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Energy Procedia 49 (2014) 1858 – 1868

Energy Procedia

SolarPACES 2013

Optimized integration of renewable energies into existing power plant portfolios

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Abstract

Fossil fuel importing as well as exporting countries of the MENA region have recognized their enormous potential of power generation by renewable energy (RE) technologies and the associated benefit for their national budgets, and therefore have formulated ambitious targets for RE deployment. However, only few countries have a detailed master plan that shows how RE technologies can be integrated efficiently into their existing power plant portfolio. Capacity expansion of RE and conventional technologies must be adjusted and optimized in order to minimize total generation costs of the entire system while maintaining security of supply. Within the last three years, DLR has developed the capacity expansion and unit commitment optimization model REMix-CEM (Renewable Energy Mix – Capacity Expansion Model) in order to support authorities of the MENA region in the process of integrating RE technologies efficiently in the short-term and transforming their strongly growing fossil-fuel dominated power systems of today towards higher RE shares. REMix-CEM optimizes the capacity expansion of conventional and RE technologies from a state-owned utility perspective starting from the existing power plant portfolio by modeling the hourly performance of each single existing and candidate unit. The paper presents an overview of the developed methodology as well as the characteristics and capabilities of REMix-CEM by presenting a case study for the electricity sector of the Hashemite Kingdom of Jordan for the years 2013 – 2020.

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
Keywords: Power Sytem Optimization; Capacity Expansion, Unit Commitment, Renewable Energies, Concentrating Solar Power, MENA, Jordan

Nomenclature

BUS	Back-Up System/Boiler
CAPEX	Capital Expenditures
CSP	Concentrating Solar Power

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doi:10.1016/j.egypro.2014.03.197

CCGT	Combined-Cycle Gas Turbine
DE	Diesel Engine
DNI	Direct Normal Irradiation
GIS	Geographic Information System
HFO	Heavy Fuel Oil
LFO	Light Fuel Oil
MILP	Mixed Integer Linear Problem
OCGT	Open Cycle Gas Turbine
OPEX	Operation Expenditures
O&M	Operation and Maintenance
PB	Power Block
PV	Photovoltaics
RE	Renewable Energies
REMix-CEM	Renewable Energy Mix – Capacity Expansion Model
SF	Solar Field
SM	Solar Multiple
ST	Steam Turbine power plant
TES	Thermal Energy Storage
WACC	Weighted Average Cost of Capital

1. Introduction and background

Fossil fuel importing as well as exporting countries of the MENA region have recognized their enormous potential of power generation by RE technologies and the associated benefit for their national budgets, and therefore have formulated ambitious targets for RE deployment. However, only few countries have a detailed master plan that shows how RE technologies can be integrated efficiently into their existing power plant portfolio. In the first section of this paper, the general methodology for an optimized integration of RE technologies into an existing power plant portfolio is presented. Afterwards, the capacity expansion and unit commitment optimization model REMix-CEM, which is the core of the methodology, is introduced briefly, and the approach for modeling CSP plants within the power system optimization model is highlighted. In the second part of the paper, results of a case study for the electricity sector of the Hashemite Kingdom of Jordan for the years 2013 – 2020 is presented.

2. Methodology

2.1. General methodology

The developed methodology for an optimized integration of RE technologies into an existing power plant portfolio is shown in Figure 1 and is described in detail in [1]. In a first step, technology specific hot spots for the most promising RE technologies (e.g. CSP, utility-scale PV and wind power) of a country are identified using geographic information systems (GIS). Hot spots are determined by a site-ranking analysis applying different ranking criteria for spatial data such as primary energy resource availability and distance to existing infrastructure like substations, transmission grid, streets, pipelines etc. Hourly resource availability and other meteorological data at the identified hot-spots, as well as detailed information about the investigated power system and techno-economic data of existing and candidate power plants, serve as input for the step-wise capacity expansion optimization model REMix-CEM. Within step 2, capacity expansion is optimized from a state-owned utility perspective in 1 to 5 year planning steps taking into account the existing power plant portfolio of today. In a third step, the results are evaluated and a least cost strategy for the short-term integration of RE into the power supply system is identified.

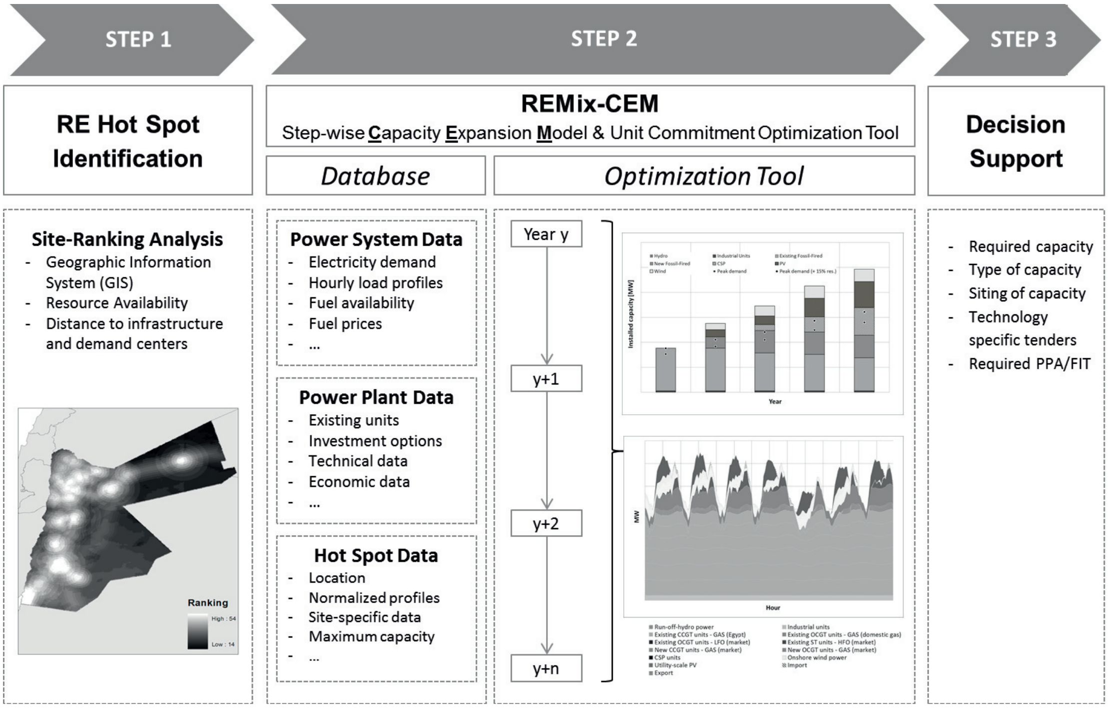

Figure 1: Methodology for an optimized integration of renewable energy technologies into existing power plant portfolios

2.2. The power system optimization model REMix-CEM

REMix-CEM is a multi-node power system optimization model formulated as a mixed integer linear optimization programming problem (MILP). The model can be used for dispatch optimization (including start/stop decisions) of a defined power plant portfolio or for a step-wise capacity expansion optimization taking into account an existing power plant portfolio and a set of candidate units. The optimization model consists of several modules which are used to model the performance of different conventional and RE power generation technologies within a national power supply system. Calculating on an hourly basis and single unit level, REMix-CEM considers relevant restrictions on system level (peak-, secondary- and tertiary-reserve, grid transfer capacities, fuel availability, etc.) and unit level (part-load efficiency, start-up costs, minimum up and down times, etc.). The transmission grid is modeled in a simplified way and treated as a generic transportation network with defined transfer capacities between each pair of nodes.

Traditionally, when the expansion of power generation capacity is optimized, a load duration curve approach is applied. When fluctuating RE technologies like wind power or PV are included in the capacity planning process, the installed capacity of these technologies is set exogenously instead of being optimized. The power generation of these fluctuating (non-dispatchable) RE technologies is subtracted from the original hourly load profile, resulting in a residual hourly load profile. In a next step the residual load profile is transformed into a residual load duration curve which is used to minimize the total discounted system costs of the required dispatchable power generation capacity that is needed to meet the residual demand. The advantage of this approach is that due to its relative simplicity long planning time-frames can be optimized. However, using the load duration curve approach leads to the loss of information about load chronology and temporal availability of RE technologies. Thus, the disadvantage of the load duration curve approach is that expansion of RE and conventional capacity cannot be adjusted and optimized simultaneously. Furthermore, operating constraints of thermal power generation units cannot be taken into account even though the importance of these constraints increases significantly when fluctuating RE technologies are integrated into the power supply system. Such constraints are typically addressed within unit commitment optimization models where the hourly dispatch (including start/stop decisions) of a defined power plant portfolio is optimized in order to meet hourly demand. However, neglecting these issues during capacity expansion optimization can lead to sub-optimal capacity mixes with significantly higher total generation costs of the system [2].

Instead of the load duration curve approach, REMix-CEM uses real-time annual hourly load time-series for a step-wise capacity expansion optimization. The model optimizes the unit commitment of already existing and candidate conventional and RE units over one year on an hourly basis taking into account annual capital costs of candidate units as well as annual O&M costs of all units (existing and candidate units) of the system. The optimization is carried out for planning steps of 1 to 5 years starting from the existing power plant portfolio. The results of the previous step serve as input for the next planning-step. The advantage of the step-wise approach is that capacity expansion of RE and conventional units can be optimized simultaneously and relevant system and unit constraints can be modeled. The disadvantage is that only the next planning step is optimized instead of the entire planning time-frame (e.g. 30 years) due to computation time constraints. Hence, the results of the step-wise optimization may differ from results which would have been obtained when the entire planning time-frame would have been optimized. However, the approach ensures the maintaining of electricity supply over time and identify a least cost strategy for the short-term integration of RE technologies since RE are only integrated when their utilization contributes to lower total system costs.

Eq. (1) shows the objective function of the optimization problem for each planning step (variables: uppercase letters; parameters and scalars: lowercase). The total system costs, consisting of CAPEX and OPEX of the existing and candidate generation units, as well as the costs and revenues for electricity imports and exports respectively, are the subject of minimization.

$$C^{SYSTEM} = \sum_{x\in X}\sum_{n\in N} C^{CAPEX}_{n,x} + \sum_{u\in U}\sum_{n\in N} C^{OPPEX}_{n,u} + \sum_{n\in N} C^{IMPORT}_{n} - \sum_{n\in N} C^{EXPORT}_{n} \Rightarrow minimize \qquad (1)$$

C^{SYSTEM}: Total system costs [€]
$C^{CAPEX}_{n,x}$: CAPEX of candidate unit [€]
$C^{OPPEX}_{n,u}$: OPEX of existing or candidate unit [€]
$X(U)$: Set of candidate units; subset of U
C^{IMPORT}_{n}: Power import costs [€]
C^{EXPORT}_{n}: Power export revenues [€]
U: Set of all units (existing and candidate)
N: Set of model nodes

The minimization of total system costs is subject to several constraints on system (e.g. spinning reserve requirements or grid transfer capacities) and unit level (e.g. minimum load level, start-up times, etc.). In total more than 130 equations are utilized within REMix-CEM. Only the most important restriction on system level is presented at Eq. (2). The equation ensures that the energy balance at each model node is full filled in each hour of the year. Power generation of all existing and candidate units must meet hourly load in each hour of the year at each node of the system. Domestic power transmission between model nodes is possible as well as power imports into and exports out of the investigated system at nodes which are connected to other systems.

$$\sum_{\forall u\in N} P^{NET}_{n,u,t} + \sum_{\forall n\in N} TRANS^{DOMESTIC}_{n,t} + \sum_{\forall n\in CN} IMPORT_{n,t} - \sum_{\forall n\in CN} EXPORT_{n,t} = load_{n,t} \qquad (2)$$

$P^{NET}_{n,u,t}$: Net power generation of unit [MW]
$TRANS^{DOMESTIC}_{n,t}$: Transmission between nodes [MW]
$IMPORT_{n,t}$: Power import [MW]
$CN(N)$: Set of model nodes which are connected to other systems (countries)
$EXPORT_{n,t}$: Power export [MW]
$load_{n,t}$: Load [MW]
T: Set of hourly time-steps (1 – 8760)

2.3. Modeling of CSP within REMix-CEM

Besides the restrictions on system level several restrictions on unit level are applied in order to model conventional and RE power generation units. Therefore, REMix-CEM consists of several modules which represent different power generation technologies (e.g. conventional fossil technologies, hydro power technologies, CSP, etc.). Within the single modules different sub-technologies (e.g. CCGT, Diesel Engines, CSP-Parabolic Trough, etc.) are modeled on single unit scale. The CSP module of REMix-CEM allows the detailed modeling of the technical and economic performance of dry- and wet-cooled parabolic trough CSP plants within the entire system. Technical characteristics such as part-load efficiency and ramping limits of the turbine, ambient temperature effects on dry cooling systems, auxiliary power for the solar field, thermal energy storage and power block, time and fuel requirements for start-up, minimum on- and off-line time of the plant, etc. are taken into consideration.

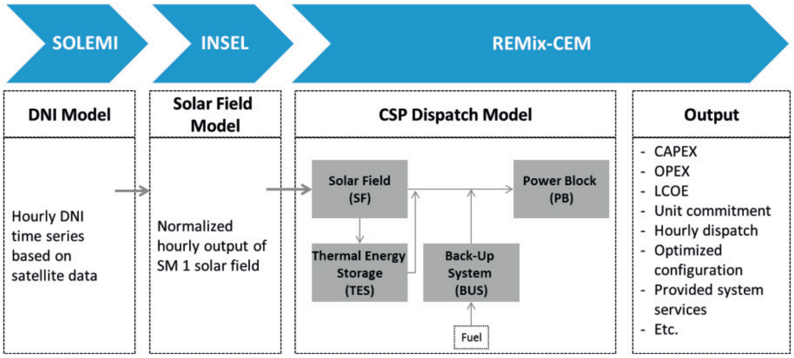

Figure 2: Integration and modeling of CSP plants within REMix-CEM

Figure 2 shows the integration and modeling of CSP plants within REMix-CEM. Direct normal irradiance (DNI) data at the respective hot spot is derived from the satellite data based DNI model SOLEMI [3]. Hourly DNI values and other site-specific hourly time-series like wind velocity and ambient temperature serve as input for a CSP solar field model developed within the modular simulation software INSEL [4]. Hourly thermal power generation of a Parabolic Trough SM 1 solar field is calculated and normalized by the solar field model. The hourly thermal generation profile, together with hourly ambient temperature values and techno-economic parameters, serve as input for the CSP dispatch model of REMix-CEM. Within the CSP dispatch model, the single CSP units are composed of the four major subsystems solar field (SF), thermal energy storage system (TES), fossil back-up boiler system (BUS) and power block (PB) including steam turbine and cooling system (dry or wet). The hourly performance and interaction as well as the associated costs of these four major subsystems are modeled in detail. Thereby the configuration of each CSP unit can be optimized (size of SF, TES and BUS) in relation to the entire system. Major results of the CSP module are annual CAPEX and OPEX, LCOE, hourly dispatch, provided spinning reserve, and optimal plant configuration. Please refer to [1] for a more detailed description of the CSP dispatch module.

3. Case study Jordan

Jordan has experienced a significant increase of both peak load and annual electricity demand within the last decade due to a strong growth of economy and population. The peak load of Jordan's interconnected system has increased from 1200 MW in the year 2000 to 2790 MW in 2012. In the same period electricity generation increased from 7375 GWh/y to 16596 GWh/y. The strong escalation will continue for the upcoming years (about 8% per year) resulting in an expected peak load of 8500 MW and electricity demand of 53700 GWh/y in the year 2030. Jordan has to install about 7000 MW (ca. 400 MW per year) of new firm power generation capacity until 2030 in order to maintain security of supply.

In Jordan, electricity generation highly depends on fossil fuel imports. From 2004 till 2009, gas imports from Egypt through the Arab Gas Pipeline well below market prices were increased constantly resulting in a share of about 90% on electricity generation in 2009. The rest was covered by heavy fuel oil (HFO) and Diesel/ light fuel oil (LFO) imported slightly below market prices (see Figure 3 (a)). However, since the resignation of Hosni Mubarak the Arab Gas Pipeline, which also supplies Israel, has been attacked several times resulting in a significant decrease of gas imports. In 2012, electricity generation by gas decreased to less than 20%. In addition, the price for gas was increased by a factor of three resulting in a price of more than 5 USD/MMBtu. During the next years, gas prices will be adapted step-by-step to European gas prices. Figure 3 (b) shows the development of average HFO prices and average electricity generation costs in Jordan from 2001 till 2012. HFO prices increased sharply since 2005 but increased gas imports prevented an increase of the average electricity generation costs of the system. However, since 2010 the strong dependency on fossil fuels imports, especially on cheap gas from Egypt, and the associated high risk has caused significant pressure on Jordan's national budget. Due to the unreliable gas supply, Jordan has had to generate 80% of its electricity by expensive HFO and LFO. Consequently, average electricity generation costs increased sharply about 265% compared to the year 2009. In 2012, average electricity generation costs of Jordan's power plant portfolio were as high as 145.69 Fils/kWh (ca. 0.16 €/kWh) [5, 6].

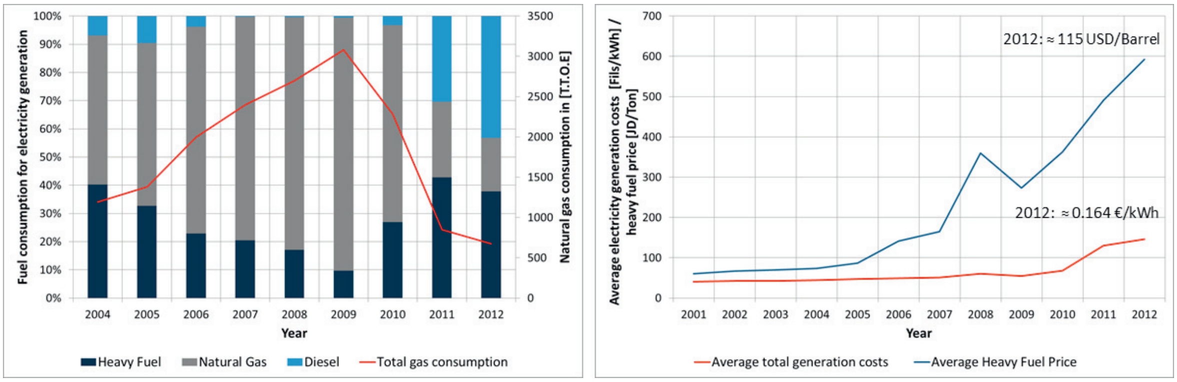

Figure 3: (a) Fuel consumption for electricity generation; (b) average heavy fuel prices and electricity generation costs (data [5])

Jordan's authorities have identified the challenges of the electricity sector and therefore are looking for suitable solutions to keep up with the increasing electricity demand, to make Jordan more independent from fossil fuel imports and to provide electricity at affordable prices in the future. The following case study presents a strategy how RE technologies could be integrated efficiently into Jordan's existing power plant portfolio and capacity expansion of RE and conventional technologies could develop until 2020. Therefore, the described step-wise capacity expansion approach is applied and the planning steps 2016 and 2020 are optimized by REMix-CEM starting from the existing power plant portfolio of Jordan in 2013.

Hot-spots	Node	Resource availability
CSP-1 / PV-1	4	DNI / GHI: 2609 / 2284 kWh/m²/y
CSP-2 / PV-2	3	DNI / GHI: 2399 / 2192 kWh/m²/y
CSP3 / PV-3	2	DNI / GHI: 2417/ 2158 kWh/m²/y
Wind-1	4	Wind speed*: 7.2 m/s
Wind-2	3	Wind speed*: 7.3 m/s
Wind-3	1	Wind speed*: 6.2 m/s
Wind-4	5	Wind speed*: 6.6 m/s

*at 50 m a.g.l.

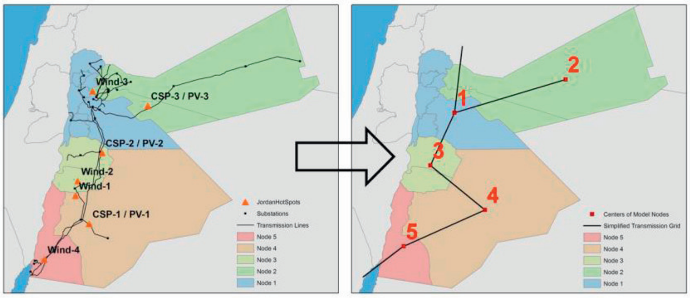

Figure 4: Resource availability at RE hot spots, existing transmission grid of Jordan, and assumed transmission model

Within the case study, five model nodes and seven RE hot spots are defined (see Figure 4). The simplified transmission grid was derived from Jordan's existing transmission grid. Hot spots for solar power (utility-scale PV, CSP) were taken from [1] where a site-ranking analysis for PV and CSP hot spots in Jordan was carried out applying different ranking criteria for spatial data such as resource availability (DNI, GHI) and distance to substations, transmission grid, streets, and electricity demand. RE hot spots for wind power were derived from literature [7].

Table 1 gives an overview of the general assumptions applied for the case study. For 2013 it was assumed that gas availability is restricted to the same amount as in 2012 (550 t.t.o.e.). For the planning step 2016 it is assumed that there is no possibility to import gas from other countries than Egypt due to long construction times of new pipelines or liquefied gas terminals. However, it is assumed that gas supply from Egypt becomes more reliable again (1000 t.t.o.e.). Furthermore, due to the long construction time of coal plants and related infrastructure, power generation by coal is not an option in 2016. For 2020, two different scenarios were investigated. At scenario 1, gas, coal, HFO and LFO are available without any limitation. However, since there is no adequate infrastructure to transport coal easily inland, coal plants are only an option at node 5 (Aqaba region with sea access). At scenario 2, only LFO, HFO and a limited amount of gas (1000 t.t.o.e.) are available for power generation in Jordan.

Table 1: General assumptions for the Jordan case study

Number of model nodes:	5 (net transfer capacity between nodes: 500 MW)
Number of RE hot spots:	7 (Solar Power: 3, Wind Power: 4)
Investment options:	Wind Power, utility PV (fix), CSP-Parabolic Trough, ST-Coal, CCGT, Diesel Engines, OCGT
Max. RE expansion per planning step:	Wind: 1000 MW (250 at each hot spot), utility-scale PV: 3000 MW, CSP: 1000 MW
Fuel price escalation:	1.5% p.a. (except for Egyptian gas which will reach market prices in 2016)
Assumptions 2013:	Only existing power plant portfolio available to meet demand
	LFO, HFO and Egyptian gas (restricted to 550 t.t.o.e.) only available fossil fuels
Assumptions 2016:	600 MW DE-HFO to be built at node 1(Amman region) as already decided by authorities [8]
	LFO, HFO and Egyptian gas (restricted to 1000 t.t.o.e.) only available fossil fuels
Assumptions 2020:	Scenario 1: All fossil fuels are available without restrictions
	Scenario 2: No coal, gas restricted to 1000 t.t.o.e., HFO and LFO without restrictions

In this paper only a small selection of input data can be presented due to space limitation. For additional information please contact the author. Table 2 and Table 3 show the major assumptions for the power system of Jordan. The assumption for the total investment costs of the candidate units are shown in Table 4. For all investment options project financing is assumed with 40% own capital (15% discount rate) and 60% loans (5% interest rate) resulting in a WACC of 8.1% (incl. 30% income tax). For thermal power generation units (including CSP) a PPA duration of 25 years, for fluctuating RE units of 20 year is assumed.

Table 2: Assumptions for the electricity system of Jordan in 2013 (data [5] and own assumptions)

	Unit	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**	**Total**
Load distribution	-	0.625	0.025	0.125	0.075	0.15	1
Peak load	MW	1925	77	385	231	462	3080
Total existing power plant capacity	MW	2109	150	393	-	655	3526
CCGT units– Gas, LFO	MW / # Units	1647 / 5	-	373 / 1	-	-	2020 / 6
OCGT units – Gas, LFO	MW / # Units	200 / 8	150 / 5	20 / 1	-	-	370 / 14
ST units – Gas, HFO	MW / # Units	363 / 7	-	-	-	655 / 5	1018 / 12
Industrial units – HFO, LFO	MW	20	20	20	20	20	102
Other units (hydro, biofuel, etc)	MW	0	16	0	0	0	16

Table 3: Assumptions for the development of the electricity system of Jordan 2013 – 2020 (data [5] and own assumptions)

	Unit	2013	2016	2020
Electricity demand	GWh	18733	21814	28292
Peak load	MW	3080	3800	4940
Coal price	€/kWh$_{th}$	0.010	0.011	0.011
Gas price	€/kWh$_{th}$	0.015	0.030	0.031
HFO price	€/kWh$_{th}$	0.058	0.060	0.064
LFO price	€/kWh$_{th}$	0.068	0.071	0.075

Table 4: Assumption for investment costs – values adjusted for 30°C site conditions (data: 9 - 12] and own assumptions)

Technology	Unit	2016	2020
ST-Coal (wet cooling)	€/kW	1975	1975
CCGT-Gas/LFO (dry cooling)	€/kW	1565	1565
OCGT-Gas/LFO (peak load plant)	€/kW	670	670
DE-Gas/HFO (base load plant)	€/kW	1050	1050
DE-LFO (peak load plant)	€kW	800	800
Utility-scale PV – fixed mounted	€/kWp	1400	1110
Onshore wind power	€/kW	1385	1360
CSP parabolic trough (dry cooling)			
Solar field and HTF system	€/m²	265	225
TES	€/kWhth	31	26
Power block	€/kW	680	650
Cooling system	€/kW	245	235
Back-up system	€/kWth	45	42
Contingency*	€/kW	710	680

*Contingency: project costs, owner's costs, interests during construction, etc.

Figure 5 shows the results for the step-wise capacity expansion and share of power generation until 2020. Besides the 600 MW of DE-HFO, only RE power generation technologies are installed at planning step 2016. This indicates that according to the applied assumptions power generation by RE technologies is significantly cheaper than power generation by LFO or HFO (no coal available, gas availability restricted). For the planning step 2016, 1000 MW of wind power, 1441 MW of utility-scale PV, 1000 MW CSP (6 units x 167 MW), and 600 MW DE-HFO (12 units x 50 MW) are added to the existing power plant portfolio of Jordan in 2013. In average the six CSP plants have a 1.9 SM, a 10 h TES and a BUS capacity of 80% of the thermal gross capacity of the turbine in order to replace as much expensive oil as possible and to provide strongly required firm and dispatchable capacity. For the planning step 2020, capacity expansion differs according to the two investigated scenarios. At scenario 1 (no fuel restrictions), 1000 MW (2 x 500 MW) of coal-fired steam power plants are added to the existing portfolio of 2016. Furthermore, 400 MW of DE-HFO (8 x 50 MW), 400 MW of DE-LFO (8 x 50 MW), 220 MW of wind power, and 397 MW of PV are installed. No additional CSP plants are installed in 2020 at scenario 1. Additional required firm and dispatchable capacity is provided only by the coal-fired steam plants and Diesel Engines. Assuming scenario 2 for the planning step 2020, 1100 MW of DE-LFO (22 x 50 MW), 100 MW of DE-HFO (2 x 50 MW), 188 MW of wind power, 156 MW of PV, and 248 MW of CSP are added to the portfolio of 2016.

The share of power generation by RE on total power generation is increased significantly from almost 0% in 2013 to almost 43% in 2016. A significant part of power generation by expensive HFO and LFO is replaced by the large-scale introduction of RE. For the planning step 2020, the share of RE technologies on total power generation is not further increased since RE now mainly competing with natural gas and coal (scenario 1). In fact, in scenario 1 the share decreases to 36%. However, total power generation by RE increases about 11.5% compared to 2016. For scenario 2 the share of RE on total power generation keeps constant by 43%. The total power generation of RE increases to more than 12150 GWh/y which represents an increase of 17% compared to 2016. Due to the large-scale introduction of RE, Jordan's power generation mix is diversified and becomes significantly more independent from fossil fuel imports and the associated high risk of fossil fuel price escalations.

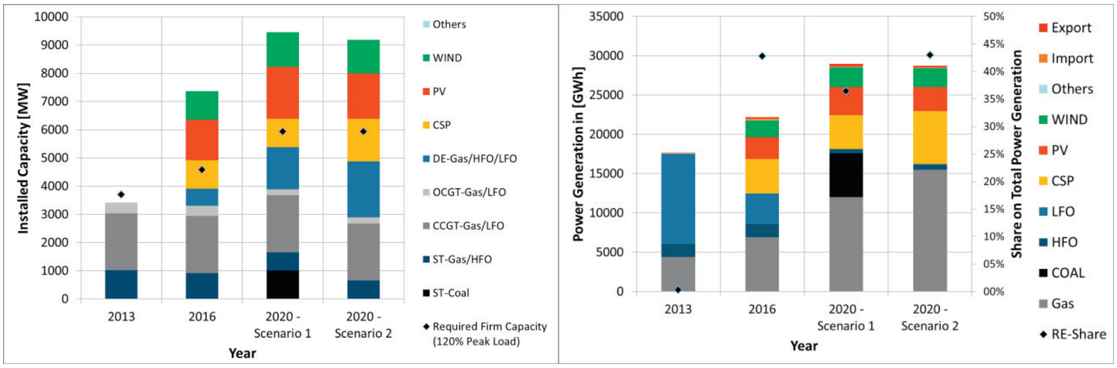

Figure 5: (a) Development of generation capacity; (b) Development of power generation share.

Figure 6 shows the development of the spatial distribution of the generation capacity until 2020. In 2013 the generation capacity is mainly installed close to the large demand centers Node 1 (62.5% of annual demand) and Node 5 (15%). Until 2020, the capacity is distributed much more over the five different model nodes due to the large-scale deployment of RE in regions with lower demand (Node 2 – 4).

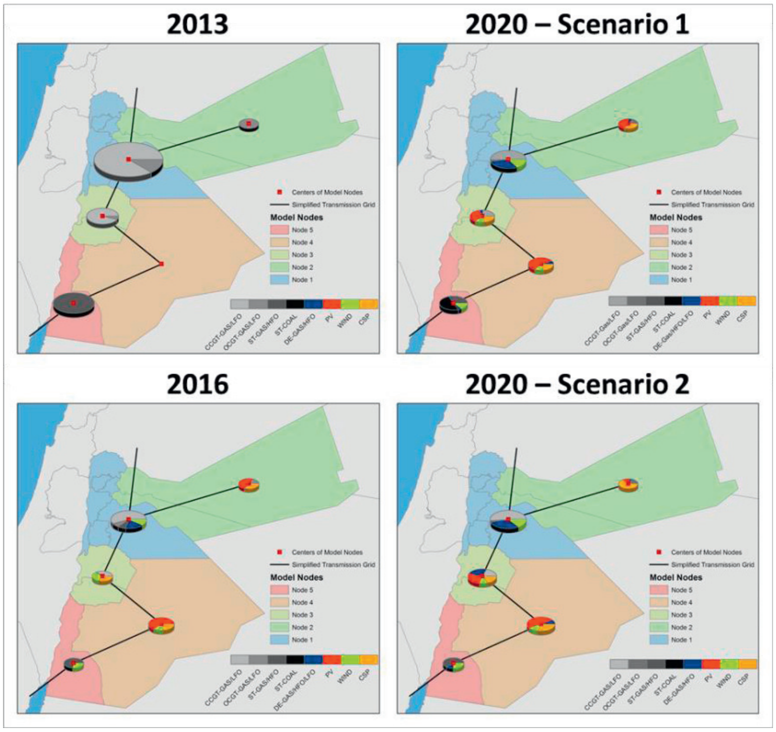

Figure 6: Development of spatial distribution of power generation capacity in Jordan from 2013 – 2020

Table 5 shows the development of the average total system costs of Jordan and the performance of selected units until 2020 according to the investigated scenarios. Due to the large-scale integration of RE technologies average generation costs of the system can be reduced from 0.163 €/kWh in 2013 to 0.124 €/kWh in the planning step 2016. Until 2020, average system costs are further decreased to 0,100 €/kWh at scenario 1 and 0.109 €/kWh at scenario 2. Furthermore, Table 5 shows that the CSP unit installed in 2016 has considerably higher LCOE than the wind power and PV units installed in the same year. However, since the CSP unit has significantly lower generation costs than the Diesel Engine burning expensive HFO, the CSP technology is highly valuable for Jordan's system and is the preferred option for strongly required firm and disptachable generation capacity in 2016. The CSP unit is equipped with a relatively large solar field, storage, and back-up system in order to replace large amounts of expensive oil and deliver highly required firm and flexible capacity. Comparing the performance of a CCGT unit which is part of the initial power plant portfolio of 2013 and the CSP unit installed in 2016, it can be observed that the CCGT unit has clearly lower LCOE in 2016. However, the LCOE of the CCGT increase significantly in 2020 (especially in scenario 1) due to the assumed fossil fuel price escalation and the decreased utilization due to the introduction of fluctuating RE and ST-Coal units with low variable generation costs (scenario 1). In contrast, the utilization and therefore the LCOE of the CSP unit keep constant over time since the low variable generation costs of the CSP unit guarantee utilization ones the unit is installed. This fact represents a great advantage of CSP compared to conventional technologies which also represents dipatchable capacity but guarantee no constant generation costs over time.

Table 5: Development of specific average total system costs and performance of selected power plants until 2020

			2013	**2016**	**2020 - Scenario 1**	**2020 - Scenario 2**
Specific Average Total System Costs		[€/kWh]	0.163	0.124	0.100	0.109
CCGT existing still 2012 at Node 1 - 373 MW (gross) - ACC cooling	Utilized fuel		Gas	Gas	Gas	Gas
	Variable costs at full load	[€/kWh]	0.036	0.061	0.071	0.071
	LCOE	[€/kWh]	0.050	0.080	0.160	0.099
	Full load hours	[h]	8655	7536	1685	6353
	Number of Start-Ups	[-]	1	2	18	19
Diesel Engine - installed in 2016 at Node 1 - 50 MW (gross)	**Utilized fuel**			HFO	Gas	HFO
	Variable costs at full load	[€/kWh]	-	0.167	0.091	0.175
	LCOE	[€/kWh]	-	0.226	0.202	0.299
	Full load hours	[h]	-	1916	905	940
	Number of Start-Ups	[-]	-			
CSP-PT - installed in 2016 at Node 4 - 136 MW (gross) - SM: 1.92, TES: 10 Flh, BUS 80% - ACC cooling	LCOE	[€/kWh]	-	0.126	0.126	0.126
	Full load hours	[h]	-	5260	5147	5136
	Number of Start-Ups	[-]	-	208	213	225
Utility-scale PV - installed in 2016 at Node 4	LCOE	[€/kWh]	-	0.089	0.089	0.089
	Full load hours	[h]	-	1962	1962	1962
Wind - installed in 2016 at Node 4	LCOE	[€/kWh]	-	0.077	0.080	0.084
	Full load hours	[h]	-	2290	2180	2055

Figure 7 shows the development of the unit dispatch for the planning steps 2013, 2016 and 2020 (scenario 1) exemplary for the 29th week. The midday-peak which is served by expensive fuel oil in 2013 is replaced by relatively cheap utility-scale PV plants. Furthermore, due to its low generation costs at very good sites onshore wind power is used as a cheap "fossil fuel saver". CSP plants are operated as mid merit power plants (about 5000 Flh) increasing significantly the share of RE on the overall power generation and providing strongly required firm and flexible power generation capacity. Since CSP units are fully dispatchable due to the TES and back-up system, power generation by the CSP units can be increased during morning hours when power demand increases and PV generation is at low levels. During hours of high PV generation the output of the CSP units is reduced and thermal energy is stored in the storage system for later use. In the evening hours CSP generation is increased again when PV generation decrease and power demand increase simultaneously, making CSP a very valuable power generation option for Jordan's power supply system.

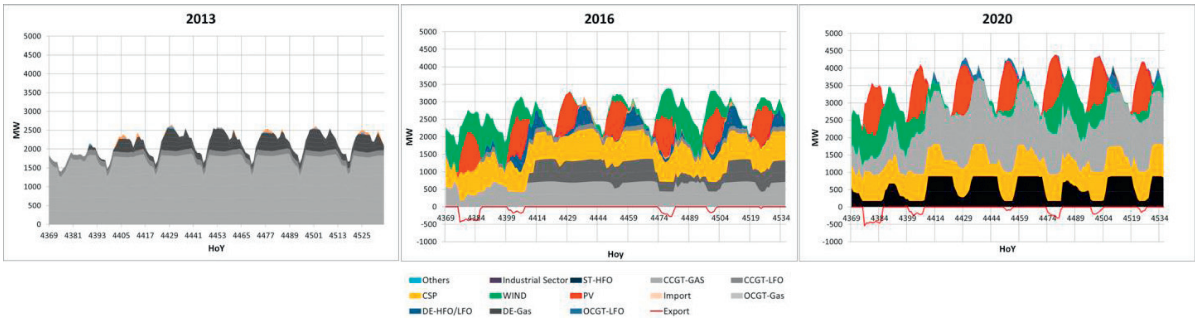

Figure 7: Summer week extract from the annual hourly power dispatch of the entire system in 2013, 2016 and 2020 (Scenario 1).

4. Conclusions

Optimizing the integration of RE technologies into an existing power plant portfolio requires a detailed modeling of the characteristics of different power generation technologies. Due to its characteristics CSP can play a key role for the MENA region when transforming the existing power systems towards RE. Hence, modeling the characteristics of CSP plants properly within power system optimization models is crucial for assessing the potential and the future role of this dispatchable RE technology. The paper has shown how CSP plants can be integrated into a power system optimization model. Furthermore, within the Jordan case study it was shown that, under the applied assumptions, CSP plants and other RE are already competitive in the short-term, especially in strong increasing electricity sectors with a significant share of power generation by LFO and HFO. It was shown that a well balanced mix of all available RE technologies can decrease significantly Jordan's high electricity generation costs of today and can make Jordan significantly more independent from possible future fossil fuel price escalations or availability restrictions. In order to make the results of this case study more reliable, sensitivity analyses should be carried out in order to investigate the uncertainties of the input data and the associated risk and influence on the results.

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