Combined CSP – PV plants for MENA Region

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ABSTRACT

This paper presents the first outcomes of the ongoing project HYMENSO – Hybrid Concentrated Solar Thermal Power (CSP) and Photovoltaic (PV) plants for MENA Region – which has the main goal to investigate the optimal configuration of solar power plants for selected sites in Jordan, Tunisia and Algeria. This technology hybridization is becoming popular since it can harvest the advantages of both systems: easy installation and low LCOE (levelized cost of electricity) for PV, versatility and dispatchability of CSP. Additionally, fossil back-up with natural gas is also analyzed. The project HYMENSO is funded by the participants' countries in the framework of ERANETMED.

The initial task in the project consists of data collection such as meteorological data (including validation of satellite-derived irradiation), local costs, water availability, grid demand and energy policies. With the selection and generation of the techno-economic parameters, hybrid CSP-PV plants are designed and simulated in order to select the optimal configurations. Project partners in Jordan, Tunisia and Algeria will gather measured data from pilot CSP or PV plants to validate their performance models and simulate the hybridization between the two technologies. The knowledge gained will be transferred to other organizations and stakeholders.

This paper presents preliminary results with focus on the simulation of the hybrid systems. It has been demonstrated that the configuration options of the CSP and PV systems are very wide, depending on further boundary conditions and regulations such as limitation of CO_2 emissions, if fossil back-up is used, or expected satisfaction of the electricity demand. Further local conditions as available land size and water availability will play a role when selecting a specific configuration. Important to notice is that for countries with a high fossil fuel price, such as Jordan, the hybridization with natural gas reduces the overall LCOE only until a share of the generated energy of about 20%, higher use of fossil fuel is for such sites rich in solar irradiation not of noticeable advance.

1. INTRODUCTION

A common topic for the Middle East and North African (MENA) countries is the increasing local energy demand combined with high energy costs and short reserves of fossil fuels. Energy policies support the growing usage of renewable energy in order to minimize the CO_2 emissions and be less dependent on foreign energy sources. There are several technologies to address this issue. The difficulty is how to combine renewable energy technologies in a way that large amount of renewables can be fed into the electrical grid without affecting its stability due to the fluctuations of the natural resource (wind and sun) while keeping the overall costs low and maintaining an overall high system efficiency. The ideal solution will consist of technologies locally developed and manufactured, that use renewable resources as primary energy source, operate fully flexible and dispatchable and that can be applied on utility-scale power plants as well as on rural micro grids without generating problems to the grid stability.

In opposition to the excellent availability of solar radiation in the MENA countries, relatively few photovoltaic (PV) and Concentrated Solar Power (CSP) applications exist. This leads to a lack of practical experience regarding the conceptual design, operation strategies, capital and operational costs, impact on the electrical grid, etc., hindering the technology shift. The consciousness of the value of energy storage and dispatchability also should be increased, in order to boost the use of renewable energies.

A strong knowledge basis about renewable energies is present in all academic and research institutions participating in this project. Nevertheless, low practical experience exists in relation to fitting the energy generation to the demand profiles of the country and the costs related to it. Additionally, due to the reduced number of operating solar power plants in the region, there is low integration of the local industry in solar projects and, therefore, the reaction time for the development of new solar projects is still too long.

The successful application of adequate solutions depends on the extension of the technical and economic knowledge, therefore the importance of the capacity building and dissemination of these facts. The project HYMENSO should serve as a reference to guide local researchers and industry about the factors that affect the configuration of solar power plants, the different options available, the possible combination with fossil fuels and their techno-economic performance for different sites.

To cover these objectives researchers from Europe (Germany and Greece), North-Africa (Tunisia and Algeria) and Western-Asia (Jordan) are cooperating in order to share general and local knowledge, validate the calculations and disseminate the results

The project HYMENSO is funded by the participants' countries in the framework of ERANETMED (see Section 5).

2. INPUT DATA

2.1. Meteorological Conditions

The data required for the simulation of the hybrid solar power plants is acquired by the enerMENA stations (project led by DLR's Institute of Solar Research, financed by Germany's Federal Foreign Office) installed on five countries in the MENA region [1], [2]. Figure 1 shows the location of the meteo stations available. For simulation purposes, a complete year of data without gaps was prepared.

Moreover, a methodology for the generation of solar irradiances, global horizontal irradiance (GHI) and direct normal irradiance (DNI), based on atmospheric products from various sources, has been developed. Satellite data from Moderate Resolution Imaging Spectroradiometer (MODIS v.6) and Radiative Transfer Model outputs are imported into a successive multi-linear interpolation algorithm for the generation of solar datasets with high temporal resolution. The algorithm represents the calculation of direct normal and global solar irradiance for clear sky and cloudy conditions. The reliability of the generated solar products is examined by the validation with real measurements from stations located in the MENA region. After the statistical assessment, a statistical bias correction method is followed in order to increase the accuracy and the reliability of the modeled solar irradiances. The proposed methodology is separated in three steps for the creation of the final solar products including simulation, validation and correction. The statistics for GHI, as a function of ground—based measurements, is presented in Figure 2.

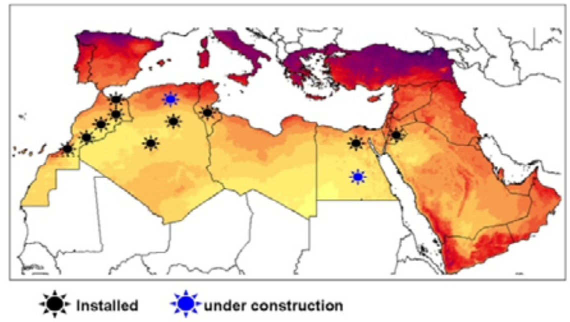

Figure 1: Location of enerMENA meteo stations. Source: DLR

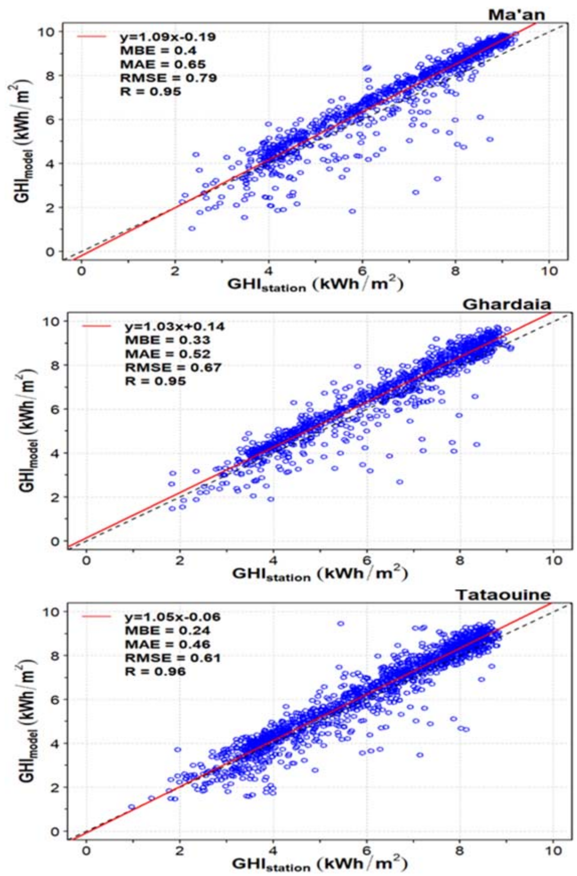

Figure 2: Validation of modelled GHI data. Source: University of Patras, Greece

2.2. Energy Market

A common topic to the MENA countries is the increasing local energy demand combined with high energy costs and short reserves of fossil fuels and that has led them to adopting renewable energy policies and strategies that support the usage of renewable energy broadly. However, with growing use of renewable energy, a potential issue has arisen; the difficulty of how to combine renewable energy technologies in a way that large amount of renewable can be fed into the electrical grid without affecting its stability due to the fluctuations of the natural resource (wind and sun) while keeping the overall costs low and maintaining an overall high system efficiency.

The ideal solution will consist of technologies locally developed and manufactured that use renewable resources as primary energy source, operate fully flexible and dispatchable. This paper handles this issue in MENA region by hybridization of solar energy technologies which have a great importance in this region because it is rich of high rates of GHI and DNI radiation. The optimum configuration of hybrid PV-CSP systems has been determined for Jordan, Tunisia and Algeria to cover electrical demand harvesting the advantages of both technologies: easy installation and LCOE for PV, versatility and dispatchability of CSP because of its capability of storing energy by using thermal energy storage.

The share of Renewable Energy from the total energy or electricity production is low compared with European countries. However, the local market is still growing and Jordan achieved high growth rate in the field of renewable energy. Currently, Jordan is located on the third place in the region with respect to the installation of renewable energy projects and number one in the region with respect to the share of renewable energy per capita. Also, Jordan has a local market for PV production. The market in Algeria and Tunisia is still growing very quickly. The market can absorb large number of renewable energy projects. The domestic PV industry needs a regional market to export its products.

The energy market data from MENA countries Jordan, Tunisia and Algeria, where the study is conducted, has been collected to identify the boundary conditions in these countries for simulation, such as the load curve characteristics.

The volume of electricity generated in 2016 in Jordan reached 19390 GWh registering a growth of 2.5% of that in 2015 while the electricity consumed for the same period reached 16669 GWh recording a growth of 3% approximately comparing with that in 2015, MEMR (2016). However, the peak load of the electricity system was 3250 MW in 2016.

Indeed, the integration of renewable energies into the national energy mix in Algeria constitutes a major challenge in the preservation of fossil resources, the diversification of electricity production ways and the contribution to sustainable development. Achieving the renewable energy program will allow to reach by 2030 a part of renewables of about 27 % in the national report of electric production.

After collection of energy market data from Jordan, Algeria and Tunisia, the HYMENSO team decided that the Solar Park in Ma'an City in Jordan, the Ghardaia city in Algeria and Tataouine in the south of Tunisia are the best sites for simulating a hybrid CSP-PV plant, because of their high rates of GHI and DNI and their proximity to enerMENA stations. This proximity allows using available solar radiation data of high accuracy.

After study and discussion, it turns out that these sites have the necessary factors to build a hybrid CSP-PV plant due to the fact that they are close to the public grid, main roads and water sources and the most important thing: they are rich in solar radiation.

Ambitious plans and targets were specified by the three countries to increase the use of renewable energy and many policies and laws are employed to encourage using it. Currently, they have potential PV plants but unfortunately, only Algeria has CSP plant whereas Jordan and Tunisia have not tried this technology yet.

2.3. Hybrid Solar Power Plants

Together with the project partners, the CSP and PV technologies to be simulated were selected based on their local relevance, technologic maturity and proven performance. The resulting selection is as follows:

CP1: CSP plant with parabolic trough collectors using thermal-oil heat transfer fluid (HTF) in the solar field, with indirect molten salt thermal energy storage system (TES), including a fossil-fuel back-up system and a polycrystalline single axis tracked PV plant.

CP2: CSP plant with parabolic trough collectors using molten salt as HTF in the solar field, with direct molten salt thermal energy storage system, including a fossil-fuel back-up system and a polycrystalline single axis tracked PV plant.

CP3: CSP plant with central solar tower using molten salt as HTF, with direct molten salt thermal energy storage system, including a fossil-fuel back-up system and a polycrystalline single axis tracked PV plant.

For the definition of the economic and technologic situation, the year 2020 was selected for the simulations.

A nominal net electrical output of the hybrid plants of 100 MW is selected. This size is close to many currently deployed CSP plants worldwide and therefore sufficient information regarding costs and performance is available [3].

The PV plants are considered here as complementary to the CSP plants. During the optimization process PV capacities from 0 to approx. 250 MW were analyzed.

Battery systems to store electrical energy from PV are currently not competitive compared to CSP plants with thermal energy storage [4]. For this reason, battery systems have not been included in this study.

Due to the relevance for the MENA countries, fossil back-up systems are considered by incorporating a natural gas heater to the CSP plant. The relationship between the Levelized Cost of Electricity (LCOE) and the CO_2 emissions is analyzed. For comparison, solar-only plants are also simulated.

Figure 3 below shows a simplified sketch of the case CP3:

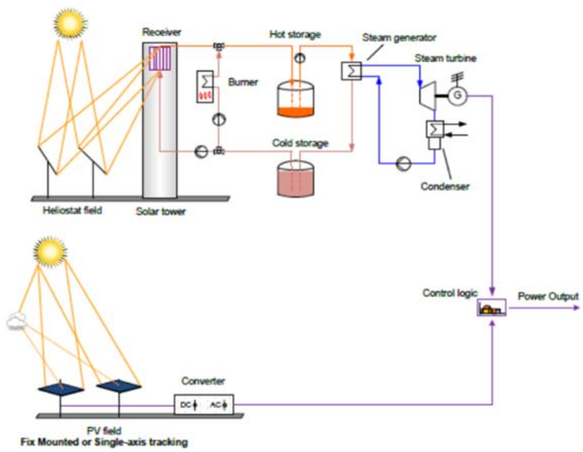

Figure 3: Exemplary CSP + Natural Gas Burner + PV plant. Source: DLR

3. TECHNO-ECONOMIC MODELLING

Based on the input data presented on Section 2, the hybrid CSP-PV power plants were conceptually designed and techno-economically simulated. This work package is a central part because the results provide useful examples for future solar power plants in MENA.

This section presents the main assumptions used for the simulations, describes the methodology followed and presents the results obtained.

3.1. Input Parameters

The tables below summarize the reference inputs for the case CP3; based on them, all configurations were determined depending on the parameter variation (see section 3.2 below). More information and data for the other configurations can be provided upon request.

Table 1: Reference system CSP. Source: DLR

Item	Unit	Value
Heliostat		
Heliostat type/name	Multi-facetted glass metal heliostat with 2-axes drive, pedestal mounted	
Net reflective area per heliostat	[m²]	121
Number of facets	[-]	28 (4x7)
Annual mean reflectivity	[%]	91.23
Beam error	[mrad]	3.50
Solar Tower		
Type	[-]	Concrete
Number of towers	[-]	1
Height	[m]	275.7
Diameter	[m]	15
Solar field – system definition		
Field layout	[-]	Surround
Solar Multiple (SM)	[-]	2.4
Number of heliostats	[-]	8860
Optical efficiency of solar field design	[%]	68.5
Total land area	[m²]	5,407,294
Solar receiver		
Receiver type	External, cylindrical tube receiver	
Heat transfer fluid (HTF)	[-]	Solar Salt
Thermal power design	[MW]	628.3
Receiver efficiency design	[-]	0.886
Optical height receiver	[m]	265.7
Receiver aperture area	[m²]	1242
HTF inlet temperature	[°C]	290
HTF outlet temperature	[°C]	580
HTF design mass flow	[kg/s]	1437
Mean flux density design	[kW/m²]	575
Storage system general		
Storage type	Two-tank sensible	
Storage medium	[-]	Solar Salt
Storage capacity in full load hours	[h]	10
Total effective capacity	[MWhth]	2618
Temperature hot / cold tank	[°C]	580 / 290
Heat losses	[MWth]	0.59
Power block general		
Design net electrical Power	[MWel]	100
Design gross electrical Power	[MWel]	112.1
Design gross efficiency	[%]	42.82
Cooling type	[-]	Air Cooled Cond.
Design condenser conditions	[mbar / °C]	155 / 54
Desing auxiliary electricity demand	[MWel]	5.605
Offline auxiliary electricity demand	[MWel]	1.401
Desing auxiliary electricity demand HTF system	[MWel]	6.5
Start-up time (hot)	[min]	15
Start-up time (warm)	[min]	40
Start-up time (cold)	[min]	360
Max. ramp rate as [% of gross capacity/min]	[%]	4-8
Live steam parameters	[°C / bar]	565 / 165
Reheat steam temperature	[°C]	565
Inlet / outlet temperature HTF steam generator	[°C]	239 / 565
Thermal input	[MWth]	261.8
Auxiliary burner		
Fossil fuel	[-]	Natural gas
Thermodynamic efficiency of burner	[%]	93

Table 2: PV System Technical Parameters. Source: DLR

Item	Unit	Value
PV Manufacturer	-	JA Solar
PV Module Type	-	JAP6 72-320/3BB
Tracking (yes/no)	-	yes
Nominal Module Power	W	380
Nominal Module Efficiency	%	19.6

Number of serial modules	-	20
Number of parallel module strings	-	220
Number of Systems	-	100
Collector distance (shadowing)	m	9.50
Inverter Manufacturer	-	SMA
Inverter Type	-	SunnyCentral CP1000-XT **
Nominal Inverter Power	kW	1,190
Nominal Inverter DC Voltage	V	688
Inverter design efficiency	%	98.7
Wiring losses at full power (STC), AC+DC	%	1.44
Module quality + module array losses	%	1.1
Other losses (soiling?)	%	2
PV / Battery (yes/no)	-	no
Availability	%	98
Degradation	%/y	0.5
Module plane inclination	°	variable
Structure size N-S	m	6
required power factor	Cos(phi)	1.0

Table 3: Economic Parameters. Source: Hymenso Partners

Item	Unit	Value
SPECIFIC CAPEX CSP		
Heliostat Field (incl. Land & HTF)	€ per m² mirror aperture	Tunisia: 103.68 Algeria: 103.72 Jordan: 104.42
Tower (275.5 m height)	Mio. €	28.4
Receiver	€/kWth	97
Thermal Storage	€/kWhth	22.6
Power Block (incl. Cooling)	€/kWel	968
Fossil Backup System	€/kWth	50
Contingency	% of DC	26 %
SPECIFIC OPEX CSP		
Insurance Rate	% DC/y	included in O&M
O&M Misc.	% DC/y	2.3 %
Water Cost for CSP plant	€/m³	Tunisia: 0.20 Algeria: 0.04 Jordan: 0.06
Natural Gas price	€/MWh LHV	Tunisia: 25.80 Algeria: 2.13 Jordan: 28.86
SPECIFIC CAPEX PV	**Unit**	
Modules	€/kWp	809
Inverters	€/kWp inverter	incl. in modules cost
Trackers	€/kWp	154
SPECIFIC OPEX PV		
O&M Misc.	% DC/y	1.5 %
Insurance Rate	% DC/y	included in O&M
Water Cost	% DC/y	0 %
Financial Assumptions		
Debt Period	y	25
Discount rate	%	7 %
Annual degradation	%/y	0.3 %
Availability	%	97 %

3.2. Methodology and Operation Strategy

The approach proposed is to cover the selected electrical demand with hybrid solar plants and determine for each technology case and site the best configuration by minimizing the LCOE. Due to the currently low cost of natural gas, it is important to determine the CO_2 emissions and analyse which limitations should be set for solar power plants, in order to avoid optimization towards high fossil fuel consumption. Additionally, solar-only cases are also analysed.

The assessment of the key design parameters as well as the annual yields is performed with the simulation tool INSEL [5]. The DLR started using INSEL several years ago and contributed to extend the tool capabilities by including new modules (e.g. CSP library, Desalination library) in the commercial library. In addition, the tool has been used within several research projects and pre-feasibility studies [6], [7], [8]. INSEL has undergone and successfully passed an in-depth validation procedure with best-available tools for the analysis of CSP, PV and battery systems. The expected performance difference in comparison to such tools is of up to approx.. ±2 % (net power generation on annual basis) [6]

Sensitivity analyses and parametric studies can be carried out without the utilization of the INSEL graphical user-interface by means of batch scripts.

The variation of the design parameters lead to a combination of 700 different configurations per case and country selected, with the following parametric mesh:

- CSP thermal energy storage: 3 to 21 full-load hours (FLH) capacity in steps of 3h
- CSP solar multiple: 1.8 to 3.4 in 0.2 steps plus 1.4 case
- PV installed capacity (nominal DC): 0 to 227.2 MW in 28.4 MW steps

An important factor for the optimization of the plant configuration is the energy output that the plants need to fulfil. Especially the load profile is relevant due to the volatile incoming power from the sun and affected by the weather conditions. For this reason, local demand curves for the countries were generated based on the local market research performed by the partners.

The demand profile selected for summer and winter for Ma'an, Jordan is shown below:

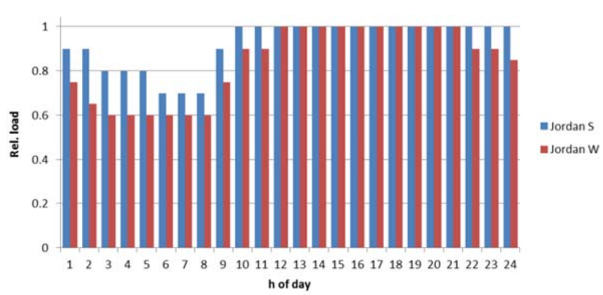

Figure 4: Exemplary demand profile. Source: DLR

The operation strategy of the hybrid solar power plants is shown graphically on Figure 5 below. It represents the operation of seven consecutive days in summer. The light yellow area is the energy generated by PV, the orange area is the energy from CSP and the stripped brown-yellow area is the energy from natural gas. The red line corresponds to the charge level of the thermal energy storage, the blue line is the direct solar irradiance and the black line is the electrical demand for the time selected.

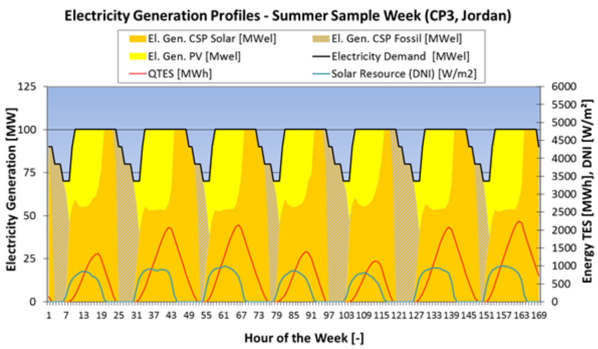

Figure 5: Daily energy production example. Source: DLR

3.3. Optimization Results

3.3.1. With fossil fuel

As mentioned above, due to the importance on the participant countries (especially in Algeria) hybridization with natural gas is considered. For this reason, the configurations with the lowest LCOE are presented according to the relative emission in g CO_2 per kWh generated electric energy. Results with emissions above 200 g/kWh are not presented because in that case it makes more sense to use the natural gas in a more efficient way, for example with a gas turbine, than burning it within a solar power plant.

The legend below each bar in the charts displays the main parameters of the configuration that obtained the lowest LCOE, which are: solar multiple (SM), thermal storage capacity in full load hours (TES) and the nominal PV capacity in MW. The curve shown in purple is the LCOE per configuration in €cent/kWh. The sections of each bar represent the amount of net electrical energy per technology source. The total net electrical output (Enet) is practically constant for each case, which corresponds to the electricity demand per year defined for each location. Figure 6 to Figure 8 show part of the results for the three technology combinations for the site in Jordan.

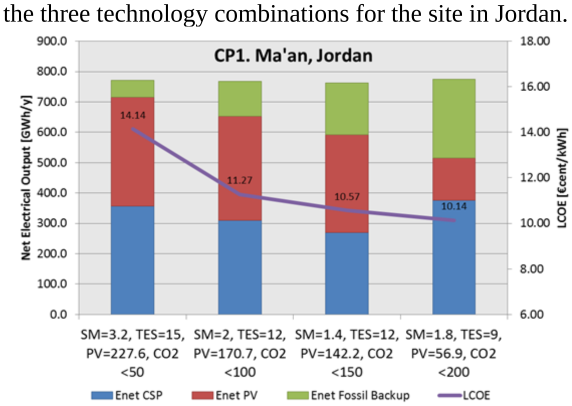

Figure 6: Simulation results. Case CP1, Jordan. Source: DLR

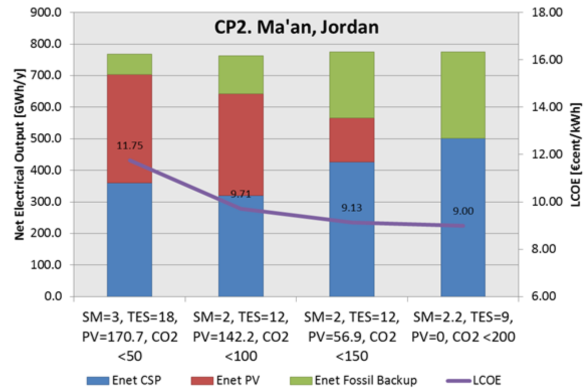

Figure 7: Simulation results. Case CP2, Jordan. Source: DLR

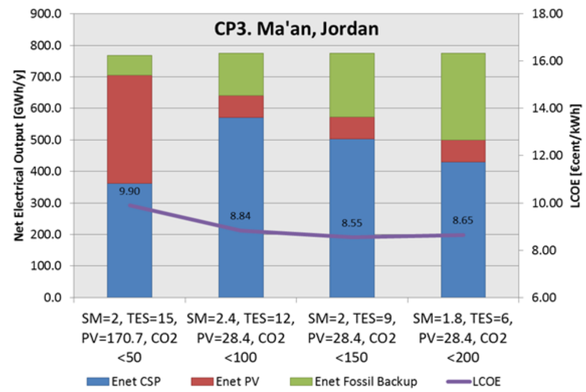

Figure 8: Simulation results. Case CP3, Jordan. Source: DLR

3.3.2. Solar Only

In order to analyse the impact on the costs and the energy supply of solar-only plants, the same cases have been simulated, without fossil HTF-heater. For these diagrams, instead of displaying the CO_2 emissions the demand covered in percentage (%Demand) for the plants configurations with the lowest LCOE are displayed.

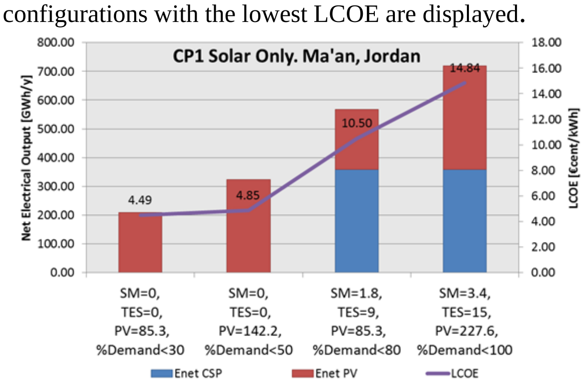

Figure 9: Simulation results. Case CP1 Solar-Only, Jordan. Source: DLR

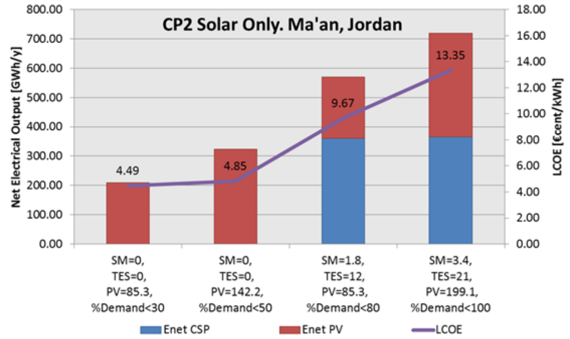

Figure 10: Simulation results. Case CP2 Solar-Only, Jordan. Source: DLR

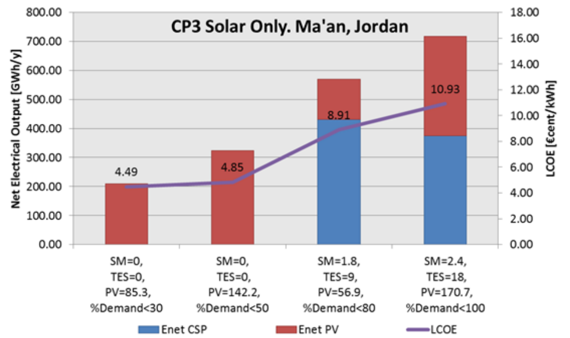

Figure 11: Simulation results. Case CP3 Solar-Only, Jordan. Source: DLR

3.4. Analysis of the Simulation Results

Based on the simulation results, the outcome can be summarized as follows:

- In general, due to the still low natural gas price compared to electric energy from solar power plants, the LCOE is lower if the permitted CO_2 emissions are high.
- For the case of Jordan, with the highest natural gas price among the three countries analyzed, the LCOE curve becomes flat for lower emission levels than the other two countries. This means that permitting more CO_2 emissions do not reduces the LCOE considerably, which is positive for solar power plants.
- In the case of Algeria, with a natural gas price about 90% lower than the price of Tunisia and Jordan, the LCOE decreases practically linear with the use of natural gas. Therefore if only the electricity price is considered, the preferred configuration will be that with less PV and CSP installed and the highest natural gas consumption, leading to higher greenhouse gas emissions.
- For the solar only cases, because electrical batteries are not included, PV systems provide the lowest LCOE until about 50% of the energy demand is covered. After 50% the combination CSP+PV is required.
- By comparing the solar only results with the results with natural gas used, it can be seen that the LCOE difference is not so high if fossil fuel is avoided as long as not all the demand is covered. For instance in the case of Jordan, the case CP3 with CO_2 100g/kWh has a LCOE = 8.84 €cent/kWh; while the case CP3 solar-only with 72% demand covered has a LCOE = 8.91 €cent/kWh (<1% difference).
- For the case of large thermal energy storage (selected for low CO_2 emissions), its capacity is not completely required during summer days with good solar irradiation. On the other side, during winter it allows the plant to operate continuously over several days even if a couple of cloudy days occur. For the strategy selected, the TES is not charged with energy from fossil fuel; this could be done if approved in the power purchase contracts.
- For the solar only case, obviously not 100% of the demand can be covered all the time. Nevertheless, in sunny days a large fraction of the demand can be covered (even 100% for some cases, also in winter) while after several cloudy days the generation gets to zero.
- In general it can be seen that the combination of PV + CSP with thermal storage can cover large part of the local demand for a electricity price not much higher than a solar plant hybridized with natural gas. Also it has been shown that the operation of the plant is flexible, and it can run for several days continuously.

4. CONCLUSIONS

This paper presents simulation results of hybrid CSP-PV plants as result of the project HYMENSO. It uses local boundary conditions of MENA participating countries such as meteorological, demand and cost data in order to investigate the configuration with optimized LCOE. It analyzes the results of plants with natural gas back-up and solar-only plants.

To restrict the extension of this paper a selection of results for the location of Ma’an in Jordan has been shown.

In general, it can be said that the conditions in the analyzed MENA countries are excellent for the deployment of CSP-PV plants. The load curves can be satisfied to a large extension with solar-only plants or to its totality if fossil back-up is allowed.

In order to give to scientists and stakeholders a tool to develop CSP-PV hybrid plants, the ongoing project HYMENSO includes complementary activities such as:

- Operation of local existing CSP or PV installations in Jordan, Algeria and Tunisia for validation of simulation tools
- Set up of knowledge-transfer materials such as guidelines for design and simulation of solar plants
- Implementation of training activities and workshops at the partners’ institutes
- Dissemination of project results.

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