Investigation of Inverter Reliability and Repair Strategy on the Availability of Photovoltaic Systems under Economic Aspects

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Abstract: The purpose of this paper is to investigate the influence of inverter reliability and maintenance strategy on the power availability and the economical operation of different photovoltaic (PV) system concepts. The widely used string concept and a concept based on module-integrated inverters were analyzed for different system sizes and shading scenarios. In order to represent the dynamic failure and repair behavior of the individual PV systems as realistically as possible, individual Petri net models were created. The models were used to determine the power availability of the PV systems during their operating time within a Monte Carlo simulation. The failure and repair behavior were varied as part of a parameter study. Subsequently, to evaluate the economic operation of the PV system, the profitability of the PV systems was calculated. For this purpose, all cost and remuneration rates were taken into account on the basis of the location Germany.

It is shown that the reliability of the inverter and the choice of maintenance strategy have a significant influence on the availability and thus profitability of the PV system, which was to be expected. However, with the help of the simulation, this influence could be quantified for the different application scenarios. From a certain degree of shading, module-integrated concepts perform better than the string concept. However, with no or slight shading, they do not achieve the same profitability of the string concept for a larger system. The optimal repair strategy, with which the profit becomes the greatest, is always individual and depends on the exact system design and the respective application scenario. In the case of module-integrated variants, it is always not worth repairing the system until several components have failed.

1. INTRODUCTION

The recent situation in Europe has shown that the discussion about a country's energy supply can no longer be conducted only in terms of sustainability and global warming. Security policy and energy strategy are also taking on an increasingly important role [1]. Fossil energy sources such as mineral oil and gas are not only limited and cause environmental damage, but also make countries that do not possess significant natural resources dependent on imports from third parties. The only way out is an independent energy supply based on renewable energies, without dependence on suppliers. Solar energy in particular can make a large contribution to this. It can be used almost everywhere in the world, the only requirement besides the sun is sufficient space for a PV system. The most reasonable solution is to use the space that already exists − such as the unused rooftops in urban areas.

For residential applications, there are several PV system designs to choose from, based on a string inverter or for example on several micro inverters in a module-integrated solution. To promote the expansion of these systems, they must be economical at the end of the operating lifetime. Therefore, high reliability and availability of the PV system is a key factor, especially to avoid expensive repair costs and to generate as much electricity as possible. The specific application scenario must also be taken into account, such as the solar radiation at the respective location, the compensation and cost rates, as well as the system size and individual shading cases.

The impact on PV system performance due to shading or individual component failures, can be very different for both concepts [2]. Most analyses of the energy output of different PV system concepts are limited to the investigation of different shading cases with full functionality and do not consider reliability aspects, such as the influence of individual component failures or different maintenance strategies. However, the reliability and lifetime of a PV system, as well as its repair strategy, has a significant impact on the profitability and sustainability [3, 4]. This is exactly the focus of this paper, which investigates the influence of reliability and repair strategy on the availability and thus on the profitability of grid-connected PV systems. For this purpose, the string and module inverter concepts are investigated for different shading scenarios and system sizes within the framework of a simulation based on Petri nets. Thereby, the focus is placed on the inverter, since it is the central element and the most complex part of the PV system.

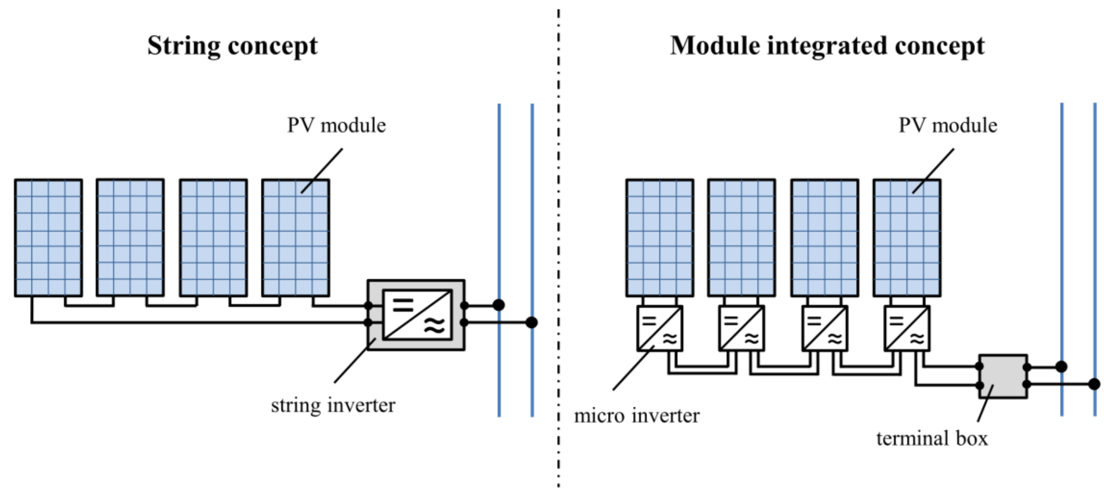
2. STATE OF THE ART − GRID-CONNECTED PV SYSTEMS

In this section, the structure and functionality of the string and module inverter concept of a grid-connected PV system is explained. The structure of a full-cell module and the effects of shading on the performance curves of the PV system are explained in more detail.

2.1. Structure and Functionality of String and Module Inverter Concept

In this paper, two different PV system concepts are investigated. Both concepts have PV modules, which convert the solar radiation of the sun into electrical direct current. The structure of the PV module is described in chapter 2.2. In the string concept (SC), all PV modules are connected in series and combined to form a string [5], see Fig. 1. A single inverter is connected to the string, which converts the direct current into alternating current and ensures the grid-connected energy feed-in. In the module integrated concept (MIC), a separate micro inverter is integrated into each PV module [5]. This inverter is smaller in power size than the string inverter, since it only must convert the power of a single PV module. Subsequently, each inverter feeds into the power grid separately or bundled via a terminal box.

Figure 1: Structure of the different PV system concepts

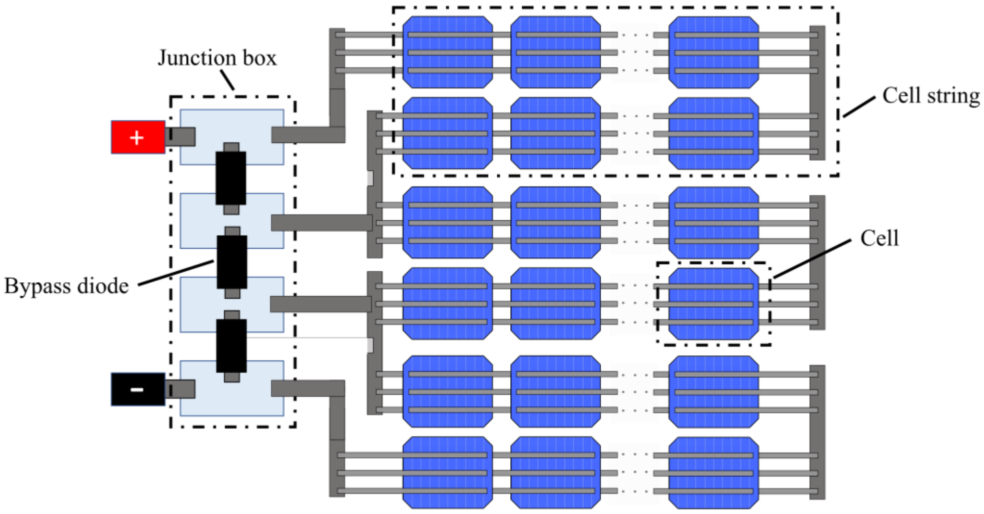


The main difference between the concepts is the number and the interconnection of the individual inverters. This leads to different advantages and disadvantages, which are not considered in detail here. In the context of this paper, it is important to note that the concepts react differently to shading scenarios and that the failure of individual components has different effects on the entire PV system depending on the concept [3, 5].

2.2. Structure of a PV Module

A PV module consists of single solar cells that are connected to each other. A solar cell consists of a p-n junction, which generates a voltage as soon as solar energy hits it. The phenomenon that generates electrical energy at a p-n junction is called photoelectric effect. More details can be found in [6]. In conventional full-cell modules, 60 to 72 solar cells are connected in series. The module is divided into three cell strings with 20 to 24 solar cells in each. A bypass diode (BD) is connected antiparallel to each cell string, see Fig. 2.

Figure 2: Structure of a full cell module

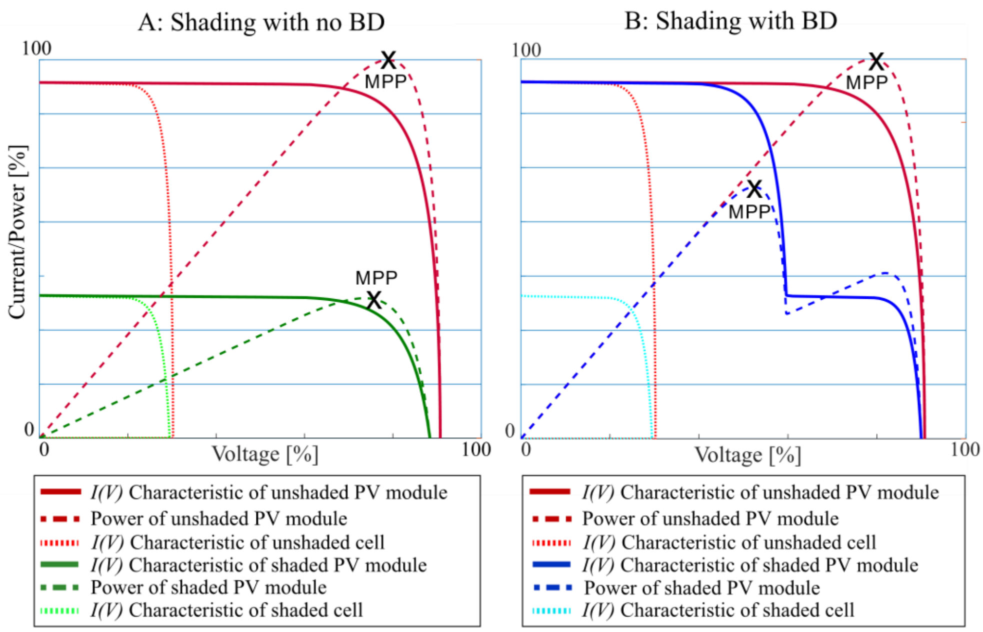


The bypass diodes are located in the junction box and are used to reduce power losses in case of shading and to avoid damage in the solar cells due to hot spots. How the bypass diodes affect the performance in case of shading is shown in the next section.

2.2. Characteristics of PV Systems and Control of the Operating Point

For each solar cell, the ratio between current (*I*) and voltage (*V*) results in a characteristic curve as shown in Fig. 3. To obtain a usable voltage for a PV module, several solar cells are connected in series. The *I(V)* characteristic of the PV module is obtained by summing the voltage values of the individual solar cells. The current remains almost constant. In the string concept, several PV modules are connected in series, which means that the voltages of the individual PV modules are also summed up, resulting in a higher power output in the characteristic curve of the PV system.

Figure 3: Characteristic curve of a PV cell and a PV system



The power output of the PV module or PV system results from the product of the current and voltage at the operating point. It is maximized when the area under the *I(V)* characteristic curve reaches a maximum. This operating point is called maximum power point (MPP) and is set automatically either for the entire string (SC) or for each individual PV module (MIC) by using the DC/DC converter of the inverter [5, 7]. This mainly happens when the characteristic curve of the PV module or system changes due to uneven power output of the individual cell strings. This can be caused by defects, different orientations of the PV modules or shading.

If a solar cell is shaded, the current drops, which changes its characteristic curve, see Fig. 3. If the shaded solar cell is still operated at a higher current, a negative voltage is produced, turning the solar cell into a consumer. For this reason, the characteristic curve of the entire PV module and, in the case of the string concept, of the entire string also decreases. The current is therefore largely determined by the shaded cell, see Fig. 3 A. The consequence is a drastic power reduction of the PV module or the overall PV system. To prevent this bypass diodes are used, which become conductive as soon as the voltage in the cell string becomes negative and exceeds the forward voltage. In this way, the bypass diode short-circuits and bypasses the cell string. This allows the current to be maintained in the rest of the PV module or in the entire string, see Fig. 3 B. In this way, shading only leads to a slight power reduction of the shaded cell string and not the whole PV module or PV system. At the same time, the bypass diodes also limit heat dissipation due to the negative voltage applied to the shaded cell, which prevents hot spots from occurring [8]. Both the control of the MPP and the effects of shading behave differently for the two concepts. In the string concept, these always affect the entire string of the PV system. Within the module integrated concept, only the individual PV modules are controlled and affected by shading.

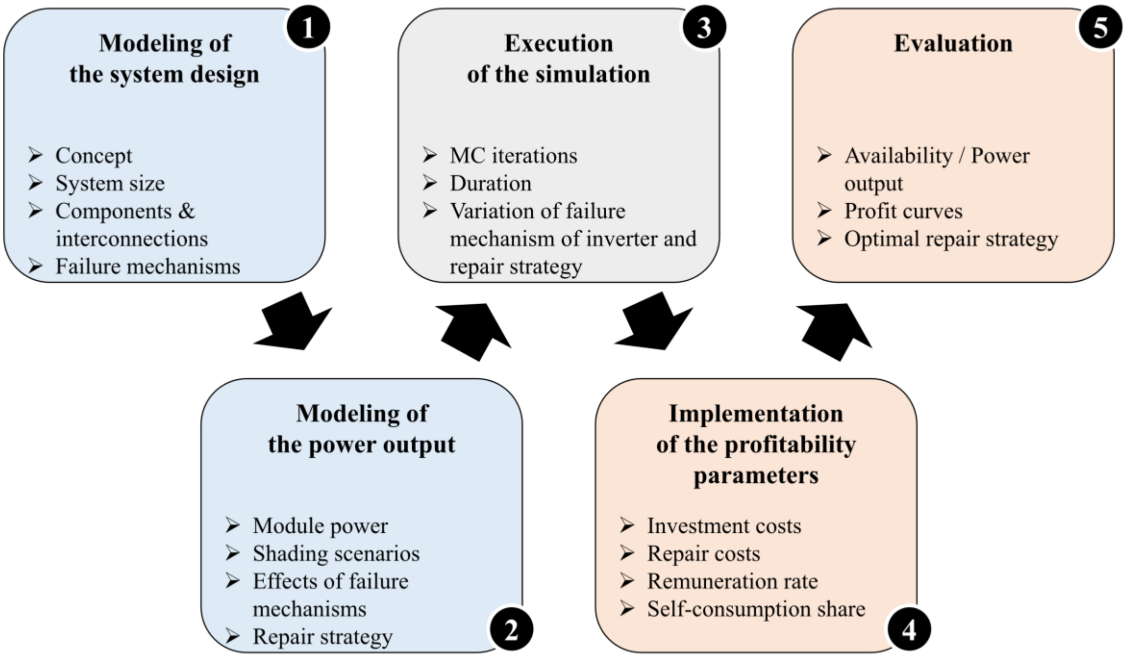
3. APPROACH

The profitability of a PV system is determined by its remuneration through energy feed-in and by the investment and repair costs. The remuneration is directly related to the available power produced. The available power is influenced by the reliability of the individual components and by the repair strategy of the PV system. The higher the component reliability of a PV system, the fewer failures occur. This leads to higher power availability and less repair costs. In addition, component failures can either be repaired immediately or after a certain number of components have failed. On the one hand, the repair process increases power output, but on the other hand, it also increases repair costs. There must be an optimum at which the repair strategy delivers the maximum possible profit. To address this issue, the dynamic failure and repair behavior of the different PV systems will be modeled using Petri nets [9]. The purpose is to investigate the influence of the reliability of the inverter as well as the impact of the repair strategy of the PV system on its power availability and thus on its profitability. Both the string and module integrated concept will be analyzed for different system sizes and shading cases.

The procedure consists of 5 steps and is shown in Fig. 4. First, the system design of the different PV system concepts is modeled using Petri nets (step 1). Then, the logic for the effects on the power output of the PV system is implemented (step 2). After that, the simulation is carried out (step 3). With the help of the defined profitability parameters (step 4), the profitability of the PV systems can be evaluated considering the respective application scenario (step 5). The individual steps are explained in more detail below.

The structure of the individual PV systems is modeled with the help of Petri nets. For this purpose, a separate Petri net model is created for each system concept and the system sizes of 3, 10 and 20 PV modules. Only the relevant components inverter and PV module are modeled, considering their electrical interconnection and reliability block diagrams. The inverter is modeled as a single component and the PV module as a conventional full-cell module consisting of cell strings and bypass diodes. For the bypass diodes, the two failure mechanisms open circuit and short circuit are also taken into account [10]. More details regarding the modeling of the PV system can be found in [11].

Figure 4: Procedure of the simulation based on Petri nets



2.1. Step 1: Modeling of the System Design

The reliabilities of the individual components or failure mechanisms can be described by a Weibull distribution [12]. Since the influence of the reliability of the inverter is to be worked out, only its Weibull distribution is varied within the simulation as a part of a parameter study. Under the conservative assumption that there is no failure-free time, the threshold parameter γ is set to 0. The analysis shall be limited to fatigue failures only. Therefore, a shape parameter β of 3 is used. The scale parameter η is varied between 22 years and 62 years, depending on the concept, to model different reliabilities of the inverter.

The Weibull parameters of the PV module failure mechanisms are constant and are not varied. In addition, bypass diodes predominantly fail only when shading is present [13]. Therefore, a failure of the bypass diodes within the simulation is only considered if the corresponding cell string is shaded.

2.2. Step 2: Modeling of the Power Output

In step 2, the logic for the effects on the power output is implemented. The available power of a PV module depends on its nominal power, the radiation intensity, and the efficiency of the rest of the electronics. The nominal power of a PV module is set to 400 Wp, and the efficiency of the electronics is set to 95 %. For the radiation intensity, the location Germany with an approximate average annual irradiation of 1000 kWh/kWp at perfect orientation is used [5]. The shading of a PV module has a negative influence on the power characteristics of one or more PV modules and thus on the power output of the PV system. To take this into account, the logic for a daily shading cycle has been implemented. This consists of a period of 8 hours where no shading and a period of 4 hours where shading occurs. Thereby 5 different shading scenarios were considered:

- Case 1: No shading
- Case 2: Shading of a cell string
- Case 3: Shading of two cell strings
- Case 4: Shading of an entire PV-Module
- Case 5: Shading of three entire PV-Modules

In addition, it is also important to note that, depending on the concept, a failure of one component has different effects on the performance of the entire PV system. An example of this is the bypass diode of a PV module, which can fail in a short circuit and in an open circuit. The first failure mode causes the PV system to directly lose the power of one cell string. In the string concept the second failure mode can lead to a power reduction of all PV modules in case of shading. In the module integrated concept, it leads to a power reduction of only one PV module. In addition, the failure of the string inverter leads to a total failure of the PV system, whereas the failure of one micro inverter only leads to a power loss of a single PV module. Due to this fact, the Petri net models become very complex.

If a failed component causes only a slight power loss of the PV system, it often does not make sense to repair the component immediately due to the high repair costs. Therefore, it is practical to wait until several components have failed and repair them all at once. To take this into account, a power limit is introduced. If the power of the PV system falls below this limit, the repair process is executed. The choice of the power limit basically describes the repair strategy and is varied during the simulation. Power reductions from R1 = 100 W to R9 = 4000 W are considered, see Table 1. The subsequent repair process corresponds to a normal distribution with a mean time of 3 days and a standard deviation of 1 day. It should be noted that the limit always refers to a power reduction caused by failures and not by shading.

Table 1: Overview of the variation of the power limits to start maintenance

power limit to start maintenance	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**
power reduction [W]	100	150	300	600	1000	1500	2000	3000	4000

2.3. Step 3: Execution of the Simulation

Since the time-related failure behavior of the individual components were defined with the Weibull distribution as a probability distribution function, different failure times result in each simulation run. Accordingly, the result of power availability and profitability is also "random" for each simulation run. For this reason, a Monte Carlo simulation is performed with 1500 replications. This number of replicates have been shown to still provide statistically sufficiently accurate results while keeping the time required for the simulation within reasonable limits.

The lifetime of a PV system is up to 20-25 years [14]. To exceed this lifetime, the simulation time was adjusted to 35 years. A simulation is always performed for each system design, i.e. each individual Petri net model. The string and module integrated concept, with a system size of 3, 10 and 20 modules, as well as the 5 different shading scenarios were modeled. Within the simulation, both the scale parameter of the Weibull distribution for the inverter(s) and the power limit at which a repair should be performed are varied within a parameter study. The output of the simulation is the power availability of the PV system and the number of repair operations as well as the number of components repaired in each simulation.

2.4. Step 4: Implementation of the Profitability Parameters

The profit of a PV system depends on the total costs incurred up to the end of the operating time and the remuneration. To determine the profitability of the PV system, the investment costs as well as the repair costs, consisting of material costs and a fixed rate for the mechanic, have to be considered. Often, a PV system only becomes profitable as soon as the generated energy is used by the customer [15]. For this reason, in addition to the feed-in compensation, the energy savings through self-consumption is also taken into account for the remuneration. Therefore, the specific feed-in compensation rates and electricity costs of the respective country must be included. The cost and compensation rates have been adjusted to the location of Germany. For the calculation of the electricity savings, a self-consumption share of 20 % was assumed.

2.5. Step 5: Evaluation

In step 5, the simulation results are evaluated. The power availability and the profitability of the PV system are defined as target values. By that, the influence of the reliability of the inverter and the maintenance strategy of the PV system on the availability and profitability can be determined. The different system designs are investigated for different system sizes and shading cases. In this way, the optimal repair strategy can be derived for each application scenario.

4. RESULTS

In this section, the results of the simulation are presented. The influences of the reliability of the inverter and the repair strategy of the PV system on the availability and profitability of the PV system are investigated. At the same time, the string concept and the module integrated concept are compared.

4.1. Power Availability of the PV System

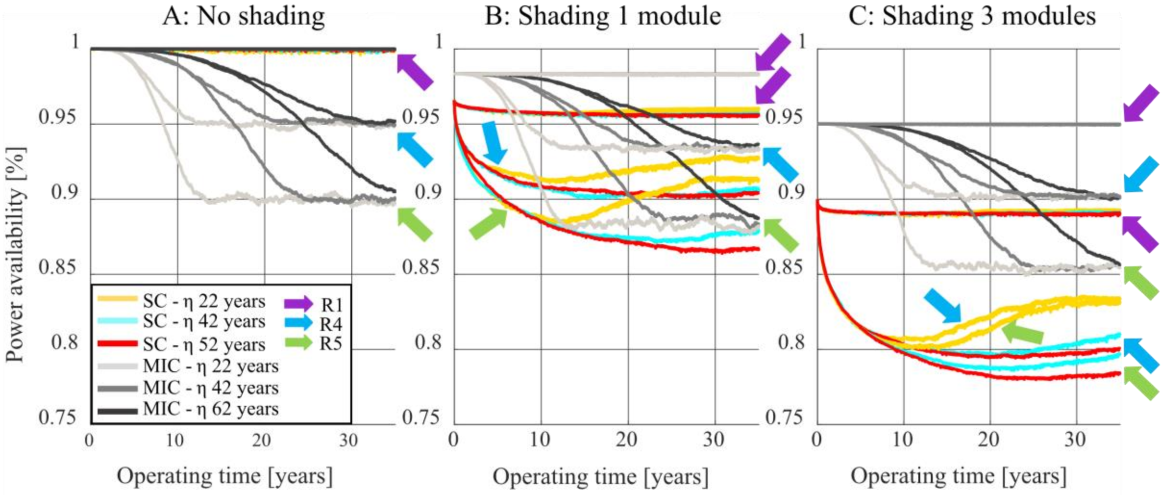
As the operating time increases, the individual components of the PV system eventually fail, depending on their lifetime. According to the failure, a power reduction is the result. That leads to the fact that the PV system must not only take on the two states completely failed or completely intact. For this reason, the target value power availability is defined, which results from the ratio of the currently available power to the maximum possible power. A power availability of 100 % thus corresponds to the nominal power of the PV system without shading and failures.

Fig. 5 shows the power availability over the operating time of the PV systems. The value was averaged over the 1500 replications of the simulation. For the different concepts, the shading case 1: no shading (see Fig. 5 A), shading case 4: shading of 1 PV module (see Fig. 5 B) and shading case 5: shading of 3 PV modules (see Fig. 5 C) were investigated for a system size of 10 PV modules. For a better overview, only the results of the repair strategies R1, R4 and R5 are shown.

In the case of no shading, the curves of the SC and MIC always start at 100 % at the begin of the operating time, since there are no failures yet and thus the nominal power is available. In the SC, a failure of the inverter always leads directly to a total failure of the PV system, which means that the repair process is always started immediately. The repair time of a few days is very short compared to the lifetime of the PV system, which causes the individual curves all to be close to a power availability of 100 %.

For the higher repair limits, the failed micro inverters at the MIC do not always have to be repaired immediately. Accordingly, the power availability initially drops and is therefore significantly lower than that of the SC. After a transient process, a limit value of the power availability is reached. The reason for this is that the power availability of the system is influenced by two dynamically opposing processes. The failure behavior leads to a reduction, while the repair behavior leads to an increase of the power availability. Thus, an oscillatory system is created in which the power availability has settled only after a certain operating time, when both processes are in equilibrium. The lower the repair limit is, the lower the limit value of the power availability is since repairs are carried out later. The lower the scale parameter of the Weibull distribution of the inverter and thus its reliability, the earlier the curve drops and the earlier the system has settled. Accordingly, a high reliability also leads to a higher power availability over the operating time.

Figure 5: Power availability of a PV-System with 10 modules under different shading scenarios



If shading is present, the power availability of both concepts no longer starts at 100 %, since the shading leads to a reduction in power, see Figure 5 B and C. The MIC is slightly more affected by shading than the SC due to its individual control of each PV module, which causes its power availability to start at a higher base level. In the MIC, it can be seen that the behavior of the curves for the shading cases remains identical except for the height of the power levels. Higher shading simply shifts the curves to lower power availabilities, due to the higher power reduction of the PV system.

Due to the shading, the bypass diodes in the PV modules can now also fail, which can be seen in the drop at the power availability of the SC. It is interesting to note here that the power availabilities with a inverter scale parameter of $\eta = 22$ years increase again significantly after about 12 years of operation. The reason for this is that from this point on there is an increased probability of failure of the inverter. If it has failed, the repair process is started immediately, whereby the bypass diodes that have already failed up to this time are also repaired. This leads to an increase in power availability. With a scale parameter of $\eta = 42$ years, this phenomenon only starts shortly before 30 years of operation due to the longer lifetime of the inverter. With a scale parameter of $\eta = 52$ years, on the other hand, no increase can be seen, since the inverter almost never fails within the considered operating time of 35 years.

While for the SC in case B the curves for a scale parameter of $\eta = 22$ years differ significantly with the variation of the maintenance strategy, they almost coincide in case C for the repair limits R4 and R5. Here, the reliability of the inverter is significantly responsible for the course of the curves. The reason for this is that due to the higher shading, the power reductions due to failures of the bypass diodes are lower overall. Accordingly, the repair limits R4 and R5 are reached here only after the failure of the inverter, which starts the repair process regardless of the repair strategy. The exact availability curve is therefore always very individual and depends on the specific interaction of the inverter reliability, the bypass diode reliability, the respective shading case, the system size and the used repair strategy.

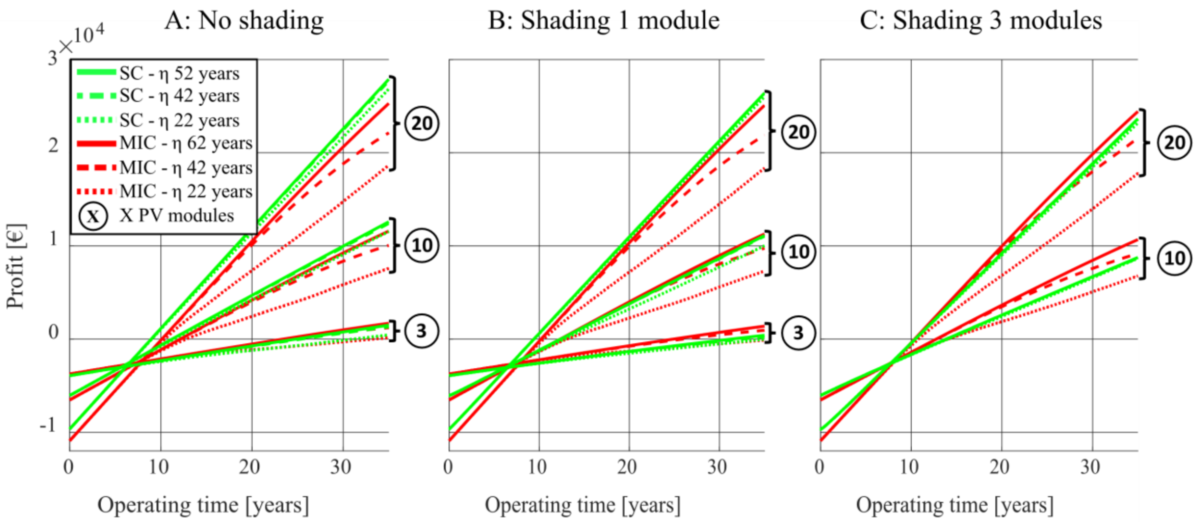
The failure behavior or the repair strategy influence the power availability and the number of repair operations of the PV system. A higher power availability automatically leads to a higher remuneration of the PV system. However, this is usually associated with increased repair costs, which has a negative impact on the profitability of a PV system. The MIC has higher power availability with greater shading compared to the SC, but is also more expensive to purchase. Thus, evaluating the PV system based only on the power availability curve is not meaningful. In order to make an accurate statement regarding the profitability of a PV system, the investment costs and all repair costs incurred during the operating lifetime must also be considered. For this reason, the following section examines the profitability of the PV system concepts for the different application scenarios.

4.2. Profitability of the PV System

The profit was calculated over the operating time for the different PV system concepts, considering all costs and compensation rates, as well as a self-consumption share of 20 %. For the profit curves, it should be noted that the results do not give a generally valid profit prediction for the respective PV system concept. Changes regarding the system design or the application scenario as well as the cost and remuneration rates lead to a change on the profit curve.

Fig. 6 shows the profit curves of the PV system concepts for the same shading scenarios as in the previous section. The different system sizes were investigated for varying scale parameters of the inverter. For comparison, only the curve of the optimal repair strategy is used for each set-up. This ensures that only the maximum possible profit is compared. For the smallest system size, shading scenario 5 (shading of 3 PV modules) was not investigated, since the entire PV system would be shaded. In reality, this would indicate a very poor system design, hence it was not considered in this study.

Figure 6: Profitability of the PV-System for different shading scenarios



The profit curves all start at a negative value due to the investment costs. The larger the system, the higher the initial investment costs and the lower the curves start. It should be noted here that the SC is cheaper than the MIC for the respective system size. In general, it can be observed that a larger PV system with its higher number of PV modules leads to a steeper increase in the profit curves. This increase exceeds the additional costs due to the higher initial costs after about 12 years, making larger PV systems more profitable after a longer operating period.

The higher the reliability of the inverter, the higher the profit curves due to fewer failures. For the SC, the influence of reliability is not that significant, since only a single string inverter is used in the system. Due to the high reliability values, there is often no failure during the operation time. For MIC, reliability becomes more important with system size. This is also quite reasonable, as the number of module inverters used automatically increases, and with it the probability of a failure.

It should be noted that the power size of the string inverter is significantly higher than that of the module inverter and therefore higher reliability is much easier to achieve for the smaller micro inverters. For a comparison of the different concepts, thus, the curves of the higher reliability values of the module inverter should rather be considered.

If there is no shading, the MIC cannot compete with the SC due to the higher initial costs. Shading reduces the power output of the individual PV system concepts, causing their profit curves to drop. However, the impact of shading affects the SC more than the MIC, where each individual PV module can be set at its own optimal operating point. The larger the PV system, the smaller the influence, since proportionally a smaller part of the PV system is shaded. It can be seen that with increasing shading, the profit curves of the MIC are higher than those of the SC. This is especially evident for small systems with a large amount of shading.

4.3. Influence of the Maintenance Strategy

As already described, the profitability of the PV system depends on the maintenance strategy. For this reason, all evaluations were always carried out with the different power limits to start maintenance, see Table 1. The optimal repair strategy results from the curve that gives the highest profit after 25 years of operation. These curves are shown in Figure 6. An overview of the corresponding optimal repair limits is shown in Table 2. As already mentioned, the shading case 5 was not investigated for the smallest system size.

Table 2: Overview of the optimal power limits to start maintenance

	Module integrated concept				String concept			
System size	η	**Shading case 1**	**Shading case 4**	**Shading case 5**	η	**Shading case 1**	**Shading case 4**	**Shading case 5**
1.2 kWp / 3 PV modules	22	R4	R3	-	22	R1	R3	-
	42	R5	R5	-	42	R1	R3	-
	62	R5	R4	-	52	R1	R3	-
4 kWp / 10 PV modules	22	R6	R6	R5	22	R1	R1	R4
	42	R9	R7	R7	42	R1	R3	R5
	62	R9	R7	R8	52	R1	R3	R4
8 kWp / 20 PV modules	22	R7	R7	R6	22	R1	R3	R5
	42	R9	R9	R8	42	R1	R3	R4
	62	R7	R9	R8	52	R1	R3	R5

The optimal repair limits vary greatly for the MIC and are between R3 = 300 W and R9 = 4000 W. Above a repair limit of 600 W, at least one module inverter has also always failed. As a tendency, it can be said that it is worthwhile not always to repair immediately and rather to wait until more components of the PV system have failed. However, the exact optimal repair limit always depends on the individual system design and the application scenario as well as the reliability of the components. Therefore, the system size, the individual shading scenario and also the exact compensation and cost rates must always be considered.

With the string concept, on the other hand, the repair process is always started immediately after an inverter failure. Since no bypass diodes could fail in shading case 1, repairs must always be carried out immediately at R1. The only differences therefore arise in the repair of the bypass diodes for shading cases 4 and 5. Here it is worth waiting until several bypass diodes have failed. Again, the exact value depends on the individual system design and the application scenario as well as the reliability of the components.

5. CONCLUSION AND NEXT STEPS

In this paper, simulation models for different PV system concepts were developed based on Petri nets. With these, a realistic modeling of the PV systems was possible, considering dynamic processes such as failure and repair behavior. In this way, the PV systems could be analyzed in terms of their power availability and profitability within the framework of a Monte Carlo simulation. The string concept and the module integrated concept were investigated for different system sizes and shading scenarios. The aim was to investigate the influence of the inverter reliability and the maintenance strategy of the PV system on its availability and profitability. With this approach, a much more realistic analysis of the PV system is possible.

It has been shown that the reliability of the inverter and the choice of maintenance strategy have a significant impact on the availability and thus the profitability of the PV system. However, the exact results are always highly dependent on the individual system design and application scenario. In general, the larger the PV system, the greater the impact of inverter reliability of the MIC. With increasing system size, the number of micro inverters used also increases automatically and thus also the influence of reliability. With greater shading, the module-integrated concepts perform better than the string concepts. However, if the shading is slight, the SC achieves a higher profitability, especially with a larger system size.

It has been shown that in the case of MIC, the PV system should not be repaired immediately after the failure of a single module inverter. Rather, it should be waited until several components have failed, which can then all be repaired together. However, the optimal repair strategy is always individual and depends on the exact system design and the respective application scenario.

For the further step, more failure mechanisms or also aging effects of the PV module could be implemented. In addition, the focus could be set more on the analysis of the reliability of the PV module to determine its influences on the power availability and profitability. Furthermore, the application scenario of PV systems is very diverse due to the countless influencing factors. For the selection of a suitable system concept and design, different influences such as shading, radiation intensity, cost and compensation rates, self-consumption as well as the maximal possible system size and budget must be taken into account. By extending the simulation models and implementing additional input parameters such as further shading cases or location specific influencing variables, the optimal system design could be identified for any application scenario. In addition to that a profitability prediction could be given. Beyond that, a worst-case scenario analysis can be used to derive reliability targets for individual components of the PV system to achieve a certain level of profitability. More details about this procedure can be found here [11].

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