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Impact of Decentralized PV Systems Installation on Transmission Lines During Peak Load Situations – Case Study Amman, Jordan

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Abstract

An increased installation of decentralized small scale photovoltaic (PV) and/or photovoltaic-thermal (PVT) systems for electricity generation within growing urban areas might influence the need of a grid extension because electricity is provided close to the place where it is needed. Thus, for the metropolitan area of Amman / Jordan characterized by a strong increase in electrical energy demand, the effects of selected variants of such an installation strategy of decentralized PV / PVT systems is assessed in detail. Additionally, for the various PV / PVT installation variants a DC power flow analysis focused on the degree of capacity utilization of the most important transmission lines providing electricity for the metropolitan area of Amman / Jordan is carried out. The results show a positive impact for higher installed electrical capacities of decentralized PV / PVT systems related to the capacity utilization of the existing lines. In this context, PVT systems lead to more efficient overload reductions than PV for the investigated case.

Keywords: ;

1. Introduction

Jordan is characterized by a strongly increasing demand for electricity due to a growing population as well as an ongoing industrialization. In order to cover this increasing demand for electrical energy in a more sustainable way in the years to come, renewable energy should be used in a clearly expanded manner. In addition, it is important not to endanger the security of electricity supply. For example, during a heat wave and a correspondingly strong increase in the demand for electrical energy due to additionally used cooling devices, the transmission grid characterized by already widely used transportation capacities is subjected to very high loads. This has been the case for example in 2015. On August 4th, 2015, the highest load to date occurred in Jordan causing substantial overloads in the transmission lines South of Amman. Thus, various measures must be taken to ensure a high degree of supply security during such days with high ambient temperatures and thus high electricity demand. One measure could be the increased decentralized installation of PV systems within Amman metropolitan area in order to reduce the residual load which will also result in reducing load flows to Amman region. [1, 2]

Against this background, the overall aim of this paper is to assess potential effects of the installation of photovoltaic (PV) and photovoltaic-thermal (PVT) systems to reduce electrical overloads in the transmission grid of Jordan related to the Amman metropolitan area exemplarily for the day with the highest load situation. For this purpose, August 4th, 2015, is taken into consideration. Especially for such high load situations, a decentralized electricity generation from photovoltaic systems might be beneficial to reduce the load to be covered by conventional power plants.

Typically, for Jordan as well as other MENA-countries the highest yearly electrical load usually correlates directly with the highest daily mean temperature [3, 4]. Additionally, at days with high ambient temperatures, the load peak shifts from the evening to noon due to the significantly increased usage of air conditioning systems operated by electrical energy; this will make the increased integration of electricity from PV / PVT systems even more promising. Therefore, an increase in decentralized installations of PV or PVT systems might be beneficial for the overall load situation on such high load days; one positive effect might be a relief of the degree of the capacity utilization of the existing transmission lines.

2. Background

Below some background information are provided. This is true for PV / PVT-systems as well as the overall electricity system of Jordan.

2.1. PV / PVT-systems

Photovoltaic (PV) modules can convert solar irradiation directly into electrical energy [5]. The main parameters

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determining the conversion efficiency related to the influencing meteorological parameters are irradiation on the module surface and the modules' temperature [6, 7]. An increase in module temperature has a negative effect on the electrical efficiency of the PV modules. For silicon based PV modules this value reaches approximately -0.4%/K [6].

One way to overcome this disadvantage and to improve the overall performance and thus the electrical power output of a PV system is to reduce actively its modules' temperature [8]. This is possible based on different technological approaches. Air- and fluid-based cooling systems are under discussion and partly offered on the market [9, 10]. The main factors for the module temperature are the ambient temperature, the wind speed and the solar irradiation [11]. With these cooling approaches, reduced temperatures of modules can be achieved while efficiency increases are well documented, where fluid-based cooling systems always lead to higher efficiencies [12–14].

For a fluid-based cooling system, a cooling fluid is pumped through pipes attached at the rear side of a regular market mature PV module while functioning as a heat sink. Such a PVT-system is operated with a mixture of Glycol and water to allow for a certain frost resistance. The dominant variables here are the flow rate through the cooling system and the inlet temperature of the cooling fluid [10, 13]. Different operating strategies can be used to generate either an increased output of electrical or thermal power [15]. This paper focuses on maximum electrical output to estimate the potential effects on the characteristic curves of PV/PVT systems.

In addition to an increase in electrical conversion efficiency due to lower module temperatures, low-temperature heat can be gained and used for numerous down-stream processes; this could be the provision of hot water e.g. provided by heat pump systems where the low temperature heat from such PVT cooling systems is used as a heat source [16–18]. Thus, if there is a demand for low temperature heat, PVT systems can contribute towards a better integration of the electricity and the heat sector, and thus better interlink renewable energy systems in general [12, 13, 17, 19].

For countries like Jordan, characterized by high ambient temperatures and high solar irradiation in average, and especially during summer time, PVT-systems can reduce the efficiency drop of PV-systems during hot and sunny days.

2.2. Jordanian electricity system

The Kingdom on Jordan has been characterized by an overall electricity demand of ca. 16.2 TWh in 2015. This electricity demand is increasingly growing especially due the fact that the population is increasing and industrialization is progressing. [3, 20, 21]

Electricity generation in Jordan is realized almost exclusively by power plants operated by fossil fuel energy. The electricity generation units under operation in 2015 are characterized by a total installed electrical capacity of 4,266 MW. Units with 2,526 MW realize direct combustion of natural gas, and plants with 814 MW are operated by diesel fuel. Units with a conventional steam cycle contribute with an installed electricity capacity of 787 MW. Conversion units using renewable sources of energy are limited to systems based on hydroelectricity, wind and biogas as well as to a very minor extend PV. Altogether, these options do not exceed an electrical capacity of 139 MW related to the year 2015 [20].

The high voltage electrical grid in Jordan covers the overall Hashemite Kingdom. It mainly consists of overhead lines with voltage levels of 132 and 400 kV, shown in figure 1 [20]. While there is a strong accumulation of transmission lines in the metropolitan area of Amman, the rural areas of Jordan are supplied by very few lines only.

One crucial point of the transmission system in Jordan is the connection between the two substations "Queen Alia International Airport" (QAIA) and "Qatrana". This transmission system's bottleneck is located between these substations and overloads in these lines could cause a serious blackout in the Amman metropolitan area. These lines are critical as they connect the main demand area of Amman with the South of Jordan and the interconnector with Egypt. Because Egypt is responsible for controlling Jordan's grid frequency, an overload on these lines could lead to a blackout in the Amman metropolitan area. Relatively small percentages of overload can be tolerated for a short amount of time, but with frequently repeated overloads problems can occur [22].

The integration of large PV capacities into an existing electricity grid has already been investigated many times, where the focus was often on the distribution network plane or focused on studying the changing load curves due to additionally installed PV systems. The challenges integrated here by the fluctuating behavior of the PV systems can be eliminated with well-designed and technologically adapted planning. Especially for Germany there are several studies to integrate much larger shares of PV feed-in than in Jordan, and at the same time even provide system services. [23–25]

Figure 1 shows also that the majority of Jordan's conventional power plants are located in the wider Amman area and supply the metropolitan area directly [14].

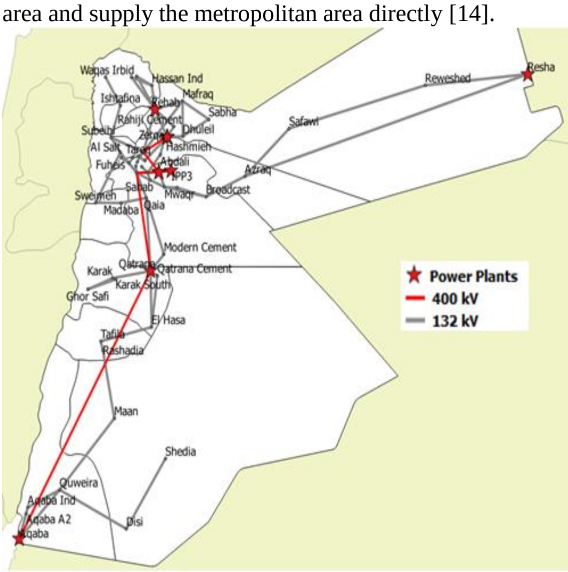

Figure 1. Transmission lines and Power Plant Park of Jordan

2.3. Peak load day

In figure 2 exemplarily Jordan's highest load day during the year 2015 (i.e., 4th of August) is shown being also the hottest days in 2015 [3, 4, 26]. The peak power at this day sums up to 3,205 MW. The curve shows that the daily demand peaks between 12:00 and 18:00; this peak is typically during the evening hours at days where there is not such a high demand for cooling devices. The highest share of Jordan's load on that day was demanded within the metropolitan area of Amman with a share of 37.7 % related to the rest of the country [3].

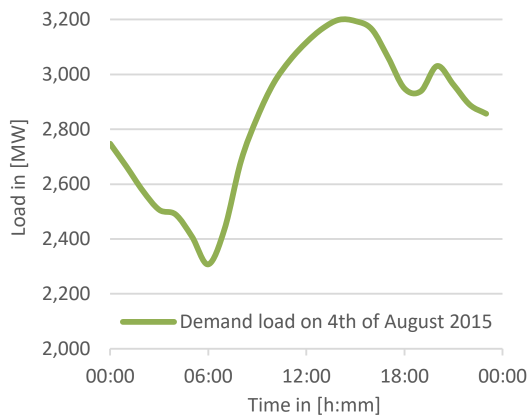

Figure 2. Peak load day in 2015 for Jordan

3. Assessment approach

With an increased installation of decentralized PV / PVT-systems in the metropolitan area of Amman, an electricity conversion shift towards Amman as major area of demand could occur. The electrical energy coming from solar irradiation is used directly, mainly by households, at the place of provision. This results in a decreased residual load to be covered by the conventional electricity provision system (i.e., power plants operated by fossil fuel energy). A consequence of such a strategy could be reduced capacity utilization of the transmission lines surrounding and supplying the Amman metropolitan area. Such an approach could decrease possibly occurring overloads within parts of the existing transmission lines especially during high load situations and reduce additionally necessary grid extensions due to a strongly growing demand. To investigate and quantify the impact of the integration of such PV / PVT-systems on Jordan's transmission system related to the Amman metropolitan area, simulated PV and PVT characteristic curves are combined with a direct current (DC) power flow analysis, whereby the focus of this paper lies on the shifting loads of the transmission lines.

Thus, this effect of a decentralized installation strategy of PV and PVT-systems on the transmission grid is assessed. First, a load analysis of the investigated load situation is realized. Then, characteristic curves of PV and PVT-systems are modelled for various installation variants. This is realized based on a physical model allowing for the simulation of the theoretical differences between PV and PVT-systems. Based on the simulated PV and PVT generation curves the residual load for the investigated day is calculated for the various variants. The resulting residual load is then used to carry out a DC power flow analysis with the aim of quantifying the maximum load situation at the investigated day. Based on these results, conclusions are drawn whether a decentralized installation of PV / PVT-systems could contribute to reduce potential overloads within the transmission grid. This overall procedure is shown in figure 3 and outlined in detail below.

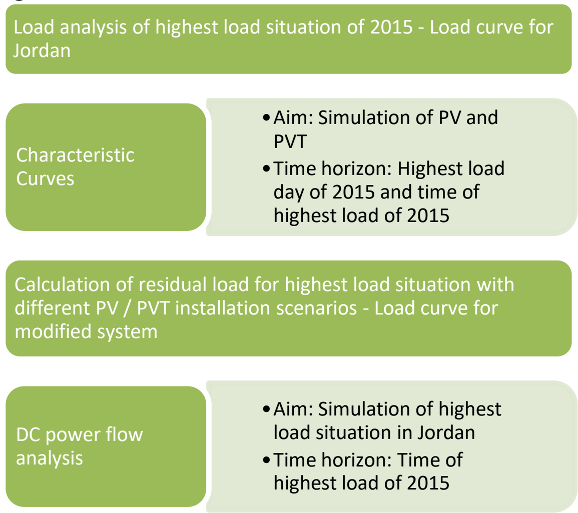

Figure 3. Schematic description of procedure

3.1. PV power provision

PV and PVT-systems show different characteristic electricity provision curves due to the cooling device used for PVT-systems. This results in higher efficiencies in general and especially during high temperature situations (e.g. around noon) if the cooling temperature is kept constant. Therefore, such PVT-systems are typically operated with a constant cooling-fluid inlet temperature (e.g. groundwater as a possible cooling fluid source shows basically the same temperature throughout the overall year) [27]. To simulate such effects a quasi-stationary (hourly based) simulation model of PV and PVT-systems has been developed based on the physical characteristics of these systems. The simulated system is shown in figure 4. In order to calculate the electrical yield, the following aspects were modelled.

- Mixed convection heat transfer is assumed at the surface of the PVT-system, consisting of natural and forced convection with heat transfer coefficients dependent on the actual wind speed and its direction. The driving temperature gradient occurs between the module temperature and the ambient temperature.
- On the back of the PVT-system natural convection heat transfer is assumed depending on the module characteristics and the temperature gradient between the module and the ambient temperature.
- Forced convection heat transfer is assumed by fluid cooling in the tubes as a function of a fluid velocity dependent heat transfer coefficient as well as the temperature gradient between fluid and module temperatures. A constant cooling-fluid inlet temperature is assumed.

- The remaining irradiation energy minus the mentioned heat losses is responsible for heating up of the modules. This heating up of the PV-module depends on material properties, the modules' mass and module temperature.
- The electrical power of a regular market-mature PV cell is finally simulated as a function of irradiation and temperature-dependent electrical efficiency. Increasing module temperatures reduce the efficiency and increase the heat to be dissipated by convection in the system under consideration.

By drawing up the balance of incident radiation, electrical conversion and the resulting calculated heat flows, an equation system was created being the basis for the simulations realized here. Since both the electrical conversion and the heat flows within the balance limits are directly dependent on the unknown module temperature, the latter can be calculated iteratively under the assumption that an equilibrium can be maintained. After calculating the module temperature, all heat flows of the system can be calculated.

Due to the temperature dependence of the electrical efficiency of the PVT-system, the module temperature strongly influences the electrical yield of the overall system. Thus, based on the calculated module temperature, the electrical yield of the PVT-system can be quantified. The aim of the simulated characteristic curves is to make a statement about the possible additional yield of PVT modules under their ideal conditions (high radiation and high temperatures). These theoretical differences between PV and PVT systems are used in this paper to estimate the bandwidth of the effect on the transmission lines.

3.2. DC power flow analysis

The PV / PVT power generation reduces the residual power demand to be covered by the grid and thus by the fossil fuel-based power plants providing electricity for the Amman metropolitan area. To investigate the effect of this reduction exemplarily for different expansion variants for PV / PVT-systems related to the free capacity of the transmission lines around the Amman metropolitan area a DC power flow analysis is carried out [28, 29].

Within such a DC power flow analysis, demand and generation side are connected and the electrical load on each transmission line is simulated. Three main assumptions have been made to enable such a simulation [30].

- The line impedance is significantly greater than the resistance of the line. Based on this assumption, transmission losses within the system are neglected.
- All voltages within the system are equal, implemented through a "per Unit" system within the calculation. As a result, reactive power is no longer calculated.
- The phase angle differences are assumed to be very small for a linearization of the sine term.

These assumptions lead to equation 1 [31].

$$P_1 = Y_{bus}\,\Delta\delta \qquad (1)$$

P_1 is the power flow between every substation, Y_{bus} is the admittance matrix of the system (including all impedances and resistances) and $\Delta\delta$ are the phase angle differences. After inverting the admittance matrix, equation 2 follows.

$$\Delta\delta = Y_{bus}^{-1}\,P_2 \qquad (2)$$

P_2 is the net performance of every substation. All phase angle differences are calculated in relation to a neutral point. The result of the phase angle differences is inserted in equation 1 and the load flow between all substations is calculated.

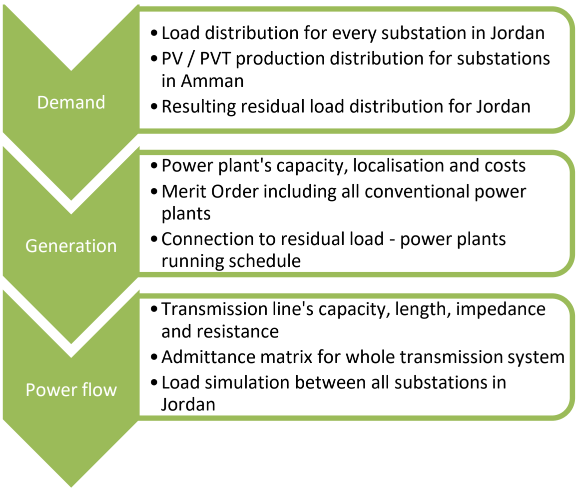

Figure 5. DC power flow methodology

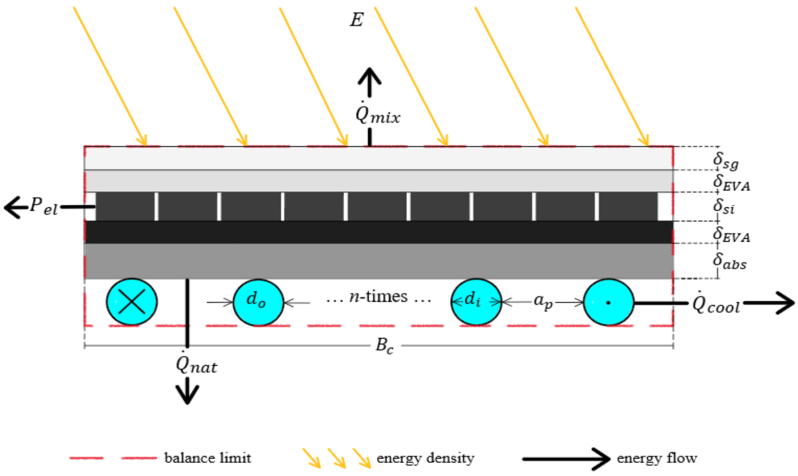

Figure 4. Balance limits of simulated PVT-module

Figure 5 shows the DC power flow methodology applied here. Thus, the methodological procedure is divided into three main steps:

- determination of the overall and distributed demand of a system,
- determination of the overall and distributed generation of a system and
- calculation of the resulting power flows between all substation within a system.

A spatial breakdown of the load demand at the investigated time of maximum load was used to calculate a base variant (i.e., current situation) with no additional decentralized installed PV / PVT-systems. Based on this spatial distribution, the decentralized installed PV / PVT-capacity is then divided among the various substations already under operation within the Amman metropolitan area. This results in spatially differentiated residual loads.

Data on the power plant park, its spatial connection to the transmission grid (feed-in points) and the costs of the individual power plants are the basis for determining the generation side. Based on this, a merit order is created for all conventional power plants under operation related to the time frame of this assessment. The combination with the previously defined residual loads makes it possible to calculate different power plant loads and their spatial distribution at the time of peak load.

By summarizing the properties of the transmission lines (capacitance, length, impedance, resistance) the admittance matrix of the transmission grid is created. Based on the equations described above, the load flow between the substations in Jordan can be calculated. To compare each line's load with its possible capacity, a percentage for the load situation for all lines in Jordan can be quantified and overloaded lines can easily be detected.

4. Case Study

Within this assessment in total four variants with different amounts of decentralized installed capacities are investigated related to the situation given in 2015 (figure 6). This base variant with no additional decentralized installation of PV / PVT-systems was defined first. Based on this, four variants with 500 MW and 1,000 MW either as PV or PVT-systems were fixed.

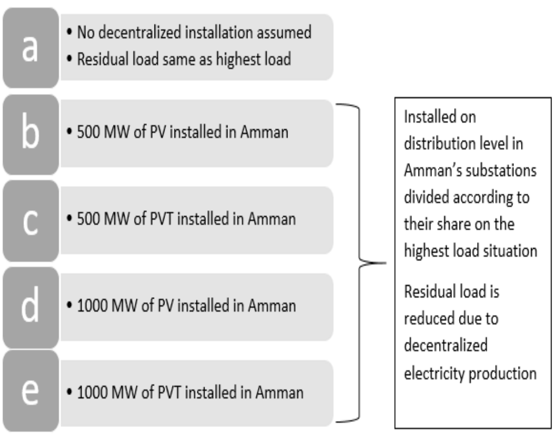

Figure 6. Description of investigated variants a to e (Amman means the overall Amman metropolitan area)

For the assessment of the variants (a to e) defined in figure 6 both methodological steps outlined in section 3 need to be realized separately. The necessary input parameters taken into consideration to realize such an assessment are discussed below. While the input parameters for the first part of the methodology outlined in section 3 are primarily compiled from data sheets of the PV-modules assumed to be installed here, the input parameters of the DC power flow analysis are taken from data resulting from Jordan's National Electric Power Company (NEPCO).

4.1. PV power provision

The input parameters used for the model approach discussed in section 3.1 are shown in table 1. Thus a combination of two 280 W modules with a combined 560 W capacity is assumed to be installed here [32]. All PV / PVT-systems are modular and therefore linearly scalable. Thus, the results of a single system can be scaled up to the required capacities of the defined variants. Losses due to shading as well as due to pollution are not taken into consideration even due the fact that these effects might lower the electrical yield slightly.

Table 1. Input parameters for PV / PVT model

Description	Formula symbols	Input value	Unit
Width of collector [32]	B_K	1.984	m
Length of collector [32]	L_K	1.640	m
Total area of silicon cells [32]	A_Z	2.920	m²
Electrical nominal efficiency of PV-collector [32]	η_{NK}	17.21	%
Angle of installation with regard to vertical	γ_K	60	°
Critical Rayleigh-number [33]	Ra_c	900,000	-
Coolant volume flow	V_K	60	l/h
Inner pipe diameter	d_{iR}	6	mm
Outer pipe diameter	d_{aR}	8	mm
Number of cooling pipes per module	n	24	-
Standard test temperature [32]	T_S	25	°C
Temperature coefficient for electrical collector efficiency [32]	$m_{T.K}$	-0.41	%/K
Mass of aluminum frame [34]	M_R	2	kg
Material thickness of solar glass [32]	δ_{SG}	3.2	mm
Material thickness of EVA-film	δ_{EVA}	1	mm
Material thickness of silicon cells [6]	δ_Z	200	µm
Material thickness of absorber plate [34]	δ_{Abs}	0.5	mm

Additionally, the following data are used.

- Direct and diffuse irradiation, air density, ambient temperature and wind speed from historic data from Amman on the 4th of August 2015 with a time resolution of one hour [4].

- Cooling-fluid properties of the Glycol-water-mixture (i.e. temperature dependent thermal conductivity, heat storage capacity, density and dynamic viscosity) [10, 35].

4.2. DC power flow analysis

For the DC power flow analysis the following data for the year 2015 are used [20]. This is true for the different data categories.

- Demand data of the individual substations in Jordan, divided temporally and spatially (data for all 62 substations with a time resolution of 15 min throughout the year 2015). From this, the residual loads were calculated in combination with the variants already presented by assuming that the additional decentralized PV / PVT capacities were installed in the Amman metropolitan area as a percentage of their share related to the maximum load [3].
- Generation data of the power plant park, the costs incurred and the spatial distribution of the individual power plants, from which both the merit order used and the power plant schedule depending on the assumed variants were calculated [36].
- Transmission network data for all existing transmission lines in Jordan in 2015 (data for 80 transmission lines), including capacities, lengths, impedances and resistances as well as the respective connections to existing substations, distributed locally throughout the country [3, 22].

5. Results

Below the results of the various variants defined in section 4 based on the methodological approach presented in section 3 are discussed.

5.1. PV power provision

Results. Figure 7 shows the simulation results for the different PV and PVT efficiencies for different cooling-fluid inlet temperatures and the uncooled PV case. The graphic makes it obvious that the electrical efficiency strongly depends on the cooling-fluid's inlet temperature. Because for the (uncooled) PV system the module temperature increases over the first part of the day a lower electrical efficiency occurs related to the cooled PVT system. This decrease in efficiency also occurs for the cooled PVT systems, but to a significantly lesser extent. Typically, the lower the cooling-fluids inlet temperature is the higher the overall efficiency is in general.

Figure 7 makes it obvious that while the average efficiency of the (uncooled) PV-system for August 4th, 2015, was calculated as 14.9 %, the efficiency of the PVT-system ranged from 16.9 % for 30 °C inlet temperature up to 17.9 % for 15 °C inlet temperature of the cooling fluid. This resulted in an average relative efficiency increase of up to roughly 20 % due to these cooling efforts for the simplified model used under these extreme external conditions.

Figure 8 shows the electrical power output for the module defined in table 1 simulated also for August 4th, 2015. An increased additional yield of the cooled PV systems can be seen above all during the midday hours. The variations in the electrical output of the cooled systems vary considerably less than in the uncooled system. The electrical yield for this investigated day for the PV-system is calculated with 3.0 kWh while PVT-systems show a simulated yield ranging from 3.7 kWh for 30 °C inlet temperature up to 3.9 kWh for 15 °C inlet temperature. This represents a daily electrical yield increase of close to 30 % caused by the higher average efficiencies due to the cooling activities.

For the subsequent combination of the simulated characteristic curves for PV and PVT-systems (the latter with 15 °C as inlet temperature for all following results in order to be able to make a simplified statement about the theoretically maximal effect possible) with the DC power flow analysis, all electrical power outputs for the four variants defined in section 4 have been calculated. For realizing this with the historical weather data of August 4th, 2015, the respective electrical power output has been simulated. The results show that while an installed capacity of 500 MW PV results in a maximum power output of 341.7 MW on this day, 500 MW PVT sum up to 461.2 MW (i.e., an increase of ca. 35 %). For the variant with an installed capacity of 1,000 MW, PV reached a maximum power output of 683.5 MW while PVT showed a power output of 922.3 MW. Compared to the first two variants here the values are roughly doubled as it has been expected.

The simulated characteristic curves for PV and PVT-systems are then combined with the load curve for the same day (i.e., August 4th, 2015). This has been realized for all variants defined in section 3.

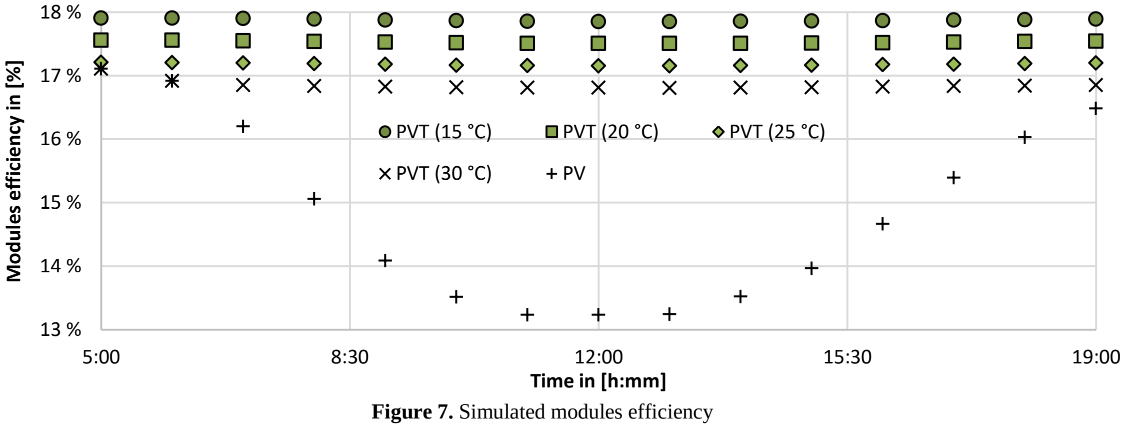

Figure 7. Simulated modules efficiency

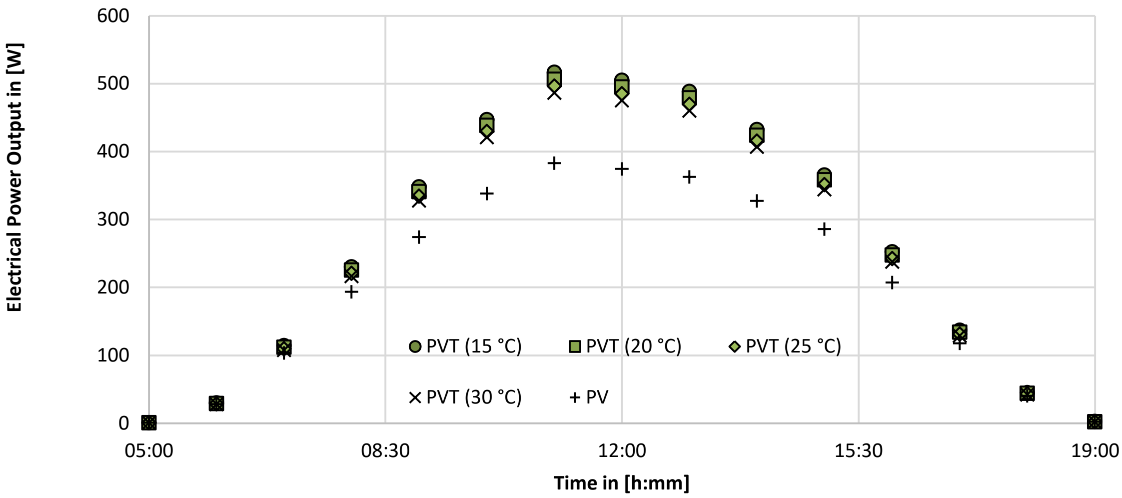

Figure 8. Simulated electrical power output

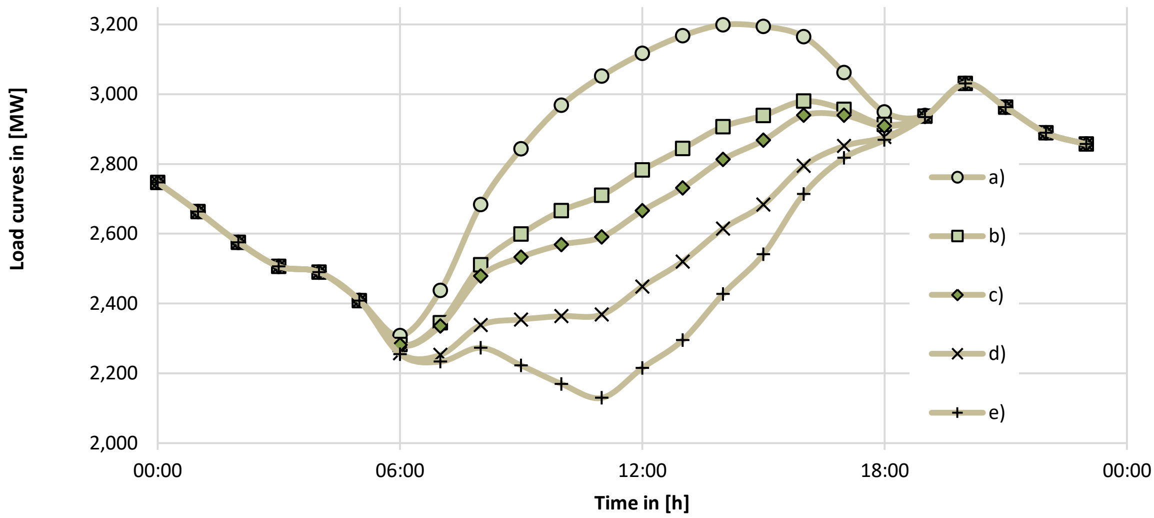

Figure 9. Resulted theoretical load curves for August 4th, 2015

Figure 9 shows the resulting theoretical residual load curves; these are the load curves that are still to be covered by energy coming from the conventional power plant park. The graphic makes it obvious that due to higher efficiencies – PVT-systems showing higher electrical power outputs at noon – these systems result in lower resulting load demands at these hours of the day. The extent to which this effect can occur is only estimated theoretically and would have to be validated by real measurements. Nevertheless, a peak shaving effect for the noon peak was detected in all variants in a different intensity due to the additional installed PV / PVT-capacities. Thus, regardless of the assessed variant, a positive effect in the form of a reduction of the noon peak was clearly observed. However, the evening peak was not changed regardless of the installed capacity (i.e., no PV / PVT energy provision during night hours).

Discussion. The simulation results for the assumed PV and PVT-systems show a strong theoretical increase in module efficiency if the system is cooled. A small variation occurs due to different cooling-fluid inlet temperatures; generally, it can be stated that the cooler the inlet temperature is the higher the overall efficiencies are. During sunrise and sunset, the effect shrinks to zero, whereas during noon with high irradiation, the cooling effect leads to clearly higher efficiencies compared to “classical” PV-systems without a cooling device (i.e. only natural cooling due to convection). This cooling effect results in higher noon peaks for the PVT electricity provision; and considerably higher electrical yields throughout the overall day are the consequence. Even in low irradiation cases, like in the early morning of the investigated day, a cooled system leads to higher efficiencies. In this simplified model, the theoretical improvements become clear.

For the integration of the four variants of PV and PVT-system installation and the resulting effects on the highest load day of Jordan in 2015, the electrical power output varies considerably. Comparing PV with PVT-systems, a strong increase was detected for the maximal electrical power output. This results in a theoretical higher peak shaving potential for PVT-systems due to their more effective electrical conversion when irradiation and temperatures are peaking within the course of a day. Comparing the two 500 MW and the two 1,000 MW variants, PVT-systems show a clear advantage for peak shaving. How large this effect can be under real conditions must be validated with measurements.

5.2. DC power flow analysis

Results. Results for the DC power flow analysis are shown below for the five previous defined variants. These results show for the base variant overloads between QAIA and Qatrana as well as overloads within Amman metropolitan area. Table 2 lists all lines and their percentage overload for all five variants.

For the base variant five different overloaded lines are identified (table 2). The overload between Amman North and Tareq occurs due to the high demand within the central Amman area. All power plants in the Amman metropolitan area are located in the surrounding area so high loads need to be transmitted. The same applies to the overloaded lines around Hashmieh where electricity from the Samra power plant is transmitted to central Amman. Problematic are the overloads on both transmission lines starting in Qatrana.

Table 2. Overloaded lines in all variants

Line between	*Capacity*	*Calculated load*	*Ratio*
-	[MW]	[MW]	%
Base variant (a)			
Amman North – Tareq	264.0	379.1	143.6
Samra – Hashmieh	105.6	142.8	135.2
Hashmieh – Zerqa	105.6	142.8	135.2
Modern Cement – Qatrana	105.6	106.2	100.6
Qatrana – QAIA	105.6	121.3	114.8
500 MW PV variant (b)			
Amman North – Tareq	264.0	307.1	116.3
Samra – Hashmieh	105.6	126.3	119.6
Hashmieh – Zerqa	105.6	126.3	119.6
Qatrana – QAIA	105.6	111.1	105.2
500 MW PVT variant (c)			
Amman North – Tareq	264.0	287.1	108.7
Samra – Hashmieh	105.6	121.9	115.5
Hashmieh – Zerqa	105.6	121.9	115.5
1,000 MW PV variant (d)			
Samra – Hashmieh	105.6	112.7	106.7
Hashmieh – Zerqa	105.6	112.7	106.7
1,000 MW PVT variant (e)			
Samra – Amman North	800.0	815.7	102.0

- The 500 MW PV variant reduces the total number of overloaded lines from five to four. This occurs due to a higher electricity production from PV, leading to a lower residual load in the Amman metropolitan area. Also, the remaining overloaded lines show a decrease in their overload percentage and a reduction of the risk of system failure.
- For the 500 MW PVT variant a reduction of the total number of overloaded lines down to three is counted. Most importantly, the line between Qatrana and QAIA is not overloaded anymore. The overload percentage for the three remaining lines decreases even more, with additional positive aspects for the grid stability within the overall Amman area.
- The 1,000 MW PV variant only shows two remaining overloaded lines connected to Hashmieh and the total overload percentage decreases in comparison to the previously described variants.
- The variant for 1,000 MW of PVT installed in Amman area show that all five overloads from the base variant are reduced and are now below the line-specific maximum capacities. Nevertheless, one new line shows an overload between the power plant in Samra and the substation of Amman North. With only 2 % of overload on this line just minor changes are necessary.

To visualize these overloads and the resulting effects of Jordan's transmission system, figure 10 shows the loads on every transmission line for the highest total load situation for Jordan in ratio to the specific capacities of each line.

Discussion. The results of the DC power flow analysis show a clear effect within the transmission system of Jordan. As expected with a higher share of decentralized electricity production by PV or PVT-systems fewer overloads occur.

Most of the investigated variants show a relaxed situation for the previously overloaded transmission lines between Qatrana and QAIA. The variant with 1,000 MW PVT installed causes a new overload within Amman area. Following this, an installation of too high capacities can lead to subsequent challenges; i.e. different transmission lines can get overloaded. An optimum, especially designed regarding the investigated system needs to be detected. Additional interactions with the transmission grid could result from the decentralized installation of PV systems. Further studies would have to be carried out to determine which effects could occur and which measures would have to be taken to maintain grid stability. The grid loads found in this paper apply only to the considered highest load situation.

All simulations for the load situations within Jordan's transmission system support the statement that the decentralized installation of PV or PVT-systems in the Amman metropolitan area could be beneficial for the overall grid stability by avoiding overloads.

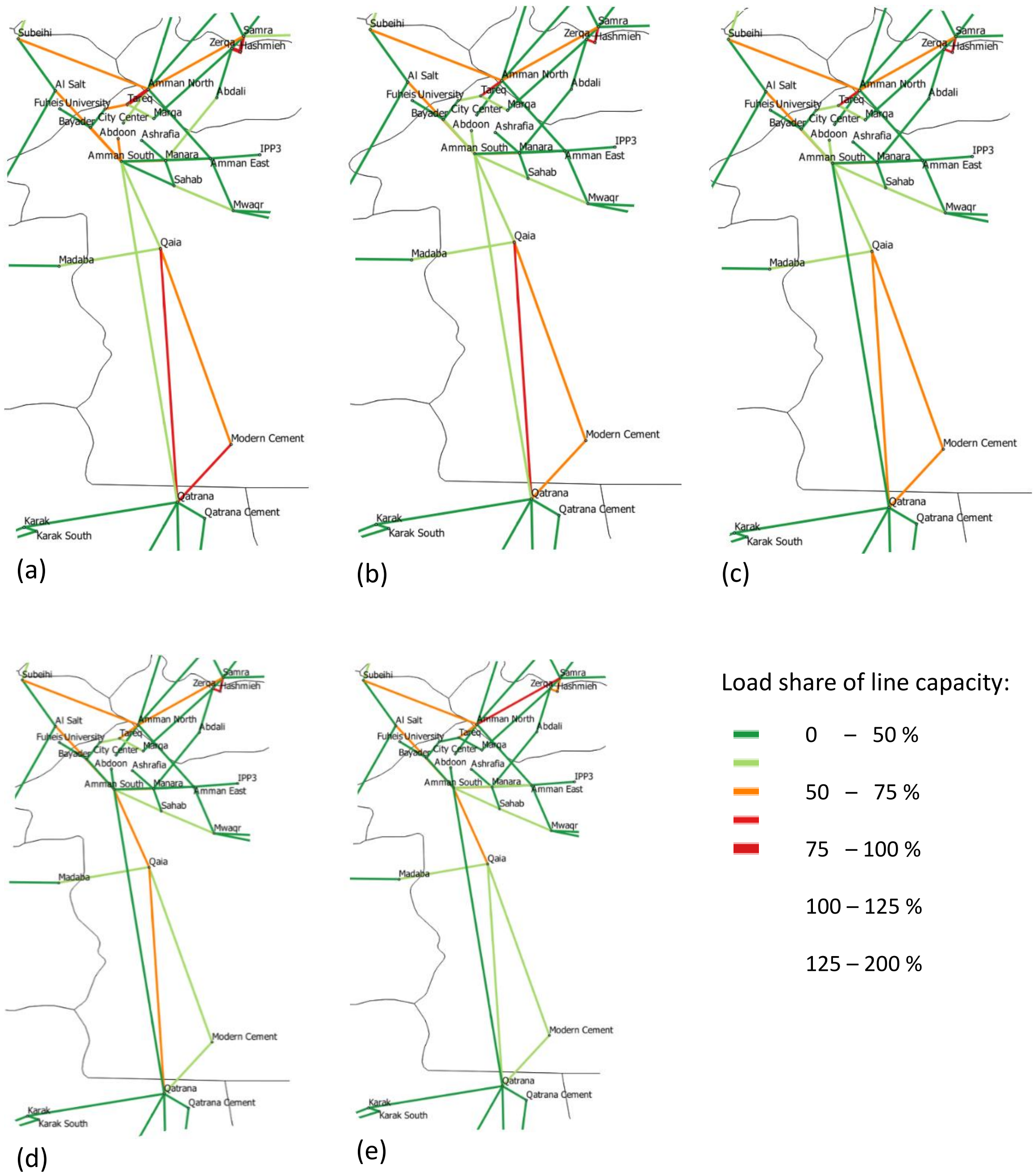

Figure 10. Load situations in Amman's transmission lines for (a) base variant, (b) 500 MW PV variant, (c) 500 MW PVT variant, (d) 1,000 MW PV variant and (e) 1,000 MW PVT variant

6. Conclusion

In this paper, the potential effect of a decentralized installation of PV / PVT-systems in the metropolitan region of Amman on the transmission grid is investigated. The scope of the study is the 2015 peak load case in which overloaded lines occurred. The aim is to assess whether a decentralized installation of PV / PVT-systems would have prevented the overloaded lines.

The following results were achieved:

- PVT-systems are more efficient than PV-systems at shaving the noon peak, leading to a more homogenized residual load curve over the peak load day in 2015.
- A decentralized installation of 500 MW PV in the metropolitan region of Amman still leads to overloaded transmission lines in the main investigated lines for the day of the highest demand. For the investigated variants with 500 MW PVT and 1,000 MW PV these lines show no more overloads. However, a decentralized installation of 1,000 MW PVT leads to new occurring overloads within the system.
- For the aim of reducing the overloads in the focused transmission lines, PVT-systems show a more efficient reduction compared to PV-systems, if the same capacity is installed.

Validating these results by the real implementation of PV / PVT-systems in a larger scale can help to improve the overall integration of renewable energy sources and especially of PV / PVT-systems in countries with a high supply of solar irradiation and compatible load curves in high load / high temperature situations. In order to investigate how the transmission grids behaves in low load situations due to the additional installation of PV systems, further studies would have to be carried out.

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