

Comparison of different solar energy utilization methods: photovoltaic systems and solar thermal power plants

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Abstract—This paper presents a comparison between small-scale PV systems and solar thermal power plants. The studied PV system consists of crystalline silicon solar modules and inverters. For small-scale solar thermal power plants organic Rankine-cycle was considered and four different collector types were investigated, both concentrating and non-concentrating ones. The analyses are based on a self-made model and Matlab simulation. The main comparison criteria are the electrical efficiency and the specific energy production, since these are the most important factors influencing the financial return. The possibility of the cogeneration and thermal energy storage are also assessed, since they largely influence the payback time and dispatchability of the plants. Several different geographical locations are investigated and compared, since meteorological conditions of the plant sites largely determine the amount of produced energy and the efficiency. The monthly fluctuation of energy production is also presented besides the annual aggregated values.

Index Terms—Renewable energy sources, Solar energy, Photovoltaics, Solar thermal power, Concentrating solar power, Simulation

I. INTRODUCTION

Photovoltaic (PV) systems convert the incoming solar radiation directly into electricity. The installed capacity of PV systems have largely increased in the last decade and exceeded 138 GW by the end of 2013 [1]. This significant growth started in Europe, but in the last year Asia has taken the lead in newly installed capacities. The typical size of the commercial PV systems vary from the very small household-scale systems to the large utility-scale plants, whose basic configuration is quite similar due to the modularity of the system.

The solar thermal power plants perform indirect electricity production, where the heat produced in a solar collector is converted into electricity using a thermodynamic cycle. The first solar thermal power plant was built between 1984 and 1990 in California, which proved the functionality of the technology, but the more significant dispatch only started around 2006, after a long stagnation. The common name of this technology is concentrating solar power (CSP), since the solar collectors used in these plants concentrate the solar radiation in order to achieve higher temperatures and thereby a higher efficiency. The installed capacity of the CSP plants was just above 3,4 GW by

the end of 2013, which is still far behind the total capacity of PV systems, but the continuation of the growth is expected due to the number of further plans still under planning or construction [2].

The massive spread of PV systems is enabled by the small system capacity, which made it possible for the most people to invest in this renewable electricity generation technology. The main purpose of this article is to investigate the applicability of small-scale solar thermal power plants, - which are still barely studied - and compare them with the currently popular PV systems. Organic Rankine-cycle was considered as the thermodynamic cycle of the solar thermal power plants, since it allows the electricity generation in smaller scales also from lower temperature heat sources. The ORC is similar to the conventional Rankine-cycle, but it uses an organic fluid instead of water as working fluid, which results a higher efficiency and simpler structure with more favourable pressure values for the cycle. ORC makes it possible to utilize heat produced also in non-concentrating collectors, therefore these applications were also analysed in spite of their unconventionality.

The method of the different technologies' investigation is model based simulation, which is easy and inexpensive. The next section presents the main principles and simplifications of the created model, whose are followed by the different simulation results and conclusions

II. MODELS OF THE SOLAR-THERMAL AND PHOTOVOLTAIC SIMULATIONS

The main goal of the simulation models is to describe the effects of the meteorological conditions on the operation of the plants. The input data are the most defining meteorological attributes; the solar radiation and the ambient temperature. The most important output data are the generated power and electrical efficiency, since these are the most appropriate criteria of comparison between the different power plant types, but the models are able to determine also a number of other characteristics and properties. Choosing the right parameters are especially important to emphasize the relevant characteristics of a given system. More accurate and complex models can be created using a larger number of parameters, but in this case the result only applies reliably to that well-specified

system, which makes it harder to draw general conclusions. The created models are using only parameters which are easily accessible from data sheets or can be easily estimated based on practical experiences, and are not varying largely in case of different configurations of the same power plant type. A simulation program was developed in Matlab, it is based on different models presented below.

A. Photovoltaic Systems

The model describing the PV systems has two main parts: one for the power estimation of the solar modules and one for taking account the effect and losses of the inverter and DC wires. The model describes the behaviour of crystalline silicon solar cells and solar inverters with the best accuracy, since these are the most commonly used elements in grid-connected PV systems. Both parts of the model use only data that are provided on the data sheets by the manufacturers, so the calculation can be applied on any system.

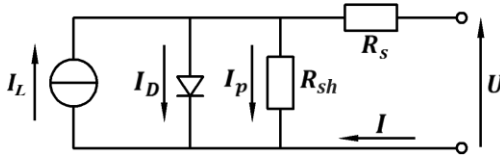


Fig. 1. Single diode equivalent circuit of a solar cell

The model of the solar cells is based on the single diode equivalent circuit of the cell (Fig. 1). This equivalent circuit reflects the physical working principle of the solar cell, since the current source stands for the charge separation caused by the absorbed light, the diode represents the recombination occurring on the p-n junction and the real cell's internal losses are taken into consideration as resistances. Equation (2) can be written based on the equivalent circuit:

$$I = I_L - I_0 \cdot \left(\exp \left(\frac{e(V + I \cdot R_s)}{n \cdot k \cdot T_c} \right) - 1 \right) - \frac{(V + I \cdot R_s)}{R_{sh}} \quad (1)$$

where I [A] and V [V] are the current and voltage of the solar cell, I_F [A] is the light current, I_0 [A] is the diode saturation current, e [C] is the elementary charge, n is the diode ideality factor, k [J/K] is the Boltzmann constant and R_s and R_{sh} [Ω] are the series and shunt resistances. The shunt resistance was neglected, since it has only a very small effect on the cell characteristics. Townsend's [3] equations were used to determine the reference values and radiation and cell temperature dependence of the unknown parameters. The I-V and P-V characteristics of the solar modules can be determined by the numerical solution of (2) in case of any weather condition.

Knowing the characteristic makes it possible to calculate not only the power of the MPP, but the power, current and voltage of the module at any operating point, which enables the accurate loss calculations of the system. As a main advantage this method takes into consideration the temperature and irradiance dependence of the solar module with a sufficiently good accuracy. The meteorological data contain only the ambient temperature, therefore it is important to find the relationship between the cell and ambient temperatures in case of different irradiance levels. In the cell temperature calculation a constant

overall heat transfer ratio is considered, whose value is determined based on the nominal operating cell temperature (NOCT), which is a measured data by the manufacturer.

The input voltage and current of the solar inverter can be determined using the results of the solar cell model, the number of parallel strings and the modules connected in series in each string, considering the voltage drops occurring on the wires. The losses of the inverter depend on its input power and voltage. At a constant voltage the loss on the shunt elements is constant, the loss on the switching elements is nearly proportional to the transmitted power and the losses on the series elements are quadratic. The inverter losses as a function of the DC power are estimated with a second-degree polynomial, which properly fits to the measured point in the data sheet, while the voltage dependence is calculated with linear interpolation. The inverter model also takes into consideration the input power and voltage limits of the device, if the MPP conditions of the solar modules exceed these limits the model calculates the actually achievable best operating point.

B. Solar Thermal Power Plants

The model of the solar thermal power plants consists of two parts, the model of the organic Rankine-cycle and the solar collector model. A schematic of the assumed ORC can be seen in Fig. 2. The organic working fluid generally leaves the turbine in superheated steam phase due to its special characteristics, therefore an internal heat exchanger is required after the turbine. This heat exchanger is a common element of ORC systems, since it considerably improves the cycle efficiency.

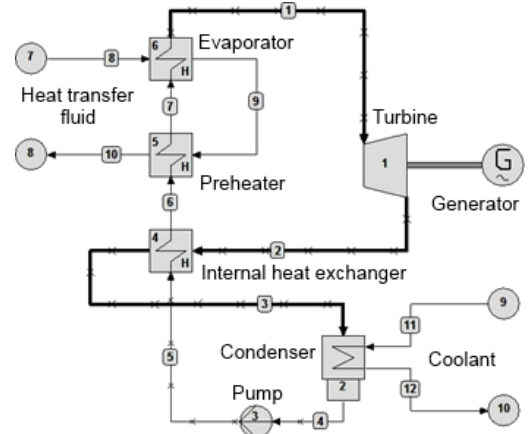


Fig. 2. Schematic of an ORC system

The ORC model is based on fundamental thermodynamic and energy balance equations. The relationship between the different state variables is computed with the FluidProp solver, which contains a large variety of fluids and uses the latest physical models in the calculations. The losses occurring in the turbine and pump are taken into account with an internal efficiency of 70% in both cases, while for the generator and other electric devices a 95% efficiency is considered. The temperature profiles of the heat exchangers are calculated according to the pinch point method, where a minimal 5 or 10 °C temperature difference is used depending on the properties of the heat exchanging fluids materials. The pressure drops and heat losses in the pipes and apparatus were neglected

due to their uncertain values, but the resulting errors are roughly compensated by the moderate turbine efficiency.

The aim of the collector model is to calculate the heat received by the heat transfer fluid in case of given inlet and outlet temperatures and weather conditions. The collector efficiency can be determined through the analysis of the heat losses. The overall heat transfer coefficient is usually presumed to be a linear function of the temperature difference, that leads to this standard equation [4]:

$$\eta_{koll} = \eta_o - a_1 \cdot \frac{\Delta T}{S} - a_2 \cdot \frac{\Delta T^2}{S} \quad (2)$$

where ΔT [°C] is the temperature difference between the ambient and the absorber tube, G [$\text{W} \cdot \text{m}^{-2}$] is the irradiance, η_o is the optical efficiency, a_1 [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$] is the primary and a_2 [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-2}$] is the secondary heat loss coefficients. The parameters of (1) are determined by measurement and provided on the data sheet by the manufacturer, which makes this method a reliable way of calculation. The temperature difference between the environment and the absorber changes along the length of the collector due to the increasing temperature of the heat transfer fluid, which makes the collector efficiency continuously changing by the location. The heating of the heat transfer fluid is described by an ordinary differential equation, therefore the accurate result can only be determined by solving this either numerically or with the separation of variables method. The pressure drops in the pipes, the temperature dependence of the material properties and the temperature difference between the absorber and the heat transfer fluid are neglected in this model.

Since the small-scale solar thermal power plants are even less mature technology than the PV systems, in absence of reliable experiential data some operation specifications have to be determined using optimisation methods. The type of the working fluid and the evaporation and condensation temperatures have the biggest impact on the cycle efficiency. A number of technical, safety and environmental aspect have to be taken into account while selecting the most appropriate working fluid. R245fa (pentafluoropropane) is chosen in low-temperature applications and toluene in case of higher temperatures, since these provided the best efficiencies between the given conditions and also practical applications can be found using these fluids. The condensation temperature depends on the implemented cooling system, in this model air cooling was considered, which makes the condensation temperature fluctuating always 20 °C above the ambient temperature.

A higher value of evaporation temperature results a better cycle efficiency, but it requires a higher heat transfer fluid temperature, which reduces the collector efficiency. The overall efficiency of the power plant is the product of the cycle and collector efficiencies, and has a maximum at an optimal evaporation temperature, as it can be seen in the Fig. 3. Since the collector efficiency largely depends on the irradiance, the optimal evaporation temperature also decreases with lower solar radiation. The heat input to the ORC always varies with the weather conditions, therefore most of time the ORC works in off-design conditions, where the evaporation temperature is

determined by the flow rate of steam into the turbine and the governing method of the turbine [5]. The analyses of the different control methods have shown that the sliding pressure control is the best choice, since in this case the real evaporation temperature in part load conditions decreases to almost the same extent as the theoretical optimum temperature.

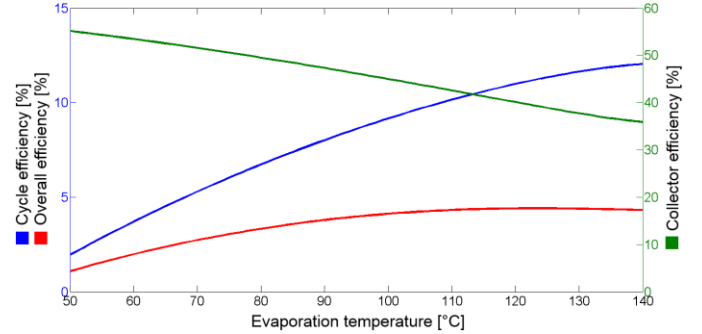


Fig. 3. Efficiencies as a function of evaporation temperature in solar thermal ORC systems

III. COMPARISON OF DIFFERENT SOLAR POWER PLANT TYPES

Three different types of solar power plant were examined: PV systems and solar thermal plants with both concentrating and non-concentrating collectors. Due to the large variety of non-concentrating collector and significant differences between the different types, three of them were chosen, which increases the total number of analysed systems to five. In most of the calculations the nominal power was considered to be 100 kW. The specifications of these plants are listed below, all important calculation parameters can be found on the data sheets of these devices or in the previous section.

1. PV systems: Bosch c-Si M60 250 W_p solar modules with Fronius Agilo 100.0-3 central inverter.
2. ORC with flat plate collector: EURO C20 AR solar collector and ORC with R245fa working fluid.
3. ORC with evacuated tube collector: Sonnenkraft VK25 solar collector and ORC with R245fa working fluid.
4. ORC with evacuated flat plate collector: SRB Energy UHV C1 solar collector and ORC with toluene working fluid.
5. ORC with parabolic trough collector: SEGS LS-2 solar collector and ORC with toluene working fluid.

Before presenting the results it is important to reveal that which indicators are the most influential criteria of comparison, and in which way and what extent are they influencing the feasibility of the projects. In case of energy producing units the financial return is the most important factor. The following considerations are based on the dynamic economic model, which summarises the cash flows of different periods taking into account the time value of the money. The investment cost of the solar power plants occurs in the first year, while the income comes from the sold electricity over the lifetime of the plant. For easier comparison of plants with different nominal power the specific investment cost and specific energy production should be used instead of their absolute values. The specific energy production is the ratio of the produced electricity and the nominal power of the plant, therefore it is an equivalent indicator to the capacity factor.

In solar power plants the efficiency has only a secondary importance, since they are not using any fuel unlike the fossil power plants. The efficiency influences mainly the required collector or module area to achieve a given nominal power, thereby also the specific investment cost, although the efficiency itself is not enough to determine the costs since the different collectors have different costs per unit area. The specific energy production directly determines the expected revenues from the sold electricity, but due to the different investment cost of each plant types it cannot determine the payback period in itself. The efficiency and the specific energy production are not comprehensive indicators without the detailed knowledge of different costs, but still the best comparison criteria for the different power plant types.

A. Electrical Efficiency

The electrical efficiency of solar power plants largely depends on both the irradiance and ambient temperature. At a given irradiance the efficiency increases linearly with decreasing ambient temperature in case of all investigated systems, regardless of the actual irradiance level, and can be well described with a constant temperature coefficient. The temperature has the biggest effect on the efficiency of PV systems. In solar thermal power plants this linear characteristic only applies to air cooled systems, where the condensation temperature can follow the variation of the ambient temperature, in cases of water cooling the efficiency change is much less significant.

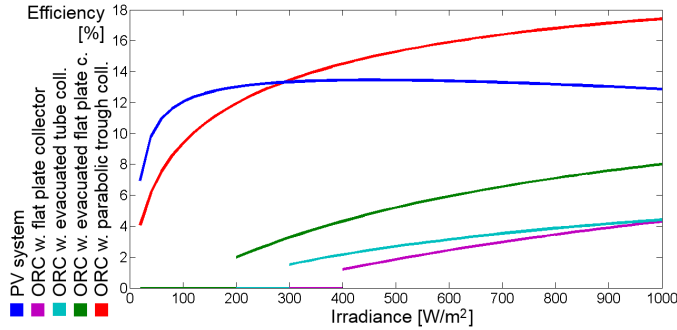


Fig. 4. Electrical efficiency of different solar power plants as a function of solar radiation

The efficiency as a function of the irradiance was fundamentally different in case of different power plants, which is shown in the Fig. 4. The PV systems can work with the best efficiency in the moderate irradiance range. Higher irradiance causes the more intense warming of the module, which leads to a higher cell temperature and therefore a slight decrease in efficiency, while at low irradiance the constant losses of the system are becoming more important and sharply decreasing the efficiency. The efficiency of the solar thermal power plants is the best at high irradiance, and significantly decreases at lower irradiance due to the strong irradiance dependence of the collector efficiency. The achievable temperature in the flat plate collector, evacuated tube collector, evacuated flat collector and parabolic trough collector increasing in this order, and the efficiency curves are situated also accordingly in the diagram. The concentrating parabolic trough collectors enables a quite

high efficiency in a wide range of irradiance, while only much lower efficiency can be achieved using non-concentrating collectors.

B. Annual Energy Production

The calculation of the expected annual energy production is very important in the payback calculations, but it is also a very good comparison criterion since it contains the effect of different weather conditions with the appropriate weight to their real occurrence. The calculations are based on the Meteonom 6.1 meteorological database, which contains hourly radiation and temperature data for an average, representative year.

The calculations were performed to a site near the Hungarian city of Debrecen (47,5°N, 21,6°E). The PV modules and non-concentrating collectors are able to utilize both the beam and diffuse radiation, therefore the global irradiance data was used projected to a plane with 35° tilt, which is the optimum under the given conditions. The concentrating collectors can only use the beam radiation, which can be calculated based on the direct normal irradiance (DNI) corrected with the cosine effectiveness depending on the incidence angle [5]. The parabolic trough collectors can be aligned on a north-south or east-west horizontal axis, and there is a big difference in irradiance between the two cases. The north-south alignment ensures a better incidence angle in the morning and evening, and therefore a smoother energy production over the day, but the cosine effectiveness reduces largely in the winter. In case of east-west alignment the situation is reversed, the energy production varies increasingly over the day, but fluctuates less with the seasons. Daily fluctuation is generally better, because it can be smoothed with an energy storage, which is not possible in case of the seasonal changes. The annual irradiation is although better with north-south alignment (1115 kWh/m²) than with east-west (972 kWh/m²), therefore this layout was considered. The annual global irradiation is 1535 kWh/m², so the concentrating collectors can only utilize approximately 25% lower irradiation than the non-concentrating collectors and PV modules.

TABLE I. ANNUAL ENERGY PRODUCTION DATA

	Annual energy production [MWh]	Nominal efficiency	Annual average efficiency	Specific energy production [kWh/kW]	Capacity factor	Collector/module area [m²]
PV system	133.0	15.20%	13.17%	1330	15.18%	658
ORC w. flat plate collectors	77.8	3.75%	1.90%	778	8.88%	2667
ORC w. evaporated tube collectors	96.7	4.12%	2.59%	967	11.03%	2427
ORC w. evaporated flat plate collectors	107.4	7.63%	5.34%	1074	12.26%	1310
ORC w. parabolic trough collectors	95.6	17.34%	14.99%	956	10.91%	572

The calculation results are presented in Table I, all of them apply to a power plant with 100 kW nominal power. The annual efficiency is lower than the nominal in all cases, but the difference is only significant by the ORC systems with non-

concentrating collectors. These systems also have a low energy production in spite of the large collector area. The efficiency of the concentrating ORC system is the best among the examined plant types, but their energy production is still behind the PV systems due to the lower value of the beam irradiation. The PV systems can achieve the highest energy production since they are able to efficiently utilize even the low irradiance.

C. Cogeneration and Energy Storage

In terms of electricity production the PV systems may be the best choice, but the indirect energy conversion performed in solar thermal power plants offer the option of combined heat and power generation and thermal energy storage, something that is not feasible in PV systems. In case of cogeneration the available heat demand is important in the examined small-scale power plants the best ways to utilize the produced heat are building heating and domestic hot water production. A back pressure turbine was assumed for the cogeneration, where all of the heat rejected in the condenser can be utilized. A higher temperature of the produced heat causes a bigger decrease in the power output, therefore 75 °C heat temperature was assumed, which is a low value compared to the conventional district heating temperature levels, but can be well used in modern heating systems. The results are summarized in the Table II, where all data applies to 1000 m² collector area, and the last column shows the case of heat production in collectors without power generation.

TABLE II. HEAT AND POWER PRODUCTION DATA
WITH AND WITHOUT COGENERATION

Temperature of produced heat: 75 °C	Electricity production [MWh]	Cogeneration		Heat production [MWh]
		Electricity [MWh]	Heat [MWh]	
ORC with flat plate collectors	29.2	-	-	752.0
	1.90%	-	-	48.99%
ORC with evaporated tube collectors	39.8	10.3	432.5	712.5
	2.59%	0.67%	28.18%	46.41%
ORC with evaporated flat plate collectors	82.0	62.4	495.2	721.2
	5.34%	4.07%	32.26%	46.98%
ORC with parabolic trough collectors	167.1	130.9	567.1	806.7
	14.99%	11.74%	50.86%	72.35%

In case of flat plate collectors the cogeneration is not feasible due to the frequent low irradiance and collector temperature. In case of evacuated tube collectors the heat production leads to a massive reduction of power production. As far as a sufficiently large heat demand is available, using these collectors only for heat production is generally more profitable than establishing a solar thermal power plant. In the ORC systems with evacuated flat plate collectors or parabolic trough collectors a considerable amount of heat can be produced at the expense of the expense of a slight decrease in produced electricity, which makes the cogeneration a favourable opportunity.

PV systems directly produce electricity from the solar radiation, therefore the only storage opportunity is the storage of electricity, commonly with batteries. Due to the high cost of batteries the vast majority of the PV plants do not have any

storage capability, the power output is fully dependent on the weather, which makes the PV a non-dispatchable energy source. In solar thermal power plants the thermal energy storage is a low cost and common storage possibility that allows dispatchable energy production the whole day. The dispatchability is one of the most important advantages of the solar thermal power plants, since they do not necessitate the increase of spinning reserves unlike the non-dispatchable generating units, or they may even be able function as a reserve.

The annual energy production is basically determined by the installed collector area, and in case of a thermal energy storage the ORC only have to be sized to an average radiation instead of the peak, which decreases the cost of the ORC system and partially compensates the costs of the thermal storage. The storage cost depends largely on the efficiency of the heat engine and the temperature levels. A higher ORC efficiency enables to produce the same amount of electricity from a lower stored amount of heat, while the same heat can be stored in less mass and volume in case of higher storage temperature. Among the examined solar thermal plant types the parabolic trough ORC systems are capable to the highest temperature, therefore in their case is the storage the most economical.

IV. GEOGRAPHICAL DIFFERENCES

The detailed comparison was performed to a single geographical location, but since the performance of the plants largely depends on the location-specific weather conditions, several different plant sites were examined for a full comparison. The former results have shown that ORC systems with flat plate or evacuated tube collectors are far behind the others in all aspects, therefore these were excluded from the further investigations. The list and the main attributes of the examined plant sites are shown in Table III. The selected sites are representing areas with different climatic conditions in Europe, and are mostly in countries where a great importance is attached to renewable energy sources. In the following part the northern and southern attributes are used to characterize the sites. It is important to note that the presented effects do not only depend on the latitude, but there are some tendencies to be observed.

The latitude, longitude and altitude are the geographic coordinates representing the sites, and “Inc.” stands for the optimal inclination angle of a tilted plane where the annual global irradiance is maximized. A positive difference between the latitude and inclination means the better utilization of radiation in summer, while the negative means the same in winter. This difference is positive in all examined sites, since the radiation is everywhere higher in the summer, but its value is lower in case of the southern sites, which means a lower difference between the summer and winter insolation. T_{mean} is the yearly average temperature according to the used meteorological database, H_{total} is the global irradiation and H_b is the beam irradiation, where NS and EW stand for the north-south and east-west alignments. North-south alignment was considered for all plant sites, since it everywhere results about 15% more irradiation than the other case. Even though the beam irradiation is nevertheless lower than the global irradiation in

TABLE III. GEOGRAPHICAL AND METEOROLOGICAL DATA OF EXAMINED PLANT SITES

Site	Latitude	Longitude	Altitude	Inc.	T mean [°C]	Htotal [kWh/m ²]	Hb (NS) [kWh/m ²]	Hb (EW) [kWh/m ²]
Copenhagen	55.7°N	12.4°E	30 m	41°	8.2	1206	860	750
Munich	48.4°N	11.8°E	440 m	36°	9.0	1352	948	827
Debrecen	47.5°N	21.6°E	110 m	35°	10.5	1535	1115	972
Pisa	43.7°N	10.4°E	1 m	36°	14.7	1702	1313	1126
Seville	37.4°N	5.9°W	25 m	33°	19.8	2014	1654	1407
Tunis	36.8°N	10.2°E	2 m	32°	19.2	2084	1720	1493

all cases, the difference in northern sites is about 30%, it is less than 20% in the southern ones.

A. Energy Production and Efficiency

The two most important indicators, the specific energy production and the efficiency were calculated for each site and power plant type. Besides the produced electricity the purchase price and the investment cost are also influencing the financial return, which can vary in different countries. However, these differences are continuously decreasing due to the European market integration, reducing price level differences and increasing centralized policy recommendations, therefore the specific energy production becomes even more important in a longer term. Table IV shows the simulation results, where the EF and PT abbreviations are standing for evacuated flat collectors and parabolic trough collectors respectively. The PV systems are able to produce the most energy in all sites and the parabolic trough concentrating systems produce the least due to the lower value of beam irradiation.

TABLE IV. SPECIFIC ENERGY PRODUCTIONS ON DIFFERENT PLANT SITES

Site	PV	EF ORC	PT ORC
	Spec. energy prod. [kWh/kW]		
Copenhagen	1068	801	737
Munich	1194	911	813
Debrecen	1347	1074	956
Pisa	1472	1223	1129
Seville	1700	1510	1428
Tunis	1774	1585	1486

The amount of produced energy largely differs in the different sites, the main reason is clearly the difference in solar irradiance. The efficiency is the ratio of the produces energy and the incoming solar radiation, therefore it shows that how effectively can the plant utilize the available solar resource. The annual average efficiencies of the different systems are shown in Table V.

The efficiency of the PV systems is higher in the northern sites, the main reason is the lower ambient temperature. The variation of the efficiency is nevertheless much less significant than the difference of solar irradiation, therefore the PV systems produce definitely more electricity in sunnier areas, the reversed change of efficiency just smoothens this character. The solar thermal power plants are able to operate more efficiently in southern areas due to the typically higher solar radiations.

The rate of change is higher in the case of the non-concentrating plant, while the efficiency of the assessed CSP plant changes only very slightly. The installation of solar thermal power plants is recommended primarily in southern areas, since there not only the irradiation, but the electrical efficiency is also higher.

TABLE V. AVERAGE EFFICIENCY DATA ON DIFFERENT PLANT SITES

Site	PV	EF ORC	PT ORC
	Average efficiency		
Copenhagen	13,49%	5,07%	14,98%
Munich	13,44%	5,14%	14,99%
Debrecen	13,35%	5,34%	14,99%
Pisa	13,16%	5,49%	15,03%
Seville	12,84%	5,72%	15,09%
Tunis	12,95%	5,80%	15,10%

B. Fluctuation of Energy Production

The previous results only deal with the annual aggregated energy production, but the temporal distribution of the produced electricity is also an important factor. Due to the probabilistic nature of the weather conditions the examination of daily or weekly intervals has no real meaning, but the monthly aggregated data can show a good picture from the seasonal changes. Fig. 5 shows the monthly distribution of the solar irradiation for all sites during the examined representative year. This diagram shows that not only the value of the irradiance is higher in the southern areas, but the differences between the summer and winter values are smaller, which results in a more balanced energy production over the year.

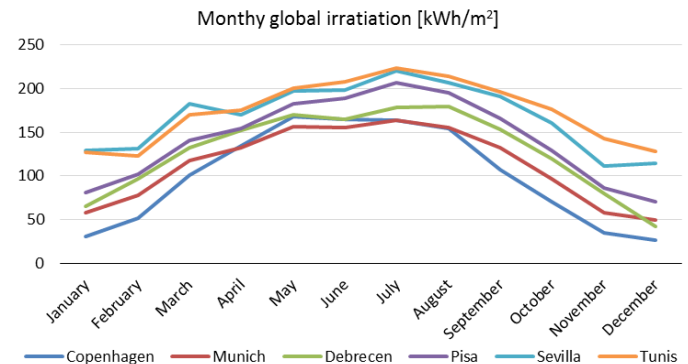


Fig. 5. Monthly variation of solar irradiation

Similar diagrams can be made based on the beam irradiation and the energy production of different plant types. The coefficient of variation (CV) is a statistical indicator, which enables the description the monthly fluctuation using one single number. The CV is the ratio of the standard deviation to the average value, therefore it is a dimensionless number and enables the comparison between the data sets with different units and means. Table VI contains the CV values based on the monthly distribution of the global and beam irradiation, indicated with H_{total} and H_{beam} , and of the produced energy in PV systems, evaporated flat plate collector and parabolic trough collector ORC systems, indicated with E_{PV} , $E_{EF,ORC}$ and $E_{PT,ORC}$ respectively. A higher CV means a higher difference between the values applying to summer and winter months.

TABLE VI. COEFFICIENTS OF VARIATION BASED ON MONTHLY DISTRIBUTIONS OF DIFFERENT VALUES

Site	Coefficient of variation (CV)				
	H_{total}	E_{PV}	$E_{EF,ORC}$	H_{beam}	$E_{PT,ORC}$
Copenhagen	56,0%	54,7%	65,5%	78,5%	83,5%
Munich	38,4%	35,9%	43,4%	57,5%	60,8%
Debrecen	36,7%	33,8%	41,9%	52,8%	55,1%
Pisa	33,9%	31,0%	39,4%	56,5%	59,6%
Seville	22,6%	19,7%	24,7%	41,3%	43,0%
Tunis	20,8%	17,5%	22,4%	40,1%	41,8%

The variation of the global and beam irradiation is decreasing towards the southern areas, therefore the variation of the energy production also changes accordingly. The CV of the electricity production of PV systems is slightly lower, while the CV in case of the solar thermal power plants is slightly higher than the CV of the irradiation they utilize, which can be explained with the effects previously detailed in connection with the Table V. The energy production of the CSP plant has the highest fluctuation, which is caused by the higher variation of the beam irradiation. In northern places the solar power plants producing much less energy in winter than in summer, while in southern areas they are able to produce a remarkable amount of electricity also in winter. This trend is particularly true for the CSP plants.

V. CONCLUSION

The results have shown that also the low-temperature heat produced in flat plate or evacuated tube collectors can be utilized to electricity production using organic Rankine-cycle, but these systems are generally uneconomical due to their very low efficiency. The evaporated flat plate collector was the only non-concentrating collector which is able to produce heat at a sufficiently high temperature to achieve a still low but acceptable efficiency. The concentrating collector ORC plants have a relatively good efficiency, but their specific energy

production is lower than the others' since they cannot utilize the diffuse radiation. In the aspect of produced electricity the PV systems are the best, their main disadvantage is only their non-dispatchability. The solar thermal power plants are dispatchable energy sources due to the inexpensive thermal energy storage, and also suitable for combined heat and power generation, which can bring extra revenues to the plant.

Several different geographical locations were examined, what has shown that the electricity production is mainly determined by the solar irradiation regardless to the smaller changes of the efficiency. The efficiency of PV system is nevertheless better in northern sites, while the solar thermal power plants has a relatively better efficiency in the south, which should be taken into consideration while choosing the most appropriate plant type. In the aspect of the monthly fluctuation of the produced electricity the southern plant sites and the PV systems are more favourable.

All three plant types have their own disadvantage, which makes them difficult to compare: the PV systems are non-dispatchable, the non-concentrating solar thermal plants have low efficiency and the concentrating solar power plants utilizing only a lower proportion of the solar radiation. Currently the amount of the produced energy is the most important factor, which makes the PV systems the most favourable choice, what corresponds to the global installed capacity data. In case of a high penetration of non-dispatchable energy generating units, without the development of a cheap electricity storage method, the dispatchability will have a great importance, which could encourage the installation of solar thermal power plants in the future.

VI. REFERENCES

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