Modelling and analysis of large scale solar energy integration in the Moroccan power system

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***Abstract*—This paper presents a study of large scale solar energy integration in the Western Mediterranean power system, considering a future scenario with increased renewable energy production and increased demand. The study is performed using a new open source software package for stepwise optimal power flow analysis that takes into account the variability in renewable energy availability, power demand and energy storage dynamics. The modelling approach, suitable for high level analyses of large, interconnected power systems, is presented with emphasis on how solar power generation and storage systems are represented. A positive assessment of the approach is provided by means of a comparison with real data for the present day situation.**

***Index Terms*—Solar integration, grid integration, optimal power flow, storage values.**

I. Introduction

Most countries today have targets for renewable energy integration which imply significant changes for the power system. One reason is that the introduction of power plants in new locations where renewable energy resources are good leads to changes in power flow and potentially new bottlenecks in the transmission grid. Due to long planning and construction times it is important to identify potential grid bottlenecks at an early stage. Another reason is that solar and wind power are based on naturally variable resources, adding to the challenge of ensuring the balance between power consumption and production at all times. It is important that power demand can also be met when wind and solar power production is low, either via imported power, energy storage or alternative generation capacity.

Although wind and solar power are variable, there is a smoothing effect when considering large areas. The negative effects of the variability can therefore be reduced thorough power exchange between regions and countries, provided that the transmission capacity is sufficient. For this reason, it is highly relevant to consider how a large, interconnected system is influenced by large scale renewable energy integration.

In this study, the western Mediterranean region has been considered, with particular emphasis on Morocco. As a suitable tool for performing the analysis a new open-source software package called PowerGAMA has been utilised. This tool is considered suitable as it allows analysis of very large systems taking into account variable energy resources, power consumption, energy storage integration and power flow equations.

The study demonstrates the application of this new, lightweight, open source software package for high-level analysis of large scale solar energy integration in interconnected power systems. The approach is applied on a 2030 Moroccan case study, giving valuable insight into potential power system bottlenecks, energy mix, total cost of generation and price variations. The results are useful in understanding power system impact of large scale integration of renewables, and for timely planning of grid reinforcements.

II. The PowerGAMA open source tool

PowerGAMA [1] is a Python-based lightweight simulation tool for high level analyses of renewable energy integration in large power systems. The simulation tool optimises the generation dispatch, i.e. the power output from all generators in the power system, based on marginal costs for each timestep over a given period, for example one year. It takes into account the variable power available for solar, hydro and wind power generators. It also takes into account the variability of power consumption. Moreover, it is flow-based meaning that the power flow in the AC grid is determined by physical power flow equations.

Since some generators may have an energy storage (hydro power with reservoir and concentrated solar power with thermal storage) the optimal solution in one timestep depends on the previous timestep, and the problem is therefore solved sequentially.

PowerGAMA does not include power market subtleties such as start-up costs, limited ramp rates, forecast errors, unit commitments, and assumes a perfect market where generation dispatch is determined by generator costs and power flow constraints. Due to these simplifications it will tend to overestimate the ability to accommodate large amounts of variable renewable energy.

The tool is an open source re-implementation of the basic functionality of SINTEF's Matlab based Power System Simulation Tool (PSST) [2], [3]. However, there are some significant differences: The new package is written from scratch with an ambition to be easy to use. As it does not depend on any commercial software it is free to use. Furthermore it is built around a universal and flexible generator model with the possibility to specify variable energy "inflow" and storage for any generator type. Data is stored to disk during the timestep iterations reducing potential computer memory problems. On the other hand, it is not as optimised as PSST regarding simulation speed.

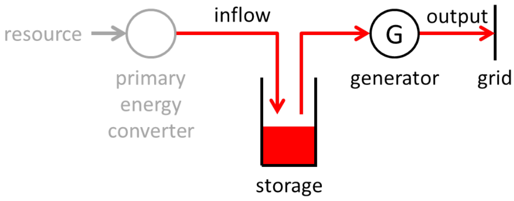

Figure 1. Power generation model.

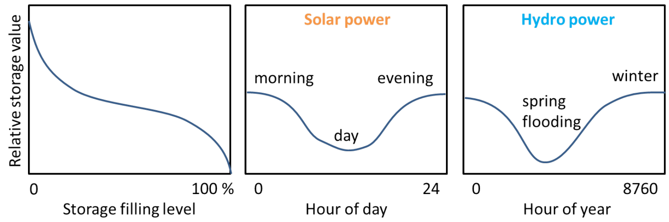

Figure 2. Illustration of typical storage values with dependence on filling level (left) and time variation for solar power with hourly storage (middle) and hydro with seasonal storage (right)

A. Power system representation

The power system is represented by nodes, branches, loads (consumers) and generators (producers). Typically, the grid model is a reduced, simplified, version of the real grid. *Nodes* are buses in the grid, and associated with each node there may be one or more loads and generators. *Branches* represent connections between the nodes. These are characterised by active power transmission limits and by an impedance. The analyses applies a linearised version of the power flow equations such that only the branch reactance is relevant. *Loads* are characterised by the demand, which may vary from timestep to timestep, and by a load shedding cost which is added to the system cost for any demand that cannot be supplied.

Generators are the most complex elements of the grid model and are described in more detail below.

The power market is considered perfect such that generators with the lowest marginal costs are always favoured. That is, power is assumed traded such that the overall cost of generation is always minimised, to the extent allowed by the power flow equations and branch capacity constraints.

B. Power generation and storage

Power generators are described by the same universal model, illustrated in Figure 1. Different types of power plants are simply distinguished by their different parameters. It is assumed that power inflow is given as input, and so the resource and primary energy converter parts shown in fray in Figure 1 are not modelled.

Wind and solar PV power are similar. The inflow represents the available electrical power in the wind or solar radiation. Zero storage implies that power not used is lost. The cost is almost zero, such that unless restricted by grid constraints, the output power from a the generator will equal the available power. Solar CSP and hydro power *without* any storage can also be modelled in this way.

CSP and hydro *with storage* uses a different approach. To ensure a sensible scheduling of the power output the base cost of these generators has to vary with different parameters. If the storage is close to its upper limit, the price should be low in order to avoid spillage, and if it storage level is low, the price may be high, depending on how critical the storage is for the system.

For fuel based generators, such as coal, gas, oil, nuclear and biomass, one may assume zero inflow but full, infinite storage. Then there is always fuel available in the storage and output is restricted by generator output limits only.

The cost of generation is assumed to be the marginal cost times power output for all generators. Start-up costs and ramp rates are not considered. For generators without storage, this cost is given by the fuel price.

For generators with a storage, the marginal cost is given by *storage values*, which depend on filling level and time of day or year. Storage values reflect the value of adding energy to the storage. Generator with an associated storage will therefore produce if the cost of alternative generation is higher than the storage value at any given time, or in other words, if the nodal price is higher than the storage value. Different storage value functions represent different storage utilisation strategies. In general, the storage value should be high when power should be saved for later, and low when power should be supplied to the system. Such use of storage values are inspired by *watervalues* used for modelling and planning of production for hydro power generators with storage [4], [5].

Storage values curves are given as input, as functions of storage filling level and time. If the storage is nearly full, the storage value is low, since adding to the storage may lead to energy spillage. If the storage is nearly empty, the storage value is high. For predictable seasonal or daily inflow patterns, the storage value is low just before a peak in the inflow, and high before a dip. An illustration of how the storage values may vary with filling level and time is given in Figure 2 for solar consentrated power with small storage (hours) and for hydro power with large reservoir for seasonal storage.

C. Stepwise optimal power flow algorithm

A flow chart outlining the main algorihm implemented in PowerGAMA is shown in Figure 3. The core of the algorithm is an optimal power flow (OPF) problem which is formulated as a standard linear programming (LP) optimisation and solved for each time step using an external solver. For each timestep, the LP formulation is updated with correct values for power consumption, power inflow, and storage values.

The OPF solution gives the generation dispatch with the overall lowest generation cost. Based on generation and inflow, storage levels are then updated before iterating to the next timestep.

In order to formulate the OPF problem as a LP problem it is necessary to linearise the power flow equations, arriving at what is commonly referred to as the DC power flow equations. This implies that only active power flow is considered, and that

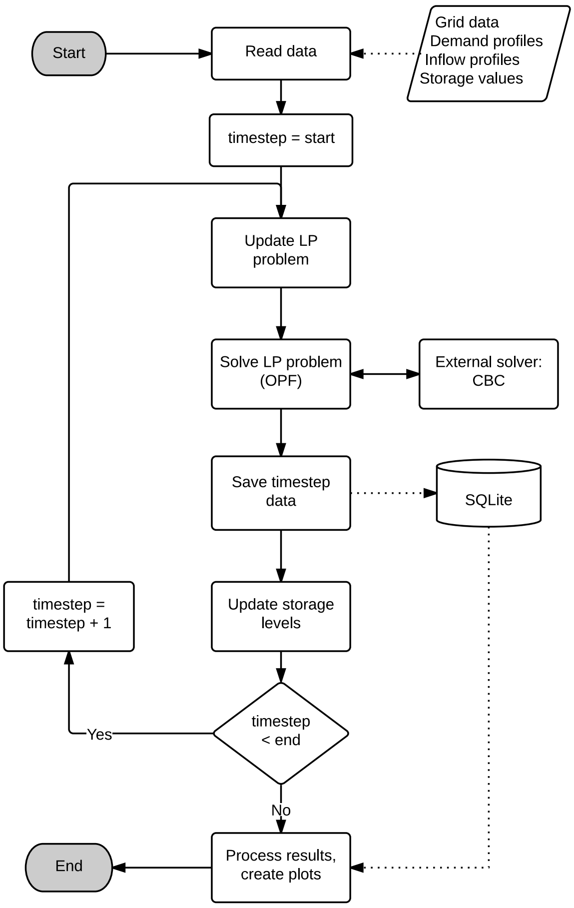

Figure 3. Main algorithm

voltage magnitudes are assumed to equal to nominal values throughout the grid. For the level of accuracy required by the type of analyses where the approach described here is relevant, this approximation is considered appropriate.

III. Grid model

The system included in the study consists of countries around the western Mediterranean: Portugal, Spain, France, Switzerland, Italy, Tunisia, Algeria and Morocco. The European part is represented by a subset of an existing reduced grid model for Europe [6]. The European model is also manually updated with wind and solar generators. Tunisia and Algeria have been represented in a very simplified way with only a few nodes in each country. For Morocco, a reduced grid model has been obtained from a detailed model using bus aggregation methods described below.

These various grid model parts have been merged together to give a model covering the western Mediterranean region. In total, this model has 786 nodes, 1300 branches, 557 generators and 577 loads.

A. Reduced Moroccan model

A general algorithm for grid model reduction has been applied for Morocco, with the aim to arrive at a reduced, "equivalent" 43 node model that pertains power flow characteristics. The purpose of this reduction is to reduce computational demands and to arrive at a model more suitable for high level analyses involving multiple countries. An added benefit is that the reduced model can more easily be be shared amongst research partners, as the model reduction involves an aggregation and obscuration of sensitive grid data.

The procedure is based on and described in more detail in [7], [8], [9]. It should be emphasised that this approach is a *static* reduction based on a snapshot of the power system at one particular point in time. This of course gives a reduced model that is less accurate for other times.

The starting point of the reduction procedure is a detailed model of the system in PSSE raw format. The reduction algorithm consists of two main steps. The first step groups nodes into clusters based on similarity of power transfer distribution factors (PTDFs). If power injections at two nodes result in similar PTDFs, the two nodes are considered similar. The k-means procedure with this similarity measure is used for node clustering.

The second step computes equivalent reactances for the branches in the reduced model. This is done by minimising the weighted errors between zonal PTDFs derived from the full model and PTDFs derived from the reduced model, and between cluster average node voltage angle in the full model and node voltage angles in the reduced model. The first minimisation objective ensures similarity of power flow and the second minimisation objective ensures realistic voltage angles and therefore physical reactance values.

B. Grid data

In addition to the basic description of the grid in terms of nodes, branches, generators and nodes, it is necessary to provide additional parameters for the stepwise optimal power flow analysis. This includes parameters such as marginal generator costs; generator capacities; storage capacities; wind, solar and hydro power inflow; storage value curves, and consumption profiles.

Marginal costs for different generator types have been obtained from the OffshoreGrid project [10]. Power inflow data is generated based on Reanalysis dataset [11] for wind and solar. Hydro inflow is approximated using Norwegian hydro reservoir inflow pattern with low values in the winter and large values during spring, due to snow melting. This is considered adequate for the Alps where most of the hydro capacity is located in the present model. No hydro reservoirs are included in the present model. The consumption profiles are based on profiles from the TradeWind project [2] for the European countries. For the northern African countries, the profile for Morocco [12] has has been used, but adjusted according to time zone shifts. The total consumption for each country has been retrieved from U.S. Energy Information Administration (EIA)[1].

Some generators have been added to the model manually. This is the case for wind and solar generators in Europe and

[1] http://www.eia.gov/(accessed 2014-08-01)

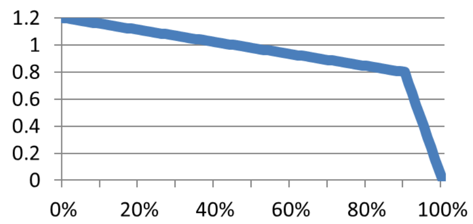

Figure 4. Storage value curves: filling level dependence.

Table I
INPUT CAPACITY FOR 2014 CASE

Generator Capacity [MW]								
Country	CH	DZ	ES	FR	IT	MA	PT	TN
Solar	0	0	4322	3189	17928	0	161	0
Wind	0	24	21674	8254	8552	0	4731	54
Hydro	14900	249	13819	20652	17095	1737	4499	62
Nuclear	3263	0	7567	63130	0	0	0	0
Fossil	100	15720	48898	24886	70771	5954	8505	2077
Other	300	0	0	0	4365	0	0	0
SUM	18563	15992	96280	120111	118711	7690	17896	2193

Table II
INPUT DEMAND FOR 2014 CASE

Demand [GWh/y]								
Country	CH	DZ	ES	FR	IT	MA	PT	TN
	58690	38010	243900	447110	311260	25141	48580	12940

all generators in Tunisia and Algeria. Information about those generators, regarding capacity, type and location, is found from mainly Enipedia [13] and various lists on Wikipedia[2]. By using Enipedia, large generator datasets have been downloaded and processed before they are added to the model. Information about large power plants has been retrieved from Wikipedia and added manually. All the additional generators are placed in the closest existing node, and the capacity is superposed with existing capacity of the same generator type in the same node.

In order to fine tune the model, scaling of grid data have been performed. Generator capacities and loads have been scaled up or down to match total values per country, according to values given by EIA. Scaling of solar, wind and hydro inflows was also performed. This was done by comparing data for annual production and total capacity. Scaling is also applied to generate different scenarios. For future scenarios with very large developments in renewable energy, new generators are added explicitly before further scaling in order to have a realistic distribution of new solar and wind generation capacity in particular.

Some concentrated solar power (CSP) plants have been modelled with storage capacity. Storage value curves for these are shown in Figure 4. The storage value decreases with increased filling level. As the storage level approaches the maximum, the value of the energy is decreasing rapidly to avoid energy spillage. These storage value curves represent a first attempt to mimic realistic storage utilisation. Improved storage value curves will give improved storage utilisation, and is a matter for further optimisation. However, for the present day simulation with very low amount of CSP with storage this has a limited impact.

IV. SIMULATION RESULTS

The PowerGAMA simulation tool stores results for each time step, so a lot of detail regarding the simulation results can be retrieved in the post processing. Important variables that provide a lot of information regarding the simulated case are described briefly in the following.

Nodal prices: Nodal prices say how much total cost of generation would increase if power consumption was increased one unit in the given node, i.e. the marginal cost of power supply at the node. The nodal price is a good indicator of the wholesale electricity price, provided the power market is a liberalised and perfectly functioning single market for the entire system. It should be noted that for a given region, the nodal price may be high even if there is plenty of cheap generation. This may happen if there is sufficient storage or transmission capacity to other regions.

Branch flow: Branch utilisation is defined as branch flow relative to branch capacity. If branch utilisation is very high it means that the connection is a bottleneck in the system. A related parameter is the branch capacity sensitivity, which tells how much the total cost of generation would increase if the capacity of the given branch was increased one unit. Large negative values correspond to large cost reductions, and should be interpreted as a branch where capacity should be increased.

Generator output: The output from each generator is such that it gives the lowest total cost of generation in the system, time step by time step. Summed up per country it gives interesting information about the generation mix. Time series can also be studied to demonstrate how the system responds to variations in demand and variable renewable energy production. For generators with storage, the time series give detailed insight into how storages are used. This is highly dependent on the chosen storage value curves, such that investigation of the results may provide insight for improving the storage value curves to reflect more optimised storage utilisation strategies.

A. Base case: 2014

The main input data for the simulation is shown in Table I andII. The power flow for a simplified power system for the Western Mediterranean area was simulated over the coarse of one year.

In Figure 5 the nodal prices is shown for the whole simulation area. For all countries except Morocco the internal branch capacity is unlimited. This is partly due to lack of data, and partly because the emphasis of the simulation is on international power exchange. Assuming unlimited internal capacities gives an optimistic estimate of how well the system can utilise cheaper generators. At the same time it is a reasonable approximation since one should expect that grid

[2]http://en.wikipedia.org (accessed 2014-08-01)

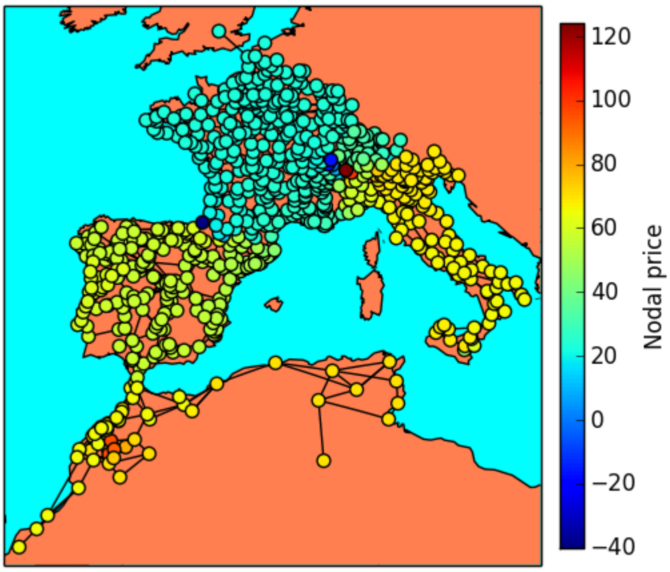

Figure 5. Average nodal prices in 2014 scenario.

reinforcements are put in place by the relevant Transmission System Operator to alleviate internal grid bottlenecks.

The largest price gradient between the countries is found around France. This is due to a large amount of cheap available nuclear power. Italy and the North African countries, on the other hand, have more expensive fossil fuels and thus have a higher average nodal price. Price gradients indicate branch limitations, hence limitations on power flow can be found between Spain and Morocco, and between France, Switzerland and Italy.

A few nodes come out with a negative nodal price. This is explained from the fact that an increased consumption in those nodes would allow a larger power transfer replace expensive generation that more than balances the cost of supplying these specific nodes. This is merely an artefact of the model reduction with unlimited capacity on internal branches but limited capacity on cross-border branches.

Morocco is the only country with domestic branch limitations. The detailed results for Morocco are seen in Figure 6. In this figure, in addition to nodal prices, the average branch utilisation is plotted. The utilisation reveals that a few branches are heavily loaded. The connections to Spain and Algeria are used at almost full capacity for the whole duration, as shown by the utilisation factor close to 1.0. Furthermore, there is a connection in the middle of Morocco which is limiting flow. This is probably an artefact of the model reduction (see Section III-A), as the reduced Morocco model has not itself been thoroughly validated.

Table III shows the simulated yearly flow for international branches from the simulation and the comparable data for exchange between the same countries for 2011. As is seen, most of the exchanges from the simulation follow the trends from the data set. The export to Germany/Great Britain correlates perfectly since no dynamics are simulated for these two countries. Other exchanges correlate well since power

Table III
ANNUAL POWER EXCHANGE. 2014 SIMULATION VERSUS DATA REFERENCE.

Inter-area flow [GWh/y]			
	Simulation	Reference	Difference
ES to MA	11613	4509	7104
MA to ES	78	1	77
ES to FR	580	2462	-1882
FR to ES	25465	4879	20586
CH to IT	25471	25612	-141
IT to CH	1373	431	942
net MA/DZ	5336	29	5307
net DE/FR	10905	20176	-9271
net GB/FR	4783	4782	1

Table IV
ENERGY MIX FROM SIMULATION AND DATA REFERENCE.

	Simulation			Reference		
Area	nuclear	fossil	renew	nuclear	fossil	renew
ES	27.4 %	33.5 %	37.2 %	19.9 %	49.0 %	31.4 %
PT		45.1 %	54.9 %		51.8 %	48.6 %
FR	82.6 %	2.3 %	15.1 %	79.5 %	8.4 %	12.4 %
CH	36.8 %	0.4 %	62.7 %	42.4 %	1.6 %	57.2 %
IT		60.1 %	39.9 %		70.4 %	29.8 %
TN		96.5 %	3.5 %		98.6 %	1.4 %
DZ		98.0 %	2.0 %		99.2 %	0.8 %
MA		87.6 %	12.0 %		88.7 %	11.5 %

flow is limited due to capacity limits. An example of this is the exchange from Switzerland to Italy which correlates well, though most of this power originates from France. The large export from France to the surrounding countries is again due to their large supply of cheap nuclear power.

Large deviations can be seen in the transfer from Spain to Morocco and from Morocco to Algeria. The exchange between Morocco and Algeria is almost non-existing in reality. However, in the simulation the Morocco–Algeria capacity is used to transfer cheaper energy from Spain and Morocco to the higher priced areas in Algeria and Tunisia. There are two major reasons for this deviation. Firstly, in reality Algeria and Tunisia cover their own consumption with domestically produced fossil fuel. In addition, the fuel price in Morocco has probably been set too low, in relative terms. The same fuel prices have been assumed for all countries. However, it should be higher in Morocco since they import all their fossil fuels and would therefore have a higher cost. For the Spain–Morocco capacity, the elevated exchange compared to statistical data is partly explained from the transfer to Algeria/Tunisia and partly explained by the capacity limit. The real capacity limit is lower than the thermal limit used in simulation. All branches have been input with their full rated capacity. However, transmission lines are governed by the many different operational objectives, and the full thermal capacity will not be available on the market at all times.

The resulting energy mix for one year simulation for all the

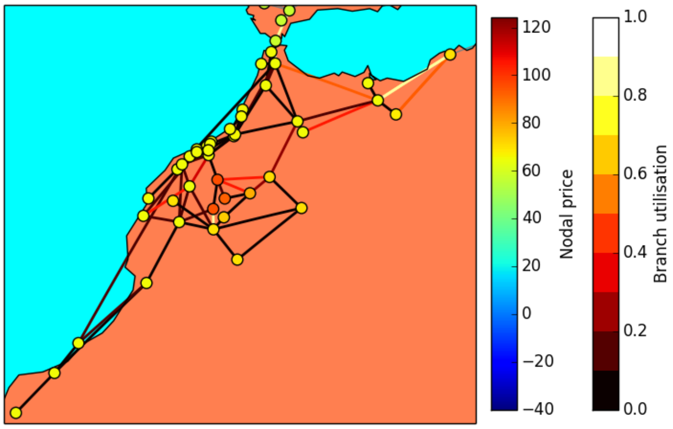

Figure 6. Average branch utilisation in Morocco in 2014 scenario.

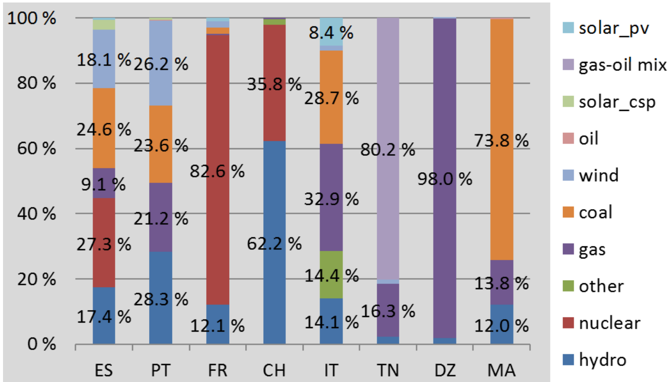

Figure 7. Energy mix in 2014 scenario.

included countries is shown in Figure 7. Table IV shows the energy mix of the countries included in the simulation and the comparable data for 2011. The model has been coarsely tuned to obtain comparable results for one full year of operation. As the table shows, the energy mix for the 2014 scenario is close to 2011 data. Some differences are seen. In general, the renewables have a higher share than the reference for 2011. For Italy in particular, this difference is large, 40% versus 30%. The main reason for the differences is that the renewable production was tuned to a higher total production for each country.

Some deviations between simulation results and real data are inevitable because of the approximations made in the simulations. Apart from the obvious simplification of the power market as a single market with a single one hour trading horizon, the use of reduced grid models and linearised power flow also lead to some errors in the simulations. Another important factor for the trustworthiness of the results is the accuracy of the input data, such as assumed generator costs, placement and capacity of each (aggregated) generator, and others.

B. 2030 scenario

For analysis of future integration of renewable energy, the 2014 model has been modified to represent a future 2030 scenario, with new power generation including large solar power plants. The work on this scenario is on-going and the results presented here are preliminary observations. The grid model for the scenario has been obtained by a two-step procedure. First, additional generators have been included for wind and solar power, with a reasonable geographic distribution of generation capacity. Then, all generator capacities have been scaled per country and type to give the desired total values. Similar scaling has been done for loads. Multiple sources have been used for the specification of the scenario: Demand and generation capacities for European countries as well as generator costs are according to [10], except for solar and wind capacity which has been taken from [14], and nuclear capacity in Italy which has been assumed zero; Data for the northern African countries has been collected within the EuroSunMed project. Planned new HVDC connections (ES–DZ, IT–TN, CH–FR) have also been included, but no other grid reinforcements.

Figure 8 shows resulting average nodal prices in Morocco and surrounding area. The very significant price variations within Morocco indicate a mismatch between the location of generation capacity and branch capacities. As noted previously, the reduced Moroccan model should be validated before making any firm conclusions from these results. However, it is a generic problem that adding new generation, wether

Table V
INPUT DATA, 2030 CASE. DEMAND, GENERATION AND COSTS

	CH	DZ	ES	FR	IT	MA	PT	TN	
Power demand (Gwh/y)									
	75200	95025	406560	604120	436410	62850	70320	32350	
Generation capacity (MW)									Cost (€/Mwh)
Coal			12930	1750	10820	2005	1220		60.0
Gas	1300	15596	34140	25980	44750	5240	5720	2077	70.0
Oil		124	5200	8330	5510	446	920		162.0
Other								655	50.0
Nuclear	3200		7500	60310					11.0
Hydro	20100	3570	14760	21320	17440	2000	4780	655	3.0
Solar CSP		6500	30000				0	595	0.5
Solar PV	800	2800	5707	13913	28206	2000	5613	1930	0.5
Wind	600	1730	35707	47354	22598	2000	8324	1520	0.5

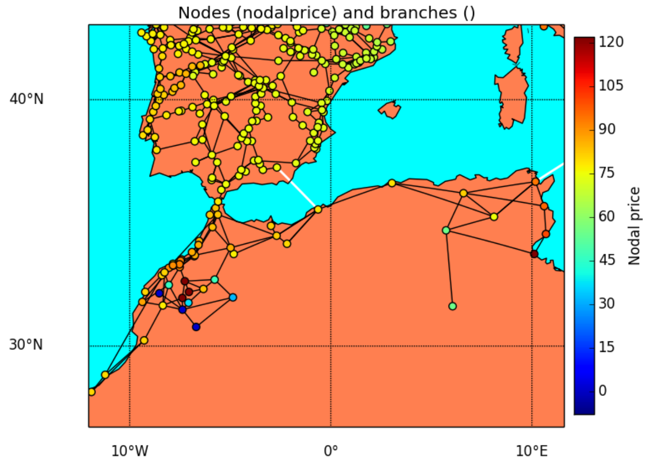

Figure 8. Average nodal prices in 2030 scenario.

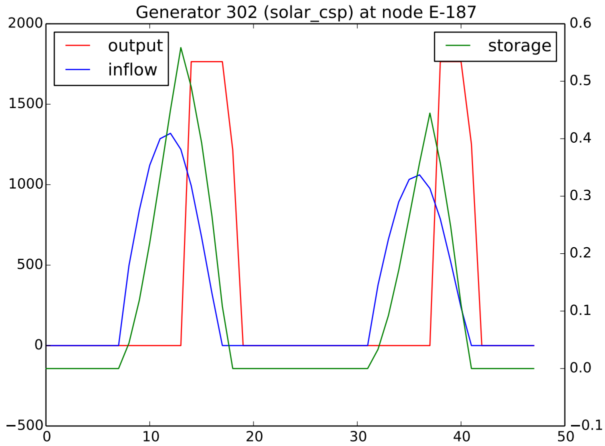

Figure 9. Storage utilisation. Example showing inflow, output and storage level for a CSP power plant in Spain. Inflow and output are shown on the left axis in units of MW, and storage level is shown on the right axis as a fraction of the full storage capacity.

explicitly or by up-scaling will lead to grid bottlenecks unless the grid is simultaneously reinforced. A short-cut to get around this problem is to assume infinite capacities within the country, assuming appropriate grid reinforcements will have been done by 2030. Planned further work will investigate these grid bottlenecks and analyse the cost–benefits of grid investment options.

Figure 9 illustrates how the storage value method determines storage utilisation. The figure shows a 48 hour extract for a CSP power plant. The difference between output and inflow gives the change in storage filling. As seen from the Figure, the storage is used such as to shift the output from daytime towards the evening when demand and therefore prices are higher. In the example shown, the generator capacity is higher than the maximal inflow. This is due to low solar irradiation on these particular days.

V. Conclusions

This paper has described a modelling and simulation approach suitable for investigation of large scale integration of renewable energy in geographically large, interconnected grids. An open source Python implementation of this approach has been presented and demonstrated on a case consisting of the Western Mediterranean region, with particular emphasis on Morocco. The grid model used in simulations consists of an open European model plus a new reduced model of Morocco and very simplified models for Algeria and Tunisia.

The results indicate a reasonable match between simulations and the real power system when considering the present day situation. There is a good match between data and simulations regarding power generation mix, indicating that the assumed generation costs and capacities are fairly accurate. Some very significant discrepancies regarding power exchanges between different countries are due to the very simplified market model assumed in the simulations, and an over-estimate of actual transmission capacity between Morocco and Algeria, in particular.

Preliminary observations from a 2030 scenario for this region were presented, but a more thorough validation of the grid model and added detail in the scenario datasets are needed before firm conclusions can be made.

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