

# Conceptualizing a new circular economy feature – storing renewable electricity in batteries beyond EV end-of-life: the case of Slovenia

Matevz Obrecht

*Faculty of Logistics, University of Maribor, Celje, Slovenia*

Rhythm Singh

*Department of Hydro and Renewable Energy, Indian Institute of Technology Roorkee, Roorkee, India, and*

Timitej Zorman

*Faculty of Logistics, University of Maribor, Celje, Slovenia*

## Abstract

**Purpose** – This paper aims to forecast the availability of used but operational electric vehicle (EV) batteries to integrate them into a circular economy concept of EVs' end-of-life (EOL) phase. Since EVs currently on the roads will become obsolete after 2030, this study focuses on the 2030–2040 period and links future renewable electricity production with the potential for storing it into used EVs' batteries. Even though battery capacity decreases by 80% or less, these batteries will remain operational and can still be seen as a valuable solution for storing peaks of renewable energy production beyond EV EOL.

**Design/methodology/approach** – Storing renewable electricity is gaining as much attention as increasing its production and share. However, storing it in new batteries can be expensive as well as material and energy-intensive; therefore, existing capacities should be considered. The use of battery electric vehicles (BEVs) is among the most exciting concepts on how to achieve it. Since reduced battery capacity decreases car manufacturers' interest in battery reuse and recycling is environmentally hazardous, these batteries should be integrated into the future electricity storage system. Extending the life cycle of batteries from EVs beyond the EV's life cycle is identified as a potential solution for both BEVEOL and electricity storage.

**Findings** – Results revealed a rise of photovoltaic (PV) solar power plants and an increasing number of EVs EOL that will have to be considered. It was forecasted that 6.27–7.22% of electricity from PV systems in scenario A (if EV lifetime is predicted to be 20 years) and 18.82–21.68% of electricity from PV systems in scenario B (if EV lifetime is predicted to be 20 years) could be stored in batteries. Storing electricity in EV batteries beyond EV EOL would significantly decrease the need for raw materials, increase energy system and EV sustainability performance simultaneously and enable leaner and more efficient electricity production and distribution network.

**Practical implications** – Storing electricity in used batteries would significantly decrease the need for primary materials as well as optimizing lean and efficient electricity production network.

**Originality/value** – Energy storage is one of the priorities of energy companies but can be expensive as well as material and energy-intensive. The use of BEV is among the most interesting concepts on how to achieve it, but they are considered only when in the use phase as vehicle to grid (V2G) concept. Because reduced battery capacity decreases the interest of car manufacturers to reuse batteries and recycling is environmentally risky, these batteries should be used for storing, especially renewable electricity peaks. Extending the life cycle of batteries beyond the EV's life cycle is identified as a potential solution for both BEV EOL and energy system



---

sustainability, enabling more efficient energy management performance. The idea itself along with forecasting its potential is the main novelty of this paper.

**Keywords** Electricity storage, Scenario analysis, Battery electric vehicle, EV, EOL, Beyond end-of-life, Forecast, Photovoltaic, PV, Self-sufficiency

**Paper type** Research paper

A new circular  
economy  
feature

---

897

## 1. Introduction

### *1.1 Defining challenges for sustainable electricity storage*

Today's society's well-being relates strongly to electricity for our daily necessities. Electrification of the last corners of the Earth is planned. New, more sustainable technologies that use electricity, such as electric vehicles (EVs) and heat pumps, are expanded massively. As the population grows, the need for more energy is additionally magnifying. With the wish of a luxurious lifestyle of developed countries and industrialized economies, 25% of the most developed countries alone use up 75% of the world's energy supply (Dincer, 2000). Due to limited energy supply, renewables' potential and limited financing, the need to use energy more efficiently and smartly is being prioritized (Obrecht and Denac, 2016). To close the gap, the energy system must become more self-sustainable. The term self-sustainability became a significant factor over recent years. A system can be simply explained as sustainable if, through its operations, it expands or maintains the set of options and choices it has itself started with (Zeleny, 1997).

The awareness of self-sustainability and energy supply resilience is increasing, especially in Europe, which is highly dependent on imported energy, causing a socio-economic and political vulnerability. Renewables are getting attention due to being more sustainable and economically feasible for small investors and households. However, being dispersed and having intermittent electricity production, they are challenging for supply network resilience (Hammad, 2020) and stability. International agreements such as the Paris agreement or the EU New Green Deal (European Commission, 2019) all promote the rise of the share of renewables in the energy mix with the final goal to achieve climate neutrality and a zero-carbon energy production system. Zero-emission mobility is also one of the embraced goals.

In the near future, dispersed renewables, such as PV power plants, will produce sufficient electricity for energy use in households and even exceed it and become huge players in the energy industry. However, because solar radiation depends on weather and season, efficient storage of excess electricity is crucial for system stability and sustainable business operations in energy systems based on renewables. Households that invested in photovoltaic (PV) power plants are of particular importance for system stability and can become electricity self-sufficient, especially if they also have their EVs with appropriate battery. Even if the interest in sustainable technologies for electricity production is increasing for the general population, there is still a worldwide challenge of saving energy and managing excess electricity in time of large output and covering shortages in low or zero production time. PV power plant's electricity output varies throughout the day. Maximum production is reached on sunny days with no clouds between 11 am and 4 pm. Some solar systems generate twice the electricity in Summer than in short days of Winter (Igenergy, 2019). Since most of the electricity is used in the morning hours and evenings, much excess electricity is not being used efficiently or is even lost through the day or stored. On the other hand, in the mornings and evenings, when the solar panels do not work at their full power and electricity is needed, electricity can be supplied to the grid from the storage units (Raugei and Frankl, 2009).

To manage this challenge and to stay on track with sustainable energy development, energy storage must be further developed and implemented on a bigger scale, ideally simultaneously with increasing dispersed renewables' production capacity to store electricity until the demand is identified. Different energy storage methods (e.g. pump hydropower

plants; hydrogen production with electrolysis, batteries) have their advantages and disadvantages. This paper focuses on investigating battery storage; therefore, it focuses on examining batteries' pros and cons. Batteries are seen as a potential solution since they could be easily connected to the grid; technology is already well known; transmission efficiency is very high, etc. Battery EV (BEV) is generally perceived as a clean alternative, and they are marketed as "zero-emission" because of their null tailpipe emissions. However, the BEV use-phase produces environmental impacts through processes that occur in various locations (i.e. power plants, battery production and raw material extraction) (Samper-Naranjo, 2021). One of the most challenging disadvantages of batteries is their raw material supply, which can even outweigh all advantages of storing electricity in batteries. Producing batteries for energy storage is not the most sustainable solution since the lack of appropriate minerals and limited supply of materials (e.g. lithium) is to the European Union (EU) interests to seek answers in existing assets or beyond the end-of-life (EOL) of battery containing products. Many battery-related elements', such as Co, Mn, Ni, Cu, Al and Li, increased demand aggravates shortage of resources, Co and Li in particular and some are already listed on the list of the European critical raw materials due to high strategic importance and risky supply (Lombardo *et al.*, 2020). The aforementioned concerns pose some considerable challenges for a transition to BEVs in the light of the upcoming eco-design paradigm in the automotive industry. This is so because though EVs outperform conventional propulsion technologies in terms of their lifetime CO<sub>2</sub> equivalent emissions, resource availability is also an essential pillar of the eco-design paradigm (Hirz and Brunner, 2015; Staniszewska *et al.*, 2020).

At the end of 2019, there were 4.79 million battery EVs in the world (Statista, 2020a), and their number is expected to rise above 250 million by 2030 (IEA, 2019). The average lifetime for a vehicle is assumed to be 150,000 km (without battery replacement). This is a typical glider that corresponds to ten years of life expectancy, which reasonably represents an actual European passenger vehicle (Samper-Naranjo, 2021; Dun *et al.*, 2015). Since battery life is dependent primarily on charging cycles, it can be seen that EV batteries will still be operational after the EOL of EV. Therefore, there is enormous potential to seek energy storage possibilities beyond EV end-of-life.

Due to composite materials and battery structure, batteries are incredibly complex and expensive to recycle (especially lithium extraction) (Hočevár, 2017). Remanufacture is also problematic, and due to hazardous materials and metal compounds, they are inappropriate for energy recovery. Therefore, relating used but operational batteries from used EV after the end of their life cycle is a viable solution that enhances circular economy strategy R3 – reuse (increasing lifespan of products or their parts) (Kirchherr *et al.*, 2017).

### *1.2 Reviewing the current state of the art*

Nowadays, it is hard to imagine a world without batteries. However, the first batteries based on a zinc rod negative electrode were made in the late 19th century. Not long after that, the widely known lithium battery came into existence (Scrosati, 2011).

Batteries in transportation increased their industrial popularity after the first mass sold hybrid car Toyota Prius (Zolot *et al.*, 2002). The benefits of having an EV became clearer, and nowadays, EVs are becoming cheaper than conventional internal combustion vehicles (Hoekstra, 2019). Hoekstra evaluates that currently available technology could electrify more than 70% of transport-related energy demand, leading to a massive reduction of transport-related emissions. On the other hand, mass production of batteries, e.g. lithium batteries, could cause negative impacts of resource depletion. Armand and Tarascon (2008) stated that if we replace all 800 million cars and lorries existing in the world with EV or plug-in hybrids powered with 15 kWh lithium-ion battery, 30% of the total global lithium reserves would be

used. Of course, this is unimaginable and impossible due to lithium distribution and concentration in mixed materials.

Lithium-ion batteries are emerging as top competitor technology because of their higher power and energy density than lead-acid or nickel-metal hydride chemistries. Because of these features, they are the most used in EV manufacturing. However, the current recycling infrastructure for strategic metals is limited, despite projections that millions of EV will hit the road and all-time high EV sales. One of the leading EV manufacturers, Tesla sold over 145,000 T's Model 3 EV across the worlds, followed by Nissan LEAF, Tesla's Model S and Model X (Statista, 2020b). No matter that lithium batteries' EOL recycling has not yet fully developed. Recycling rates are globally meager, and the motivation of benefiting from the waste has yet to come (Wang *et al.*, 2014; Leon, 2020).

It is argued that newer generations of EV batteries can be fully recycled (Lombardo, 2020). "Umicore" is identified as the leading EV battery recycler, using a process of chemical break down of EOL EV batteries by which they follow the circular economy framework to recycle the broken down batteries into feedstock for new batteries. "American Manganese" has also developed a recycling process that can purify almost all recovered material (Umicore, 2019; Ozkan-Ozen *et al.*, 2021); however, this is far from being feasible for broad commercialization. No matter what, reuse strategy would be preferable from the circular economy perspective. If the EV battery does not have the full capacity anymore, the number of available filling cycles and the capacity is still more than enough to be used as a home power bank or even professional energy storage. If such a priority is not present, the newer batteries could still be entirely recycled (Lombardo *et al.*, 2020).

The amount of batteries is also increasingly challenging. Less than 5,000 tons of lithium-ion batteries were evaluated to be dumped in the EU in 2020, and this is about to rise to 120,000 tons by 2030 (Hočevár, 2017). Digitalization and the development of connected mobility could be a step forward to more efficient battery-related waste management, enabling more efficient planning of available resources for energy storage and, consequently, better operational performance of energy storage systems. One of the first such projects was implemented in Japan, where Nissan has been working on repurpose EV batteries. In 2014, they installed a 600 kWh storage system based on new batteries at a 10MW solar farm (Cleantech, 2020). The benefits of integrating battery storage were also revealed by a study that has shown that peak grid electricity was reduced by 8% between 17.00 and 19.00 with smart batteries on the chosen 74 dwellings (Gupta *et al.*, 2019). Australia also announced to installation of renewable energy storage units that would support 1.2 million homes and 30,000 businesses. The announcement was part of a plan to shift the country to 90% renewables by 2030 (Hutchens, 2016). Korkas *et al.* (2016) predicted that PV generation, battery storage and optimal grid management at prosumer sites would lead to 28% of saving by optimizing electricity distribution at peak hours and storing it in off-peak hours.

### 1.3 EV and EV battery lifetime expectancy

Car manufacturers consider the lifespan of EV to be considerably longer. This can also be argued by the up-to-8-year warranty that comes with most EV batteries (Ahmadi *et al.*, 2017). Other than the battery warranty, the EV charging cycles enables a significantly longer life expectancy of almost 29 years (Casals *et al.*, 2019). Studies explain that an average EV battery can conduct 6,700 charging cycles before they reach 80% capacity (Bento *et al.*, 2018; Wolfs, 2010). Due to the average personal vehicle mileage traveled in Europe (12,009 km annually or 32.9 km daily) and an average range of EVs, an EV can run for multiple days without charging. Evaluating the number of charging cycles and relating them to average daily mileage traveled, the battery's ideal lifespan could be even up to over 150 years.

An EV's overall lifespan is hard to determine, but it is expected to last longer than internal combustion vehicles. [Dun et al. \(2015\)](#) explain that the average life expectancy of a new internal combustion vehicle is app. 8–10 years or 150.000 miles, but there is no fixated number since it depends a lot on maintaining a chosen car. However, EV are expected to have a longer life expectancy due to less moving parts, but the degradation in capacity and quality of batteries in EV their service life is many times assessed to be approximately eight years. After that, batteries in EVs need to be replaced before the remaining capacity decreases to 70–80% of their original level to avoid unexpected driving malfunction ([Tang et al., 2019](#); [Hossain et al., 2019](#); [Weisbaum, 2006](#)). However, energy storage does not need full battery capacity; therefore, batteries can be used even with 80% capacity. The EOL of EV is set to be 15–20 years, and a secondary EV battery lifetime was estimated to be additional 15 years ([Warner NA, 2013](#)).

#### *1.4 Defining the gap, scope and goals*

Energy storage is one of energy companies' priorities but can be expensive and material and energy-intensive. The use of EV's battery is among the most exciting concepts on how to achieve it, but they are considered to be connected on the grid only when in the use phase as a vehicle to grid (V2G) concept. Because reduced battery capacity decreases car manufacturers' interest in reusing batteries and recycling is environmentally risky, these batteries should be used for storing principally renewable electricity peaks. Extending the lifespan of batteries from EV beyond the EV EOL is identified as a potential solution for both EV EOL and electricity storage. Forecasting its potential for future development is the most valuable added value of this paper since the gap was identified among studies related to energy storage in integrating used batteries. Therefore, the purpose of this paper is to forecast the potential to reuse EV batteries beyond EV EOL for electricity storage. These evaluations apply to prosumers with integrated PV power plants in the future.

This paper also aims to identify the potential of storing excess electricity produced in dispersed and volatile production sites with a particular emphasis on electricity production from PV power plants with the integration of used batteries from EV. Much attention for EV batteries' EOL solution focuses on the circular economic model and strategies, but a lack of focus on reuse strategy is identified. Since the first batch of battery EV is about to reach their EOL, the potential to use them for renewable electricity storage is evaluated. The following is the research question: how much electricity from PV systems could be potentially stored in reused/remanufactured batteries after Bev EOL. In Slovenia, an EV battery recycling method is not yet available but would be an opportunity for a lot of companies or individuals to establish an EOL EV battery station. The 9R model, which consists of hierarchical terms: Recover, Recycle, Repurpose, Remanufacture, Refurbish, Repair, Reuse, Reduce and Refuse, is said to be applied to the framework of EV batteries, which should result in the reduction of battery-related wastes. Considering the EV batteries as the end-product, this approach qualifies as a Reuse (R3) strategy in the 9R circular economy framework ([Potting et al., 2017](#)). However, from the BEV perspective, the approach discussed in the paper qualifies as a Remanufacture (R6) strategy. As these strategies, Reuse (R3) and Remanufacture (R6), extend the lifespan of a product and its parts, respectively, the approach discussed in the paper is poised to enhance significantly the circularity of the batteries in particular and the BEVs overall. In the paper, we aim to apply the 9R circular economy framework's reuse strategy for batteries and foresee the future amount of available batteries from EVs and relate them with the forecasted amount of electricity produced from solar power plants. Such a circular economy approach for analyzing the synergy between EVs and renewable energy growth is vital for these upcoming technologies. As both these technologies are poised to play a very crucial role in the coming decades, the synergistic analysis discussed in this paper might help dispel some of the viability concerns for these promising upcoming green technologies.

## 2. Methodology

### 2.1 Data selection and forecasts

Data for the research were gathered from viable sources and special databases related to researching EV and EV batteries EOL such as Web of Science, Scopus, Science direct as well as statistical databases SURS, Eurostat, Statista and PV portal reviewing journals not included in these databases. The focus was on papers published from 2014 on. The study was made as a case study based on data for registered EV and solar PV installed in Slovenia.

The information regarding solar panels was gathered from yearly based reports about the installation of PV panels in Slovenia. The solar panels' overall power produced over the years was determined by the power from solar PV systems at the end of each year, divided by the number of existing PV systems across the country. PV systems are used to define the solar PV power plant. Solar PV system average power is considered for electricity production calculations by 1 kWp within one year in optimal weather conditions. Available data of existing PV systems in Slovenia were used for the forecast of future state.

For the forecast of EVs in use, batteries available and energy produced from PV power plants, separate forecasts were made to estimate the number of EV and number of installed PV power plants. Based on the forecasted number of installed PV power plants, electricity production was evaluated, and consequently, needed storage capacity was forecasted. The number of batteries available for reuse was forecasted based on the gathered information on past, current and predicted EV sales and use. Forecasts were made from 2020 to 2040. To archive prosumers' self-sustainability on the future market on PV power plants, EV batteries were selected. Forecasts were made with forecasting software using Exponential Triple Smoothing, which also considers seasonality. Forecasts were predicted as a linear trend of past registrations of EV and the number of installed PV power plants. The forecast could be done with different functions, but a linear trend was selected due to the expected higher increase until 2030 and slower increase between 2030 and 2040. Forecast of available EV batteries was based on the polynomial trend function. In each forecast, upper and lower confidence intervals were assessed to evaluate more optimistic and more pessimistic market development variations. Calculations were made for beyond EV EOL. Due to a longer lifetime of EV compared to internal combustion vehicles, EV lifespan was set to be 20 years for scenario A and 15 years for scenario B. Only 80% of the available battery storage capacity after the EV EOL was considered as useable for integration with the PV systems.

An impartial assessment of the above methodology would clearly show that the methodology used in this paper is simple and straightforward yet captures sufficient details for making a reasonable long-term forecast. Though more levels of details can be added to develop a more sophisticated model, the present methodology is aimed at producing first-cut estimates for a long-term planning perspective.

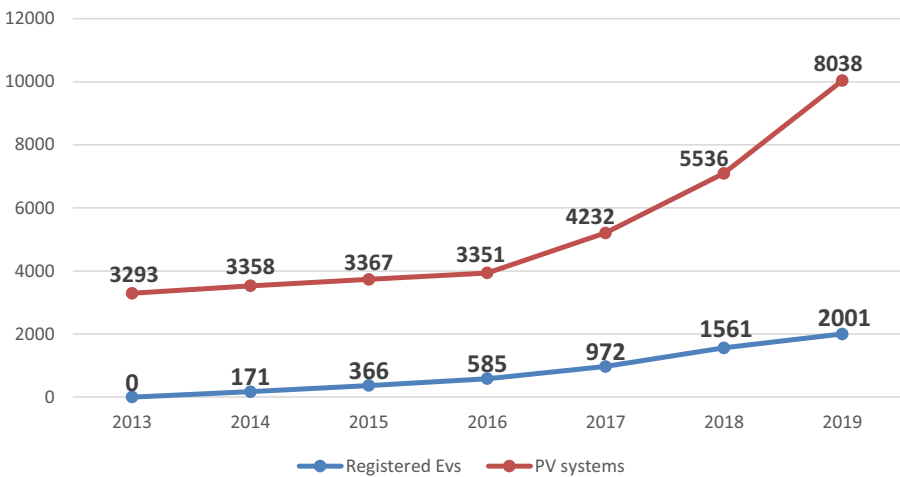
### 2.2 Slovenian case study details

First, looking into Slovenia's sold EVs over the past years, most sold EVs in Slovenia are BMW i3, followed by Nissan Leaf and Renault Zoe, which have the highest market share (Božin, 2019; SiStat, 2020). Božin, 2019 as shown in Figure 1, the total number of registered EV in Slovenia was 2001 and relatively steady growth. In the forecast of available EV's batteries for electricity storage, statistics on EVs sold from 2013 to 2019 were used to forecast EV batteries' future availability beyond EV end-of-life. Due to the relatively small share of EV, the future number of EV in operation might be higher.

The interest in PV solar panels in Slovenia began to bloom in the first half of the decade throughout the past decade. After that, we can see coming to a stall in rising, as shown in Figure 1. From the latest information, the current number of solar panels across Slovenia is 8,038 with a combined power of 313,2 MW (PV portal, 2019).



**Figure 1.**  
Number of registered  
EVs over and installed  
PV power plants in  
Slovenia from 2013  
to 2019



**Source(s):** SiStat

We know many different varieties of EV batteries. After gathering information, it was found that the average capacity of all new EV batteries on the market is 56.9 kWh (Table 1), and their average consumption is 18.5 kWh per 100 km. Consequently, their average range is approximately 308 km.

Figure 2 shows that the number of installed solar PV started to grow fast in 2017 and average power is also increasing in the same period. Average peak power of installed PV system in 2019 was 19,6 kWp.

### 3. Results

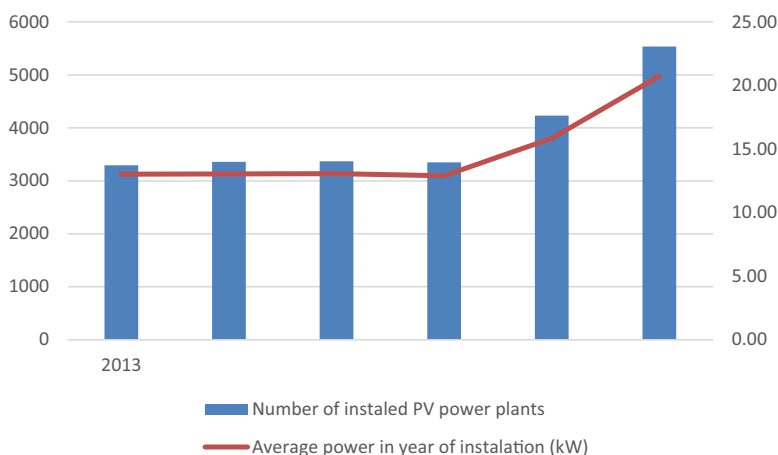
We see a moderate increase in the EVs market share the last few years from the gathered data. The total number of registered EVs in 2018 was 1,561. The exact number of EVs in Slovenia in 2019 was 2001. As for the number of PV systems, we can identify that from 2013 to 2019 the number of PV systems did not boom as much as expected in examined period. Exception is recent increase in 2019. It would be judicious to conclude that the PV systems use in Slovenia is relatively small, given the country's sizeable solar energy potential (Stritih *et al.*, 2013).

In 2018, Slovenian residential and commercial consumers spent 3,368 GWh of electricity (SiStat, 2020). If we divide the used electricity with the 824,618 households (SiStat, 2020) that Slovenia has, we can see that an average Slovenian consumer has spent 4084, 32 kWh of electricity in year 2018. If we further divide the number by 365 days, we get the result that an average user uses 11.19 kWh on a daily basis.

From that information alone, we can foresee that an electric car battery has more than enough space to store electricity, since it has the capacity for storage up to five days' worth of electricity usage.

**Table 1.**  
Average EV battery  
information

EV battery capacity (AVG)	56.9 kWh
EV energy consumption (AVG)	18.5 kWh/100km
Calculated average range	308 km
<b>Source(s):</b> calculations based on <a href="#">Ev-database, 2020</a>	



Source(s): PV portal, 2020

**Figure 2.**  
Number of installed PV  
systems and their  
average powers in the  
year of installation (in  
kW) in Slovenia from  
2013 to 2018

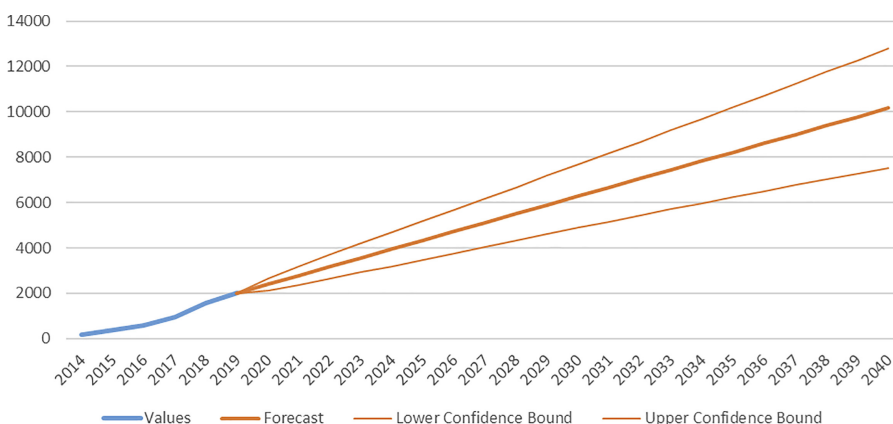
We also need to consider that the number for daily used electricity is not yet completely correct, since the exact numbers of consumed electricity in the country are not referred to households and commercial sector alone, but on the national electricity consumption.

The forecasts were made with Excel forecast tools based on gathered information of the past years. The confidence interval in the forecast will be set at 90% to get precise results.

Forecast of EV until 2040 was made based on the gathered information in the methodology section from trustworthy sources.

EVs were already looking very promising by the current sales in Slovenia. Figure 3 shows the forecast on a 90% confidence interval for year 2040. It states that the number of registered EVs will rise to 10,169 EVs, with lower confidence bound of 7,540 EVs and upper confidence bound of 12,798.

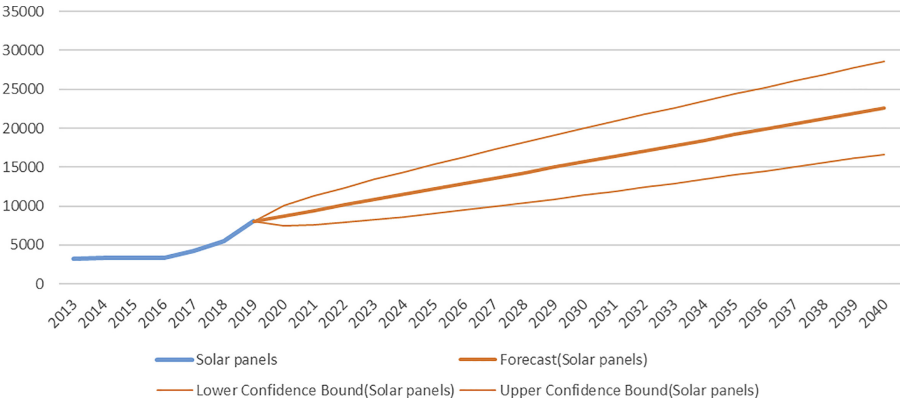
Forecast for the quantity of solar PV systems predicted to be operational in 2040 was made based on the source PV-portal information. It was made on a 90% confidence interval and resulted in estimated 22.630 (Figure 4) solar panels by the end of 2040. The interval shows the precise time when solar panels became popular in the household section of self-sufficiency, which is at the end of the year 2016. The lower confidence bound shows the



**Figure 3.**  
Forecast of the number  
of available EVs from  
2020 to 2040



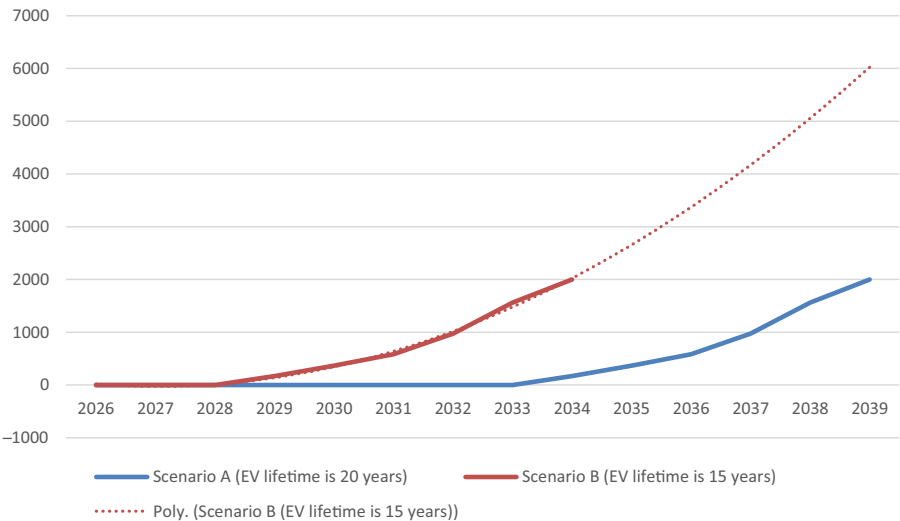
**Figure 4.**  
Forecast of the number  
of installed solar PV  
systems from 2020  
to 2040



estimated number of 16.666 solar panels. The upper confidence bound is pointed in the direction of 28.595 solar panels, as shown in Figure 4. The whole market share of solar panels is expected to be 356% bigger from the year 2019 based on the upper confidence bound. We believe that the recent movement of self-sufficiency will bring a boom in the market sales of solar panels in the near future.

As for forecasting the battery availability, EVs' lifespan was a complex determination; thus, our forecast is actually based on forecasted lifetime of EVs, which leads to EV and EV battery EOL and not directly on the actual availability of used but operational EV batteries. EVs' lifespan is expected to be longer than those of internal combustion vehicles. It all depends on the maintenance the cars get from their owners. If the EV is used in an ideal environment, under ideal circumstances and regularly maintained, the forecast number of batteries will rise after the estimated 20 years of using EVs (scenario A). So, the confidence interval in such a case would be 100%. As shown in Figure 5, the estimate of available car batteries in 2039 would be 2001 batteries. Because the reliability of the availability of EV's batteries can vary, scenario B with a 15-year lifetime of EV was examined to determine the

**Figure 5.**  
Forecast of the number  
of EVs batteries  
beyond EV EOL for  
electricity storage for  
scenario A (lifespan of  
EV is 20 years) and  
scenario B (lifespan on  
EV is 15 years with  
polynomial trend line)



EV's battery availability. In scenario B (15 years), it is shown that the first available batteries beyond EV EOL would be available in 2029 so that would be nine years from now on. In 2040, approximately 6,000 EV batteries will be available for electricity storage in Slovenia, according to scenario B. If EV lifespan is decreased to 10 or 12 years and equals internal combustion vehicle lifetime, the number of available batteries would be substantially higher.

From the calculations, we can see that in 2040 the available electricity storage for the means of household self-sufficiency will be approximately 91.085,52 kWh (Table 1). That also concludes that probably in year 2030 there will not be any viable energy storages from used EV, since the average lifespan of an EV, from our standpoint, is calculated to be around 20 years. If we look at scenario B, in case of a 15-year car lifespan in the year 2030 there would be 20.825,4 kWh of available storage, and if we put into account the 20% capacity drop of lithium-based used batteries, there would be 16.660,32 kWh worth of electricity storage.

The specific yield of PV systems in Slovenia has been reported as 1, 000 to 1, 200 kWh/kWp/year, and average power of installed PV systems in 2019 was 19.90 kWp. Based on this information, a calculation of Slovenia's PV panels' overall production is possible. For the measurement of PV panels' output, we took the average number of 1,100 kWh/kWp/year. Results revealed that the overall average output of PV system is 21.89 kWh in a year, and total solar electricity production in 2040 is forecasted to approximately 495.31 GWh in optimal weather conditions (Table 2). The lower confidence bound of the forecast is 29,16 kWh and the upper bound is considered to be 55,41 kWh.

For the storage available in EVs, there is to be considered about 578.559,2 kWh in the year 2040, which is a compromising number for using a smart grid system and predicting the possible future capacity for household electricity storage enabled by digitalization and smart grid implementation. The overall project shows a healthy increase in the number of solar PV systems, EVs and electricity storage units, thus making the possibility of self-sufficiency one

2040 energy storage forecast	Lower confidence bound	Forecast	Upper confidence bound
Total combined power of PV system	419.03 MWp	450.28 MWp	481.54 MWp
Average PV systems annual production	460.03 GWh	495.31 GWh	529.69 GWh
Average daily production of PV solar electricity	1,260.36 MWh	1,357.01 MWh	1,451.20 MWh
Number of EVs	7,540	10,168	12,798
Theoretical available EV battery storage capacity on the market (in case of 100% battery performance of all EVs)	429,026.0 kWh	578,559.2 kWh	728,206.2 kWh
Battery storage capacity (Scenario A – EV lifetime is 20 years) beyond EV EOL		113.86 MWh	
Battery storage capacity (Scenario B – EV lifetime is 15 years) beyond EV EOL		341.57 MWh	
Battery storage capacity (Scenario A – 80% battery performance) beyond EV EOL		91.09 MWh	
Share of average daily production of PV solar electricity that can be potentially stored in EV batteries (Scenario A – 80% battery performance) beyond EV EOL	0.0722 (7.22%)	0.0671 (6.71%)	0.0627 (6.27%)
Battery storage capacity (Scenario B – 80% battery performance) beyond EV EOL		273.26 MWh	
Share of average daily production of PV solar electricity that can be potentially stored in EV batteries (Scenario B – 80% battery performance) beyond EV EOL	0.2168 (21.68%)	0.2013 (20.13%)	0.1882 (18.82%)

**Table 2.**  
Potential PV electricity  
storage in EV batteries  
beyond EV EOL  
in 2040

step closer to reality. The estimate for available EV's batteries over the years shows that the first storage units will be available in 2034, since the overall start of EV sales was considered late. As for the battery capacity itself, we can safely assume that the near future capacity will drastically expand.

According to calculations and forecast, Slovenia could achieve medium energy storage of electricity produced by solar PV systems in batteries from EV after its EOL. Regarding calculations, electricity storage in EV batteries would enable storing 6.27–7.22% of electricity from PV systems in scenario A (if EV lifetime is predicted to be 20 years) and between 18.82 and 21.68% of electricity from PV systems in scenario B (if EV lifetime is expected to be 20 years), which is significant amount regarding that EOL batteries are not a part of the forecasted energy storage system in the future. Using used batteries beyond EV EOL would also significantly decrease the energy-storing system's investment price. Therefore, the energy storing system would be more sustainable and efficient from a financial perspective. Due to rising number of PV systems as well as increasing sales of EVs, it is forecasted that available batteries from used EV will increase even faster than PV installations. The most important thing is that batteries will become available approximately at the same time when significant share and peak power of PV systems is achieved, therefore enabling efficient management of energy storage planning.

#### 4. Discussion

It is forecasted that the trend of high EVs sales will additionally boom in the future, and we can expect to overcome the forecast and hit the 12,798 EVs in Slovenia in 2040. We consider that the forecast for EVs will move toward the upper confidence bound, based on the boom in sales, and the overall recent popularity of EVs. The overall quantity of storage units and storage capacity might also increase above the upper confidence bound. [Candelise et al. \(2013\)](#) predicted that PV panels' prices will drastically fall to be available for the broader public in the near future, and this has already happened to some degree and is expected to continue. Therefore, PV systems will also boost in the future due to attractive investment price and return on investment. It is said that the costs of lithium-ion batteries will fall slowly over the near future, making such self-sufficient concepts even more available ([Yu, 2018](#)) due to the decreasing price of EV and the fast-developing industry of batteries.

The general public also perceives EV to be environmentally friendly; they are getting potential users' attention because the fuel economy for EV is considerably higher than that for internal combustion vehicles. Because of the increased demand for EV and their expected lifetime, many EVs and consequently used batteries will be available on the market in the next years. This would enable efficient reuse of EV batteries and at the same time lower the rates of battery-related (also hazardous) waste. After the EV EOL, batteries should be inspected to examine their current state and potential for electricity storage. Monitoring battery performance during the use phase of EV would be even better because a more accurate forecast of available battery capacity for electricity storage would be enabled. Since batteries tend to lose their power over time, they are not as useful for reuse in EV manufacturing since EV batteries need to be light and have an immense capacity. However, they are ideal for energy retention for nonmobility uses. This is also following the circular economy R3 strategy and can be further developed to circular economy strategy "smarter product use and manufacture" to enable even better energy storage performance beyond EOL. The other positive impact is to provide such technologies for implementation by the interested companies and households, which could lead to significant improvements of resilient, sustainable and reliable energy supply. This will also be consistent with a combination of United Nation (UN) Sustainable Development Goals: "Responsible consumption and production"; "Affordable and clean energy"; "Sustainable cities and

communities” as well as “Industry innovation and infrastructure”. Energy system would also become leaner, more efficient, digitalized and smarter, and their general performance would increase which is in accordance with findings of [Obrecht et al. \(2020\)](#).

Another exciting aspect of this entire study is the future growth trends of PV. A possible future scenario is that PV power plants might become a key part of energy systems with an installed capacity to produce more electricity during sunny days than anticipated energy demand. In that case, without energy storage, PV power plants will not meet their wished full potential. The benefit of having electricity storage also fixes some of the PV panels’ problems like seasonality; for instance, winter has shorter day intervals, which means less sun; therefore, less electricity is created. On the other hand, summer consists of longer days and consequently the output of PV plants rather high. There are also legislation specifics like net-metering that can be calculated yearly, monthly, weekly or, in the future, maybe even daily basis. This would completely change PV power plant feasibility, and such plants would not be rational without energy storage.

In 2020, Slovenia agreed to the Integrated National Energy and Climate Plan in which the goal is to reduce total greenhouse gas (GHG) emissions by 36% based on the year 2005; at least 35% improvement energy efficiency and to archive at least 27% share of renewables ([GOV, 2020](#)). To backup the 27% of share renewables and increase energy efficiency, the plan is to self-sustain most of the buildings by the installation of solar PV systems ([GOV, 2020](#)) that could be integrated into a smart grid and energy storage scheme. According to this forecast, Slovenia could develop an advanced energy storage system based on storing solar PV electricity in batteries from EV after its EOL. According to calculations, electricity storage in EV batteries would enable storing 6.27–7.22% of electricity from PV systems in scenario A (if EV lifetime is predicted to be 20 years) and 18.82–21.68% of electricity from PV systems in scenario B (if EV lifetime is expected to be 15 years), which is above our expectations. If EV lifespan is decreased to 10 or 12 years the same as conventional vehicles, the amount of available batteries would be substantially higher and potential energy storage share even higher. Since using batteries from EV after EV end-of-life is seen as an innovative solution for energy storage following the circular economy reuse strategy, it is evaluated that such an approach would significantly improve energy management’s sustainability performance. It would also enable efficient energy distribution without severe demand for rare materials related to battery production and raw material supply and would make energy supply more resilient.

This study has focused on electricity from PV systems, but Slovenia also has other possibilities in achieving renewables expansion. Most of the Slovenian hydropower potential is already exploited; therefore, potential increase of hydropower is not expected to be as significant as PV systems. Another possibility is the installation of wind power plants. At the moment, Slovenia has two wind power plants, one 2.3 MW and the other 0.9 MW ([Agen, 2020](#)), but the country has enough space and technical potential for significant expansion of wind energy. The crucial obstacle here is finding an optimal location and position of a wind power plant. The geothermal potential is also relatively high, but the water temperature is mostly appropriate for distant heating and not electricity production.

This research is focused only on the trends and future of EVs batteries, but studies show that batteries will not be the only competitors in the electricity storage market. Pumped hydro systems (PHSs), superconducting magnetic energy storage, hydrogen pallet handling systems (HPHSs), compressed air energy storage (CAES), thermal energy storage (TES) and community energy storages (CESs) are starting to show promising results in the future of electricity storages ([Rodrigues et al., 2017](#)). Studying the potentials of other storage technologies should also be done in the future research of smart energy storage. A significant limitation of this study is forecasting based on a linear model. For future EV battery-based energy storage research, different trends should be investigated and cross-examined in

different countries and geographical areas (e.g. Asia, USA and Europe). Future works can also focus on determining an EV's lifespan for real and detailed results. Another dimension that future works in this domain could focus upon is the factors affecting this approach's market uptake, like consumer behavior patterns and other implementational aspects.

## 5. Conclusion

As technology arises, new business models make energy management more efficient, sustainable and efficient. Electricity storage is one such solution for managing excess renewable electricity production and balancing it with volatile energy demand, and studies show that electricity storage is being increasingly considered in the energy mixes of the future. It is also confirmed that lithium-ion batteries can be a financially viable energy storage solution in the demand side, energy cost management applications (Nottrott *et al.*, 2013). In this research, we came to the conclusion that a huge potential for solar electricity storage in used batteries beyond EV EOL is to be exploited. To determine the quantity of used but operational and available EV batteries in 2040, we have forecasted the development of EV rise as well as predicted future production of electricity from solar PV systems. It was calculated 6.27–7.22% of electricity from PV systems could be stored in batteries from EVs in scenario A (if EV lifetime is predicted to be 20 years) and 18.82–21.68% of electricity from PV systems in scenario B (if EV lifetime is expected to be 20 years) even if 80% battery capacity is considered. This is high enough to sufficiently limit the demand for rare materials to produce special batteries for electricity storage.

EV batteries' potential for means of storage is benefiting for the self-sufficiency of, e.g. homes and commercial sector and the implementation of a circular economy and more sustainable management of energy systems. At present, EV batteries still have linear economy EOL, and because of specific and costly recycling processes, heavy metals and toxic elements in batteries, new solutions ranked higher on circular economy prioritization strategies should be implemented. Using batteries from EV beyond EV EOL is one such solution that significantly increases the sustainability performance of energy systems and EV simultaneously. Since newer lithium-ion batteries will have more than 6,700 charging cycles and can hold electricity for five days or more, we can confirm that the reuse stage is a more appealing way of using operational EV batteries beyond EV EOL. Environmental, social and economic benefits can be identified within this solution, such as more efficient battery waste management, EV recycling and reuse, higher energy management performance and a general increase in an energy system's sustainability and decreased need for high power of electric power plants. In light of all these foreseeable benefits likely to accrue by implementing the battery reuse strategy discussed in this paper, it would augur well for the policymakers to have a synergistic policy approach for EV growth and renewable energy growth. A detailed policy for the ground implementation of the mechanisms to facilitate battery reuse between EVs and PV power plants should be deliberated upon, taking the relevant stakeholders on board.

## References

- Agen, R.S. (2020), "Wind power plants", available at: <https://www.agen-rs.si/izvajalci/ove-ure/obnovljivi-viri-in-soproizvodnja/register-deklaracij-za-proizvodne-naprave> (accessed 12 August 2020).
- Ahmadi, L., Young, S.B., Fowler, M., Fraser, R.A. and Achachlouei, M.A. (2017), "A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems", *International Journal of Life Cycle Assessment*, Vol. 22, pp. 111-124.
- Armand, M. and Tarascon, J.M. (2008), "Building better batteries", *Nature*, Vol. 451 No. 7179, pp. 652-657.

- Bento, A., Roth, K. and Zuo, Y. (2018), "Vehicle lifetime trends and scrappage behavior in the U.S. Used car market", *Energy Journal*, Vol. 39 No. 1, pp. 159-183.
- Božin, U. (2019), "Most sold electric cars in Slovenia", *Avto Finance*, available at: <https://avto.finance.si/8952879/Lestvica-top-elektricnih-avtov-na-slovenskem-trgu> (accessed 26 January 2020).
- Candelise, C., Winskel, M. and Gross, R.J.K. (2013), "The dynamics of solar PV costs and prices as a challenge for technology forecasting", *Renewable and Sustainable Energy Reviews*, Vol. 26, pp. 96-107.
- Casals, L.C., Amante García, B. and Canal, C. (2019), "Second life batteries lifespan: rest of useful life and environmental analysis", *Journal of Environmental Management*, Vol. 232, pp. 354-363.
- CleanTech (2020), "Circular economy and EV batteries", available at: <https://www.cleantech.com/ev-batteries-creating-a-circular-economy/> (accessed 2 January 2021).
- Dincer, I. (2000), "Renewable energy and sustainable development: a crucial review", *Renewable and Sustainable Energy Reviews*, Vol. 4 No. 2, pp. 157-175.
- Dun, C., Horton, G. and Kollamthodi, S. (2015), *Improvements to the Definition of Lifetime Mileage of Light Duty Vehicles*, Ricardo-AEA, Harwell.
- European Commission (2019), *The European Green Deal*, COM/2019/640 final, EC, Brussels.
- Ev-database (2020), "Tesla cybertruck", available at: <https://ev-database.org/car/1250/Tesla-Cybertruck-Tri-Motor> (accessed 5 September 2020).
- Gov, S.I. (2020), *National Energy and Climate Plan*, available at: [https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/nepn/dokumenti/nepn\\_5.0\\_final\\_feb-2020.pdf](https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/nepn/dokumenti/nepn_5.0_final_feb-2020.pdf) (accessed 12 August 2020).
- Gupta, R., Bruce-Konuah, A. and Howard, A. (2019), "Achieving energy resilience through smart storage of solar electricity at dwelling and community level", *Energy and Buildings*, Vol. 195, pp. 1-15.
- Hammad, M.A., Jereb, B., Rosi, B. and Dragan, D. (2020), "Methods and models for electric load forecasting: a comprehensive review", *Logistics and Sustainable Transport*, Vol. 11 No. 1, pp. 51-76, doi: [10.2478/jlst-2020-0004](https://doi.org/10.2478/jlst-2020-0004).
- Hirz, M. and Brunner, H. (2015), "ECO-design in the automotive industry-potentials and challenges", *Proceedings International Conference Management of Technology-Step to Sustainable Production*, pp. 1-10.
- Hočevár, B. (2017), "Who is going to pay for recycling of EV batteries?", *Finance*, 11 April 2017, available at: <https://oe.finance.si/8855867/Kdo-bo-placal-recikliranje-baterij-za-elektricna-vozila>.
- Hoekstra, A. (2019), "The underestimated potential of battery electric vehicles to reduce emissions", *Joule*, Vol. 3 No. 6, pp. 1412-1414.
- Hossain, E., Murtaugh, D., Mody, J., Faruque, H.M.R., Haque Sunny, M.S. and Mohammad, N. (2019), "A comprehensive review on second-life batteries: current state, manufacturing considerations, applications, impacts, barriers & potential solutions, business strategies, and policies", *IEEE Access*, Vol. 7, pp. 73215-73252.
- Hutchens, G. (2016), "Australia's energy storage", *The Guardian*, available at: <https://www.theguardian.com/environment/2016/may/05/greens-want-12m-households-to-install-renewable-energy-storage> (accessed 26 January 2020).
- IEA (2019), *Global EV Outlook 2019: Scaling up the Transition to Electric Mobility*, Technology Report, IEA, Paris.
- Igenergy (2019), "When do solar systems work best", available at: <https://www.igenergy.com.au/faq/did-you-know/what-time-of-the-day-and-during-the-year-does-a-solar-system-work> (accessed 12 August 2020).
- Kirchherr, J., Reike, D. and Hekkert, M. (2017), "Conceptualizing the circular economy: an analysis of 114 definitions", *Resources, Conservation and Recycling*, Vol. 127, pp. 221-232, doi: [10.1016/j.resconrec.2017.09.005](https://doi.org/10.1016/j.resconrec.2017.09.005).



- Korkas, C.D., Baldi, S., Michailidis, I. and Kosmatopoulos, E.B. (2016), "Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage", *Applied Energy*, Vol. 163, pp. 93-104.
- Leon, E.M. and Miller, S.A. (2020), "An applied analysis of the recyclability of electric vehicle battery packs", *Resources, Conservation and Recycling*, Vol. 157, p. 104593, doi: [10.1016/j.resconrec.2019.104593](https://doi.org/10.1016/j.resconrec.2019.104593).
- Lombardo, G., Ebin, B., Foreman, M.R., Steenari, B.M. and Petranikova, M. (2020), "Incineration of EV Lithium-ion batteries as a pretreatment for recycling – determination of the potential formation of hazardous by-products and effects on metal compounds", *Journal of Hazardous Materials*, Vol. 393, p. 122372, doi: [10.1016/j.jhazmat.2020.122372](https://doi.org/10.1016/j.jhazmat.2020.122372).
- Nottrott, A., Kleissl, J. and Washom, B. (2013), "Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems", *Renewable Energy*, Vol. 55, pp. 230-240.
- Obrecht, M. and Denac, M. (2016), "Technology forecast of sustainable energy development prospects", *Futures*, Vol. 84, pp. 12-22, Part A, doi: [10.1016/j.futures.2016.09.002](https://doi.org/10.1016/j.futures.2016.09.002).
- Obrecht, M., Kazancoglu, Y. and Denac, M. (2020), "Integrating social dimensions into future sustainable energy supply networks", *International Journal of Environmental Research and Public Health*, Vol. 17 No. 17, p. 6230, doi: [10.3390/ijerph17176230](https://doi.org/10.3390/ijerph17176230).
- Ozkan-Ozen, Y.D., Kazancoglu, Y. and Mangla, S.K. (2021), "Synchronized barriers for circular supply chains in industry 3.5/industry 4.0 transition for sustainable resource management", *Resources, Conservation and Recycling*, Vol. 161, p. 104986.
- Potting, J., Hekkert, M.P., Worrell, E. and Hanemaaijer, A. (2017), *Circular Economy: Measuring Innovation in the Product Chain (No. 2544)*, PBL Netherlands Environmental Assessment Agency, Hague.
- Raugei, M. and Frankl, P. (2009), "Life cycle impacts and costs of photovoltaic systems: current state of the art and future outlooks", *Energy*, Vol. 34 No. 3, pp. 392-399.
- Rodrigues, A., Machado, D. and Dentinho, T. (2017), "Electrical energy storage systems feasibility; the case of Terceira Island", *Sustainability*, Vol. 9 No. 7, p. 1276.
- Samper Naranjo, G.P., Bolonio, D., Ortega, M.F. and García-Martínez, M.J. (2021), "Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain", *Journal of Cleaner Production*, p. 125883, doi: [10.1016/j.jclepro.2021.125883](https://doi.org/10.1016/j.jclepro.2021.125883).
- Scrosati, B. (2011), "History of lithium batteries", *Journal of Solid State Electrochemistry*, Vol. 15 Nos 7-8, pp. 1623-1630.
- SiStat (2020), "Statistical office of Slovenia", available at: <https://pxweb.stat.si/SiStat> (accessed 15 November 2020).
- Staniszewska, E., Klimecka-Tatar, D. and Obrecht, M. (2020), "Eco-design processes in the automotive industry", *Production Engineering Archives*, Vol. 26 No. 4, pp. 131-137, doi: [10.30657/pea.2020.26.25](https://doi.org/10.30657/pea.2020.26.25).
- Statista (2020a), "Worldwide number of battery electric vehicles in use from 2012 to 2019", available at: <https://www.statista.com/statistics/270603/worldwide-number-of-hybrid-and-electric-vehicles-since-2009/> (accessed 12 January 2021).
- Statista (2020b), "Worldwide electric car sales", available at: <https://www.statista.com/statistics/960121/sales-of-all-electric-vehicles-worldwide-by-model/> (accessed 26 January 2020).
- Stritih, U., Osterman, E., Evliya, H., Butala, V. and Paksoy, H. (2013), "Exploiting solar energy potential through thermal energy storage in Slovenia and Turkey", *Renewable and Sustainable Energy Reviews*, Vol. 25, pp. 442-461.
- Tang, Y., Zhang, Q., Li, Y., Li, H., Pan, X. and Mclellan, B. (2019), "The social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanism", *Applied Energy*, Vol. 251, p. 113313, doi: [10.1016/j.apenergy.2019.113313](https://doi.org/10.1016/j.apenergy.2019.113313).

- 
- Umicore (2019), "Umicore annual report", available at: [https://www.umicore.com/storage/annualreport\\_2019/2020-03-30-umicore-ar19-en-interactive.pdf](https://www.umicore.com/storage/annualreport_2019/2020-03-30-umicore-ar19-en-interactive.pdf) (accessed 5 September 2020).
- Wang, X., Gaustad, G., Babbitt, C.W., Bailey, C., Ganter, M.J. and Landi, B.J. (2014), "Economic and environmental characterization of an evolving Li-ion battery waste stream", *Journal of Environmental Management*, Vol. 135, pp. 126-134.
- Warner, N.A. (2013), *Secondary Life of Automotive Lithium Ion Batteries: An Aging and Economic Analyses*, Ohio state university, Ohio.
- Weisbaum, H. (2006), "Internal combustion car's life expectancy", *NBC*, available at: [http://www.nbcnews.com/id/12040753/ns/business-consumer\\_news/t/whats-life-expectancy-my-car/#.Xi3MmGhKhpg](http://www.nbcnews.com/id/12040753/ns/business-consumer_news/t/whats-life-expectancy-my-car/#.Xi3MmGhKhpg) (accessed 5 April 2020).
- Wolfs, P. (2010), "An economic assessment of 'second use' lithium-ion batteries for grid support", *IEEE 20th Australasian Universities Power Engineering Conference*.
- Yu, H.J.J. (2018), "A prospective economic assessment of residential PV self-consumption with batteries and its systemic effects: the French case in 2030", *Energy Policy*, Vol. 113, pp. 673-687, doi: [10.1016/j.enpol.2017.11.005](https://doi.org/10.1016/j.enpol.2017.11.005).
- Zeleny, M. (1997), "Autopoiesis and self-sustainability in economic systems", *Human Systems Management*, Vol. 16, pp. 251-262.
- Zolot, M., Pesaran, A.A. and Mihalic, M. (2002), "Thermal evaluation of Toyota Prius battery pack", *SAE Technical Paper Series*, 2002-01-1692.

# Corresponding author

Matevz Obrecht can be contacted at: [matevz.obrecht@um.si](mailto:matevz.obrecht@um.si)