The Role of Solar Energy towards 100% Renewable Power Supply for Israel: Integrating Solar PV, Wind Energy, CSP and Storages

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MOTIVATION

Modern fossil-fuel based energy systems violate numerous sustainable development criteria: greenhouse gases emissions provoke unpredictable climate change impacts, consumption of fossil fuels leads to an increasing dangerous dependence on a small number of fuel exporting countries, and a further development of the conventional energy system does not solve the problem of the inevitable depletion of fossil fuel reserves. However, all these problems can be solved by transforming towards a renewable energy (RE) based system. Already today the utilization of different RE technologies is profitable in many regions and costs of renewables decrease further [1]. Perfect solar resources of the eastern Mediterranean drive the RE system installations in Israel. Even now distributed small-scale rooftop PV can be profitable for residential consumers. Our aim is to compute an optimal mix of technologies for shares of RE in total electricity generation from 5 to 100% and to define the cost of electricity for every configuration of the energy system.

APPROACH

At LUT we have developed an hourly resolved linear optimisation model for energy systems. This model makes it possible to define: an optimal set of technologies which are best adapted to the available resources in the region, optimal values of installed capacities for every technology and optimal operational modes of the system elements to reach least cost energy supply with respect to given constrains. One of the key features of the model is its expandability – it can easily add new energy sources and technologies. For simulating the energy system of Israel, it includes the renewable energy sources: PV rooftop (residential and commercial self-supply), ground-mounted PV (large scale plants, commercial and industrial self-supply), onshore wind turbines and concentrating solar thermal electricity generation (CSP). As a fossil fuel source we utilize natural gas. Three options of energy storage technologies are available: batteries, gas storage and thermal energy storage (TES). Energy conversion technologies are open cycle (OCGT) and combined cycle (CCGT) gas turbines, steam turbines, hot heat burner (converts gas fuel into thermal energy) and heating rod (converts electrical energy into thermal energy). All these options deliver various operational modes, many interdependencies and make a very flexible system utilization possible. Computations are made for the years 2020 and 2030 based on financial and technical assumptions (Tab. 1-3). The full system overview is presented in Figure 1.

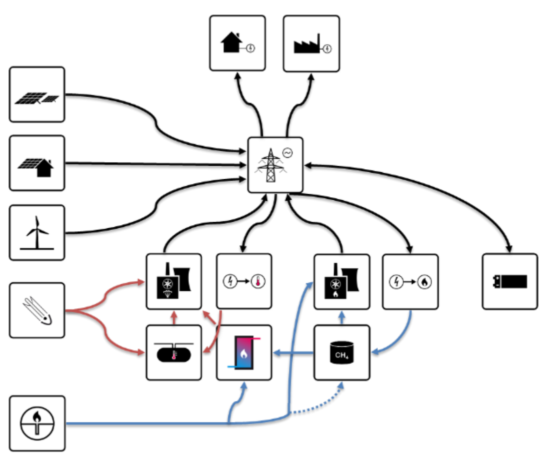

Figure 1. Full overview of the electrical energy system for the case of Israel.

Self-consumption is a very valuable part of RE-based energy systems, for this work it was assumed that only 20% of consumers in the residential, commercial and industrial sectors are willing to install their own generation capacities consisting of PV modules (rooftop in the case of residential sector and rooftop or ground-mounted in the case of commercial and industrial sectors) and batteries. The dimensioning of PV and batteries is optimized to reach minimal annual cost of consumed electricity. Excess energy can be sold to the grid for 2 €ct/kWh; variable costs of electricity are 9.4 €ct/kWh, 8.8 €ct/kWh, and 6.3 €ct/kWh for residential, commercial and industrial sectors, respectively [9]. For modelling of RE generation we have used solar irradiation and wind speed data (the spatial resolution is 0.45° latitude x 0.45° longitude) from the German Aerospace Center [2], based on NASA SSE data (Surface Meteorology and Solar Energy SSE Release 6.0).

Table 1. Financial assumptions for the energy system components for the reference years 2020 and 2030. The numbers for 2020 and 2030 are identical unless a second number indicates a change for 2030 assumptions. The financial assumptions for storage systems refer to kWh of electricity, and gas storage refers to one thermal kWh of methane at the lower heating value. Assumptions are mainly taken from Pleßmann et al. [3] but also other sources [4-8].

Technology	Capex [€/kW]	Opex fix [€/kW]	Opex var [€/kWh]	Lifetime [a]
PV ground-mounted	896 / 550	13 / 8	0	30 / 35
PV rooftop	1120 / 690	17 / 10	0	30 / 35
Wind onshore	1179 / 1000	24 / 20	0	20 / 25
CSP (solar field)	596 / 528	12 / 11	0	25
Water electrolysis	685 / 380	24 / 13	0.0012	30
Methanation	421 / 234	18 / 5	0.0015	30
CO_2 from air	641 / 356	25 / 14	0.0013	30
CCGT	750	15	0.001	30
OCGT	380	7.6	0.001	30
Steam turbine	600	12	0	30
Hot heat burner	100	2	0	30
Heating rod (Power-to-Heat)	20	0.4	0.001	30
	Capex [€/kWh]	Opex fix [€/kWh]	Opex var [€/kWh]	Lifetime [a]
Battery	300 / 150	10 / 10	0.0002	10 / 15
TES	30	1	0.0002	20
Gas storage	0.05	0.001	0	50

Table 2. Efficiencies and energy to power ratio of storage technologies. Assumptions are mainly taken from Pleßmann et al. [5].

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-discharge [%/h]
Battery	85	6	0
TES	90	8	0.002
Gas Storage	100	80*24	0

Table 3. Efficiency assumptions for the energy system components for the reference years 2020 and 2030. Assumptions are mainly taken from Pleßmann et al. [5].

	Efficiency [%]
CSP (solar field)	51
Steam turbine	42 / 43
Hot heat burner	95
Heating rod (Power-to-Heat)	99
Water electrolysis	84
Methanation	77
CO_2 from air	78
CCGT	58
OCGT	38

RESULTS

We have found an optimal structure of the energy system for different shares of RE for the cost years 2020 and 2030 (Fig. 2). For both cost years, the least cost and consequently major energy source is solar PV; however, for 2020 CSP still plays a significant role. This can be explained by the strong dependence on energy storage options: for the year 2020 CSP-TES is more competitive than PV-battery. For both years PV generation capacities increase linearly, while energy storages are not needed – till a 30% RE share. For the year 2030 PV capacities still increase linearly after the 30% RE threshold. However, for year 2020 PV stagnates after the 30% RE share threshold, due to expensive battery storage. CSP electricity coupled with TES is a lower cost source of electricity for higher shares of RE than the PV-battery alternative. For the year 2020 battery storage is not competitive and hence no batteries are installed. All needed energy is stored in thermal and gas reservoirs. The moderate wind conditions of Israel are the reason why for both cost years wind turbines are a rather high cost energy source and significant amounts of wind power capacities are installed only after a 50% RE share. The reason to install wind turbines despite rather limited full load hours and the high variability of wind in Israel is the difference of the wind and PV profiles: wind FLH are maximal during the winter months while the solar irradiation is reduced. Power-to-gas technology and gas storages are feasible in Israel only after 85% RE, due to the low annual variability of the main RE resource (solar irradiation) and the demand. Installed capacities for different technologies for the year 2020 and 2030 for 0 to 100% RE shares are presented in Figure 2.

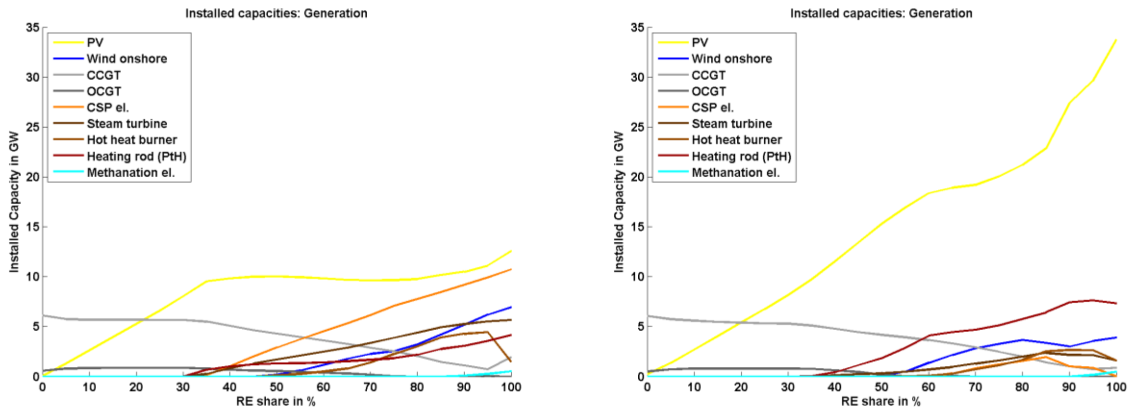

Figure 2. Installed capacities of different technologies for RE shares from 0 to 100%, for the cost year 2020 (left) and 2030 (right). The energy system is mainly defined by Figure 1 and Tables 1-3.

For computed optimal energy systems, we have calculated the levelized costs of electricity for the full energy system, the decentralized and the self-generation parts (Fig. 3). For both cost years the minimal LCOEs are reached between the 30 and 40% RE share, at which the RE share is already significant, but the system still can operate without energy storage capacities. For 2020 cost assumptions, the minimal LCOE of 6.2 €ct/kWh is reached at a 30% RE share and the system costs are equal to the 0% RE share for 6.3 €ct/kWh at 35%. For 2030 minimal LCOE is 5.6 €ct/kWh (at 35-40% RE) and at 65-70% RE LCOE is equal to 0% RE LCOE. An interesting fact is that because of PV self-consumers and the generation feed-in tariff of the centralized system, LCOE increases between 0 and 25% RE but at the same time the cost of the whole electricity system decreases. Main results for residential, commercial, and industrial PV self-generation are presented in Table 4.

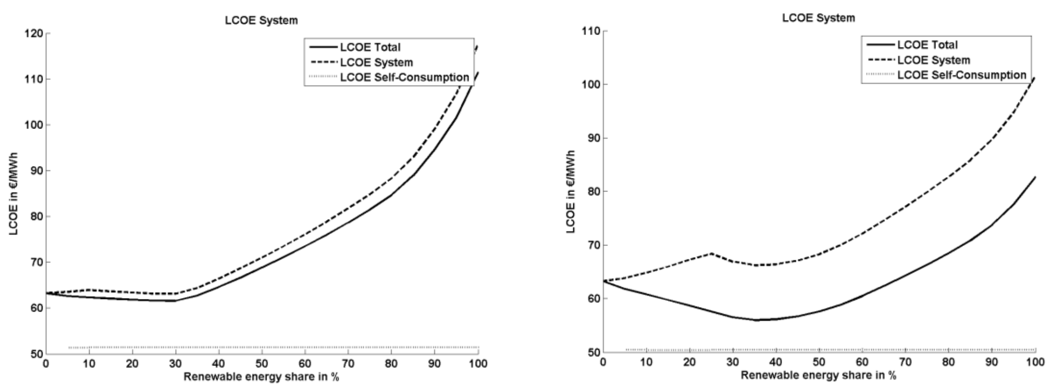

Figure 3. Levelized cost of electricity for the electricity system, based on the centralized system and PV self-consumers for RE shares from 0 to 100% for the cost years 2020 (left) and 2030 (right).

Table 4. Results for the PV self-generation optimisation for the different market segments and the cost years 2020 and 2030.

	2020			2030		
	Residential	Commercial	Industrial	Residential	Commercial	Industrial
Electricity price [€/kWh]	0.094	0.088	0.063	0.115	0.107	0.077
Self-consumption LCOE [€/kWh]	0.042	0.058	0.056	0.066	0.041	0.037
Installed capacities	Residential	Commercial	Industrial	Residential	Commercial	Industrial
PV [GW]	0.935	0.834	0.445	4.441	1.418	0.745
Battery storage [GWh]	0.000	0.000	0.000	4.061	0.105	0.000
Utilization	Residential	Commercial	Industrial	Residential	Commercial	Industrial
Self-consumption [%]	75.4	93.9	98.6	39.2	68.2	76.0
Self-coverage segment [%]	8.5	7.4	6.6	19.4	9.0	8.5
Self-coverage operators [%]	42.5	36.8	32.9	96.9	45.2	42.4

For the 100% RE scenario and the year 2020 assumptions CSP is a major source of primary energy, however half of this energy cannot be converted into electrical energy due to the limited efficiency of the steam turbines. For the 100% RE scenario and the year 2030 assumptions (Fig. 4.) PV delivers about 90% of primary energy. It can be also observed, that in a cost optimal regime a recharging of gas storages from battery and TES takes place, caused by the need to discharge batteries during the nights in case of otherwise not storable electricity on the following day.

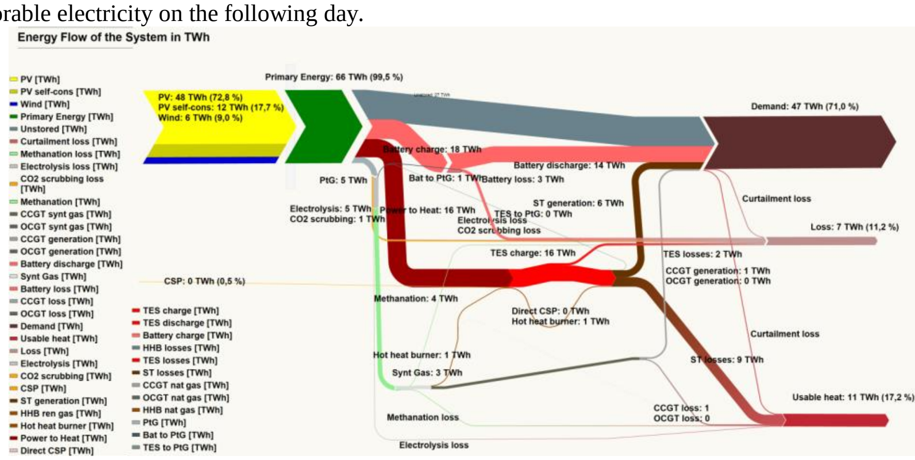

Figure 4. 100 % RE system energy flows for the year 2030.

A sensitivity analysis for battery and PV capex shows that the system LCOE depends more on PV costs than those of batteries (Fig. 5). The reason for that is a much higher share of PV costs in the total system cost (35% and 11% for PV and batteries respectively, for year 2030 100% RE scenario).

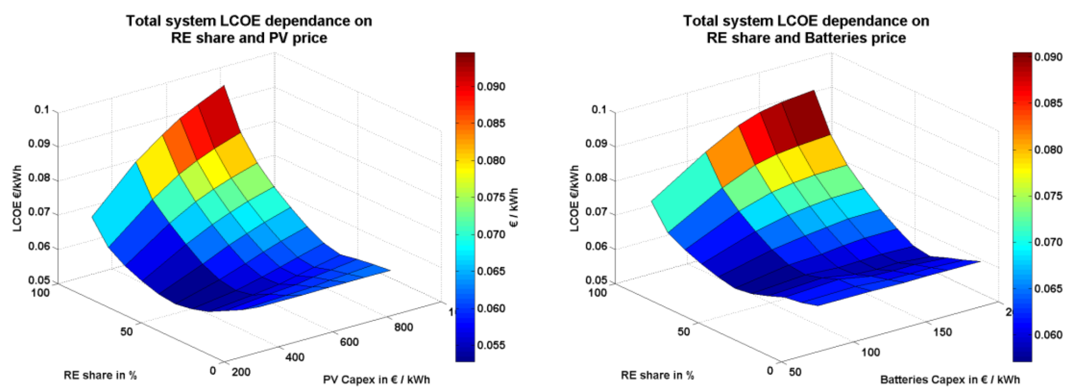

Figure 5. Sensitivity scenarios on PV (left) and battery storage (right) costs.

CONCLUSION

The excellent solar resources of Israel make it possible to reach the target of 100% RE, independent of fossil fuel supply in a rather close future. For now the development of large PV capacities is restrained by battery storage costs: before reaching a cost level of 200 €/kWh, batteries are not competitive and installations of thermal storages and CSP are cost optimal. The role of CSP remains unclear; however, the high competitiveness of PV-battery may limit CSP to a minor role. PV self-consumption plays a significant role in the energy transformation in Israel.

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