of the system operation cost: on average 1.9 \$/MWh/year ($\sigma = 0.09$) for the period 2010-2038, as detailed in Table 1.

Table 1: Mean yearly evolution of the pan-European system costs, per optimisation and scenario (\$/MWh/year) and associated σ .

Opt.	Sc.	2010–2038		2039–2050	
		Mean	σ	Mean	σ
Cost		1.64	0.09	-2.01	0.14
C.C.	CP	2.06	0.08	-2.65	0.31
M-O.		1.99	0.08	-2.71	0.33
Cost		0.43	0.05	0.39	0.02
C.C.	BAU	1.37	0.07	1.53	0.13
M-O.		1.32	0.06	1.47	0.13

C.C.: Climate change; M-O.: Multi-objective; Sc.: Scenario; Opt.: Optimisation

During the same period, the multi-objective and climate change emissions-only optimisation, under the BAU scenario, saw their operational cost increase at a pace of 1.35 \$/MWh/year ($\sigma = 0.07$) on average. The cost optimisation was even lower as the increase rate is about 0.43 \$/MWh/year ($\sigma = 0.05$). On the contrary, from the year 2039, the tendency is the opposite in the case of the CP scenario. From 2039 to 2050, the price of the power system electricity decreases at a pace of -2.46 \$/MWh/year ($\sigma = 0.26$) on average under the CP scenario. In case of the BAU scenario, the system cost

keeps on increasing at a speed varying from 0.39 \$/MWh/year ($\sigma = 0.02$) in the case of system cost optimisation to 1.53 \$/MWh/year ($\sigma = 0.13$) in the case of the environmental emission optimisation. These results are following a similar trend than those recorded by Eurostat [45]. Nevertheless, the other major model for representing the future European power system have much greater cost values and could not be easily compared [33].

Interestingly, the multi-objective optimisation follows the same pattern than the climate change emissions-only optimisation until the year 2039. After that, the multi-objective optimisation has a lower systemic cost than the emissions-only optimisation although it is not statistically significant ($p = 0.05$). Blarke and Jenkins [12] suggested to integrate more smart-grid technologies to reduce the system cost as the super-grid approach had a tendency to increase the system costs.

Furthermore, the system costs seem to have a negative correlation with the infrastructure investments level as the cheapest systems are those that received the largest investments. This correlation ranges from -0.06 (no correlation) to -0.82 (correct correlation) in the case of the environmental objective under the BAU scenario. A similar correlation level was observed with the multi-objective optimisation coupled with the BAU scenario. A summary of the correlation is provided in Appendix, [Table A.2](#).

4.3.4. Long-term climate change related emissions

The main goal of the climate policy is to preserve the rise of the earth temperature by 2°C by the end of the century. The path to achieve this goal may differ depending on the strategy to use dispatchable technologies for favouring the penetration of VRES in the transmission network. The

variation of climate change related emissions for the period 2000–2050 in absolute and cumulative terms is illustrated in [Figure 9a](#) and [Figure 9b](#) respectively.

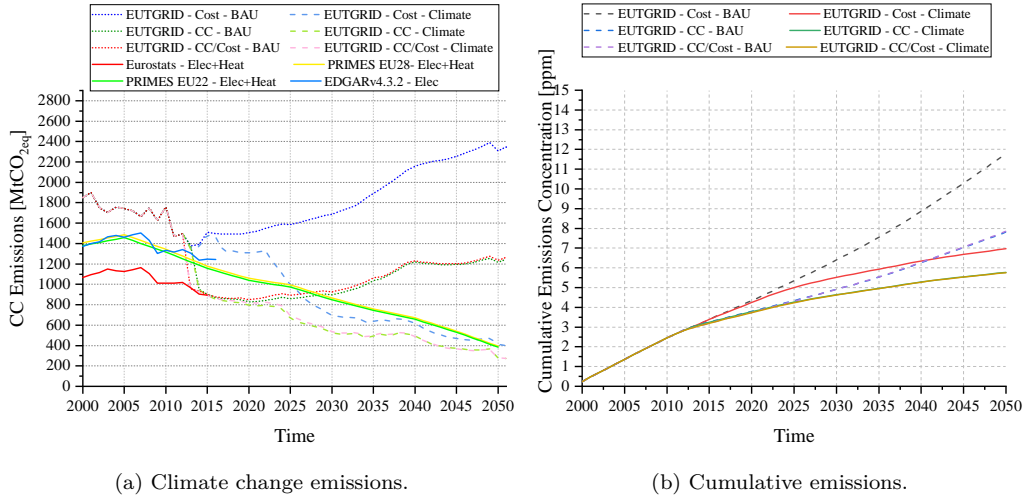


Figure 9: Emissions related to the European electricity production towards 2050, modified from [\[35\]](#).

As mentioned in the [subsection 2.3](#), the considered emissions are characterised emissions from LCA studies, therefore considering more gases contributing to the global warming. This explains mainly the reason why higher emissions are found using the EUTGRID model.

A previous study [\[35\]](#) has shown that using an environmental merit-order led to a faster decrease of the emissions resulting in reaching the reduction of climate change related emissions sooner than in a scenario only based on economic criteria. Consequently, it resulted in a reduction of the accumulated climate change emissions in the atmosphere. Implementing the multi-objective optimisation model results in emission levels equal to the single objective model driven by an emission minimisation objective. Therefore,

it is possible to reduce the emissions to the same level than the one of the single objective. On average, the emissions are lower by 23% than the cost objective function alone. As a result, less carbon dioxide equivalent emissions are accumulated in the atmosphere.

However, in the case of the BAU scenario, the emissions keep increasing in all optimisation. With the system cost objective, the emissions keep on increasing at a pace of 29 MtCO_{2-eq}/year ($\sigma = 1.09$), while the emission optimisation and the multi-objective optimisation reduce that increase by half to reach an average of 14 MtCO_{2-eq}/year ($\sigma = 0.8$). Similarly to the CP scenario, the multi-objective and environmental emission optimisation were perceptibly the same. Consequently, the accumulated emission concentration, in the BAU scenario, were higher than in the CP scenario. The biggest difference was in the system cost objective optimisation under the BAU scenario, reaching twice the amount of CO_{2-eq} (11.8 ppm) than the multi-objective optimisation under the CP scenario (5.75 ppm). The dilemma being that the system cost objective optimisation under the BAU scenario has a lower system costs through the period until 2050 while having the highest emission rate and accumulated emissions compared to all other scenario.

5. Conclusions

This study investigated the potential to manage the production of dispatchable technologies to minimise the costs and the global warming related emissions of the European power system by 2050. To this effect, two separate models have been used: the long-term energy simulation model POLES, and the power system optimisation tool EUTGRID. While POLES simulates on

a yearly basis the needs for electricity country by country, the EUTGRID model optimises the system costs, on an hourly basis, of the used dispatchable technologies. The EUTGRID model was further adapted to minimise the global warming related emissions. In this study, the augmented ε -constraints method was implemented and adapted to minimise both optimisation objectives. The results were analysed on the impacts on long-term investments, global warming related emissions, and system costs of the power system using a business as usual (BAU) and 2°C climate change scenarios (noted CP). A compromise solution of the multi-objective optimisation was selected and specifically studied regarding the system costs and global warming related emissions.

The long-term investments of the multi-objective optimisation was a fair trade-off in the case of the CP scenario but had the lowest investments in the BAU scenario. Overall, the multi-objective optimisation resulted in an infrastructure investment need of \$354 billion and \$228 billion in the case of the CP scenario and BAU scenario respectively by 2050. Furthermore, the impact of the multi-objective optimisation on the system costs demonstrated a tendency to follow the same pattern and magnitude of the mono-objective emission optimisation in both scenarios. Above all, the mono-objective optimisation on system costs was the most economical option in both scenario. Nevertheless, the multi-objective optimisation compromise solution was more economical than the emission optimisation in the BAU scenario but the emission optimisation was more economical in the CP scenario. The system costs are inversely correlated with the investments level in the power system's infrastructure. In other words, EUTGRID increases the investments in trans-

mission line infrastructures to favour exchange of electricity between clusters to minimise the system costs.

The impact on the climate change emission level were demonstrated to follow the same decline and therefore reached faster lower emission levels than any other optimisation tested. A faster decrease in the emission will result in a decrease amount of cumulative greenhouse gases in the atmosphere over time. Combined with the previous conclusions, it is hypothesised that to reach faster emission level targets will imply on the one hand less investments in the infrastructures but the prioritisation of less emitting technologies, such as gas over coal-based power plant. It will still lead to a faster increase in the system costs of about 20 % compared to a cost-optimised system. In other words, EUTGRID favours the production within clusters while shifting technology use by utilising less emitting dispatchable technologies to minimise emissions. The multi-objective optimisation therefore is a compromise between these two mono-objectives.

The method presented in this study demonstrated that policy-only solutions, combined with a traditional least-cost optimisation, has a limited impact on the contribution of the power sector to reach the emission level targets. Integrating emission objective to the management of power-plants to the least-cost optimisation would enhance faster emission reduction. The counterpart is that the system electricity price will tend to increase faster thus implying increased social impacts.

It is expected that the EUTGRID model will continue its development towards the optimisation of selected distribution networks across the defined geographical boundaries. Therefore, the multi-objective optimisation should

be carried out also in a finer defined grid and ultimately, a combined smart-grid and super-grid model based on multi-objective optimisation is carried out to support future policies. Furthermore, solutions must be found to integrate more than two objectives as it is limiting the number of evaluated scenario.

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6. Data availability

Datasets related to this article can be found at <http://dx.doi.org/10.17632/w4hp2rb2tz.1>, an open-source online data repository hosted at Mendeley Data [dataset] [39]. Further, data visualisation based on these results are available online at http://bit.ly/Energy_Louis2019a.

7. Supplemental data

Supplemental Data include one movie and can be found with this article online at ...

Appendix A. Correlation factors

Table A.2: Correlation coefficients between the grid investments and the system average cost of electricity from EUTGRID for the period 2010–2050.

Opt.	Sc.		Pearson Corr.	Spearman Corr.	Kendall Corr.
Cost		Corr. Factor	-0.23	-0.48	-0.30
		p-value	0.47	0.11	0.17
C.C.	CP	Corr. Factor	-0.27	-0.25	-0.14
		p-value	0.40	0.43	0.54
M-O.		Corr. Factor	-0.18	-0.18	-0.06
		p-value	0.58	0.57	0.78
Cost		Corr. Factor	-0.39	-0.43	-0.36
		p-value	0.21	0.16	0.10
C.C.	BAU	Corr. Factor	-0.64	-0.82	-0.61
		p-value	0.02	0.00	0.01
M.-O.		Corr. Factor	-0.67	-0.79	-0.55
		p-value	0.02	0.00	0.01

C.C. stands for climate change and M-O. stands for multi-objective.

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