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Deliverable Report
D3.1 Energy supply concepts

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1 Introduction to the project SERPIC

The project *Sustainable Electrochemical Reduction of contaminants of emerging concern and Pathogens in WWTP effluent for Irrigation of Crops – SERPIC* will develop an integral technology, based on a multi-barrier approach, to treat the effluents of wastewater treatment plants (WWTPs) to maximise the reduction of contaminants of emerging concern (CECs). The eight partners of the SERPIC consortium are funded by the European Commission and by six national funding agencies from Norway, Germany, Italy, Spain, Portugal and South Africa. The official starting date of the SERPIC project is 1st September 2021. The project has a duration of 40 months and will end 31 December 2024.

The overall aim of the SERPIC project is to investigate and minimise the spread of CECs and antimicrobial resistant bacteria/antibiotic resistance genes (ARB/ARG) within the water cycle from households and industries to WWTPs effluents, and afterwards via irrigation into the food chain, into soil and groundwater and into river basins, estuaries, coastal areas, and oceans with a focus on additional water sources for food production.

A membrane nanofiltration (NF) technology will be applied to reduce CECs in its permeate stream by at least 90 % while retaining the nutrients. A disinfection using ozone, produced electrochemically, will be added to the stream used for crops irrigation (Route A). The CECs in the polluted concentrate (retentate) stream will be reduced by at least 80 % by light driven electro-chemical oxidation. When discharged into the aquatic system (route B), it will contribute to the quality improvement of the surface water body.

A prototype treatment plant will be set-up and evaluated for irrigation in long-term tests with the help of agricultural test pots. A review investigation of CECs spread will be performed at four regional showcases in Europe and Africa. It will include a detailed assessment of the individual situation and surrounding conditions. Transfer concepts will be developed to transfer the results of the treatment technology to other regions, especially in low- and middle-income countries.

2 Report summary

The different components which are utilized in the SERPIC system consume electrical energy. To build up the process environmentally sound and, as far as possible, CO_2 emission-free, renewable energy (RE) sources (PV, wind) will be considered as prime mover. Due to the fluctuating nature of these sources, either battery storages, or back-up generators are typically used to compensate this insufficiency. An intelligent energy management system and smart grid control concept is essential to enable an individual allocation of power to different units to save storage capacity. Therefore, future water treatment units must be designed for transient operation. In the SERPIC project solar and wind energy potentials were analysed for the 4 potential demonstration sites and options for RE supply were investigated. Simulation calculations for a PV energy supply of a SERPIC reference system for Madrid and Cape Town were conducted and are summarized.

3 Deliverable description as stated in the Project Description

Simulation calculations in T3.1 will lead to optimized renewable energy supply concepts for the SERPIC plant. Calculations will be conducted for 4 different sites including the prototype site. A short report will be compiled supplying information on the required system configurations and capacities of wind and PV generators in terms of CO_2 savings and costs.

4 Methodology

The development of advanced water treatment technologies must consider the environmental impact in a holistic manner including the avoidance of greenhouse gas emissions. For the energy supply of such systems this implies the utilization of renewable energies as prime mover. Therefore, the potential of renewable energy supply was investigated in this project and estimations with focus on PV supply were derived from simulation calculations. For three different sites in southern Europe and South Africa, solar radiation data were analysed on a monthly average and on daily basis as well as wind profiles.

4.1 Analysis of weather data

For this meteorological analysis the well-known data basis Meteonorm 8 was used. Meteonorm is a unique combination of reliable data sources and high-quality calculation models. The program generates accurate and representative meteorological data for representative years and for each location on the planet. About 30 different meteorological parameters can be delivered. The data basis consists of more than 8,000 weather stations, five geostationary satellites and a globally calibrated aerosol climatology. For all locations in between these stations, comprehensive interpolation models deliver highly accurate results worldwide.

The main challenge for the utilization of wind and solar energy is their fluctuation nature during day and night-time as well as seasonal differences mainly associated with the geographical latitude if the location. For technical applications with high share of RE supply, either comprehensive energy storages are required to compensate supply gaps, a transient operation of the energy consumer must be possible to align the demand and supply side synchronically, or complementary RE sources need to be combined.

For the analysis of the solar and wind energy supply daily and monthly average values were summarized while the main interest was given to the differences between the months of highest and lowest insolation and wind speed respectively.

The solar radiation typically consists of two parts: the direct beam radiation, which is the almost parallel radiation (divergency <0.1°) and the diffuse radiation resulting from the diffusion of the direct beam radiation in the atmosphere (e.g. clouds, vapor, dust, water, …) and objects on the ground. The incidence angel of this diffuse radiation is considered to be homogeneously distributed all over the space. The utilization of both types of radiation by PV is different through optical effects as reflections which are directly associated with the incidence angle of beams hitting on the surface. Therefore, the Meteonorm solar radiation analysis differentiate between Global Radiation which is the sum of direct beam radiation and Diffuse Radiation measured on the horizontal ground including the diffuse fraction.

4.2 PV simulation tool

Based on the solar radiation data and the analysed energy consumption of the SERPIC system, the PV demand for a reference scenario, based on the production of 1 m^3/day of irrigation water, is investigated. For these investigations the simulation tool ColSim is used.

ColSim is an in-house modelling and simulation tool of Fraunhofer Institute for Solar Energy Systems (ISE). It is primarily used for Concentrating Solar Power Plants and Solar Process Heat but also for other technologies such as Carnot Batteries, Waste Heat Recovery, Solar PV power plants and buildings. It has been under development since 1999 when it was developed with the intention of simulating and testing complex control strategies in different HVAC and solar thermal systems. ColSim2.0 has an extensive component library with validated models covering a wide

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range of components. Most of the models are capable of dynamic and transient simulations based on plug flow model with capacity nodes using time series input. It has an online plotter to watch the simulation results during the simulation as well as an integrated post processor to visualize the results. Additionally, thanks to the relatively short calculation time (even with time resolution of 1 second) and parallelization, large number of simulations can be run in parallel (e.g. for optimization).

4.3 Preparation of the PV simulation deck

PV panels, battery and inverter are interlinked in a simulation deck file in the ColSim2.0 platform as well as the Meteonorm data for the selected target regions. Control parameter and selected post processing routines are implemented. The deck calculates current state values with a time resolution set to 120sec for the state of charge (SOC) of the battery, PV power and net coverage while integral values for daily, monthly, and annual sums are derived. A set up of the Colsim2.0 simulation deck is shown in **Figure 1**. All physical models deployed for the simulations are based on the Successive Approximation Model (SAM) approach.

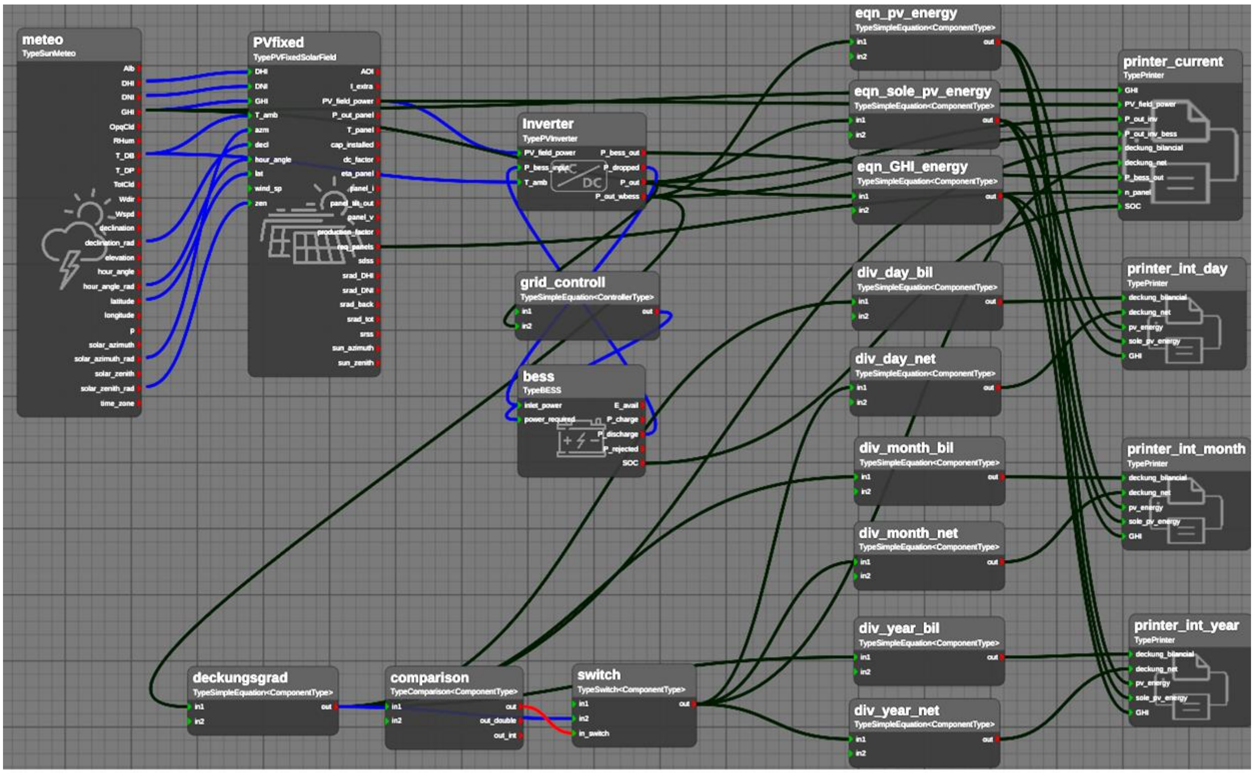


Figure 1: Colsim2.0 Simulation Deck.

For the parameterisation of the PV model, technical specifications of a typical commercial panel type JA Solar JAM72S20-460/MB are used with the following values:

- $A = 2.17\ m^2$
- $P_{MP} = 460\ W$
- $\eta_{PV} = 21.19\ \%$
- GCR = 1.7

The battery type is Li-Ion with the following values:

- $SOC_{min} = 10\ \%$
- $SOC_{max} = 90\ \%$
- $\eta_{Charge/Discharge} = 95\ \%$

The considered inverter is a typical 10-kW type with:

- η_{Inv} = 97.2 %

5 Results

5.1 Estimation of the SERPIC plant energy demand

The specific energy demand of the different components of the SERPIC system refer to a plant capacity with a total feed water treatment capacity of 500 L/d. Out of this, 80 % irrigation water and 20 % discharge water were produced which led to a total power demand of the SERPIC system of 0.63 kW. In order to receive more scalable output values from the simulations, the reference scenario was defined for a 1 m³/d irrigation water plant. Of course, the extrapolation by orders of magnitude are not accurate since the specific energy demand and efficiencies respectively of larger electrical components will be much better than of the small reference case. Nevertheless, the simulated values can be considered as „worst case scenario", when the results are extrapolated to higher production capacities.

The SERPIC reference demonstration plant, as can be seen in **Figure 2**, consists of several electrical consumers which are also summarized in **Table 1**.

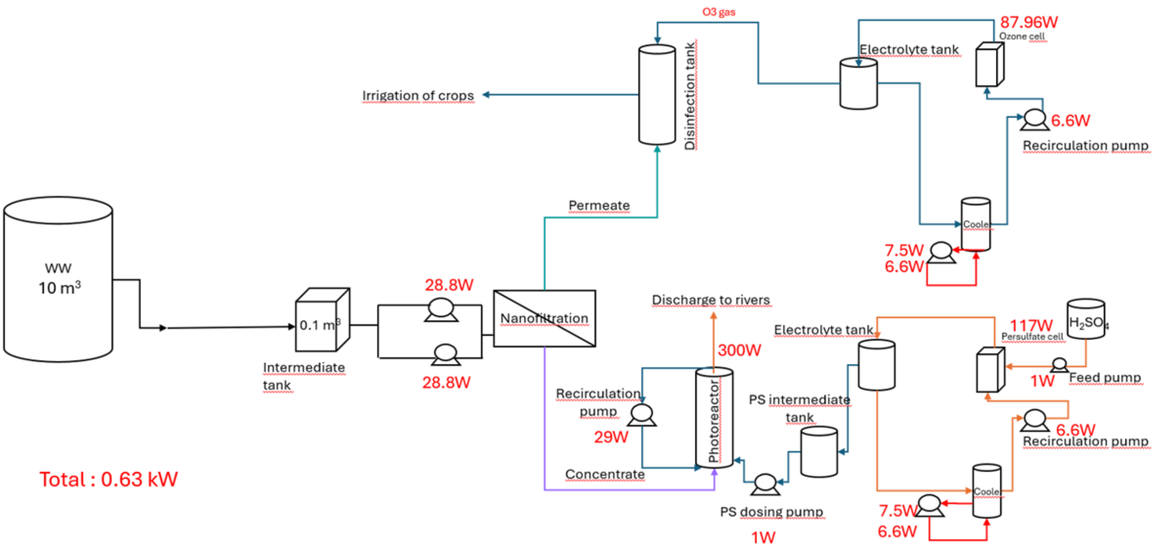


Figure 2: Hydraulic layout of the SERPIC demonstration plant including the specific energy consumptions of the different components.

Table 1: Summary of electrical components of the SERPIC demonstration system and their electrical power demand.

Component	**Power demand [W]**
NF Pump 1 (parallel)	28.8
NF Pump 2 (parallel)	28.8
Permeate route	
Ozone cell	87.96
Recirculation pump	6.6
Cooling pump	7.5 / 6.6
Retentate route	
Photoreactor	300
Circulation pump	29
Dosing pump	1
Persulfate cell	117
Acid pump	1
Recirculation pump	6.6
Cooling loop pump	7.5 / 6.6
Total	**637**

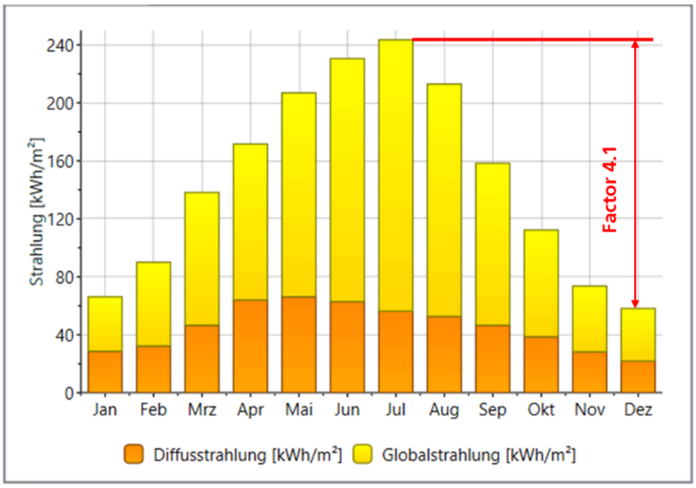
For the reference scenario, considering an irrigation water output of 1 m³/d, the related power demand is 1.8 kW which leads to an energy demand of 43 kWh/d and 15.7 MWh/y, respectively.

5.2 Analysis of meteorological data

Meteorological data are analysed for three different sites, namely Madrid (Spain), Ferrara (Italy) and Cape Town (South Africa) with respect to the utilization of renewable energies as prime mover for the SERPIC technology.

5.2.1 Madrid

Figure 3 shows the monthly average sum of global and diffuse radiation for Madrid and provides meteorological data based on monthly sums for radiation and average values of temperature respectively.



Month	H_Gh	H_Dh [kWh/m² month]	H_Bn	Ta [°C]
Jan	66	29	106	6,9
Feb	90	32	128	8,0
Mar	138	47	169	11,0
Apr	172	64	177	13,6
Mai	207	66	220	18,2
Jun	230	63	253	24,1
Jul	243	56	281	26,9
Aug	213	53	251	26,5
Sep	158	47	197	22,1
Okt	112	39	152	16,7
Nov	74	28	115	10,6
Dez	58	22	106	7,9
Annual sum	1759	545	2154	

Explanation:
H_Gh: Radiation sum of the global radiation horizontal
H_Dh: Radiation sum of diffuse radiation horizontal
H_Bn: Radiation sum of direct normal radiation
Ta: Ambient temperature

Figure 3: Average monthly sum of solar insolation and monthly average ambient temperatures for Madrid according to Meteonorm8, based on long term observation data.

The evaluation of the global horizontal insolation shows that the minimum in December is achieved with a monthly sum of about 60 kWh/m², while in July the monthly sum goes up to about 240 kWh/m². This is a difference of a factor of 4.1 which needs to be balanced by a solar PV system and is a challenge for a high penetration of solar energy as prime mover for a water treatment system. **Figure 4** shows the same global horizontal insolation for Madrid, but with a higher time resolution of kWh/day.

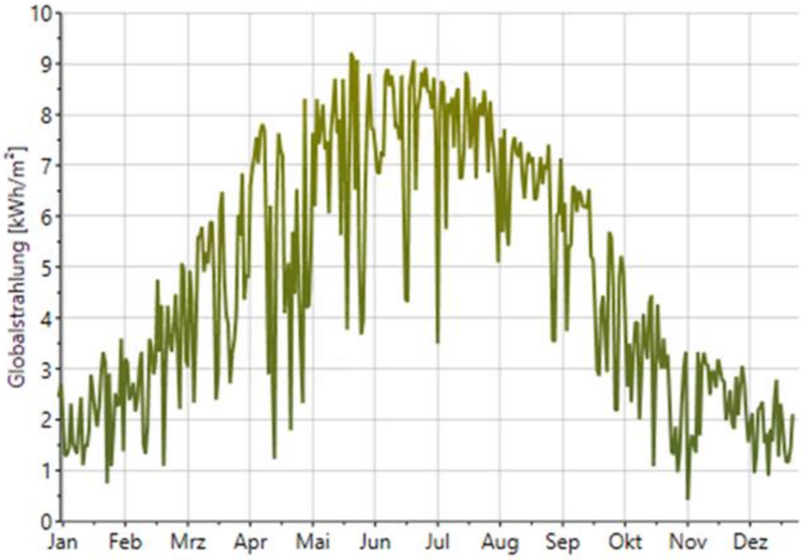


Figure 4: Average Global insolation sum in Madrid per day during the course of a year.

As can be seen in **Figure 4**, the daily global insolation sum is below 3 kWh/d in wintertime and rise up to 8 to 9 kWh/d between May and August. It can also be seen that that most time of the year intensive daily fluctuations must be expected which need consideration for the design of the PV supply system and the SERPIC water treatment plant respectively.

The comparison of the annual wind profile of Madrid, as presented in

Figure 5, shows that the weakest months are August and October with average wind speeds of 3.3 m/s. The highest values are observed in November with an average of 6.3 m/s. Between March and May, moderate wind speeds are recorded between 4.6 m/s and 5.1 m/s. Even if the annual wind profile seems to match with the solar insolation profile for compensation in November and January quite well, the available wind speed and associated energy potential seems not attractive for exploitation from economical point of view.

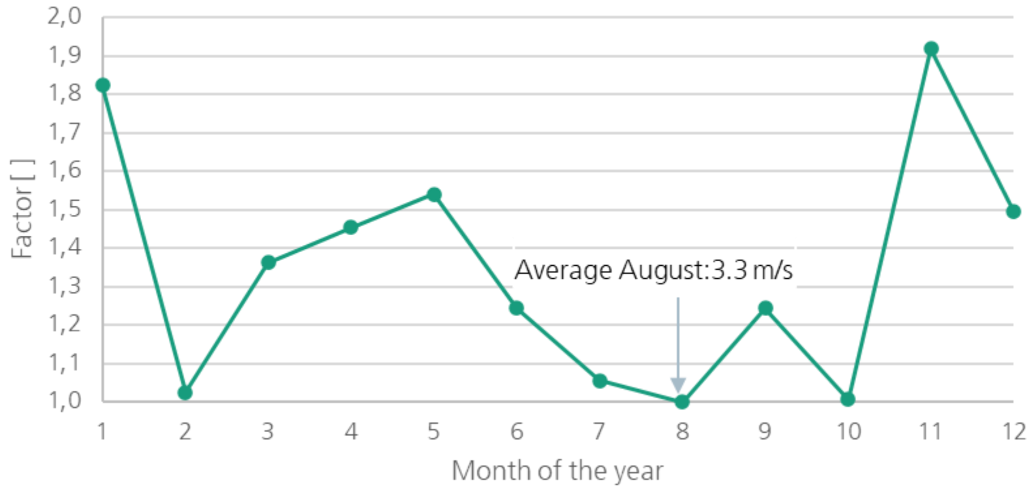
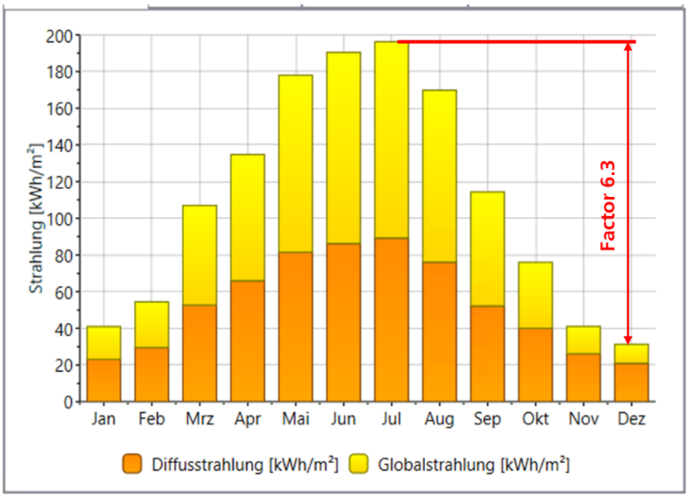


Figure 5: Wind profile Madrid - intensity factor compared to weakest month with 3.3 m/s.

5.2.2 Ferrara

Figure 6 shows the monthly average sum of global and diffuse radiation for Ferrara and provides meteorological data based on monthly sums for radiation and average values of temperature respectively.



Month	H_Gh	H_Dh [kWh/m² a]	H_Bn	Ta [°C]
Jan	41	23	58	3,1
Feb	54	30	63	5,1
Mar	107	53	107	9,8
Apr	135	66	118	14,2
Mai	178	81	152	18,9
Jun	190	86	155	23,7
Jul	196	89	164	25,8
Aug	170	76	150	25,3
Sep	114	52	116	20,2
Okt	76	40	78	15,2
Nov	41	26	43	9,6
Dez	31	21	37	4,2
Year	**1.331**	**643**	**1240**	**14,6**

Explanation:
H_Gh: Radiation sum of the global radiation horizontal
H_Dh: Radiation sum of diffuse radiation horizontal
H_Bn: Radiation sum of direct normal radiation
Ta: Ambient temperature

Figure 6: Average monthly sum of solar insolation and monthly average ambient temperatures for Ferrara according to Meteonorm8 based on long term observation data.

The evaluation of the global horizontal insolation shows that the minimum in December is achieved with a monthly sum of about 40 kWh/m² while in July the monthly sum goes up to about 195 kWh/m². This is a difference of a factor of 6.3 which needs to be balanced by a solar PV system and is, as already shown for Madrid, a challenge for a high penetration of solar energy as prime mover for a water treatment system. **Figure 7** shows the same global horizontal insolation for Ferrara but with a higher time resolution of kWh/d.

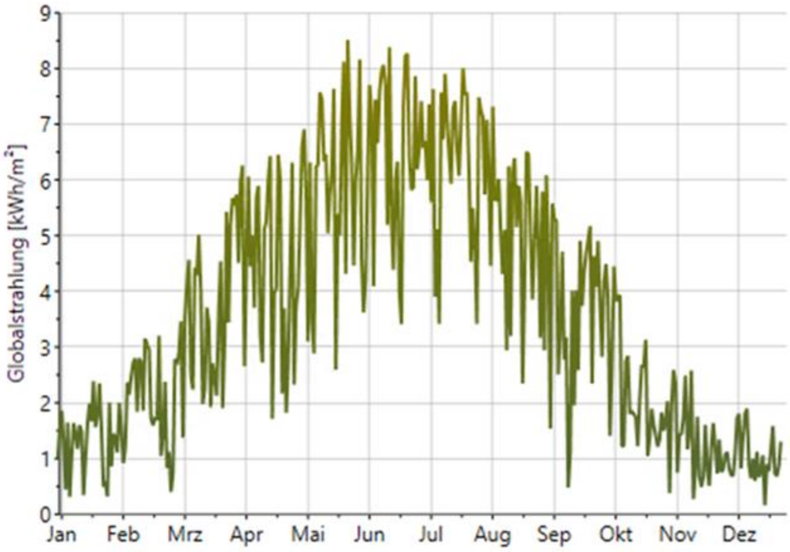


Figure 7: Average Global insolation sum in Ferrara per day during the course of a year.

As can be seen in **Figure 7**, the daily global insolation sum is below 2 kWh/d from November to January and rise up to maximum values of 7 to 8 kWh/d between June and August. It can also be seen that that most time of the year intensive daily fluctuations must be expected which need consideration for the design of the PV supply system and the SERPIC water treatment plant respectively.

The comparison of the annual wind profile of Ferrara, as presented in **Figure 8**, shows that the weakest month is October with average wind speeds of 2.8 m/s. The highest values are observed in April with an average of 6 m/s. Between January and March moderate wind speeds are recorded between 4.6 m/s and 4.9 m/s. The low wind speed and associated energy potential in October and December imply that the utilization of wind energy to complement solar energy during that period dos does not make sense. A general supply with wind energy instead of solar energy also does not seem attractive from economical point of view due to the relatively low wind speed during the year. For a conclusion detail economic analysis are required.

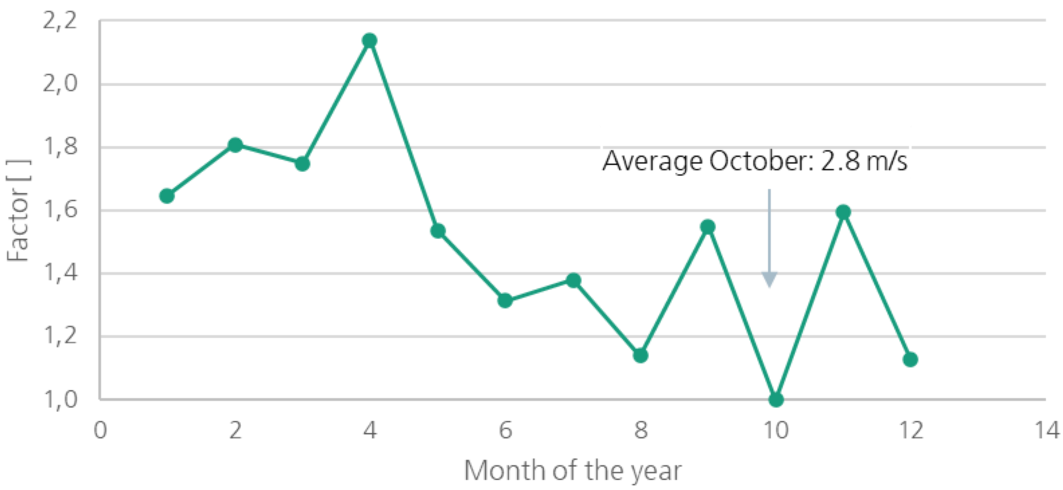
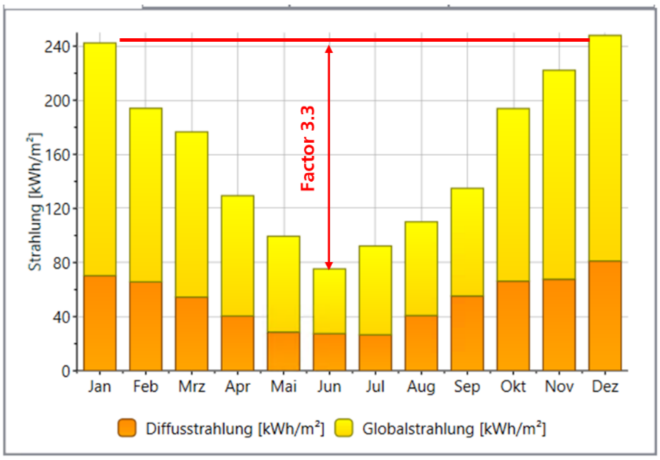


Figure 8: Wind profile Ferrara - intensity factor compared to weakest month with 2.8 m/s.

5.2.3 Cape Town

Figure 9 shows the monthly average sum of global and diffuse radiation for Cape Town and provides meteorological data based on monthly sums for radiation and average values of temperature respectively.



Month	H_Gh	H_Dh [kWh/m² a]	H_Bn	Ta [°C]
Jan	242	70	246	21,5
Feb	194	66	193	21,5
Mar	177	55	201	19,9
Apr	129	41	164	17,5
Mai	99	29	155	15,2
Jun	75	27	116	13,0
Jul	92	27	152	12,6
Aug	110	41	140	13,0
Sep	135	55	137	14,5
Okt	194	66	194	16,8
Nov	222	68	227	18,5
Dez	248	81	239	20,5
Year	**1921**	**625**	**2164**	**17,0**

Explanation:
H_Gh: Radiation sum of the global radiation horizontal
H_Dh: Radiation sum of diffuse radiation horizontal
H_Bn: Radiation sum of direct normal radiation
Ta: Ambient temperature

Figure 9: Average monthly sum of solar insolation and monthly average ambient temperatures for Cape Town according to Meteonorm8 based on long term observation data.

The evaluation of the global horizontal insolation shows that the minimum in June is reached with a monthly sum of about 75 kWh/m² while in December and January the monthly sum goes up to above 240 kWh/m². This is a difference of a factor of 3.3 which needs to be balanced by a solar PV system. In general, the high solar insolation even in winter time and moderate difference between winter and summer time compared to the investigated European sites recommend solar energy very much as prime mover for a water treatment system. **Figure 10** shows the same global horizontal insolation for Cape Town but with a higher time resolution of kWh/day.

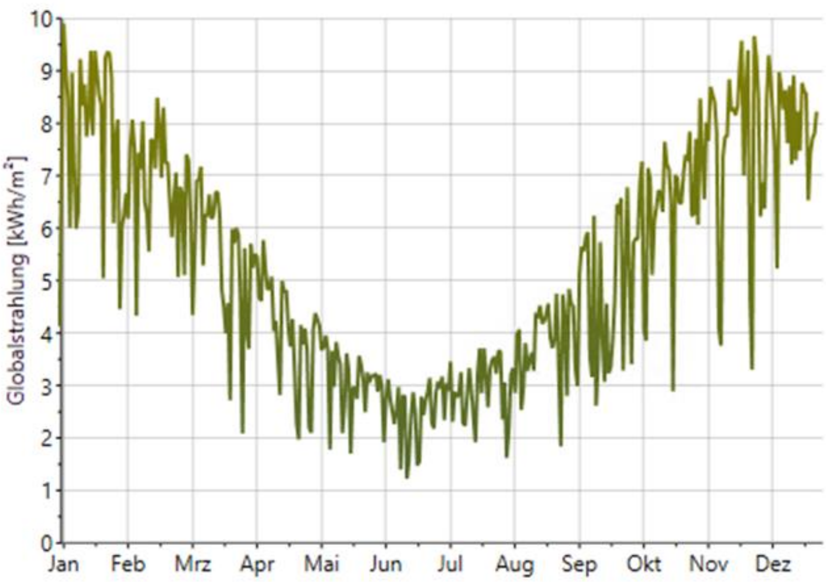


Figure 10: Average Global insolation sum in Cape Town per day during the course of a year.

As can be seen in **Figure 10**, the daily global insolation sum is below 3 kWh/d in June only and rise up to maximum values of above to 9 kWh/d in November. It can also be seen that that most time of the year daily fluctuations must be expected which need consideration for the design of the PV supply system and the SERPIC water treatment plant respectively.

The comparison of the annual wind profile of Cape Town, as presented in **Figure 11**, shows that the weakest month is May with average wind speeds of 4.8 m/s. The highest values are observed in March with an average of 10.3 m/s. Between June and September wind speeds are recorded between 7.7 m/s and 5 m/s. The relatively high wind speed and associated energy potential for all months imply that the utilization of wind energy could be an attractive alternative instead of solar PV supply from economical point of view. It does not seem attractive as complementary supply since both sources are high and low in same periods of the year. For a conclusion, detailed economic analysis for PV and wind energy are required.

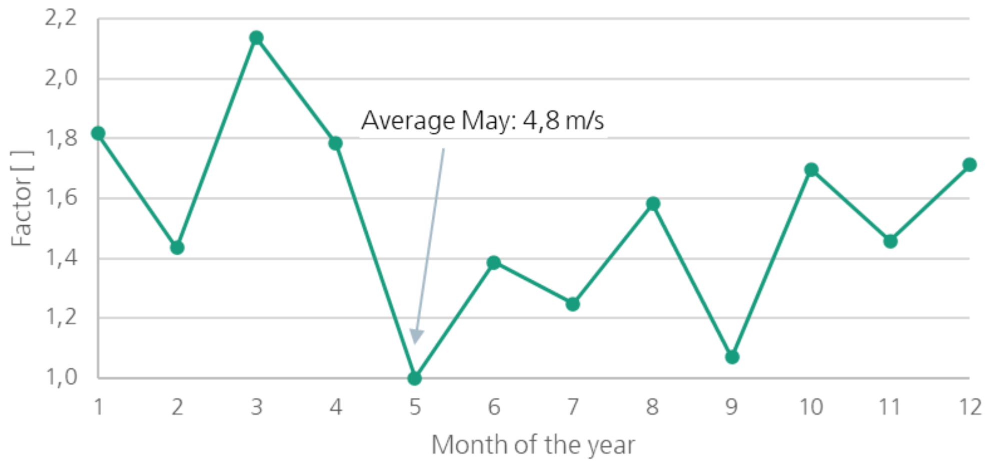


Figure 11: Wind profile Cape Town - intensity factor compared to weakest month with 4.8 m/s.

5.3 Simulation results for solar energy supply

The simulation calculations conducted with Colsim2.0 and meteorological data from METEONORM 8 were based on the reference scenario for an irrigation water output of 1 m³/d, a corresponding power demand of 1.8 kW and an energy demand of 43 kWh/d respectively. Two different locations were investigated. For southern Europe, Madrid was selected and for South Africa Cape Town.

The objective of the simulation calculations is to identify the required PV system to produce the required amounts of energy considering two different approaches:

a) 100% balance (gross) coverage → The PV system produces without battery storage as much energy as the water treatment plant needs in an annual sum, but not simultaneously.

b) Simultaneous (net) coverage → The PV system produces the energy to cover a share of the actual energy demand of the water treatment plant supported by a battery storage.

5.3.1 Results Madrid

The first target of simulation calculations was to determine the required number of PV panels (technical characteristics as specified in 4.3) to achieve the 100 % gross coverage of the annual energy demand of the SERPIC reference case. An installation tilt angle according to the latitude of 40° was considered as well as a south orientation of 180°.

The results show that 20 PV panels (type JA Solar JAM72S20-460/MB) with 9.2 kWp are sufficient to supply the same amount of energy in sum of a year as the SERPIC reference system needs. The results show that this configuration without battery storage achieves a net coverage (share of direct coverage) of 41 %.

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In the next step, the tilt angle was varied in 5° steps up to 60° to investigate if a better performance could be achieved during wintertime in order to get a more homogeneous energy supply distribution during the course of the year. The results show that no improvement is possible. While the gross coverage is reduced to 95 %, no change in the net coverage of 41 % can be achieved.

In the following step, an energy supply system consisting of a PV generator and a managed Li-Ion battery storage (specifications as defined in 4.3) was designed aiming at high net coverage ratios > 80 %. The PV system was designed with 60° tilt angle south (180°) direction and the number of panels was varied. The graph in **Figure 12** shows as an example the achievable net coverage ratio versus the installed battery capacity for the configuration with 20 panels and for 30 panels. It can be seen that for the 20 panels configuration the net coverage can be increased from 41 % without battery storage up to 77 % if a 30-kWh battery storage is integrated into the system. In comparison, an extension of the PV area to 30 panels allows a net coverage of about 85 % while a gross coverage of 141 % is achieved.

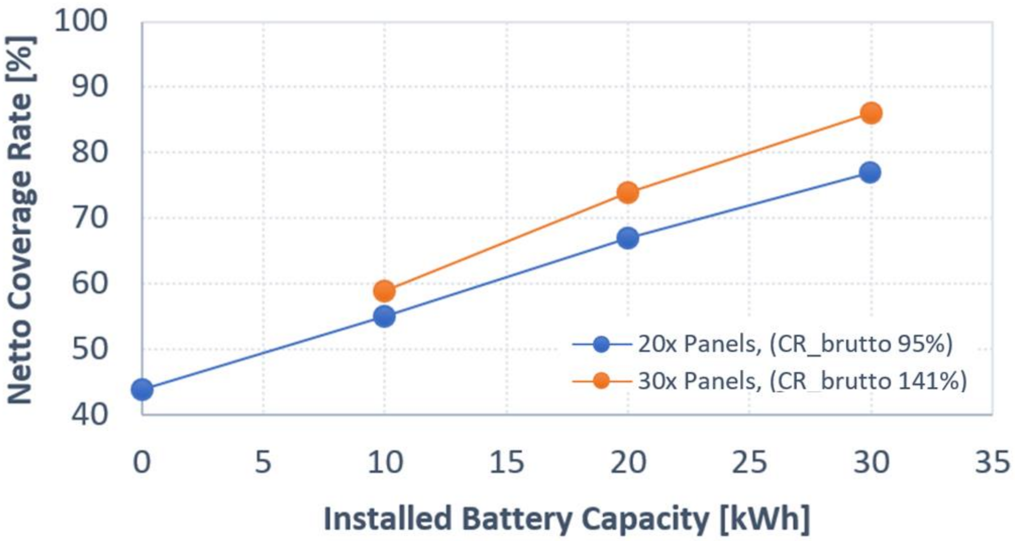

Figure 12: Net coverage of energy demand depending on installed battery capacity for two PV generator sizes simulated with solar insolation data of Madrid.

5.3.2 Results Cape Town

As for Madrid also for Cape Town the first target of simulation calculations was to determine the required number of PV panels (technical characteristics as specified in 4.3) to achieve the 100 % gross coverage of the annual energy demand of the SERPIC reference case. An installation tilt angle according to the latitude of 33° was considered as well as a north orientation of 360°.

The results show that 27 PV panels (type JA Solar JAM72S20-460/MB) with 12.42 kWp are sufficient to supply the same amount of energy in sum of a year as the SERPIC reference system needs. The results show that this configuration without battery storage achieves a net coverage (share of direct coverage) of 42 %.

In the next step again, the tilt angle was varied in 5° steps up to 65° to investigate if a better performance could be achieved during wintertime in order to get a more homogeneous energy supply distribution during the course of the year. The results show that a small improvement is possible during wintertime increasing the net coverage to 44 %, while the gross coverage is significantly reduced from 100 % to 83 %.

In the following step again, an energy supply system consisting of a PV generator and a managed Li-Ion battery storage (specifications as defined in 4.3) was designed aiming at high net coverage ratios > 80 %. The PV system was designed with 65° tilt angle in north (360°) direction and the number of panels was varied. The graph in **Figure 13** shows as an example the achievable net coverage ratio versus the installed battery capacity for the configuration with 27 and 41 panels. It can be seen that for the 27 panels configuration the net coverage can be increased from 44 % without battery storage up to 71 % if a 30 kWh battery storage is integrated into the system. In comparison an extension of the PV area to 41 panels shows on the one hand, that almost no improvement of the net coverage ration can be achieved without battery storage but on the other hand a 30-kWh battery storage allows a net coverage of almost 90 %, while in that case a gross coverage of 123 % can be achieved. It can also be seen, that for the 27-panel configuration a further increase of the battery storage beyond 30 kWh will not further increase the net coverage rate.

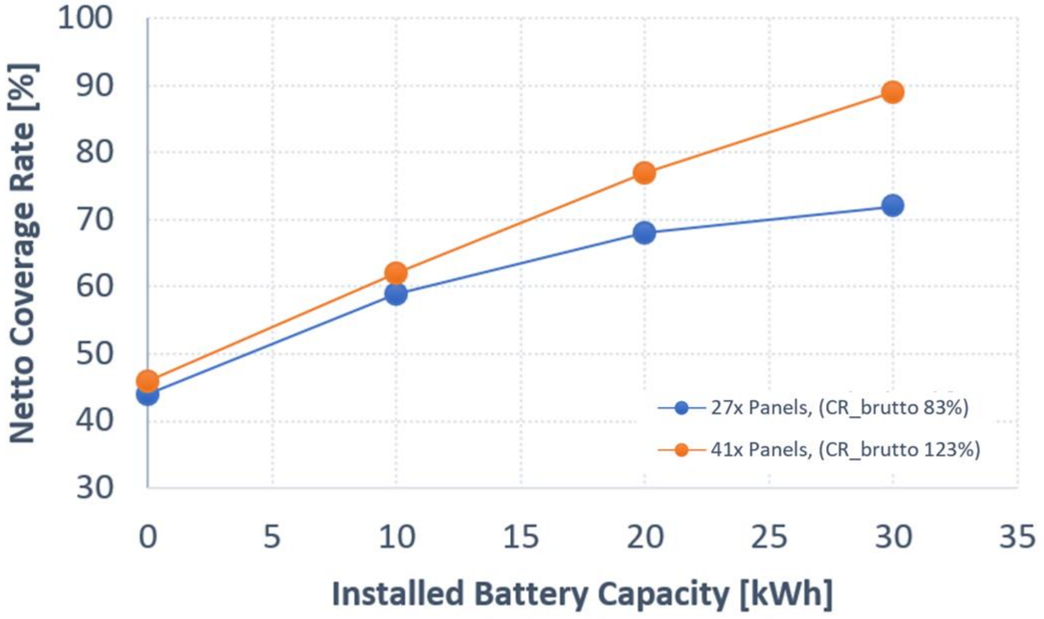

Figure 13: Net coverage of energy demand depending on installed battery capacity for two PV generator sizes simulated with solar insolation data of Cape Town.

5.3.3 Discussion

An extrapolation of the simulation calculations for Madrid and Cape Town show that in principle an operation of the SERPIC system in a standalone mode with solar energy supply is possible. A self-sufficient coverage of 100 % by solar energy will require additional, non-proportional, effort which cannot be recommended, while 85 to 90 % seem feasible. For the remaining 10 to 15 % the system must be operated with reduced capacity or shut down. For a real application of an industrial scale-up, which produces several thousand cubic meter of water per day, an economic balance between the investment into battery storage and PV generator, an oversizing of the SERPIC plant and a transient operation adapted synchronously to the PV energy supply with significant part-load periods must be compared with an economical viable feed-in and supply from the public grid to operate the system in annual gross with 100 % renewable energy. An additional option is to improve the potential of transient operation through batch operations of single sub processes. In that case components with high energy consumption could be operated intensively during periods of the day with high solar insolation and be switched off or throttled during lower energy supply periods.

In general, the operation of water treatment plants in future will rely on renewable energy supply on the one hand for sustainably reasons but also for economic reasons since renewable energies will become the cheapest option. **Figure 14** shows the cost comparison of different sources including the cost decreases between 2010 and 2022. It can be seen that solar photovoltaics has the strongest cost reduction in this period and is already below 0.2 USD/kWh. For most of the commissioned plants it is even far below 0.1 USD/kWh with an average of 0.049 USD/kWh, while onshore wind energy has average costs of about 0.033 USD/kWh.

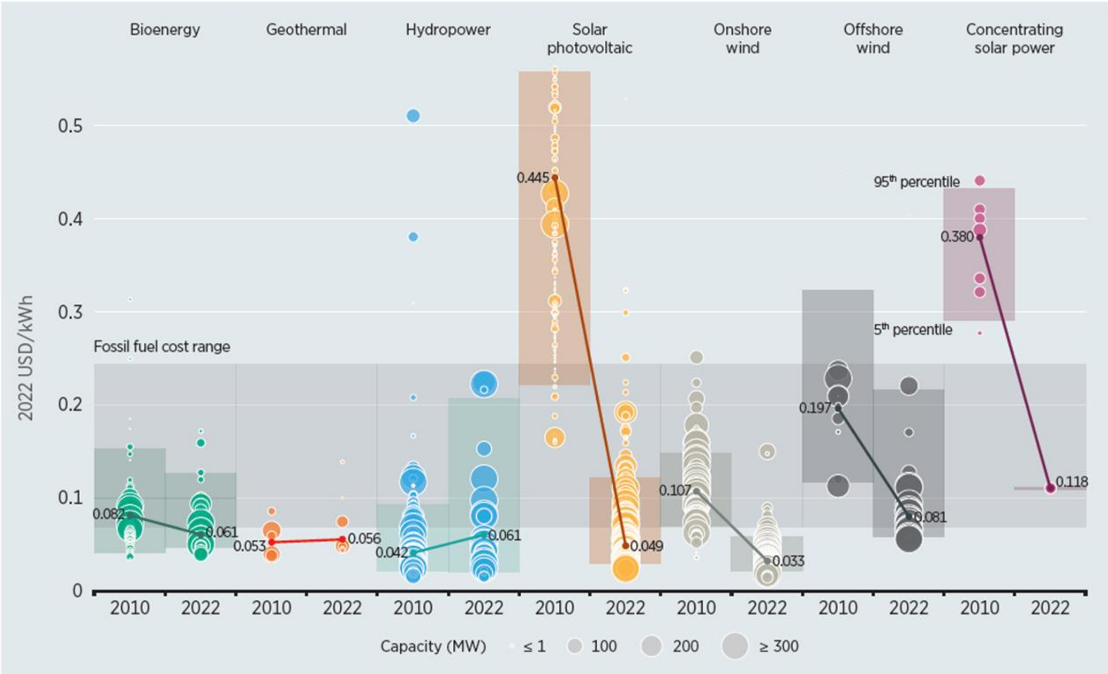

Figure 14: Global weighted average levelized cost of electricity (LCOE) from newly commissioned, utility-scale renewable power generation technologies, data for 2010 and 2022 (source IRENA).