How the future is shaped with PV and energy storages for small scale construction- economic, environmental, social and technical aspects.

Authors: Ellen Blanksvärd, Hanna Larsson and Omar Marwan Rafiq Zabian

Supervisors: Maria Abrahamsson, Bo Albinsson and Björn Sandén

Course: TRA105- Solar energy

Group: Number 5

Date: 2021-02-28

Table of content

Picture on front page: Image of solar panels, Solar panels IMG_9694 (Englart, 2014)

1. Introduction

The demand for energy is constantly increasing in the world, especially for more, renewable electricity. The aim for this study is to try answering how the future will be shaped by as photovoltaic cells (PV) and energy storage for small scale constructions that is disconnected to the grid. It will be evaluated by from technical, economic, social, and environmental aspects. Firstly, the current situation will be presented. Secondly, a discussion will be carried out to summarise and weigh the factors against each other to find a most likely outcome. The discussion is enriched by opinions from the Swedish company Nilsson Energy that was collected from a mail conversation from said company.

Small scale construction is defined in this work as a smaller building that can either be a household residence or a utility building and, that the power generated is sufficient for the users' purposes. Estimating the future on a long timescale can be difficult, the time scale that will evaluated is around ten years. This report is part of the project within the tracks course Solar Energy given by Chalmers University of Technology 21/22. The project has mostly been gathering information and make this literature review to try answering how the future is likely to be shaped by PV.

1.1 Background on the problem

Fossil fuel base production systems are not the optimum solution to generate electricity as they are not renewable. Eventually the electricity prices will increase due to scarcity of fossil fuel resources in the future, if no other reliable resources have been provided. In addition, it has several negative environmental impacts such as climate change and pollution of air and water. However, the world still relies significantly on the fossil fuel as the main source to support the way of living and the prosperity of the economy. Even in Europe, in developed countries, it was reported that "54% of the European Union's energy originated from fossil-fuel imports from non-EU countries in 2015" (Duffy et al., 2019). Which bring us to find solutions to solve this issue in a sustainable approach that are cheaper, renewable, secure, and uninterrupted. A promising one is solar energy. The main issue with solar energy that it is intermittent source of energy, which require a complementary strategy (energy storage) which can help to giving a stable source of energy whenever and however it is required.

1.2 Why Solar Energy with energy storages

Solar energy systems such as photovoltaic cells (PV) and thermal panels are suitable renewable energy systems to be installed for small scale applications especially in residential buildings, with energy storages they can achieve a cutting on the operating cost and become independent and environmentally friendly. In addition, solar energy has a positive impact on the environment (a clean source of energy), there are no greenhouse gas emissions released into the atmosphere when converting the solar energy into electricity or heat using PV and thermal panels, respectively. It can secure a limitless resource for clean energy and help moving to clean energy production, and unlike fossil fuels it will not run out.

Energy storages can give the flexibility for PV and makes it more convenient to be concerned as the main source for the electricity. The main challenge with solar energy that it is not available during the night hours which make it not able to stand alone to compete against the grid electricity. However, combining the PV system with energy storages for small scale constructions can give the independency from the grid electricity, making it a independent system to provide electricity. Nevertheless, the cost of the system and the payback period plays a significant role as will be discussed in the economic section part.

2. Technical evaluation

In the following section the technical aspects of components needed for an off-grid solution are presented, e.g. different types PV and storage energy systems.

2.1 Types of PV

During the past decades there has been an immense increase of different types of solar PV which is shown by Figure 1 below. The chart is based on the best performing cells tested in labs. The colors indicate what family of semi-conductor each technology could be categorized in (NREL, 2021a). All the technologies shown in the chart can be categorized into five families of semiconductors, these are going to be further presented below.

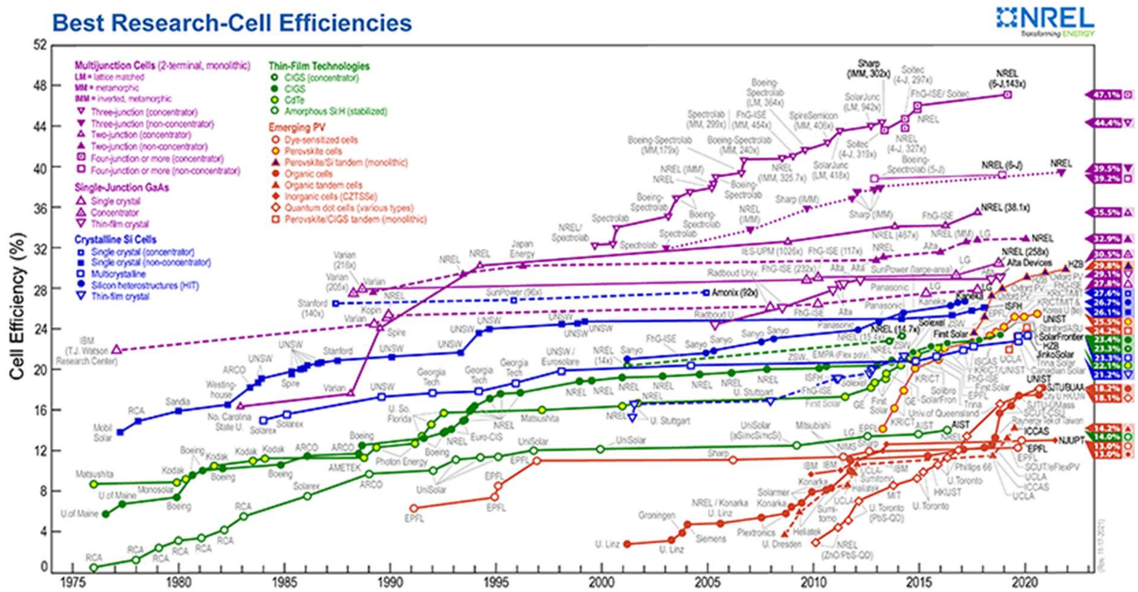

Figure 1 Presents how the cell efficiency for different type of solar cells has changed over the years. An increase of efficiency for most types can be seen. This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO (NREL, 2021a)

2.1.1 Multi-junction cells

As shown the Figure 1 the best performing cells are the multijunction cells. These are the most expensive cells for production. However, the technology can be combined with concentrated solar PV which increases the efficiency. Efficiencies up to 46% has been measured in laboratories for a four-junction solar cell. By using a 6-junction solar cell, efficiencies such as 47.1% has been achieved which is currently the highest performing cell tested in laboratory (2021b). Because of the high cost of producing the multi junction cells this technology is limited for space applications. The reason why such semiconductor can reach higher efficiencies is because it contains various materials that can absorb radiation at different wavelengths at the electromagnetic spectrum compared to a single junction cell (NREL, 2021b). The hydrogen can moreover be stored and used for production of fossil free steel as well as for fuel within car industry.

2.1.2 Single-junction cells

The highest reaching efficiency for single junction cells is the concentrator technology with an efficiency of 30.5% (NREL, 2021a). The reason for the lower efficiencies is the lower ability to absorb radiation at wavelengths on a shorter span on the electromagnetic spectrum compared to the multi-junction cell. Among the single-junction cells are the organic photovoltaic (OPV) cells. They are beneficial in the sense that the material is extremely lightweight and flexible.

2.1.3 Crystalline Silicon cells

Some of the dominating cells on the market are the crystalline Si cells. Among the crystalline cells are mono-crystalline cells and poly-crystalline cells. The crystalline Si cells are semiconductors that are used for photovoltaics but is also used in electronic to some extent (*Crystalline silicon*, 2021). In order to use the silicon for photovoltaics needs it to be purified. This is done through a process called the siemens process. Usually, this process is applied to polycrystalline materials which requires an impurity level of less than one part per billion (*Polycrystalline silicon*, 2021). These types of solar cells are called the first-generation solar cells and are the ones commonly seen on rooftops and private small scale production units. They are also used for larger scale production and is currently dominating the market.

2.1.4 Thin film technologies

Another type of solar PV is the thin film photovoltaics. This type of technology can be characterized by its flexibility and low costs. Another benefit of this technology is that it could be placed on surfaces or windows which creates new architectural areas of use. The thickness of the cell varies between 10 - 200 µm (*Thin-film solar cell*, 2021). The low usage of material per m2 enables the material to reach lower costs than average crystalline Si cells. Other areas of use could be for vehicle charging, and semi-transparent cells to place at windows etc. Today this technology has reached a maximum efficiency at a level of 21% and the efficiency continues to increase as it is continuously developing (*Thin-film solar cell*, 2021).

2.1.5 Emerging PV

Passivated emitter and rear cell (PERC) - The first PERC cell was produced in 1989 and was at the time the most efficient solar cell at the market. The technology was an improved version of the existing solar cells present at the time. They contained an increased reflective rear surface area, as well as reduced metal/semiconductor contact area (Green, 2015). This was an improvement of the previous technologies accomplishing an efficiency at a level of 18.4%.

2.2 Energy storage

The amount of energy harvest from solar is fluctuating over time, resulting that the energy needs to be stored for usage when the sun radiation is insufficient. Since solar PV is producing energy at a limited time during the day there will be an uneven distribution of electricity which will create system instabilities (Henni et al., 2021). Today there are different options on how to store energy, but every storage option equals a loss of energy. Storage solutions are also enabling a different kind of infrastructure where civilization becomes less dependent on the grid distribution (Sandén, 2021). This enables housing to become more self-sufficient. Energy storage can be long or short term, depending on the need (Puranen et al., 2021). A few of the techniques used for energy storage systems (ESS) will be more deeply investigated within this report.

2.2.1 Batteries

One of the first solutions for energy storage that comes to mind is batteries. Even if the development of new solar technologies is increasing rapidly, as discussed above, the coevolution of battery storage capacity is still lacking behind. This is one of the greatest bottlenecks for continuous development of solar PV (Sandén, 2021). Batteries offers e.g., robust operating conditions, little maintenance (Chaurasia et al., 2022), high performance and flexibility (Marocco et al., 2022). The batteries for PV system are constantly charged and discharges, which poses high demand on them. Types of batteries that is commonly used for energy storage for PV are lead acid (Pd-acid) batteries, Nickel-Cadminum batteries or Lithium-ion (Li-ion) batteries to name a few. The Pd-acid batteries can either be flooded cell type, where the electrodes are surrounded with electrolyte, or sealed/gel type where the electrolyte immobilized. The flooded type was in 2013 the most used battery type for renewable energy storage (RES). The Li-ion batteries have a higher energy density than Pd-acid (Ponnusamy, 2013). The Li-ion is now winning ground and becoming more and more used. It was the most used storage for deployed energy storage system in 2015 (Ould Amrouche et al., 2016).

What size of batteries needed can depend on several factors, the load, how long the energy is stored, temperature effects, depth of discharge and so on. To obtain a favourable system scaling the batteries is of high importance. It is beneficial to convert the direct current (DC) electricity that is gained from the PV to an alternating current (AC) that can be stored in batteries. This will lower the capacity needed, increase the efficiency of the system and decrease the cost of the battery (Mohanty P. et al., 2016).

A problem with batteries as storage is their relative short lifetime, that is around 250-1000 cycles depending on type (Ponnusamy, 2013). By coupling batteries with a supercapacitor module (SCM) that can take care of the peak current, the battery lifetime will be considerably increased. A Hybrid Energy Storage System (HEES) could be beneficial due to decreased current demand and dynamic stress of the battery, giving a performance stability. This type of system has been shown to work for the rural areas or from small industries (Hassan et al., 2022). Another way to increase the lifetime of the batteries is adding a battery-management system on the renewable energy system (Mohanty P. et al., 2016).

2.2.2 Hydrogen storage

Another storage solution is the production of hydrogen. By using high efficiency solar PV, water can be split into hydrogen and oxygen. Hydrogen is likely to some extent replace fossil fuels by gradually phasing out fossil fuel-based combustion engines. Since the product from the reaction is water, hydrogen is not contributing to global warming thus its product does not have a long residence time in the atmosphere. Another benefit of hydrogen is its ability it to balance the grid. By producing hydrogen where distribution of electricity is high, system losses of energy is reduced (Lundblad & Fast, 2021). Hydrogen has the highest energy density out of all materials and is therefore of biggest interest to use as energy storage. Hydrogen can be used as seasonal energy storage (Puranen et al., 2021), especially good in those areas where the climate and therefore also the solar radiation changes a lot over a year. By having both hydrogen storage and batteries together can the levelized cost of energy (LCOF) be 35% lower than the same system with only batteries thus hydrogen is cost-effective for long-term storage (Marocco et al., 2022).

For energy storage with hydrogen is an electrolyzer (EL), a H_2 storage and a fuel cell (FC) needed. The electrolyzer converts the electricity to chemical energy in form of hydrogen gas that is then stored under high pressure until later use. The energy can then be accessed from a fuel cell (Marocco et al., 2022).

2.2.3 Thermal storage

Thermal energy storage (TES) is another storage solution. Generally, a medium is either heated or cooled and then kept in that state until the energy should be utilised. The material can undergo a temperature increase or decrease, a phase transition or a chemical reaction occurs. TES can be divided into three main types, sensible heat storage (SHS), latent heat storage (LHS) and thermo-chemical storage (TCS). For SHS is mostly water used as a bulk material that is heated and stored, but polymers, concrete or cement can also be used. The energy density is low compared to the other TES methods, but the low cost gives it an advantage. One of the main challenges is keeping the elevated temperature for a long time. In LHS the energy density is increased (Ould Amrouche et al., 2016). Phase change materials (PCM) are used, like paraffin wax, salt hydrates or fatty acids, where the phase of the material is changed and kept in a thermodynamic unfavourable state that will release energy when the material undergoes another phase transition. There is solid-solid, solid-liquid, solid-gas and liquid-gas PCM (Rahman et al., 2019). This technology can be applied to buildings and constructions and it is possible to cool buildings during day-time because of the PCM´s "buffering" capacity of storing heat (Bianchi, 2021). In TCS is heat or cold released by a reversible reaction like e.g., adhesion at a surface.

Thermal storage cannot only be coupled with a turbine and give electricity, it can also be used to for heating or cooling buildings. Heat stands for about 50% of the energy need for both buildings and in industries.

2.3 Grid integration vs small grids/off grid

There are two types of PV systems, the stand-alone system and the grid feeding system. One often wants to extract the most energy from the PV plant, which is when the system is working on the maximum power point, MPP. For a stand-alone system without storage does this mean that the load should always be the same as the gained electricity from the panels. Naturally, this is hard to always achieve, so the system operates most often off-MPP. Whereas stand-alone system with storage and grid feeding system mostly work at MPP, either by charging a battery of providing the grid with energy (Panigrahi et al., 2020).

2.3.1 Integrated system

There are many standards regulating the transition from the PV panels to the grid, from power quality recommendations, safety measures, communications between the grid and the PV. These can be international or national, some of the international ones are called, IEEE 1547-"IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems" and ICE 61727- "Photovoltaic (PV) Systems—Characteristics of the Utility Interface" (Panigrahi et al., 2020).

As more renewable energies are available, a shift in the market can be seen where energy consumers also provide electricity as producers and become- prosumers. It is assumed that this will play a vital part in the change towards a more sustainable future (Gržanić et al., 2022).

2.3.2 Stand-alone system

As previously mentioned, a problem for the use of solar energy is the periodicity with periods with high energy production, and those with low. Therefore, to know how much and what type of storage is needed, being able to predict the energy production can be very important. For example, by making a weather forecast or an hourly prediction of the solar radiation. There has been efforts made to use machine learning to achieve this to create smart-grids but there is still a long way to go until this can be implemented (Rangel-Martinez et al., 2021). This is both valid for the small-scale system and for the whole grid, where energy storage can play a valuable part in both systems.

There are also suggestions to utilise mini-grids or nano-grids where a few constructions, families, or a neighbourhood share energy system with storage instead for all have their own. This can be beneficial from an economical point of view simultaneously as its more resource effective (Henni et al., 2021).

3. Social impacts and aspects

One of the sustainable developing goals that the world's leaders have agreed on is "*Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all*". The access to electricity has increased from 83% in 2010 to 90% in 2018, nevertheless still 579 million people in 2019 was without access to electricity (UN, 2021). In Rwanda for example is the national electrification rate only 54.5%

(Hagumimana et al., 2021). According to the International Energy Agency (IEA) are PV development and off-grid or mini-grid solutions an important part of rural electrification. Mini-grid solutions is believed to stand for 60% to achieve the sustainable developing goal (Richard et al., 2019). The demand of electricity will accordingly increase in the future and mostly in Africa and Asia with high solar irradiation conditions. Thus, PV is likely to play a big part of the electrification (Kristiansen et al., 2021). PV is one of the most used off-grid techniques in electrification of rural areas (Bandara et al., 2012).

For a PV system to be installed must in many cases an active decision be made. In a review article by Peñaloza et. al. where social acceptance of PV was investigated was it shown that economy, dissemination of information and sociodemographic were of concern. What effect the factors have seems to depend deeply on what area were investigated, e.g. in Asian countries was financial aspects classified as highly influential for implementation while in European is rather been seen as a hindrance (Peñaloza et al., 2022).

A big advantage for PV systems is that is can be used in isolated areas, that today don't have access to the grid. In many cases is firewood or kerosene used as energy source in these cases. An implementation of PV systems instead would therefore not only give electricity, but it can also reduce the emitted CO_2, the risk for burning injuries, health problems originating from the smoke and increase equality among the people. The living conditions are improved, therefore can other social issues also get a positive effect such as increase in democracy and mental health (Miravet-Sánchez et al., 2022).

4. Economical evaluation

The economic aspects are of biggest importance when an energy system is evaluated. Many different factors require consideration to make a well thought decision e.g., investment costs, the fluctuation in the electricity market, political and society attitude, and payback time to name a few. The price of electricity is not constant, the demand of electricity changes over the hours in a day, over a year and from place to place (Ferahtia et al., 2022). The cost of solar energy can be divided into e.g., installation, production of apparatus, maintenance, grid integration or storage system.

Companies can nowadays gain high financial returns on their green investments. The old norm that decisions which are good from an environmental standpoint always must be bad from an economical perspective is no longer true. An effect of the Kyoto protocol is a change in environmental policies, leading a way for taxes and regulations to force companies to pay for their pollution. With this type of policy instrument, an economical driving force for development is injected, increasing the demand of inexpensive, green energy (Abdallah et al., 2013). However, in an analysis of a survey of European stakeholders, one of the underlined barriers for market acceptance of PV panels are the economic aspects. Foremost the investment cost was identified as a hindrance for all countries (Peñaloza et al., 2022).

Projects relating solar energy received in 2018 26% of the total $14 billion international financing flows to developing countries for clean and renewable energies (UN, 2021). In 2020 was it reported that the electricity from solar power had the same cost as electricity from the grid in many places on earth. This is an effect on the great improvement of the solar photovoltaics that is driven by a decreasing cost. Under 2018 was it found by the International Renewable Energy Agency (IRENA) that the cost dropped with 18%. Moreover, the cost for crystalline silicon dropped with 26%-32% under 2018, compared with the preciously year when it was reduced with 1%-7%. This is a big driving force thus the silicon is needed as semiconductors in the PV (Palmer, 2020).

The energy cost for renewable energy systems has decreased and is believed to continue decreasing. The price for PV energy systems have decreased rapidly giving it a strong market present and is now a feasible solution as energy system for both residential and commercial usage (Hassan et al., 2022).

4.1 Installation and production

The price for PV modules has dropped as the demand of them has increased, for each doubling in cumulative production, the price is decreased by 20% (Abdallah et al., 2013). In Sweden has the total installed PV capacity increased from below 100 MW in 2014 to over 700 MW in 2019. The typical price of a standard module in Sweden year 2014 was 70 SEK/W_p and in 2019 the price had decreased to 4.1 SEK/W_p. The cost for the end consumer is strongly dependent on the international module market which is in constant change due to different political approaches, the demand and the efficiency of the panels (Mountain & Harris, 2017).

The price for PV systems has also decreased in Sweden, the strongest decline between 2010-2013 whereafter the price has stabilized. In 2019 was the price of small centralized PV that was grid-connected and ground-mounted 7.5 SEK/W_p, while the price for residential, grid-connected, roof-mounted and distributed PV system was 14.29 SEK/W_p (Lindahl et al., 2020). A similar cost development can be seen in US over the years 2010-2020 where the cost is steadily declining, both for residential PV systems (22 panel system) and for commercial rooftops (200 kW). Factors that could be estimated to be the driving forces for the cost decrease are higher module efficiency, from an average value of 19.2% in 2019 to 19.5% in 2020, and decrease in cost of supply chain and hardware. The cost from install labour has also declined from 2016 to 2020 (Feldman et al., 2021).

In the report by Lindahl *et al.* is it stated that a trend with decreasing created labour places per installed MW can be seen in Sweden even though an increase in installations has occurred under the same period. This could be explained by the fact that the companies are growing and that the installation process is getting more effective (Lindahl et al., 2020).

4.2 Grid integration

A grid integration implicates that one can use electricity from the grid when it is not produced from one´s PV panels, and the electricity can be sold when more is produced than is consumed. The main focus for this report is off-grid solutions but it is important to know what other solutions are available. The regulations on how the grid integration works differs from place to place. The type of PV system, the size and the power production can also affect eventual fees. As an example, the electric company eon (one commonly used in Sweden) will integrate ones PV system on the grid without any charge if the plant effect is maximum 43,5 kW and the fuse is maximum 63 A. The abundant electricity can be sold, either directly to eon or to some other company, for 1.72 öre/kWh in the North of Sweden and 2.92 öre/kWh in the South according to the contract that can be found on the webpage of eon. The prices was decided in 2019 and has not changed since then (Energidistribution, 2021).

For a grid integration to be economically viable, for industrial users, the generation cost should be around 80% of the electricity prices of 2017 according to Abdallah *et. al.*. From their conclusions is it stated that from an economical point, solar rooftop PV systems could have potential to be integrated into the supply chain (Abdallah et al., 2013).

4.3 Maintenance

When promoting solar panels is one of the selling arguments the low maintenance needed. However, in experiments done over a six-month period in South Sumatra for PV panels at an area close to an open-pit coal mining. It was it seen that the panels that was washed had 1.57 % higher efficiency compared to those covered in dust (Nurjanah et al., 2021). As mentioned below, in the model presented by Abdallah *et al*. can the maintenance cost be estimated to 1 % of the total investment cost (Abdallah et al., 2013).

4.4 Economical models

To make an economical evaluation of a PV system, the cost per kWh is a good measurement. In the work of Abdallah *et al.* a net present value (NPV) analysis was used to gain a value of this type. In the analysis five factors were taken into consideration; the up-front investment that was estimated to be in the interval of $5.8/kW for a small-scale PV system of 10-100 kW. This price also was estimated to decrease 5-7 % per year. Moreover, the cash outflow due to repayment of the loan and the payment of interest, the compensation for putting electricity to the grid where the total output was calculated, and an annual degradation rate of the panels is estimated to 0.5 % is included. A cash inflow from depreciation tax shield, and lastly, the cost for operation and maintenance per year that was assumed to be 1 % of the up-front investment. The cost per kWh was calculated for the US states and an average was found to be around $0.4/kWh (Abdallah et al., 2013).

Other models suggested for an economical evaluation of a PV system as a part of a strategy decision making is presented by Magni *et al.* in their paper "*Impact of financing and payout policy on the economic profitability of solar photovoltaic plants".* Wherein it is stated that the financial variables have a significant impact on the created value *(Magni et al., 2022)*.

Further ways to evaluate an investment is the payback time. This is a "return on investment" (ROI) method, that calculate the payback period- the time it takes until the profits equals with the initial investment cost. The equation is simple, original investment divided with the cash flow per year. This will give how many years the payback period is (Gallo, 2016). The price of panels, the predicted electricity production and electricity price are factors that will influence the payback time. In a study of solar power plants in Sarajevo would an estimated payback period be 10 years and that the lifetime of the panels is 30 years. After twenty years would the calmative net income be equal the initial investment- meaning that one would gain double the money in twenty years (Tuco et al., 2022).

4.5 The potential in Sweden

The Sweden energy agency, *Energimyndigheten*, has made a techno economical cost assessment of solar cells in Sweden. In the final report the land is divided into smaller areas where the potential electric production is the same, which varies on where in Sweden thus radiation is about 750 kW/m^2 in northwest and 1100 kW/m^2 in southeast.

The potential for roof based and ground based solar panels were investigated. For the solar cells on roofs the energy potential is affected by the direction of the building, angle of the roof and shadowing. Factors that are considered for the price and potential for ground based solar cells is the cost and use of the land it is placed on. Moreover, wind and ground based solar parks can be co-located and thereby have access to the grid at the same place, reducing the cost of power lines, this could have a potential of producing 2 GW. Other areas where co-localization has been considered are airports and landfills.

The area available in Sweden, on roof tops or on the ground will not change over time significantly (Blomqvist & Unger, 2018), nevertheless the efficiency is constantly increasing (NREL, 2021a), the panels will most likely undergo degradation, the investment cost will decrease as the technique gets more available (Blomqvist & Unger, 2018). These effects will change the price over time.

4.6 Energy storage

The cost for energy storage can vary quite much. Storing energy thermally is often less expensive than electronically, however the energy cannot be exported to the grid if stored thermally. PCM has a long pay-off time so the installation has to have a long lifetime for the investment to be beneficial. The cost for SHS was in 2016 in the interval 0.1-10 €/kWh, while for PCM 10-50 €/kWh and for TCS 8-100 €/kWh (Rahman et al., 2019).

When energy storage is used can peak loads and fluctuation be better handled which will give a longer lifetime of the system. One can also store electricity and sell it when the price is higher during the day and evening time and buy back electricity during the night to charge e.g. the batteries. This set up can be affordable, but a lot of effort is needed to make a system like this work.

5. Environment evaluation

Today, perhaps more than ever are sustainable solutions necessary. One of the main reasons behind a change in the energy market is the need for renewable energy sources. The environmental impact of e.g., PV modules and different ESS will further discussed below.

5.1 Environmental impact of PV

One good thing about PV that a high percentage of the materials used can be recycled (around 90%) (Tawalbeh et al., 2021) after the end of its life. However, if it was not a cost effect then it will be disposed. To be able to recycle then we need policies to push for it and the technology to advance to make it economically beneficial.

Even solar power generation is not ideal, it have positive and negative effects on the environment. Some of the main advantages can be summed up. Firstly, it helps in minimizing the carbon footprint from the greenhouse gases and especially the carbon dioxide emission due to less consumption of fossil fuels. Solar panels generate electricity without emitting any of greenhouse gases in similar to traditional energy sources. Secondly, it helps to improve the human health due to the reduction of SO_2 and NO_x (Hosenuzzaman et al., 2015). Thirdly, it helps in minimizing the thermal pollution, as several energy production plants through the manufacturing process require to pump water from water sources, where the water is heated in the process and then discharge it back into the water source. And lastly, PV system have a low noise and visual impact compare with other energy technologies, except during the process of installation of the system (Tawalbeh et al., 2021).

From the other side, it has drawbacks such as the mining of different raw materials such as Quartz as an example to manufacture the solar panels. Where the negative impact of mining varied materials is eventually part of the negative impact of solar panels itself. Secondly, environmental impact from the processing of the raw materials, such as quartz again as an example; processing quartz into silicon requires a lot of energy. Thirdly, the risk of leaking of hazardous chemicals might be an issue upon improper disposal of the solar panels. (Tawalbeh et al., 2021)

The environmental impact of solar PV energy generation is significantly lower than that of traditional power sources. However, the manufacturing process of PV cells and modules can still have a negative impact on air quality and global climate and thus it need further strategies to mitigate the environmental impact. Moreover, recycling of the materials is challenging process however it is essential to further reduce the environmental impact. Up to 50% lower GHG emissions can be achieved using new materials and/or recycled silicon material (Tawalbeh et al., 2021).

5.2 Environmental impact of energy storage

A successful and efficient electricity grid is built on the ability to efficiently match the supply and demand of electricity. It is also important to consider the various technologies that can help improve the grid's stability. Use of energy storages can support the future grid to be less dependent of non-renewable fossil fuel as an energy resource as it plays a significant role in damaging the environment.

Energy storages can store the excess energy generated from PV and use it for later hours when needed and therefore reduce the dependence on the fossil fuels.

But neither energy storages are ideal, it have negative environmental impact which need to be further reduced. Different energy storages have different environmental impacts, several will be addressed in this report. Firstly, batteries have impacts on the soil, the water, air pollution which could result in health issues. They may contain many harmful pollutants such as mercury, battery acid, lead, copper, and synthetic adhesives. Reducing this impact require a good method for reusing, recycling, and disposing old batteries especially that the production is still ramping up. In addition, if it was not properly disposed, then the chemicals will not be treated and then it will just pollute the earth around. Moreover, extraction of materials such as Lithium can harms the soil and causes air contamination. And not to forget to mention that if batteries end up in the ground, then it might cause heart disease for human and other creatures on earth, as it contains harmful substances which poison the soil and then it might go to rivers and lakes where it can vaporize and being release into the air. Furthermore, the environmental impact of batteries can be reduced by maintaining an efficient operation and performance as reported in Georgious et al., taking into consideration the safety measures, this is called the battery management system which is 6 functions that control and examine the battery performance (monitoring, protection, charging & discharging, communication, diagnosis, and data management) (Georgious et al., 2021).

Secondly, chemical energy storages such as the hydrogen energy storage if combined with renewable energy source such as PV, then it can be considered as having a low environmental impact. Thirdly, thermal energy storages have low environmental impact (Georgious et al., 2021), which makes it an ideal system to be combined with the PV system to maintain the low environmental impact for small-scale constructions like residential buildings.

5.3 Environmental assessment between a large-scale solar energy plant and a small-scale installation

According to the work of Nassereddine *et al.* (2016), several environmental impact assessments has been considered to compare between the solar power plant and the small-scale installation, starting from the land use where solar power plant requires a large land area (hundreds of hectares) to install the panels, in addition to all the required connection cables, thus the small-scale installation can be existed on the roofs of the different owned constructions.

Secondly, solar power plant requires transmission substations which contain oils and SF6 gas, where this is not applicable for small scale applications. Thirdly, transmission lines, the solar power plant have a major environmental impact comparing to the small-scale installation due to the required clearance for the transmission lines which disturb the ground and the vegetations, in addition to the visual pollution that is associated with it (Nassereddine et al., 2016).

5.4 A case study done in Turkey: small scale Solar PV-battery Vs the electricity grid

The figure below shows a result of a life cycle assessment study done in 2018 for environmental impact for solar PV-battery system in Turkey comparing with the grid electricity. The impact from the PV-battery system is much less than the impact of connecting to the electricity grid in all measures, this is in relation to the global warming, acidification, eutrophication, ozone depletion and photochemical oxidant and human toxicity. This is also combined with the benefit of helping the electricity balance between the supply and demand and reducing the burden and dependency of the electricity grid. In conclusion, the study shows that the PV-battery would have 1.6 to 82.6 times lower impacts than the Turkish electricity grid which contain a large mix of fossil fuels in its electricity mix (Üçtuğ & Azapagic, 2018). And when it comes to energy payback the PV-battery in turkey had given between 4.7 and 8 times more energy than it consumes over its life cycle (Üçtuğ & Azapagic, 2018) which indicate that it has much better use of resources and therefore better for the environment.

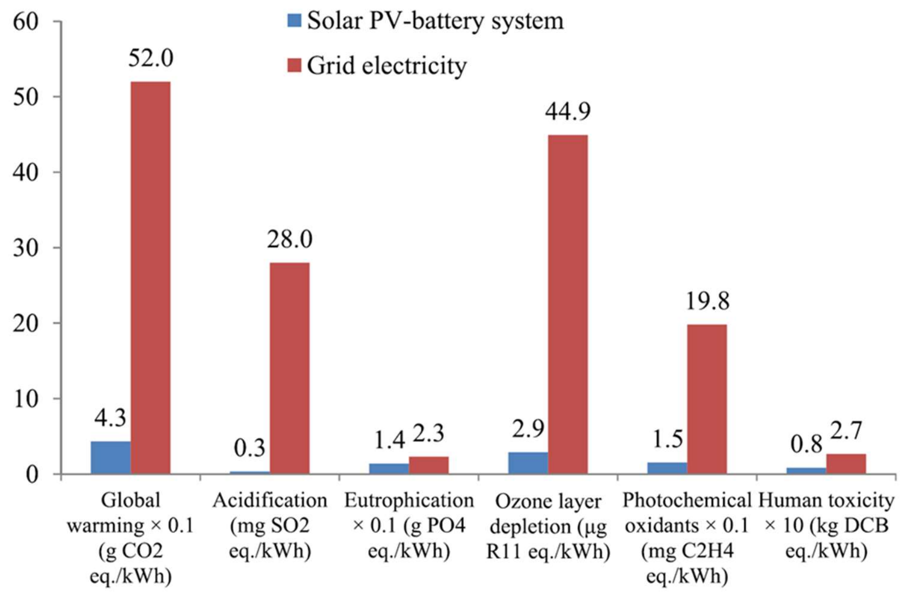

Figure 2 Life Cycle assessment comparison between the PV-battery system and the electricity grid in Turkey, the chart is taken from the paper *"Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries. Science of The Total Environment"* by Üçtuğ et al. (Üçtuğ & Azapagic, 2018)

Several factors come into consideration when we want to talk about the environmental impact and the differences between which system is better (small scale/ individual installation of PV system with energy storage or to install it in a national level). These factors are such as what kind of the electricity mix, how much of fossil fuel are in this mix, another factor is the insolation level and other climatic differences. Large amount of the environmental impact for installing a small-scale PV with energy storage comes from manufacturing of the system components especially the solar photovoltaic panels and the use of raw materials in manufacturing. In addition, human toxicity could be highly impacted with the use of batteries as an energy storage. Moreover, silicon as one of many other raw materials extracted such as polyvinyl fluoride film and solar glass have large environmental impact, as these three materials alone count of 45% of GWP environmental impact (Üçtuğ & Azapagic, 2018).

Reducing the environmental impact count into several factors such as the incentivise made on the feed-in-tariffs on solar PV, however this incentivise on solar PV is not enough, to make further reduction on the impact on the environment, incentivise for the consumer to buy energy storages are essential and need to be worked toward that target. Several policies need to be revised in order to incentive of the energy storages. The Figure 2 above clearly shows that integrating a small-scale PV-energy storage will further reduce the environmental impact over the electricity grid scenario, and this is a strong reason to push the policy makers to consider a change in the energy policies to support the PV with energy storages as a combined system.

6. Contribution to the Sustainable Development Goals

PV with energy storage system for small-scall construction can have a direct and indirect contribution to all Sustainable Development Goals, SDG. The below is a reasoning about how the system can contribute for some of the SDG goals.

Direct Contribution

Firstly, SDG 7: Affordable and clean energy. On the United Nation Development programs' website is it reported that "one out of 7 people living in rural areas with a lack of electricity. Energy contributes to 60% of greenhouse gases. And over 40% of the world population depends on non-renewable unhealthy polluted fuels for cooking" (UNDP, 2021b).

The system has a direct support to the goal target to have an affordable, reliable, and accessible energy source for everyone, especially in rural areas where the system can work even independently, generating electricity locally for even direct use or to store it for later without the need to be connected to the main electricity grid.

Secondly, SDG 13: Climate Change. As reported in (UNDP, 2021c), "the emitted CO2 globally should be dropped by 45% by 2030 comparing to 2010, and even reach a net zero by 2050 in order to limit the global warming to reach 1.5 °C. And the sea level have increased by +20 cm since 1880, with expectations to further increase to reach from +30 to 122 cm by 2100" (UNDP, 2021c).

As the system is reliable, it has direct impact on supporting the shift from the traditional carbon base energy resources such as fossil fuel which plays a major impact on the climate change and global warming, and replacing it with clean, carbon free renewable energy source. The sun is unlimited source of clean energy and with the ability of storing it, it becomes reliable.

Indirect contribution

Firstly, SDG 4: Quality Education. "57 million primary-aged children remain out of school, mostly living in sub-Saharan Africa"(UNDP, 2021a).

There might be a lack in providing schools and quality education in rural areas and in developing countries. However, being able to provide those areas with stable electricity source from the sun can support the equality of education system by allowing the student to be able to continue their education from home and stay connected with the latest update in the education system.

Secondly, SDG 8: Decent work and economic Growth. An estimate of 172 million people worldwide without work 2018, 700 million workers lived in extreme or moderate poverty in 2018 (UNPD, 2021).

Electricity is essential to be able to connect with the world through internet, sustainable and reliable source of electricity are essential to give an equal opportunity for people who live in rural areas to start a new source of income through internet and enhance their economic status and ensure a decent work, neglecting the geographical boarders.

7. Discussion

The future is unpredictable, to say something with certainty can be difficult. Within this report different factors been accounted for to make an as good prediction as possible of how the future can be shaped by PV and energy storage for small scale constructions. It is possible that some of the aspects considered will have a large impact while some may not. It is also a possibility that some eminent factors are not even known to this day. However, an evaluation where the different considerations presented will be weight against each other to find the most possible outcomes.

It is clear that the prerequisites are different around the world. Different socioeconomic states, political forces, irradiation, level of urbanization and access to resources to name a few. Therefore, different factors will have different impacts on how the future will be shaped. In areas close to the equator the irradiation is less fluctuant around the year so less long-time storage is needed. For areas closer to the poles where the length of the days and the climate changes over the year however, long-time storage is required. If there is a well-functional grid a connection to the grid a PV system without energy storage is possible and can be beneficial from an economical and resource point of view. Thus, one doesn't need to pay for a storage system and not all households need its own e.g., batteries. However, for isolated areas or where the grid is not available can off-grid solutions be advantageous.

A non-connected PV system without any energy storage is problematic, energy will then only be available when the sun shines and a lot of fluctuation in current will be the result. This is mostly true for off-grid systems, however for those that are connected to the grid will these fluctuations instead be a more centralized problem but still a problem. Moreover, the lifetime of the system and the usability will be significantly decreased. Some type of energy storage can therefore be utilised and the most versatile is some type of battery. From an economical point of view is the lead acid preferable thus the cost of it is less, however its lifetime and capacity are lower than the lithium-ion battery. The production of Li-ion batteries is increasing leading to that the cost of it can be predicted to be reduced in the future. From an environmental point of view is the Li-ion battery also favourable. However, thermal storage has generally both a lower environmental impact than batteries and cost giving it an advantage. But there are some problems with regenerate electricity when thermal storage is used. In some techno-economical evaluation as is a combination of batteries and hydrogen storage proposed.

Energy storage systems are one way of preventing instabilities due to the fluctuation in incoming radiation during a day and a year. However, many of the current technologies are not profitable relative to single household consumption. Suggestions of shared storage systems between households has been made in order to increase the profitability of energy storage (Henni et al., 2021). Using a shared storage system, each household reduces their cost required to implement the storage system. Thus, they can reduce the overall costs. The benefits that these decentralized systems hold, is the reduced susceptibility to operational disruptions. By reducing the cost for battery storage, more off grid households will be possible to implement in the future. Mini grids and shared storage systems might also be possible solutions in the future, and possibly more beneficial because of the reduced costs. However, in countries that today already has a grid that is constructed for centralized energy supply will this most likely not be a probable solution.

Nilsson Energy is a Swedish based company that specializes in renewable energy solutions, led by Hans-Olof Nilsson. In an interview with Nilsson Energy, they stated that installation of hydrogen storage is currently too expensive. However, they recommended hydrogen storage to be installed for a combination of 20 households in order to be a profitable investment. Compared to batteries, Nilsson Energy believes that hydrogen has a larger potential to cover for seasonal variations of energy supply. Today knowledge of this technology from authorities is low which makes it currently difficult to predict any future improvements of cost. The price of hardware will be reduced as the technology establishes at the market. However, the price of powering the electrolyser is still a bottleneck for the continuous development of hydrogen storage since there are many levels of energy losses in converting the solar energy to stored energy. Moreover, this process faces even greater losses by converting the stored energy to electricity. This makes hydrogen, so far, an inefficient option. Other concerns that have been raised regards the safety measures of managing hydrogen because of its explosive characteristics. Since hydrogen has been managed for more than 100 years for industrial use, Nilsson Energy claims that the safety standards are well established.

Discussing the future of off grid solutions Nilsson Energy believes that decentralized energy production in combination with storage solutions will be of significance to future energy supply. Off-grid solutions do not contribute to any additional load on the grid that will, in turn, decrease fluctuations that are difficult to manage. An increase of solar installations will put a larger load on the grid during a limited time of the day. Off grid solutions are easily manageable since they are 100% automatic and don't require much maintenance. If there will be a large increase in off-grid solutions or not is most likely dependent on the areal conditions and the political decisions. However, we believe that the implication of small grid installations could have the potential to enable a new type of urban development. The societal structure is based on the benefit of availability of goods and services and other infrastructural necessities. Off-grid solutions might enable societies to develop into less dense urban areas because it makes households less dependent of the current infrastructure.

It can be observed that the use of solar PV as source of energy have environmental advantages overcomes its disadvantages especially if it compared with the traditional energy sources (such as fossil fuel). The same can be taken into consideration about the use of energy storages as a combined and support system for more efficient use of the solar PV system. When it comes to the environmental impact, different energy storages do have different impact of the environment, the use of batteries might be a convenient solution when it comes to its efficiency and the energy density to store the energy for later use in the electricity form, however from the other hand it has a higher environmental impact comparing with other types of energy storages such as the chemical type (Hydrogen storage as an example) and the thermal energy storages. And the question is that would it be more feasible in the future to use the hydrogen storage for the small-scale construction noting that it has a low environmental impact comparing to its requirement of having a large capacity to store the desired energy, and would the use of thermal energy storages be more efficient to store the energy for later use in electricity form noting that it is an ideal system to combine with PV system for small-scale construction to ensure achieving the lowest environmental impact. And by looking at the big picture comparing the use of solar PV with energy storage in a large-scale centralized system with the use of solar PV with energy storage in small-scale decentralized system, it can be said that the consideration of decentralized small-scale system has lower environmental impact, the same has been confirmed with the case study done in Turkey previously mentioned.

In our opinion, using the solar PV with batteries as a system still and will have advantages over the use of other energy storages in the upcoming future unless there was an environmental policy driven or a breakthrough technology event occur to the other types of the storing system which will put them in the lead and into consideration for the small-scale construction.

8. Conclusions

Off-grid solutions with PV is most likely to be a significant part in the electrification of the world. Presumably, the biggest impact and influence of off-grid solutions will be in rural areas in developing countries. The development of new PV that are more efficient, have longer lifetime and to a lower price is likely to continue. The same stands for energy storage systems. Probably resulting in an increase of importance for the techniques in the future.

What energy storage that is beneficial depends on the conditions in that area and what needs are present in the small-scale construction. As an example, in Sweden a hydrogen storage can be plausible if the cost is reduced thus a long-time storage is needed for the cold winter. Thermal storage is reasonable to use if this is only utilized as heating and not electrical energy. Moreover, batteries would be the main solution for short-time storage. In warmer climates, batteries can be used on their own.

In the future is Li-batteries predicted to be the main battery type used. This based on the reducing price, longer lifetime and less negative environmental impact. The future will most likely be shaped by PV with ESS, to what extent and exactly how is difficult to predict. They are part of the society and the development of it. As shown within this project, the future of PV for small constructions is influenced of technical progress, cost, political decisions for environmental regulations, grid development, taxes etc... However, looking at the price reduction for both PV and ESS it is likely to increase in extent both in rural areas and cities all around the world.

Final words

A great thanks is given to our supervisors in the course TRA105- Solar Energy, and for the help and helpful information given by Nilsson Energy.

9. Reference

Abdallah, T., Diabat, A., & Rigter, J. (2013). Investigating the option of installing small scale PVs on facility rooftops in a green supply chain. *International Journal of Production Economics*, *146*(2), 465-477. https://doi.org/https://doi.org/10.1016/j.ijpe.2013.03.016

Bandara, K., Sweet, T., & Ekanayake, J. (2012). Photovoltaic applications for off-grid electrification using novel multi-level inverter technology with energy storage. *Renewable Energy*, *37*(1), 82-88. https://doi.org/https://doi.org/10.1016/j.renene.2011.05.036

Bianchi, M. (2021). *Thermal Energy Storage*. NREL. https://www.nrel.gov/buildings/storage.html

Blomqvist, P., & Unger, T. (2018). *Teknisk-ekonomisk kostnadsbedömning av solceller i Sverige*. https://www.energimyndigheten.se/globalassets/fornybart/solenergi/ovriga-rapporter/teknisk-ekonomisk-kostnadsbedomning-av-solceller-i-sverige.pdf

Chaurasia, R., Gairola, S., & Pal, Y. (2022). Technical, economic feasibility and sensitivity analysis of solar photovoltaic/battery energy storage off-grid integrated renewable energy system. *Energy Storage*, *4*. https://doi.org/10.1002/est2.283

Crystalline silicon. (2021). https://en.wikipedia.org/wiki/Crystalline_silicon

Duffy, P., Fitzpatrick, C., Conway, T., & Lynch, R. P. (2019). Energy Sources and Supply Grids – The Growing Need for Storage. In *Energy Storage Options and Their Environmental Impact* (pp. 1-41). The Royal Society of Chemistry. https://doi.org/10.1039/9781788015530-00001

Energidistribution, E. O. (2021). *Anslut solceller till elnätet*. https://www.eon.se/solceller/varfor-solceller/elnat

Englart, J. (2014). Solar panels In S. p. IMG_9694 (Ed.). flicker.

Feldman, D., Ramasamy, V., Fu, R., Ramdas, A., Desai, J., & Margolis, R. (2021). *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2020* (Golden Issue. https://www.nrel.gov/docs/fy21osti/77324.pdf

Ferahtia, S., Rezk, H., Abdelkareem, M. A., & Olabi, A. G. (2022). Optimal techno-economic energy management strategy for building's microgrids based bald eagle search optimization algorithm. *Applied Energy*, *306*, 118069. https://doi.org/https://doi.org/10.1016/j.apenergy.2021.118069

Gallo, A. (2016). A Refresher on Payback Method. https://hbr.org/2016/04/a-refresher-on-payback-method

Georgious, R., Refaat, R., Garcia, J., & Daoud, A. A. (2021). Review on Energy Storage Systems in Microgrids. *Electronics*, *10*(17). https://doi.org/10.3390/electronics10172134

Green, M. A. (2015). The Passivated Emitter and Rear Cell (PERC): From conception to mass production. *Solar Energy Materials and Solar Cells*, *143*, 190-197. https://doi.org/https://doi.org/10.1016/j.solmat.2015.06.055

Gržanić, M., Capuder, T., Zhang, N., & Huang, W. (2022). Prosumers as active market participants: A systematic review of evolution of opportunities, models and challenges. *Renewable and Sustainable Energy Reviews*, *154*, 111859. https://doi.org/https://doi.org/10.1016/j.rser.2021.111859

Hagumimana, N., Zheng, J., Asemota, G. N. O., Niyonteze, J. D. D., Nsengiyumva, W., Nduwamungu, A., & Bimenyimana, S. (2021). Concentrated Solar Power and Photovoltaic Systems: A New Approach to Boost Sustainable Energy for All (Se4all) in Rwanda. *International Journal of Photoenergy*, *2021*, 5515513. https://doi.org/10.1155/2021/5515513

Hassan, Q., Jaszczur, M., Abdulateef, A. M., Abdulateef, J., Hasan, A., & Mohamad, A. (2022). An analysis of photovoltaic/supercapacitor energy system for improving self-consumption and self-sufficiency. *Energy Reports*, *8*, 680-695. https://doi.org/https://doi.org/10.1016/j.egyr.2021.12.021

Henni, S., Staudt, P., & Weinhardt, C. (2021). A sharing economy for residential communities with PV-coupled battery storage: Benefits, pricing and participant matching. *Applied Energy*, *301*, 117351. https://doi.org/https://doi.org/10.1016/j.apenergy.2021.117351

Hosenuzzaman, M., Rahim, N. A., Selvaraj, J., Hasanuzzaman, M., Malek, A. B. M. A., & Nahar, A. (2015). Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. *Renewable and Sustainable Energy Reviews*, *41*, 284-297. https://doi.org/https://doi.org/10.1016/j.rser.2014.08.046

Kristiansen, A. B., Zhao, B. Y., Ma, T., & Wang, R. Z. (2021). The viability of solar photovoltaic powered off-grid Zero Energy Buildings based on a container home. *Journal of Cleaner Production*, *286*, 125312. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.125312

Lindahl, J., Dahlberg Rosell, M., & Oller Westerberg, A. (2020). *National Survey Report of PV Power Applications in Sweden, 2019*.

Lundblad, A., & Fast, L. (2021). *Hydrogen and fuel cell technology for green energy systems and electrification of vehicles*. https://www.ri.se/en/what-we-do/expertises/hydrogen-and-fuel-cell-technology

Magni, C. A., Marchioni, A., & Baschieri, D. (2022). Impact of financing and payout policy on the economic profitability of solar photovoltaic plants. *International Journal of Production Economics*, *244*, 108338. https://doi.org/https://doi.org/10.1016/j.ijpe.2021.108338

Marocco, P., Ferrero, D., Lanzini, A., & Santarelli, M. (2022). The role of hydrogen in the optimal design of off-grid hybrid renewable energy systems. *Journal of Energy Storage*, *46*, 103893. https://doi.org/https://doi.org/10.1016/j.est.2021.103893

Miravet-Sánchez, B. L., García-Rivero, A. E., Yuli-Posadas, R. A., Inostroza-Ruiz, L. A., Fernández-Guzmán, V., Chávez-Juanito, Y. A., Rutti-Marin, J. M., & Apesteguia-Infantes, J. A. (2022). Solar photovoltaic technology in isolated rural communities in Latin America and the Caribbean. *Energy Reports*, *8*, 1238-1248. https://doi.org/https://doi.org/10.1016/j.egyr.2021.12.052

Mohanty P., Sharma K.R., Gujar M., Kolhe M., & A.N., A. (2016). PV System Design for Off-Grid Applications. In M. T. Mohanty P., Kolhe M. (Ed.), *Solar Photovoltaic System Applications*. Springer, Chsm. https://doi.org/https://doi.org/10.1007/978-3-319-14663-8_3

Mountain, B., & Harris, R. (2017). Chapter 5 - Grid Versus Distributed Solar: What Does Australia's Experience Say About the Competitiveness of Distributed Energy? In F. P. Sioshansi (Ed.), *Innovation and Disruption at the Grid's Edge* (pp. 83-99). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-811758-3.00005-X

Nassereddine, M., Hellany, A., Nagrial, M., Rizk, J., & Micu, D. D. (2016, 6-9 Sept. 2016). Utilities investments into residential properties: PV solar system with energy storage. 2016 51st International Universities Power Engineering Conference (UPEC),

NREL. (2021a). *Best Research-Cell Efficiency Chart*. https://www.nrel.gov/pv/cell-efficiency.html

NREL. (2021b). *High-Concentration III-V Single-Junction and Multijunction Solar Cells*. https://www.nrel.gov/pv/high-efficiency-iii-v-solar-cells.html

Nurjanah, S., Dewi, T., & Rusdianasari. (2021, 14-15 Sept. 2021). Dusting and Soiling Effect on PV Panel Performance: Case Study Open-pit Mining in South Sumatra, Indonesia. 2021 International Conference on Electrical and Information Technology (IEIT),

Ould Amrouche, S., Rekioua, D., Rekioua, T., & Bacha, S. (2016). Overview of energy storage in renewable energy systems. *International Journal of Hydrogen Energy*, *41*(45), 20914-20927. https://doi.org/https://doi.org/10.1016/j.ijhydene.2016.06.243

Palmer, J. (2020). Solar Reaches for Grid Parity. *Engineering*, *6*(2), 105-106. https://doi.org/https://doi.org/10.1016/j.eng.2019.12.001

Panigrahi, R., Mishra, S. K., Srivastava, S. C., Srivastava, A. K., & Schulz, N. N. (2020). Grid Integration of Small-Scale Photovoltaic Systems in Secondary Distribution Network—A Review. *IEEE Transactions on Industry Applications*, *56*(3), 3178-3195. https://doi.org/10.1109/TIA.2020.2979789

Peñaloza, D., Mata, É., Fransson, N., Fridén, H., Samperio, Á., Quijano, A., & Cuneo, A. (2022). Social and market acceptance of photovoltaic panels and heat pumps in Europe: A literature review and survey. *Renewable and Sustainable Energy Reviews*, *155*, 111867. https://doi.org/https://doi.org/10.1016/j.rser.2021.111867

Polycrystalline silicon. (2021). https://en.wikipedia.org/wiki/Polycrystalline_silicon

Ponnusamy, M. (2013). An Overview of Batteries for Photovoltaic (PV) Systems. *International Journal of Computer Applications*.

Puranen, P., Kosonen, A., & Ahola, J. (2021). Technical feasibility evaluation of a solar PV based off-grid domestic energy system with battery and hydrogen energy storage in northern climates. *Solar Energy*, *213*, 246-259. https://doi.org/https://doi.org/10.1016/j.solener.2020.10.089

Rahman, M. M., Mahlia, T. M. I., Ong, H. C., Silakhori, M., Hasan, M. H., Putra, N., & Rahman, S. M. A. (2019). Phase Change Materials (PCM) for Solar Energy Usages and Storage: An Overview. *Energies*, *12*, 3167. https://doi.org/10.3390/en12163167

Rangel-Martinez, D., Nigam, K. D. P., & Ricardez-Sandoval, L. A. (2021). Machine learning on sustainable energy: A review and outlook on renewable energy systems, catalysis, smart grid and energy storage. *Chemical Engineering Research and Design*, *174*, 414-441. https://doi.org/https://doi.org/10.1016/j.cherd.2021.08.013

Richard, C., Al-Mas, S., & Hakizimana, J. D. D. (2019). The Role of Mini-grids in Rural Electrification Programmes in Africa and beyond: "The State of Art Paper". *Journal of Energy and Power Engineering*, *13*. https://doi.org/10.17265/1934-8975/2019.12.002

Sandén, B. (2021). Solar energy, resources, technologies and sociotechnical change. In (Lecture in the course TRA105- Solar Energy ed.).

Tawalbeh, M., Al-Othman, A., Kafiah, F., Abdelsalam, E., Almomani, F., & Alkasrawi, M. (2021). Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. *Science of The Total Environment*, *759*, 143528. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.143528

Thin-film solar cell. (2021). https://en.wikipedia.org/wiki/Thin-film_solar_cell

Tuco, M., Muftić Dedović, M., Šahovic, N., Čokljat, S., Cogo, L., Musić, A., Mašić, A., & Avdaković, S. (2022). Economic Analysis of the Application of Photovoltaic Power Plants - Smart City Sarajevo. In *Lecture Notes in Networks and Systems* (Vol. 316 LNNS, pp. 787-797).

UN, E. a. S. C. o. (2021). *Progress towards the Sustainable Development Goals, Report of the Secretary-General*. United Nations Retrieved from https://undocs.org/en/E/2021/58

UNDP. (2021a). *Goal 4: Quality education*. United Nations Development Programme. https://www1.undp.org/content/brussels/en/home/sustainable-development-goals/goal-4-quality-education.html

UNDP. (2021b). *Goal 7: Affordable and clean energy*. United Nations Develpment Program. https://www1.undp.org/content/brussels/en/home/sustainable-development-goals/goal-7-affordable-and-clean-energy.html?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_PaidSearch_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=CjwKCAiAtdGNBhAmEiwAWxGcUlQBhMd5LeCqmQcUm0AeZLZANOM7ZEomiOZkGJ_x3P7nZ5yj04VAfBoCeh0QAvD_BwE

UNDP. (2021c). *Goal 13: Climate action*. United Nations Develpment Program. https://www1.undp.org/content/brussels/en/home/sustainable-development-goals/goal-13-climate-action.html

UNPD. (2021). *Goal 8: Decent work and economic growth*. United Nations Development Programme. https://www1.undp.org/content/brussels/en/home/sustainable-development-goals/goal-8-decent-work-and-economic-growth.html

Üçtuğ, F. G., & Azapagic, A. (2018). Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries. *Science of The Total Environment*, *643*, 1579-1589. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.06.290