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Citation for the published version (APA 6th)
Lie, A. Ø., Rye, E. A., Svendsen, H. G., Farahmand, H., & Korpås, M. (2017). Validation study of an approximate 2014 European power-flow model using PowerGAMA. *IET Generation, Transmission & Distribution, 11*(2), 392-400. doi: http://dx.doi.org10.1049/iet-gtd.2016.0856

IET Generation, Transmission & Distribution

Research Article

ISSN 1751-8687
Received on 3rd June 2016
Revised on 9th September 2016
Accepted on 26th September 2016
doi: 10.1049/iet-gtd.2016.0856
www.ietdl.org

Validation study of an approximate 2014 European power-flow model using PowerGAMA

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Abstract: This study presents a validation study of an approximated model of the European power system in 2014. A lightweight and open-source power-flow tool is used for this study. The tool and the model are publicly available and can be adapted to study future impact of large investments in the power system, specifically large-scale integration of renewable energy. The input dataset is based on a prior work, but it has been substantially updated for 2014. To maintain all aspects of the model open-source, only publicly available data was implemented. The modelling approach and simplifications are explained. Comparison of the simulation results with actual data on cross-border flows and energy mix for 2014 shows acceptable correlation. The model is able to capture main characteristics of the power system, such as reservoir handling, hydro pump pattern, and seasonal variation on cross-border flows.

1 Introduction

The power system is changing at an ever-faster rate, introducing new technologies and solutions to meet the future requirements of a low-emission power system. This fast developing energy transition brings new challenges for the power sector. One change is that renewable energy plants will be built in locations where the energy resources are good, often away from load centres, altering power-flow patterns and likely leading to grid congestions. The transition towards more renewable energy requires many long-term investments, both in renewable generation facilities, as well as technology and infrastructure to enable the power flow from these facilities to reach the consumption centres. Due to large costs associated with infrastructure investments, long planning and construction times, and long lifetimes, it is crucial to identify the location of future production plants and potential grid bottlenecks at an early stage.

Several studies have been carried out on the impacts of European targets to increase the share of renewable energy and wind power in particular. Singh *et al.* [1] assessed the unintended cross-border electricity flows using optimal power-flow simulations in the transmission grid in Central Eastern Europe (CEE) and Central Western Europe (CWE). It was concluded that without future grid reinforcement, the Polish grid would be highly affected by inadequate grid capacity along the north–south German corridor. Schlachtberger *et al.* [2] conducted a study using a simplified capacity and dispatch optimisation model of the European power system. The focus was on identifying the amount of flexible backup capacity reserved to deal with increasing share of variable renewable energy resources (RES) in Germany. It was concluded that physical restrictions of applying the optimal solution result in a significant increase of electricity cost. Bussar *et al.* [3] applied the simulation tool GENESYS to optimise the allocation and size of different generation technologies, storage systems and transnational grids of a European power system model. The power system was modelled in the form of interconnected regions with power exchange capacity based on adjustable net transfer capacities (NTCs). Eser *et al.* [4] developed an approach based on optimal power-flow simulation to study the impact of RES penetration and grid topology in CWE and CEE. The simulations showed the grid developments that were planned for 2020 to be sufficient to handle the impact of increased renewable generation in the region. Zimmerman *et al.* [5] created an open source Matlab-based power system simulation package called MATPOWER, which can solve large-scale AC and DC OPF problems. Farahmand *et al.* [6] presented detailed analysis of the value of Nordic hydropower as a resource in providing operational reserves to the continental system using Power System Simulation Toolbox (PSST), where flow-based power market simulations were conducted using DC optimal power flow (DCOPF). The simulation toolbox considered a detailed grid model of the European power system, computing the optimal generation dispatch and flow along transmission lines for each hour of the simulation year. Kunz [7] has investigated the impact of physical network constraints on spot market results and total costs. A model of the European electricity market (ELMOD) including the physical transmission network was applied for this study. The results showed that the cost of congestion management increased fourfold in 2020 compared with that in 2008. However, congestion cost could be significantly reduced through proposed network extension.

License terms for available power system models and confidentiality issues on datasets make it difficult to share details about studies of the European power system. Although some of the tools are open source, they often require a costly license for a commercial software that hosts the tool, i.e. MATPOWER requires MATLAB licence to be executed. Therefore, it is not possible to access a version of the tool that allows freely modifying and redistributing the code. The present work addresses the open source and open data issue by establishing an open dataset [8] covering continental Europe, and analysing it with the open-source Python-based PowerGAMA tool [9]. The tool and the dataset are publicly available and can be applied to study a large-scale European power system model.

Since the current European power grid is one of the largest interconnected power systems in the world, it is sensible to simulate the whole system for multiple reasons. By utilising such a large dataset, some of the complications related to modelling the variability of RES are diminished due to cross-border flows, as peak inflow and demand varies for each country. This gives a more realistic analysis when simulating scenarios for large-scale integration of renewable energy. Additionally, the model and datasets can be used as a basis to analyse the effect of other major shifts in the energy sector, such as the impact of large power plant investments or shut downs, e.g., the nuclear phase-out in Germany, increased hydro pump power capacity, new interconnections, or future case studies of large-scale integration of renewable energy.

This validation study aims to give comprehensive insight into the modelling approach and applications. First, the modelling approach is explained, with details of the functionality of the tool, how the input data is gathered and implemented, and which modifications are necessary to tune the model. Then, the major results are analysed and their important characteristics are discussed, before concluding remarks and further work is proposed.

2 PowerGAMA python package

The analysis is performed using the flow-based power market simulator, PowerGAMA (Power Grid and Market Analysis), developed by SINTEF Energy Research [https://www.sintef.no/en/sintef-energy/]. This is a lightweight simulation tool, implemented as an open source Python package for analysis of large interconnected power systems. PowerGAMA uses linear programming to optimise the generator dispatch for all generators in the system based on marginal cost for each time-step over a given period. The market model assumes a perfect competition market, where power-flow constraints and generator marginal costs determine the generator dispatch and nodal prices, minimising the total system cost. The model takes into account grid constraints and variability in generation and demand using time-series input, and has the functionality to support energy storage and flexible loads.

PowerGAMA is an open source re-implementation of the functionality of previously developed Matlab-based Power System Simulation Tool (PSST). PSST is a tool typically used for studying the effect of large scale penetration of Wind and PV power and the corresponding grid constraints and needed grid expansion. The model has been applied in several European projects, e.g. TradeWind, OffshoreGrid, Windspeed and TWENTIES.

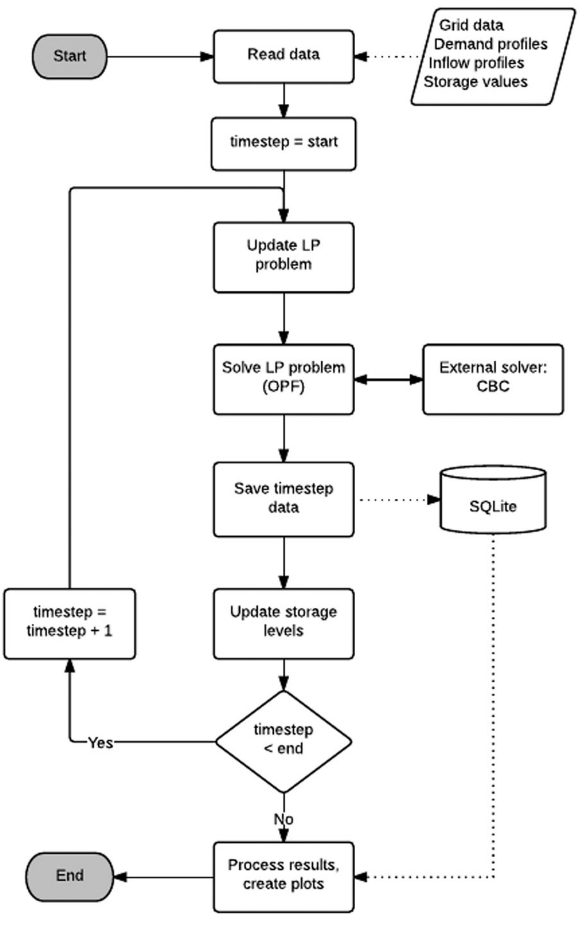

Fig. 1 *PowerGAMA flowchart*

The main algorithm implemented in PowerGAMA is outlined in the flowchart in Fig. 1. The core of the algorithm is an optimal power-flow problem (OPF) that is formulated as a standard linear programming (LP) optimisation and solved for each time-step.

2.1 Mathematical formulation of PowerGAMA

In the LP problem, the linearised power-flow equations from the DC power-flow method [10] are used, minimising the system cost for each time-step. The linear optimisation problem has the following sets, indices, parameters and variables for each time-step:

Sets:

$\mathcal{G}$ set of generators
$\mathcal{S}$: set of pumps
$\mathcal{N}$ set of nodes
$\mathcal{K}$ set of AC and DC branches

Indices:

g generator
s pump
n node
k branch

Parameters:

$C_{\rm g}^{\rm gen}$ cost, generator g (€/MWh)
$C_s^{\rm pump}$ cost, pump s (€/MWh)
$C^{\rm shed}$ fixed cost of load shedding (€/MWh)
$P_k^{\max}$ branch capacity, branch k (MW)
$P_{\rm g}^{\min}$ minimum production, generator g (MW)
$P_{\rm g}^{\rm limit}$ available power[1], generator g (MW)
$P_s^{\rm pump,\,max}$ pump capacity, pump s (MW)
$P_n^{\rm cons}$ consumption at node n (MW)

Variables:

$p_{\rm g}^{\rm gen}$ generation by generator g (MW)
$p_s^{\rm pump}$ pump power demand, pump s (MW)
$p_n^{\rm shed}$ load shedding, node n (MW)
δ_n power angle, node n (°)
$p_k^{\rm ac/dc}$ power flow, AC/DC branch k (MW)

The objective function is given as in (1), where SC denotes the operating cost of entire system. In principle, load shedding is modelled as a generator connected to the same bus as the load, and the marginal cost for load shedding is equal to load shedding penalty cost.

$$\min SC = \min\left(\sum_{g\in\mathcal{G}} C_{\rm g}^{\rm gen} p_{\rm g}^{\rm gen} - \sum_{s\in\mathcal{S}} C_s^{\rm pump} p_s^{\rm pump} + \sum_{n\in\mathcal{N}} C^{\rm shed} p_n^{\rm shed}\right) \quad (1)$$

Subject to (2)–(5)

$$-P_{ij}^{ac-\max} \le P_{ij}^{ac} \le P_{ij}^{ac-\max}, \quad i,j\in\mathcal{K} \quad (2)$$

$$-P_{ij}^{\rm dc-\max} \le P_{ij}^{\rm dc} \le P_{ij}^{\rm dc-\max}, \quad i,j\in\mathcal{K} \quad (3)$$

$$P_{\rm g}^{\min} \le p_{\rm g}^{\rm gen} \le P_{\rm g}^{\rm limit}, \quad g\in\mathcal{G} \quad (4)$$

$$0 \le p_s^{\rm pump} \le P_s^{\rm pump,\,max}, \quad s\in\mathcal{S} \quad (5)$$

where (2)–(5) are the constraints that delimit the variables. From the DC power-flow equations [10], we have the power-flow constraint (6), which describes the flow in the AC branches only

$$P_{ij}^{\text{ac}} = B_{ij}(\delta_i - \delta_j) \tag{6}$$

Energy balance constraint at each node n is given by the following equation

$$\sum_{g\in\mathcal{G}_n} p_{\text{g}}^{\text{gen}} - \sum_{s\in\mathcal{S}_n} p_s^{\text{pump}} + p_n^{\text{shed}} - \sum_{j\in n} p_{nj}^{\text{dc}} - \sum_{j\in n} p_{nj}^{ac} = P_n^{\text{cons}} \tag{7}$$

The last constraint from the power-flow equations is (8) representing slack bus

$$\delta_1 = 0 \tag{8}$$

2.2 Modelling of energy storage in PowerGAMA

The utilisation strategy of energy storage is governed by *storage values* $v(f, t)$ that indicate the value of keeping energy in the storage for the future. Storage values may depend on time t and storage filling level f. For generators associated with an energy storage, the generator cost in the objective function is set equal to the storage value, i.e.

$$C_g^{\text{gen}} = v_{\text{g}}(f, t) \quad \forall \quad g \in \mathcal{G}_{\text{storage}} \subseteq \mathcal{G}, \tag{9}$$

where the set $\mathcal{G}_{\text{storage}}$ of generators with storage is a subset of all generators $\mathcal{G}$. Thus, if the storage value is lower than the cost of alternative generation, the generator will produce, and if it is higher, the inflow is kept in the storage until the next time-step. When storage is included, the optimisation must be done sequentially because storages, and therefore generator costs, must be updated between each time step. In each time step, the storage value $v(f, t)$ is computed according to

$$v(f, t) = v_0 \hat{v}_{\text{filling}}(f) \hat{v}_{\text{time}}(t), \tag{10}$$

where v_0 is a fixed reference price for a given storage, $\hat{v}_{\text{filling}}(f)$ is a normalised function dependent on the storage filling level f, and $\hat{v}_{\text{time}}(t)$ is a normalised function dependent on time. The combination of these factors enables the tool to capture a realistic reservoir handling without the need to apply computationally demanding storage optimisation logic. The parameter v_0 and the functions $\hat{v}_{\text{filling}}(f)$, and $\hat{v}_{\text{time}}(t)$ are provided as user input per storage generator reflecting the desired storage utilisation strategy.

The function $\hat{v}_{\text{filling}}(f)$ should ensure that the storage is neither filled nor depleted completely. The function applied in this study is illustrated in Fig. 2. The function is normalised with a value one at 50% filling. As can be seen from the figure, an increased storage filling level decreases the value to ensure resources are not spilled. A reduction in the filling level increases the storage value to secure the reservoir from being emptied below acceptable levels.

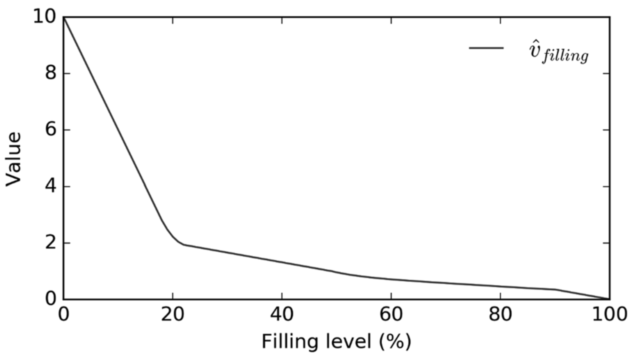

Fig. 2 *Storage value depending on reservoir filling level*

The function $\hat{v}_{\text{time}}(t)$ may be used to capture predictable seasonal or daily variations in filling level. This factor could represent the knowledge of expected inflow and electricity prices, forcing the power plants to store and generate reasonably considering the expected development in the future. In the present study, no time dependency has been taken into account, i.e., $\hat{v}_{\text{time}}(t) = 1$. As can be seen in Section 5.6, this simplified storage representation provides a reasonable match with historic reservoir handling, while being fast and flexible, as the modeller may tweak the storage value curves according to the situation.

2.3 Underlying assumptions and simplification in PowerGAMA

Some simplifications are considered in PowerGAMA, including the exclusion of limits on ramp rates, start-up costs, forecast errors and hourly barriers on the utilisation of interarea branches. Due to these simplifications, the results of the analysis are considered optimistic in terms of the power system's ability to dispatch energy, and will therefore overestimate the capacity to accommodate renewable energy production. On the other hand, PowerGAMA takes the physical power flow into account, which is a significant advantage over the power market simulators that only consider energy balance, such as the EMPS [SINTEF, EFi's EMPS — http://www.energyplan.eu/othertools/global/emps] model. An in-depth explanation of how PowerGAMA works is given in the PowerGAMA User Guide [11].

3 Input data

The dataset is built on various publicly available sources for power data, and in this section, we explain how it has been established.

The European power system is a large-scale system including many variables, and hence creating a completely realistic model and dataset that gives the correct generation mix and flow for each hour throughout a year is beyond the scope of this study. Many simplifications have been implemented, making this an approximate dataset yielding approximate simulation results. For an open dataset, this is largely inevitable as grid companies and power plants are unwilling to openly share data. This leads to lacking and inaccurate data, which is especially true for, e.g. marginal cost of generation. Nevertheless, it is possible to create a dataset that can reproduce the aggregated cross-border flow and energy production for each technology type over the course of 2014. The aim with this input data is to create a dataset that represents actual data from 2014, while being suitable for analysis of future scenarios by avoiding imposing restrictions that are case specific. Although this leads to simulation results that deviate from the actual data of 2014, the approach enables a more generally realistic hourly and seasonal dynamic of the different generator outputs and interarea flows through the year, as illustrated in this paper.

The bulk of the input grid data is obtained from the 2009 power-flow model of Hutcheon and Bialek [12], which contains approximate data on nodes, branches, generation, and consumption for most European countries. The other part of the input dataset is taken from a 2014 Mediterranean case study [13], implemented in PowerGAMA as part of the EU-funded EuroSunMed project. That study covers the countries Switzerland (CH), Spain (ES), France (FR), Italy (IT), Morocco (MA) and Portugal (PT), and except for Morocco is also based on Hutcheon and Bialek's [12] model, but updated to 2014 values. The results from the study were compared with those with the actual data of 2014 [13].

The current dataset contains 26 countries, including in total 1539 nodes, 1123 consumers, 1158 generators and 2399 branches. In addition, the model considers the exchange with neighbouring countries Norway, Sweden, UK, Ukraine and Turkey. Fig. 3

depicts all nodes and branches for the 2014 dataset, and the full scenario log can be studied in detail from [8].

3.1 Nodes

Some minor changes have been performed, listed in the scenario log. The geographic location of the nodes in the Benelux countries, Denmark and South Eastern Europe has been updated in accordance with the 2014 ENTSO-E Grid Map [14].

3.2 Branches

The input grid is taken from Hutcheon and Bialek's model of 2009 [12], where internal grids in all countries except for Morocco are modelled with unlimited branch capacity. This can be considered as a simplification that assumes the grid as adequately dimensioned. However, major changes have been made in cross-border lines. The transfer capacities on all cross-border AC lines above 220 kV have been updated in accordance with [15]. Further, if data is available from [16] for the day ahead NTC values in both directions, the capacity is scaled using the mean of the highest of the bidirectional NTCs per hour in 2014. One internal AC branch in Macedonia and an HVDC branch between Denmark West and Denmark East were added, as they were missing from the dataset in [12]. In addition, HVDC cables in Europe have been added using the 2014 ENTSO-E Grid Map and various sources on capacity listed in [8].

3.3 Consumers

The distribution of load by nodes within countries has been kept as in [12], and scaled based on 2014 data from ENTSO-E [15]. As [12] only contained Western Denmark, consumption for Eastern Denmark was added in accordance with [17].

3.4 Generators

The generator sources include, among several others, the 2014 ENTSO-E Grid Map, Enipedia, the Global Energy Observatory and the US DOE Global Energy Storage Database. The dataset includes ten generator types; coal, nuclear, gas, oil, wind, offshore wind, solar photovoltaic, concentrated solar power, hydro and other renewables. All generators were designated to one of these categories, further explained in [8]. Solar and wind power generators were manually aggregated and added to nodes for all countries, and in several countries all generators were updated. In total, 496 additional generators were added compared with [12, 13]. Ultimately, the generation capacity for all countries was scaled by type based on statistical data for 2014 from ENTSO-E [15].

The marginal costs for all solar, wind and run of river hydro generators reflect the operation and maintenance cost, and were set to 0.5 €/MWh, whereas the marginal cost of hydro with storage depends on the reference price, storage filling level and time of day, and is thus variable through the year. The fuel cost for other renewables, mostly bio fuel and waste incineration, was set to 55 €/MWh, slightly lower than that of conventional power plants as described in [18], and listed in Table 1. The penalty cost of load shedding is set to 1000 €/MWh.

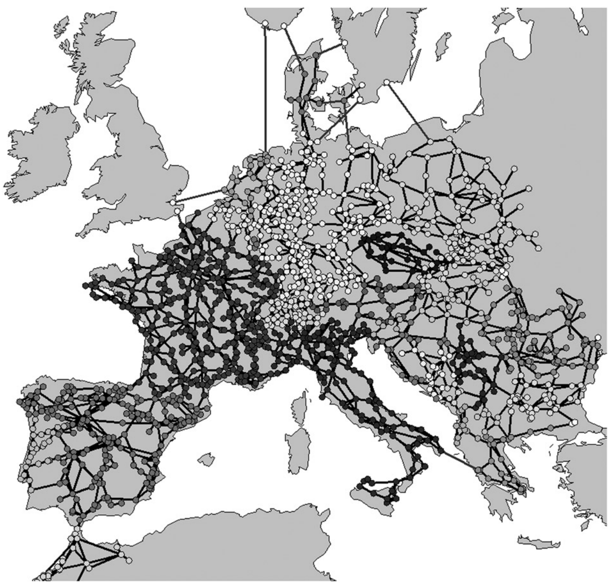

Fig. 3 *Location of nodes and branches for the 2014 dataset*

3.5 Storage

Information about storage size, mostly hydro reservoirs, is gathered from various sources. The exact locations of reservoirs are not obtained, and consequently reservoirs are added to all hydro plants and scaled based on each plant's rated capacity. The total reservoir capacity for each country is given in [8]. This approach has been successfully used in [19]. Pumped hydro locations are taken from [20], and capacity from various sources as listed in [8].

3.6 Load, inflow and storage value profiles

The hourly load profiles for consumers and inflow profiles for renewable energy generators for each country are taken from EU TradeWind project [19]. Solar and Wind inflow are based on weather data for 2012 and the storage value profiles are adapted from [13].

3.7 Inflow factors

The inflow factors for RES is calculated based on 2014 capacity and generation data from EuroStat [21] and ENTSO-E [15]. The availability factors for thermal power plants were implemented by setting their inflow factor equal to average annual availability in 2014 [22, 23].

3.8 System boundaries

The UK, Norway, Sweden, Ukraine and Turkey are represented by one node per interconnection, with generators and/or consumers modelling the power exchange with the system boundaries. In most cases, the flow is 97–100% in one direction [15], but between Norway/Sweden and Denmark/Germany, the flow fluctuates more frequently. These interconnections are modelled by a generator in Norway with an inflow profile equal to Norwegian exports and a consumer with a load profile equal to Norwegian imports.

4 Modifications of input data

The simulation results from the initial data gave insufficiently accurate results, and several updates have been made to improve the correlation between the simulated results and observed data, the detailed description of all the changes are out of the scope of this paper. However, the dataset itself, which is publicly available, includes a change log that specifies changes done to the data sources [8]. The main highlights of these changes are explained below.

Table 1 Thermal generator marginal cost

Type	Oil	Gas	Coal	Nuclear
marginal cost, €/MWh	162	70	60	11

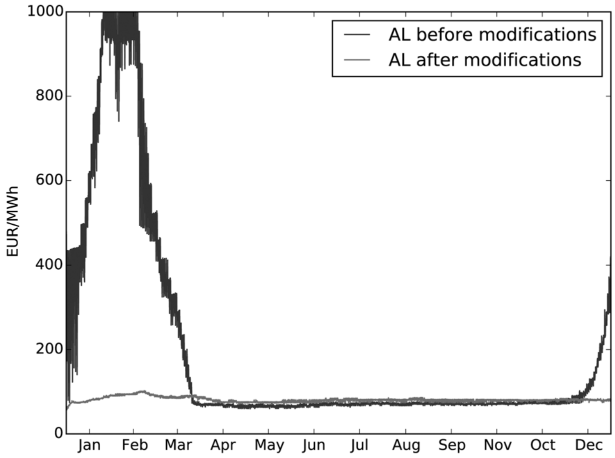

Fig. 4 *Nodal prices in Albania before and after modifications*

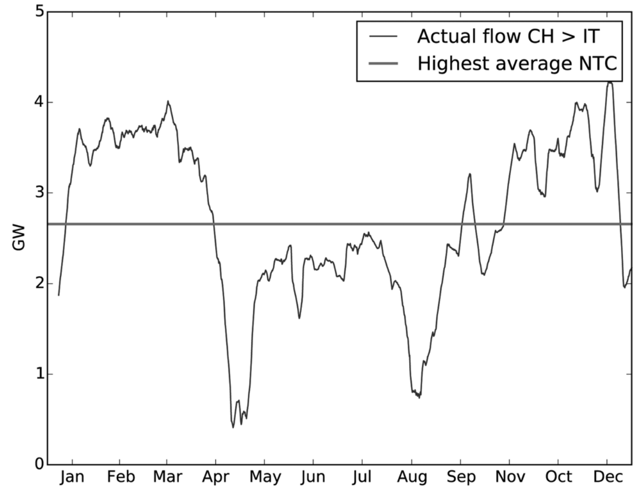

Fig. 5 *Actual flow (rolling weekly mean) and average NTC*

4.1 Hydro

Numerous iterations adjusting the storage reference price for hydro power plants, storage filling factor, initial reservoir level and dead-band value for pumped hydro storage (PHS) were performed in order to simulate the correct hydro output.

As illustrated in Fig. 4, some of the hydro inflow profiles used in the Balkan region resulted in load shedding and high nodal prices in early spring and late winter. In order to reduce the discrepancy, these profiles were changed in accordance with [24, 25].

4.2 Marginal cost

Since the preliminary input data assumes uniform marginal cost in all countries, errors concerning production and interarea flow were expected. Marginal cost modifications in ten countries have been implemented to reduce these discrepancies. Table 2 represents the modified marginal costs in given countries.

The most notable change was the marginal costs of thermal power in Italy and Germany. In preliminary simulations, Italy produced 25 TWh excess energy and Germany 25 TWh less energy compared with actual data, leading to increased irregular flows from south to north. As the coal mining production is significantly higher in Germany [26], and the gas price is higher in Italy [27] the marginal cost of coal and gas power plants was reduced in Germany and increased in Italy, which resulted in a more correct flow pattern.

4.3 Grid

Due to loop flows in the European power system [21], there is a net power flow Germany – Poland – Czech Republic – Germany. When modelling the system without capacity limits on internal branches, these flows proved hard to replicate. Since the simulated nodal prices in Germany are low and close to uniform, this leads to export to both Poland and the Czech Republic. Consequently, the same limits on internal branch capacity for Germany as used in [28] were imposed.

Using the average day ahead NTCs on interarea branches for a year also provided some difficulties. In some cases, the average NTC is lower than the average actual flow, and on other borders, they would impede significant seasonal flow variations. In Fig. 5 the actual flow from Switzerland to Italy and the average of the NTC are shown, where it highlights both the issues. If line capacities were limited by NTC values, then the total energy flow would be restricted by more than four TWh over the course of 2014.

4.4 Example with multiple modifications

To illustrate the improving effects of modifications, an example from simulation is presented. Albania, with 95% installed hydro capacity, experienced load shedding in early spring and late winter. Since the load shedding price is set to 1000 €/MWh, this impacts neighbouring countries by increasing exports and area prices. Additionally, flow from Central Europe was affected to support maximum flow to Albania, causing additional discrepancies.

The following sources of error were identified in Albania: the initial reservoir level was set too low, the hydro inflow profile was low in spring and autumn, while high in summer, which is the opposite direction of actual river discharge, and the load profile did not match actual consumption. By fixing these errors, the results were significantly improved, reducing flow deviations throughout Europe and eliminating load shedding in Albania, illustrated by the average nodal prices in Fig. 4.

This example highlights how sensitive the model is to coarse assumptions and minor errors, and a lot of time has been spent on investigating error sources like these.

5 Results and discussion

The results from the simulation in this section are compared with the actual recorded data from ENTSO-E [17], which is the most extensive database for European power system data. The emphasis in this validation study is on aggregated energy mix within a country and cross-border power exchange over the course of 2014. These indicators are easy to aggregate and compare, while still giving a sufficient representation of the high-level simulation results. Additionally, focus on seasonal variations of power flow and reservoir handling are highlighted.

5.1 Energy mix

Table 3 summarises the aggregated results for each country's generation in TWh for four generation categories. Note that the

Table 2 Modified marginal cost of thermal generator in ten countries

Country		AT	BG	CZ	DE	DK	GR	IT	NL	PL	RO
marginal cost, €/MWh	coal	58	55	56	55	56	78	68	57	56	55
	gas	65	70	56	57	57	88	78	57	56	70

Table 3 Energy mix (TWh)

	Thermal		Nuclear		Variable RES		Hydro	
AL	0.68	*−4%*	–	–	–	–	4.1	**+4%**
AT	13	*−19%*	–	–	3.9	0%	45	**+1%**
BA	9	**+3%**	–	–	–	–	5.5	*−3%*
BE	27	0%	32	0%	7.2	0%	1.3	*−3%*
BG	15	*−25%*	16	**+5%**	2.5	0%	4.6	*−1%*
CH	4.1	**+24%**	26	0%	0.6	0%	40	**+1%**
CZ	36	*−21%*	30	**+3%**	2.5	0%	3.1	**+6%**
DE	350	*−2%*	94	**+2%**	90	0%	25	**+5%**
DK	17	**+2%**	–	–	13	*−2%*	–	–
ES	100	*−5%*	58	**+6%**	63	*−1%*	44	**+4%**
FR	23	*−29%*	420	**+1%**	23	*−1%*	71	**+4%**
GR	31	**+2%**	–	–	6.5	0%	4.9	**+7%**
HR	2.5	*−16%*	–	–	0.7	0%	8.1	*−1%*
HU	8.1	*−22%*	15	0%	0.6	0%	0.2	0%
IT	180	**+5%**	–	–	38	0%	59	**+1%**
LU	1.2	*−13%*	–	–	0.1	0%	1.2	**+11%**
MA	24	0%	–	–	2	**+5%**	1.6	0%
ME	1.5	**+16%**	–	–	–	–	1.7	**+1%**
MK	5.5	**+49%**	–	–	–	–	1.1	**+2%**
NL	86	0%	3.9	*−4%*	5.8	0%	–	–
PL	140	**+2%**	–	–	7.2	0%	2.8	**+4%**
PT	20	0%	–	–	12	*−2%*	16	**+1%**
RO	22	*−6%*	11	0%	7.7	0%	19	0%
RS	28	**+10%**	–	–	–	–	12	0%
SI	5.6	**+60%**	6	0%	0.2	0%	6.1	*−2%*
SK	4.6	*−20%*	15	**+6%**	0.4	0%	4.5	**+1%**
total	1154	*−2%*	730	**+2%**	288	0%	384	**+2%**

category Thermal embraces all thermal generation including other renewables, which is mostly waste and biofuel incinerators. Nuclear and hydro power have own categories, while variable RES consists of all wind and solar technologies. The deviation between the simulated results and observed data from ENTSO-E is given as a percentage, where positive values imply a higher simulated generation than the reference.

The total aggregated generation deviates 1.7 TWh from the ENTSO-E reference. The main reasons for this deviation are insufficiently simulated pump power, and some minor cross-border connections at the system boundary that were left out of the model.

The generation accuracy varies for each country, but there are some general trends. The Variable RES generators have inflow factors based on their production time series in 2014. They have the lowest marginal costs, meaning they are dispatched first, resulting in small or no deviations aggregated over the year. Nuclear power plants have the second lowest marginal costs. These plants marginally overproduce when using actual availability factors. Hydro power plants, mostly with reservoirs, tend to overproduce. Since PowerGAMA does not support iterative water value calculations, the input modification concerning reference price and initial storage proved challenging, and did not converge towards 0% deviation. The largest discrepancies are observed in thermal production, which accounts for more than half of the total production. With mostly uniform prices, and no internal grid limitations, this is as expected. Overproduction of thermal energy within a country usually means that the country exports more energy than the observed data from ENTSO-E, while underproduction leads to higher imports, as discussed in Section 5.4. Another source of error is the coarse classification of the different thermal power plants, and the detailed results for these production types are not presented. As the thermal generators have identical behaviour in PowerGAMA, it is not deemed essential for future scenario analyses to differentiate more on these, unless a thorough fuel cost analysis is performed.

5.2 Hourly generation variation

The profiles for demand and renewable generation create a realistic daily generation profile for the power system. An example of this

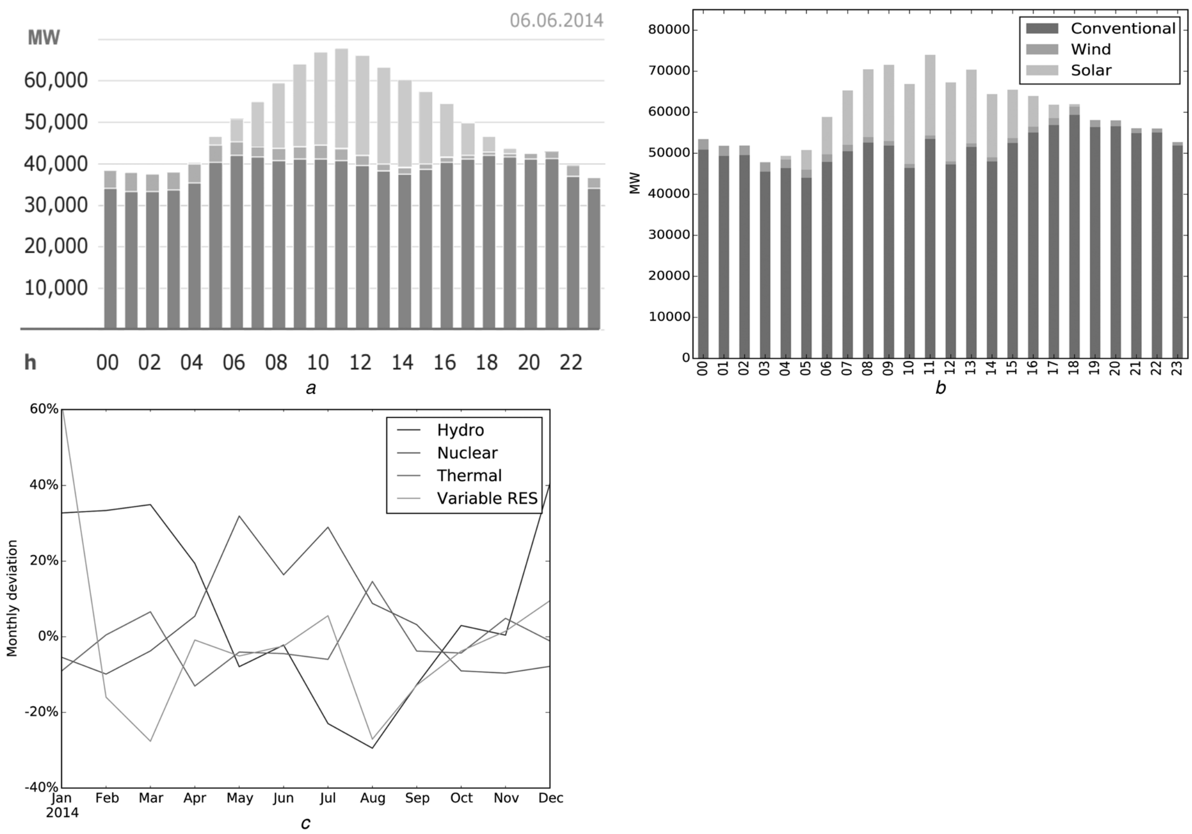

Fig. 6 *Deviation in generation mix in Germany*

a Actual generation mix 06.06.2014 [29]
b Simulated generation mix, 23.06.2014
c Monthly deviation

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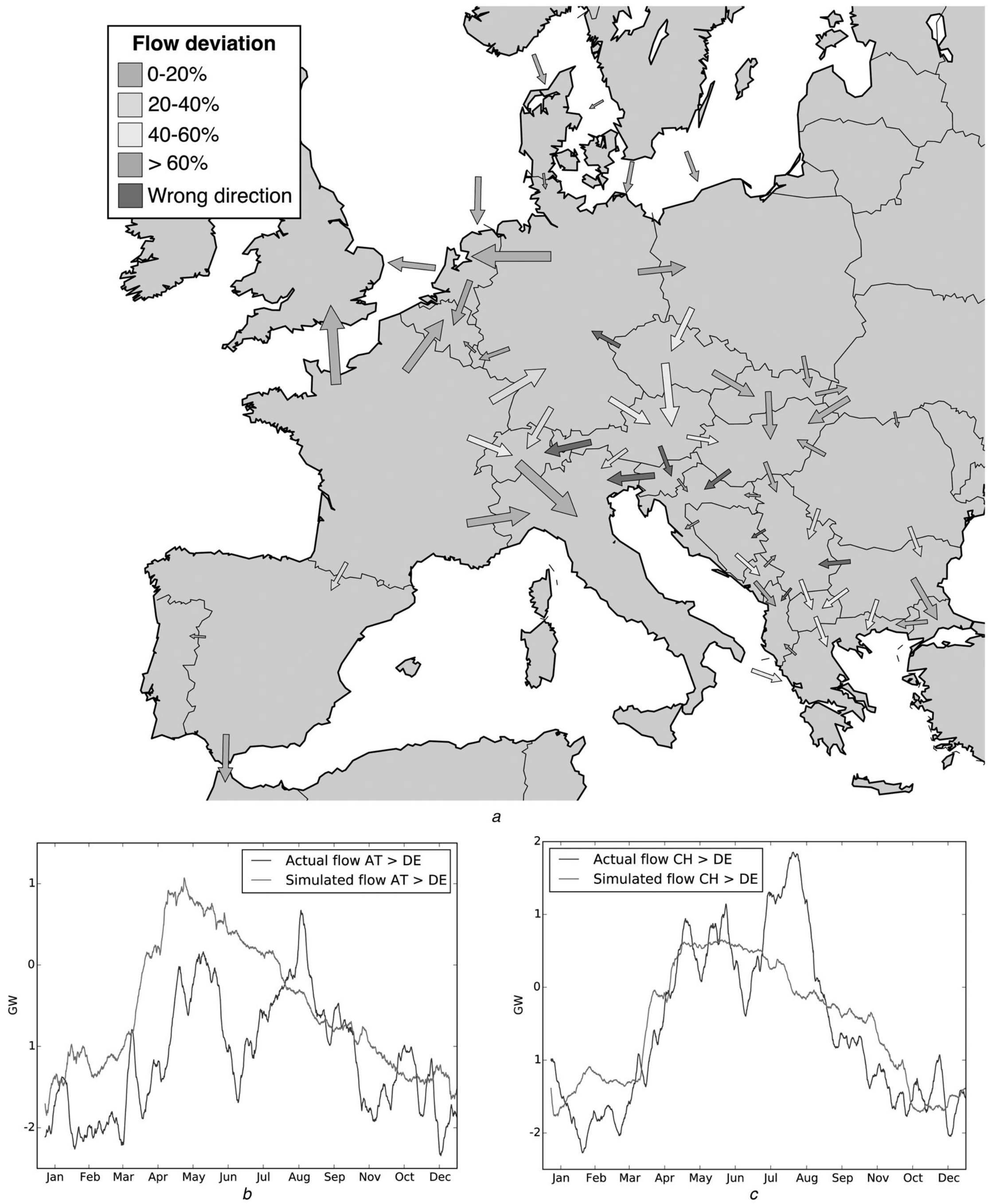

Fig. 7 *Cross-border flow deviations in Europe*

a Aggregated flow over the course of 2014
b Actual and simulated flow from AT to DE (rolling weekly mean)
c Actual and simulated flow from CH to DE (rolling weekly mean)

is from June 6, 2014 with the actual generation mix (Fig. 6*a*) and the simulated (Fig. 6*b*) generation mix of June 23, 2014 in Germany. June 23 is chosen because it is also a Friday with high solar inflow in the simulation. Around 7:00 AM the solar production increases rapidly in both cases, reaching a peak around midday, before declining towards the evening. Actual conventional generation is almost constant throughout the day, while simulated conventional generation varies more, possibly due to the exclusion of start-up and stop costs. Note that the production is higher in the simulated case, as more export is observed. Towards the evening, when both the demand and solar inflow decline, Germany becomes a net importer of energy in the simulated case. As can be seen, daily profile follows actual data.

5.3 Seasonal variation in generation

The deviation in seasonal variation of generation differs slightly from actual generation, as exemplified in Fig. 6*c*. The deviation of variable RES generation was expected; as the weather in 2014 differed from the average weather that the inflow profiles are built on. Nuclear generation, on the other hand, deviates due to the assumed constant availability factor. In reality, the availability of nuclear plants is lower in summer and higher in winter and the utilisation of available capacity is close to 100% [29]. When the utilisation of available capacity is close to 100%, meaning that the power plants are constantly running as base load when possible, this result shows that PowerGAMA may be used as a tool to find the seasonal variation in actual availability. It would

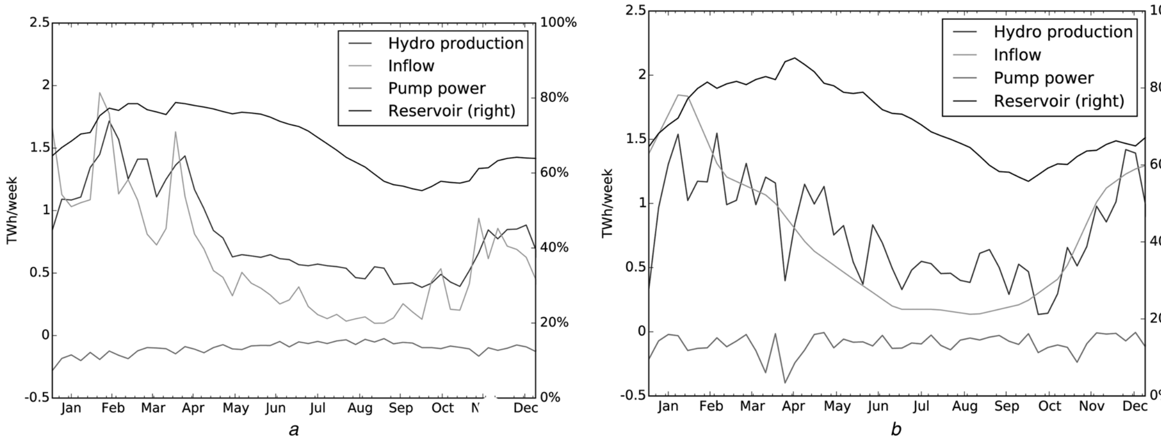

Fig. 8 *Hydro characteristics for Spain*
a Actual
b Simulated

be possible to do an analysis on the discrepancy over several years, and create an inflow profile for nuclear plants that represents the availability factor over the year.

5.4 Aggregated cross-border flow

The aggregated flows are illustrated in Fig. 7*a*. The direction of the arrow illustrates the direction of the actual net flow in 2014, the size of the arrow represents the magnitude of the actual flow, while the colours indicate the absolute deviation in simulations from actual net flow.

The simulated cross-border flow behaves reasonably well in Southwestern, Western and Eastern Europe. Most of these interconnections see not only a high share of flow going in one direction, but also interconnections with a more balanced exchange, like Spain and Portugal, see a net deviation under 20%.

The area with the highest deviating net flow is the area surrounding Austria and Slovenia. This is mainly due to the outdated grid input from 2009, causing alternated flow patterns due to grid congestions and high nodal prices in certain areas within countries. Another reason is the high marginal cost of thermal power in Greece, which was increased to facilitate exports from Italy to Greece, and to reflect the fact that the generation cost in Greece is high [30]. This enhances the southward flow, which is also generally seen in Southeastern Europe.

The imposed limits on internal branches in Germany contributed to an increased flow to the Netherlands, while the net flow in Germany – Poland – Czech Republic – Germany still proved difficult to reproduce. However, the flow from Germany to the Czech Republic shows the same seasonal variations as the actual flow, but is too high in the summer.

5.5 Seasonal variation on cross-border flow

One of the strengths of the PowerGAMA simulation tool is its ability to simulate the variability of renewable energy, and thus replicate some of the seasonal variation in the flow patterns, e.g., from areas with large hydropower production. There are many examples of this in the simulation results, and to illustrate this, flow between some countries that are dominated by hydropower production are highlighted. The rolling weekly mean of actual and simulated flow from Austria (AT) to Germany (DE) and from Switzerland (CH) to Germany (DE) can be studied in Figs. 7*a* and *b*, respectively.

As seen in the figures, even though there is a deviation between the actual and simulated cross-border flow, they follow the same seasonal trend, and the model is able to replicate this dynamic. The hydro inflow during winter is lower than the average in both Austria and Switzerland, leading to the import of cheaper energy from Germany. When the hydro inflow increases in summer, the flow reverses, and especially Switzerland exports energy to Germany. In winter, the inflow reduces and the flow reverses yet again. Note that the drop in actual imports to Germany between June and August is an anomaly for 2014, and is not present for 2013 or 2015. Specific anomalies for 2014 in general are a source of error for the aggregated comparison.

5.6 Seasonal hydro characteristics

This section illustrates hydro production, reservoir handling, and pumped storage dynamics. Generators with storage, hydro reservoirs in this case, will produce energy if the storage value is lower than the nodal price, or store energy if the storage value is higher. The storage price depends on three factors, as explained in Section 2.2. With this storage representation, the actual storage strategy of hydro producers can be replicated in detail. An example of this is from Spain in Figs. 8*a* and *b*, where the factors were adjusted to capture the actual variations.

The inflow pattern in both cases follows the same trend, leading the annual hydro production to correlate well with actual data. The storage level is around 80% from February until May in both cases, dropping through the summer and increasing towards the winter, ending at around 65%.

For this study, only the seasonal correction factor for Spain was modified in order to illustrate that the model can capture the actual seasonal dynamic. For other countries, the factor has not been implemented. In countries where the hydro reservoirs are actively managed, e.g., Austria, where the resources are almost completely emptied before the filling season, the storage filling level correlation between the simulated and the actual data is thus poor, due to the lacking seasonal factor. Further work on this part of the dataset is to manually modify the seasonal correction factor for each country to improve reservoir handling.

For PHS plants, in addition to inflow, there is also an option to add energy from the power system to the storage, increasing the filling level. This happens if the nodal price is lower than the storage price and a pre-set dead-band value. The dead-band ensures that the generating-pumping system does not continuously alternate between generating–pumping status, and indirectly takes into account the losses associated with pumping [11]. By manually modifying the dead-band value for PHS plants in all countries, the total pumping power simulated was 40.1 TWh, only one per cent lower compared with the actual data. The aggregated pump production per country also shows good precision. However, the simulated pump production is more variable than the actual data. Table 4 represents the fine-tuned parameters of PHS plants in all countries. The reference price is initially set to the average price in a given country.

Table 4 Fine-tuned parameters

Country	Dead-band	v_0[a] [€/MWh]
Austria	0.6	55
Belgium	2.1	80
Bulgaria	1.58	60
Croatia	2.5	60
Czech Republic	0.83	55
France	1.2	30
Germany	1.51	70
Greece	7.5	62
Italy	2.05	68
Luxembourg	1.89	50
Poland	1.5	60
Portugal	1.7	55
Romania	0.7	60
Serbia	0.5	60
Slovakia	0.31	60
Slovenia	0.07	60
Spain	2	47
Switzerland	1.7	65

[a]Reference price

6 Conclusions

The importance of free available benchmark European power system model with which to test the various emergent research propositions centring on the facilitation towards low-emission systems, is undeniable.

In this paper, an updated and validated version of an open dataset for the open-source tool, PowerGAMA, covering most of the European transmission network in 2014 has been provided. In creating the dataset, only publicly available information was used. Both the tool and the dataset can be widely used by researchers and students who want to investigate future impacts of investments pertaining to large-scale integration of renewables in the European power system.

Comparison of the obtained simulation results of PowerGAMA using the developed dataset with the observed aggregated historical data in 2014 (i.e. the ENTSO-E reference data) shows some discrepancies, especially in cross-border exchanges and thermal generation dispatch. These discrepancies can be attributed to the assumptions and simplifications implemented in the model, including the exclusion of limits on ramp rates, start-up costs, forecast errors and hourly barriers on the utilisation of interarea branches, as well as specific anomalies in the data from 2014.

The model responds well to modifications made to replicate the actual conditions. Adjustments pertaining to storage reference price for hydro power plants, storage filling factor, initial reservoir level, and dead-band value for PHS were performed in order to simulate the correct dispatch of hydro units. Moreover, marginal costs of thermal plants were modified to represent a realistic energy mix in the countries considered. The limits on internal branch capacity were incorporated, e.g. Germany, to reduce cross-border power exchange to the neighbouring countries.

The total aggregated energy mix deviates about 2% from the ENTSO-E reference. Even though the energy mix in each country considered is slightly different from observed data, the developed tool is capable of capturing the daily and seasonal variations in energy mix and power exchange. The simulated cross-border flow is well in agreement with observed values in Southwestern, Western, and Eastern European countries.

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