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The role of electric vehicles second-life batteries on renewable based power systems

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Abstract

Electric mobility is taking off, and it will represent a large share of the global automobile market in the next decades. The batteries of these vehicles are typically replaced while still having a significant remaining capacity, thus they are suitable for alternative uses, creating in the medium-long term opportunities for their repurpose to domestic applications or to direct coupling to renewable energy systems. This study analyses from a technical and energy balances viewpoint how a large power system can take advantage of second-life batteries to store potential excess of non-controllable renewable energy.

For that, it uses the future Portuguese power system as case study. It couples a model of electric mobility diffusion and second-life batteries availability with various EnergyPlan simulation models of the power system for the period 2030-2050, comprising sub-models of unidirectional smart charging of electric vehicles. The results are illustrated and quantified against a base case scenario, which disregard second-life battery storage. Load diagrams of the power system are shown, and it is quantified to what extent this solution may facilitate the deployment of solar-photovoltaics and reduce the needs for imports and exports and abroad interconnection capacity. Since the Portuguese power system is largely based on hydro energy, the results are shown both for the cases of a normal and a dry year.

The results show that by 2050 the second-life batteries market should represent about 38 GWh of storage capacity. On a normal year, they allow to reduce the amount of energy in excess from 0,77 to 0,03 TWh, and mostly they are operated during the summer at an average charging and discharging rates of 251 and 181 MW, respectively. In terms of renewables integration, the batteries should allow an additional 3.581 MW of photovoltaics deployment, which allow to increase the electricity renewable share by 4%. Concerning environmental benefits, the batteries allow to decrease CO_2 emissions by 0,2 Mton, which represent 3,4% of total emissions from the power system. If one considers the scenario with increased photovoltaics deployment that they allow, the reduction of CO_2 emissions ascends to 32%. For the dry year scenario, the results are that the repurposed batteries are capable to fully compensate the lower storage capacity in the dams, supplying the grid when requested. In spite of these results, it was found that the capacity factor of the second-life batteries should be low (about 5%), since the Portuguese power system already comprises a large hydro-pumping capacity to store energy, suggesting that in systems where this is not the case the batteries should become more relevant.

Keywords: second-life batteries, power systems analysis, electric vehicles, smart charging, battery storage

Resumo alargado

A mobilidade elétrica está em crescimento e irá representar uma parte muito relevante do mercado automóvel global nas próximas décadas. As baterias dos veículos elétricos são tipicamente substituídas enquanto ainda possuem uma capacidade significativa e, deste modo, podem ainda ter utilizações alternativas, criando a médio-longo prazo oportunidades para a sua reutilização em aplicações domésticas ou acopladas a sistemas de energias renováveis. A energia produzida por centrais elétricas não despacháveis, particularmente eólicas e solares, implica um desafio na sua integração na rede devido à sua intermitência. Por outro lado, existe a necessidade de armazenar parte desta energia, cuja produção nem sempre coincide temporalmente com o consumo, mas as formas de o fazer em larga escala, a menos da bombagem hídrica, são escassas. Assim, reutilizar as baterias dos veículos elétricos após o seu serviço automóvel para este efeito representa uma solução promissora a um custo reduzido. Deste modo, ao facilitar a integração de energias renováveis nos sistemas electroprodutores, as baterias reutilizadas contribuirão também positivamente para a sustentabilidade dos veículos elétricos, se os benefícios desta solução forem incorporados na sua análise do ciclo de vida.

Este estudo analisa de um ponto de vista técnico e energético de que modo um sistema electroprodutor pode beneficiar com a utilização de baterias reutilizadas para armazenar o excedente de produção por energias renováveis não despacháveis.

Para tal, adotou-se como caso de estudo o sistema electroprodutor português no período de 2030 a 2050. Este contempla um modelo de difusão da mobilidade elétrica e da disponibilidade de baterias reutilizadas com diversos modelos de simulação em EnergyPlan. Cada modelo contém ainda sub-modelos de carregamento unidirecional inteligente dos veículos elétricos. Os resultados são ilustrados e quantificados comparativamente a um cenário base que não contempla armazenamento nas baterias reutilizadas. Para a análise são mostrados os diagramas de carga do sistema elétrico e é quantificado em que medida esta solução poderá facilitar a instalação adicional de solar-fotovoltaico e reduzir as necessidades de importação e exportação de energia, bem como da capacidade de interligação internacional. Dado que o sistema elétrico português é amplamente dependente de energia hidroelétrica, os resultados são também mostrados para um ano normal e para um ano de seca.

Os resultados evidenciam que em 2050 o mercado de baterias reutilizadas poderá representar cerca de 38 GWh de capacidade de armazenamento. Num ano normal, estas permitem reduzir o excesso de energia de 0.77 para 0.03 TWh, e estão em operação maioritariamente durante o verão, com valores médios de carga e descarga de 251 e 181 MW, respetivamente. Em termos de integração de energias renováveis, as baterias deverão permitir uma capacidade adicional de 3581 MW de capacidade fotovoltaica, permitindo uma subida da produção renovável no mix eléctrico de 4%. Relativamente aos benefícios ambientais, as baterias permitem reduzir as emissões de CO_2 em 0.2 Mton, representando 3,4% do valor total de emissões do sistema electroprodutor. Tendo em consideração o cenário com a capacidade adicional de solar-fotovoltaico, a redução de emissões ascende a 32%, evidenciando que o armazenamento de energia nas baterias é mais eficaz no decréscimo das emissões quando se consideram níveis mais elevados de capacidade fotovoltaica instalada. Para o cenário que considera um ano de seca, os resultados permitem aferir que as baterias reutilizadas têm a capacidade de compensar totalmente a reduzida capacidade de armazenamento nas albufeiras, auxiliando a rede quando necessário.

Relativamente à capacidade da interligação internacional, para o cenário base sem armazenamento de energia nas baterias, obtém-se um valor de 8270 MW de capacidade de exportação necessária. No cenário com baterias, este valor decresce para 3810 MW. Desta forma, é possível dizer que as baterias reutilizadas assumem um papel relevante na rede elétrica. No cenário que de ano de seca, não são verificadas quaisquer necessidades de exportação, dado que as baterias têm a capacidade de armazenar toda a energia em excesso. Não obstante, a capacidade de importação necessária é de 2168 MW dada a produção diminuta das centrais hídricas no inverno.

Apesar destes resultados, o fator de capacidade de utilização das baterias deverá ser baixo (cerca de 5%), visto que o sistema electroprodutor português possui uma grande capacidade instalada de bombagem hidroelétrica para armazenamento de energia em albufeiras. Tal sugere que em sistemas onde isto não acontece as baterias terão um papel mais relevante.

Como trabalho futuro, dado que nos cenários testados a capacidade de armazenamento em baterias apenas começa a ser útil a partir de 2050, sugere-se um estudo que contemple mais penetração fotovoltaica, visando aferir de que modo as baterias poderiam facilitar a implantação adicional destas centrais. Este estudo poderá ser feito para vários cenários de regime hidrológico.

Palavras-chave: baterias reutilizadas, análises de sistemas electroprodutores, veículos elétricos, carregamento inteligente, armazenamento de energia

Publications

This master thesis is sustained by the following original publication, reproduced at the end of the thesis.

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List of Acronyms

BMS	Battery Management System
CEEP	Critical Excess Electricity Production
DoD	Depth of Discharge
DGEG	Direção Geral da Energia e Geologia
ECM	Equivalent Circuit Model
EIA	Energy Information Administration
EOL	End-of-Life
EU	European Union
EV	Pure Electric Vehicle
FCAS	Frequency Control and Ancillary Services
GHG	Green House Gases
HEV	Hybrid Electric Vehicle
IEA	International Energy Agency
ICE	Internal Combustion Engine
PHEV	Plug-in Hybrid Electric Vehicle
LCA	Life Cycle Analysis
LCO	Lithium Cobalt Oxide
LED	Light Emitting Diode
LFP	Lithium Iron Phosphate
Li-ion	Lithium-Ion
LMO	Lithium Manganese Oxide
NCA	Lithium Nickel Cobalt Aluminium Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
OECD	Organisation for Economic Co-operation and Development
NREL	National Renewable Energy Laboratory
PNBEPH	Programa Nacional de Barragens com Elevado Potencial Hidroeléctrico
PP	Power Plant
PV	Photovoltaic
REN	Rede Elétrica Nacional
RNT	Rede Nacional de Transporte
RUL	Remaining Useful Life
TSO	Transmission System Operator
V2G	Vehicle-to-Grid
VRLA	Valve Regulated Lead-Acid Battery

Chapter 1 - Introduction

1.1. Framework

The transportation sector assumes a very relevant role in the economy and society, providing market accessibility by connecting producers and consumers so that transactions take place, and offering mobility to people. Notwithstanding, it lacks seriously in terms of environmental sustainability. According to the European Environment Agency [1], carbon emissions from road transportation represent a value of about 18,5% of total European Union (EU) emissions. More worrying, emissions have been growing since 2013 despite the enforcement of CO_2 standards for cars and vans: in 2016, transport emissions rose 2.1% (18,7 Mt CO_2 equivalent) comparing to 2015 and are continuing to rise with 2017 oil consumption in the EU increasing at its fastest pace since 2001 [2]. Additionally, air pollution, mainly urban from vehicles exhausts, is seen as the "biggest environmental health risk" in Europe, killing around 400.000 Europeans each year and originating several billions of euros in health-related external costs [3].

The underlying reason why transport emissions are out of control is that improvements in the internal combustion engines (ICE) efficiency and the penetration of biofuels has not kept pace with increasing demand for transportation. Traditionally, governments are unwilling to introduce unpopular measures to curb car use or flights, whilst increasingly freight movement is viewed as an inevitable consequence of economic growth. Moreover, the EU has incentivized the proliferation of diesel car by giving them fiscal incentives, but those vehicles, even if they emit less CO_2, are much more polluting than the gasoline ones, especially considering the fact that several of those engines emit in real driving conditions plentiful more nitrogen oxides and other pollutants than the legislation allows and the carmakers publish [4].

However, mobility is deeply changing, by and large because electric mobility is taking off. Electric vehicles represent a more sustainable and considerably more efficient technology when compared with the one of conventional combustion engines, and do not have tailpipe emissions. Electric vehicles imply less greenhouse gas (GHG) emissions than diesel cars even when powered by the most carbon intensive electricity [5]. Electric vehicles imply even less emissions as more renewable electricity enters the grid [5]. However, the electric mobility diffusion is slow, largely due to a slow fleet turnover, but also because electric vehicles are yet to achieve cost competitiveness, essentially because their batteries, mostly Lithium-ion based, are still very expensive.

In 2017, the worldwide number of sold cars surpassed 79 million, representing an increase of about 3% over the previous year, existing about 1,2 billion vehicles in circulation [6]. The OECD's International Transport Forum predicts that by 2050 this number will probably reach 2,5 billion. Thus, electric vehicles arise as a possible solution allying their potential in the reduction of emissions of greenhouse gases and in decreasing the dependence of oil. However, the weightiest limitation to the deployment of these vehicles is the battery [7]. Despite representing a viable promising alternative for mobility, electric vehicles carry an arduous environmental issue related with the end-of-life (EOL) of their batteries, since batteries contain materials highly toxic. Logically, the growth of the market share of such vehicles will lead to an emergence of used batteries disposal in the medium-long term. This issue has been proposed to be addressed by repurposing those batteries to provide stationary low-cost energy storage, since retrieving value from those batteries with no more use in automotive service could soften the problems related to battery disposal. Given that these batteries, in most cases still hold approximately 80% of their energy capacity after automotive use, it may be achievable to repurpose them to energy storage and peak-shifting/shaving applications [8]. The repurposed batteries could be employed in single homes, office buildings, factories or in power plants.

The energy produced by non-controllable renewables, essentially wind and solar, faces a challenge concerning its variability in time and need for storage, due to the lack of large scale economically efficient storage systems, besides hydro pumping. In this context, using batteries afterwards their automotive service yields a promising solution at a reduced cost for this challenge. Thereby, by helping in the integration of renewables in power systems, second-life batteries contribute to the environmental sustainability of electric vehicles, if the benefits of this solution are taken into account on the life cycle analysis of the vehicles.

Regarding the availability of renewable energy sources, Portugal is a privileged country having a large wind, solar photovoltaic and hydro penetration. Still, its electricity export opportunities at interesting prices are limited due to the similarity with the Spanish power production profile, emphasising the need to create alternative large-scale storage systems alongside with hydro-pumping.

To enable a market of retired electric vehicles (EV) batteries, the development of effective business models is imperative. A fast market penetration of EVs is hugely restricted by the cost of batteries. Likewise, the development of grid-connected battery energy storage systems, which could increase the grid reliability and renewable energy use, is similarly conditioned by the cost of batteries. This issue has been mitigated by lower material costs, enhanced process efficiencies and by a significant increase in production volumes, leading to economies of scale [9].

1.2. Motivation and objectives

In the context presented above, used batteries of electric vehicles may represent an opportunity for their reuse for energy storage either in domestic use or by direct coupling with renewable energy generation systems. However, there are few studies, or none, addressing the impact of this solution in large scale renewable based power systems. To fulfil this gap in the literature is what has motivated this work, leading to the research question: What role can electric vehicles second-life batteries have on renewable based power systems? The purpose of this dissertation is thus to analyse and simulate energetically and environmentally the reuse of electric vehicles batteries as stationary energy storage applications. The Portuguese power system is used as case study; it already presents a significant share of renewable energy – c.a. 50% –, mostly hydro and wind. The main objectives are:

1. to assess the extent to which the incorporation of renewable energy can increase in the portuguese electric mix by using the second-life batteries, as well as the extent to which CO_2 emissions can diminish;
2. to evaluate how the incorporation of the second-life batteries can reduce energy in excess and decrease the interconnection needs, allowing a greater autonomy of the Portuguese power system.

This study couples a model of electric mobility diffusion and second-life batteries availability with various EnergyPlan simulation models for the period 2030-2050. The model allows to identify the role that the repurposed batteries may have in the system operation, and in what way they may represent a benefit by enabling a larger share of renewable energy in the system.

1.3. Dissertation structure

The present dissertation is structured in five sections.

Section 1 introduces the theme as well as the thesis' objectives and motivations.

Section 2 summarizes the state of the art, focusing in the main concepts covered in the document. The most relevant concepts addressed are related to lithium-based batteries and their several applications (including stationary energy storage) and their life cycle costs, including the ones of repurposing processes. An environmental point of view is presented, as well as some upcoming projects and recent success cases.

Section 3 presents the methodology. It includes a short description of the computation tool that was adoped, EnergyPLAN, and the model operation. The procedure that was followed to simulate the introduction of second-life batteries in the electricity system is then presented, as well as the scenarios. It also characterizes the case study, i.e., the Portuguese power system correspondent to the reference scenario (2014), as well as the future scenarios in which this study is based (2030-2050).

Section 4 summarizes the main findings of the study and the respective discussion.

Section 5 presents the conclusions, limitations and future prospects for work in this area.

Chapter 2 – Stationary Battery Energy Storage

This section covers the general aspects of battery-based energy storage systems, aiming a better understanding of the concept.

Energy storage is an indispensable component of modern sustainable power systems, contributing to solve the intermittence of renewables whilst simultaneously allowing individual energy prosumers to achieve significant levels of auto-consumption, savings and revenues, by selling energy to the power grid at times of price peak. In this context, Lithium-ion batteries have been gaining relevance, both to utilities and to domestic consumers; the Tesla power wall to store energy in excess produced by home solar photovoltaic panels is an example of the new products and solutions that are entering the market in this field [10].

From a power system perspective, the value of storage in battery banks is the ability to provide power quality, reliability and security of supply. Among many uses, this can be in the form of uninterrupted power supply to end-users, e.g. providing some reserve margin or initial power to restart the grid after a blackout [11]. An ideal energy storage system or setup should be safe, efficient, reliable, tolerant to fluctuations of external parameters as temperature or humidity, energy and power dense, long-lasting and of low maintenance. Due to their high energy density, EVs Li-ion batteries can be employed in a vehicle-to-grid (V2G)[a] dynamic, in which electric vehicles batteries charge during off-peak hours and help to support the grid during peak hours. Such combination of applications may represent a market driver for electric vehicles. The Lithium-ion technology with emphasis to its application in the auto industry is further addressed below.

2.1. Lithium batteries

The Lithium-ion batteries is a technology applied to pure electric vehicles[b] (abbreviated in this thesis interchangeably PEV or, for the sake of simplicity, EV), hybrid electric vehicles[c] (HEV) and plug-in hybrid electric vehicles[d] (PHEV) since 2009; their market has been growing mightily since then, and the trend is to stay that way. Their technical features, as mass, lifespan or power density, assume a relevant role when it comes to manufacturers and consumers to opt for this technology.

Electrochemical batteries, in generall, are made of two electrodes (the anode and cathode) and a substance in between called the electrolyte [11]. In the case of lithium batteries, the lithium ions move back and forth the anode and cathode as the battery charges and discharges. Lithium-ion batteries comprise a family of chemistries that employ various combinations of materials, which make the battery able to produce more power and store more energy than most of the alternative technologies.

Commercial lithium-ion based batteries are named after the donator in the cathode, as several lithium metal oxides are used, such as lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). Lithium nickel cobalt aluminium oxide batteries have a remarkable energy density

[a] V2G describes a system in which there is capability of controllable, bi-directional electrical energy flow between a vehicle and the electric grid. Electric energy flows from the grid to the vehicle to charge the battery, and flows in the opposite direction when the grid requires power;

[b] Electric Vehicles are propelled by a battery-powered motor, and the battery is charged by plugging the vehicle into the electric grid;

[c] A hybrid vehicle uses the combined efforts of both a gasoline engine and a battery-powered electric motor to drive the vehicle;

[d] A PHEV works like a regular hybrid, but with a major alteration to its battery that has a much higher capacity.

of 200-250 Wh/kg, being capable to perform 1.000 to 1.500 full cycles. This type of batteries is used, for instance, in the Tesla car models [12]. Within all the lithium chemistries, the most promising for the future seems to be the one based on $LiFePO_4$, suited to large capacity applications given that it is safer and life-longer when compared to others of the same typology. Current $LiFePO_4$ batteries endure up to 2.000 full cycles and tolerate wide state of charge windows (15-100%), with the cells showing constant voltages within this interval. This battery chemistry is the one presenting higher potential for use in power systems, both off- and on-grid.

Comparing Li-ion batteries with the common lead acid batteries (VRLA), Li-ion batteries present an average value of volumetric energy density of 250 Wh/l against 100 Wh/l for lead acid batteries; Li-ion gravimetric energy density is in the 100-250 Wh/kg range, while lead acid's is 25-40 Wh/kg; concerning the operating temperature interval, Li-ion batteries can withstand a wider safely temperature between 0 and 40°C, contrasting with the restricted temperature value for VRLA rounding 20°C to 25°C [11].

According to Diouf and Pode [13], other meaningfulness advantages of Li-ion batteries are related to an higher energy efficiency, longer lifespan (lead acid batteries last about only 500 charging-discharging cycles) and no memory effects. Moreover, Li-ion cells present a flat discharge curve that allows an effective use of the stored energy while maintaining the voltage practically constant.

Amongst disadvantages of Li-ion batteries, one pertains the charging time, given that Li-ion cells are very sensitive to overcharge and need a long time to be safely charged. Therefore, to ensure a safe operation of these batteries, it is necessary to protect them with an electronic circuit, given that this technology does not tolerate total discharge or overcharge, posing security issues under those circumstances, such as explosion and fire.

Li-ion batteries additionaly exhibit two main advantages comparing with lead acid batteries, being them lower life cycle cost and higher lifespan. In fact, when considered their lifespans, the cost per cycle can be significantly lower for Li-ion batteries relatively to lead-acid batteries. Given this and the above mentioned, Li-ion batteries are widely spread among the consumer electronics market such as cell phones, laptop computers and other portable electronic devices.

In spite of presenting so many advantages, Li-ion batteries are still expensive when comparing to other technologies. At the time Li-ion batteries were released on the car market in 2009, their cost was around 560 €/kWh, and in 2015 was around 385 €/kWh, contrasting with 182 €/kWh of lead acid technology [14]. By 2020, this cost should drop to half of the intitial one, i.e., 280 €/kWh [13]. Further increased demand and economies of scale are expected to bring prices further down [15].

In order to make the technology more affordable and spread it, it is necessary to develop the industry and production volumes, achieving economies of scale and cutting down the cost of rechargeable lithium batteries. Some of these parallel industries include the consumer electronic industry, military, space and medical applications and the current photovoltaic market.

In developing countries where it is verified a larger number of batteries given that normally photovoltaic systems are off-grid, they are less affordable due to the low revenues of populations. Instead, in most developed countries exist grid-tie systems not requiring the utilization of batteries because the produced energy is injected in the grid through a controller. This type of policies contributes to the encouragement and acceleration of the photovoltaic industry and hence, to a mass production leading to a price reduction. This fact represents a relevant confinement to the market of Li-ion batteries, impeding its mass introduction and usage as primary storage systems in renewable energy [13].

Nevertheless, currently, the most significant booster to the development of Li-ion batteries is the electric vehicles market. Some recent forecasts show that by 2020 about a half of new vehicle sales in some markets will consist of EVs, HEVs and PHEVs. The majority of hybrid vehicles in circulation utilizes NiMH batteries. Within a decade, it is expectable that among new vehicles 70% of hybrids and all of the plug-in hybrid and full-electric vehicles will use Li-ion batteries [16]. Thus, the future of renewable energy can be strongly connected with the electric mobility. Li-ion batteries are the most appropriate for electric vehicles due to their higher energy and power densities. Such features make these batteries smaller and lighter than other rechargeable batteries considering the same storage capacity [17].

Therefore, in spite of its incomparable and undeniable technical and feature advantages, it is extremely decisive that the cost be adjusted in order to achieve a more pronounced market penetration. To emphasize this fact, it is relevant to underline that the cost of a Li-ion battery is four to eight times the price of lead-acid and one to four times the price of NiMH [16]. Regardless of this fact, it is expected that such prices will decrease substantially due to the increase utilization of Li-ion batteries for several applications like medical equipment, consumer electronics, other backup power supplies and so on.

Amongst the cost reduction owing to the mass production, it is possible to decrease the Li-ion batteries price due to the amelioration of its design. So, as there are many possible applications, there will be different costs according to the requirements for different output needs. In Li-ion cells composition, thicker electrodes will provide higher energy densities and thinner electrodes will offer higher power densities due to the kinetic of electrochemical reactions that occur there. It is important to note that the manufacture of thinner electrodes is more expensive and to soften this question, the deployment of materials that allow thick electrodes and simultaneously attain the power requirements is imperative. Concerning production, all Li-ion cells are fabricated based on the same procedure but in the batteries manufacture, there are differences in the battery management system.

2.2. Li-ion batteries for stationary energy storage

By way of example of the usefulness of this technology, on the topic of public lightning using solar systems, this typology of batteries owning technical characteristics as no requirement of maintenance, longer lifespan and high energy density, may assume a preponderant role in city planning. Moreover, it is feasible to incorporate the battery in a light pole for public illumination while in lead-acid batteries it is necessary an extra storage box to contain it, given that the occupied volume of such batteries is about 5,6 times the Li-ion ones. Considering a density of about 3,5 times lower to VRLA and a depth of discharge (DoD) of 50%, 30% less than for Li-ion, the technical and performance advantages are notorious for Li-ion batteries, evidencing relevant aspects of cost in city management. Hence, modern solar streetlights are constituted by a LED lamp and a lithium battery pack aiming long life spans and high efficiencies [13].

Another example of application is considering off-grid solar home systems since on deep discharge it is possible to reach about 5.000 cycles leading to a system with 20 years of utilization without the requirement for maintenance ant theoretically with no electric bill to pay. Taking into account that lead-acid batteries present a lower lifespan and low power density, it is notable the benefit of using Li-ion batteries instead, despite their initial cost [17].

Grid storage is another sector that raises interest in which the energy is used to support the grid in case of immediate need at any moment in time and as such, Li-ion batteries can be adhibited to this purpose. The applications can vary between micro-grid or simply as grid assistance in peak consumption hours, accommodating peak loads. Generally, using rechargeable batteries in storage systems leads to a better integration of renewables to the energy grid. Such utilization may originate improvements in grid stability, reliability and associated costs [15]. Z. Ghassan et al., [12] presented an overview of the energy storage cost of Li-ion batteries taking into consideration different specific costs, cycle life and different utilization times, with one or two cycles per day. Battery bank specific costs were assumed to range from 100 to 300 €/kWh. The results were split in three groups, from the less competitive to the most competitive for grid-connected use. The less competitive storage costs were above 15 c€/kWh, the intermediate costs were around 10-15 c€/kWh and, the most competitive costs were below 10 c€/kWh. This last cost range would, for instance, allow the purchase of base-load power at 5 c€/kWh and sale at 15 c€/kWh during peak hours, replacing units as diesel generators. Battery banks with specific costs between 100 to 200 €/kWh showed the most competitive values. The essential conclusion is that Li-ion batteries for grid-connected use will be cost competitive if specific battery-banks costs are under 200 €/kWh with a lifetime above 2500 cycles. The study projections highlighted that Li-ion battery will, with high probability, reach storage costs of 7 c€/kWh, representing a positive long-term perspective.

In short, it is important to point out that either lead-acid or Li-ion batteries offer advantages and disadvantages for stationary storage applications. So, to opt for one of the technologies, some relevant factors must be taken in consideration as the initial cost with the installation included, the lifespan, weight and volume, temperature sensitivity, maintenance, among other less relevant aspects.

2.2.1. Stationary energy storage pilots

Along with other success cases, it is important to give emphasis to a 5 MW demonstration project of Li-ion storage system, released in 2013, in Oregon, USA, that will allow the storage of the excess electricity occasionally produced by some intermittent renewable energy sources, such as wind and solar. The purpose of this experimental project is to make electricity grids smarter and to facilitate and promote the integration of renewable sources of energy. The operation principles are quite simple with the storage system responding to regional grid conditions with the support of the demonstration transactive control. The participants can decide the way their project can provide help to local or regional need due to the automated signal. Therefore, this technology helps power producers and users to decide the amount of power that will be consumed, where and when [18].

More recently, in the Portuguese Azores Island, Graciosa, a hybrid renewable system was initiated in 2016. The project, with a 24 million € investment, counts with a 2,6 MW battery storage capacity installed in the pre-existing wind farm with an installed capacity of 4,5 MW. The project also includes the development and installation of a 1 MW photovoltaic plant, allowing the island to become practically independent of non-renewable energy sources, with a prediction that 65% of the produced energy may be from renewables. The energy management is made by a software developed by the German company Younicos, which allow to dispense the existing thermal power plant operation by using the energy stored in the batteries to provide an uninterrupted energy supply to the island [19].

Currently, the largest battery stationary storage in the world, is Tesla's 100MW/129MWh powerpack project in South Australia, which operation began in December 2017 [20]. The project cost approximately 66 million A$ and it has reached a 17 million A$ revenue during its first six months of operation. The main purpose of this Tesla project is to stabilise the South Australian electricity grid, facilitate integration of renewable energy and help in preventing load-shedding events [21].

When a deficit energy production situation occurs, or maintenance is required on the power grid in Australia, the Energy Market Operator (EMO) calls for frequency control and ancillary services (FCAS) which consists of large and costly fossil fuel-powered generators and steam turbines backup systems. The Tesla Battery system is able to provide the same service at a lower cost, quicker and with zero emissions. For instance, when a production drop by a coal power plant occurred on December 14, the Hornsdale Power Reserve (HPR) system stepped up in 140 milliseconds to maintain the normal grid performance [20].

In terms of the system operation, under normal conditions, 30 MW of the battery's discharge capacity is provided to the operator of the near Wind Farm (NEON) for commercial purposes in the National Electricity Market (NEM). The remaining 70 MW of battery discharge capacity is used for power system reliability purposes. The HPR system was configured to provide a FCAS response at any time. Data provided by Australian Energy Market Operator (AEMO) demonstrates that the regulation FCAS provided by the battery systems is rapid and precise, being able to respond promptly to a contingency situation, compared to a conventional synchronous generation unit [22]. According to the Australian Energy Week [23], the new system allowed to decrease the price of power outages by 90%, suggesting cost savings around 35 million A$ to consumers in the first four months of the Tesla system operation.

All the achieved success with the project operation led to several other projects contracting Tesla to install more powerpacks around Australia. The next project to be implemented is a 25 MW/50 MWh battery system that will be co-located and integrated with the 60 MW Gannawarra Solar Farm in Victoria [24].

2.3. Battery repurposing

2.3.1. Availability of lithium-ion batteries for repurposing

As mentioned in the introductory part of the present review, Li-ion batteries may acquire a second use for energy storage purposes considering an assurance that the cycle durability improves substantially.

The number of batteries available for repurposing after the automotive service can be predicted from the number of EVs and PHEVs sales forecasts over the desired time. A study conducted by M. Foster et al. [25], categorized the multiple forecasts in three different categories: a pessimist view, an optimistic view and a middle view. The optimist and pessimist views are both based in statistical data and analysis for future electric vehicles demand provided by the Energy Information Administration (EIA) and by the International Energy Agency (IEA). Figure 1 shows the predicted battery availability considering the middle view.

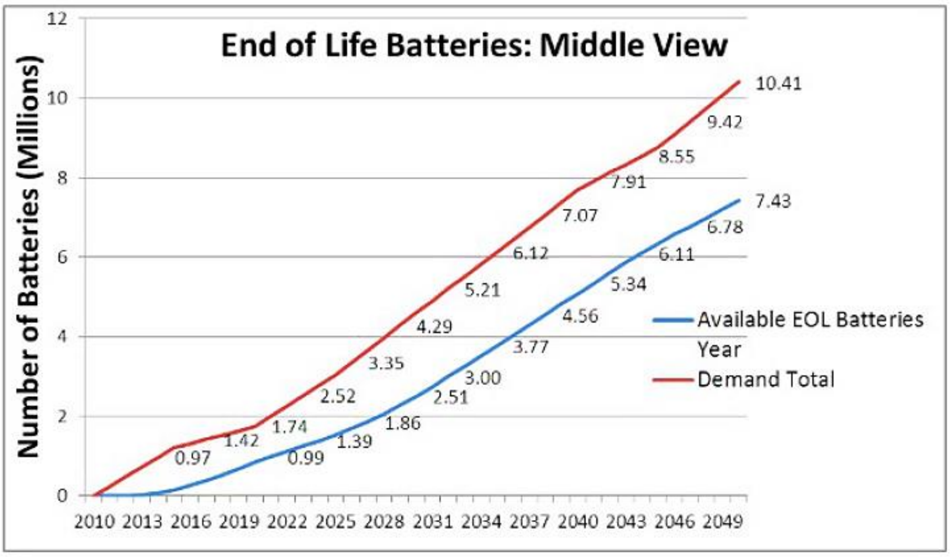


Figure 1: Availability of electric vehicles used batteries between 2010 and 2049 [25].

2.3.2 Cost-benefit analysis

After the end of automotive use, the battery can follow three paths, being them, remanufacturing, repurposing and recycling. M. Foster et al., [25] established a cost-benefit analysis for each path and studied each one independently of the remaining others.

Aiming one of the three paths above mentioned, it is need a sufficient availability of batteries. It is predicted that the available number of lithium-ion batteries for these purposes may overcome 3.000.000 by 2030 accompanied by a 50% of new vehicle acquisition.

2.3.2.1. Remanufacturing

A possible way to reduce costs on acquisition of electric vehicle batteries is to use remanufactured batteries instead of new ones. This process may avoid costs due to the production of new batteries and it encompasses a partial disassembly of the battery, removal and replacement of cells and the reassembly of the battery pack. Data from 2013 [25] show that the production costs for a new battery pack round a value of 9.000 € and for a remanufactured battery 2.000 €.

After removing the battery, a subsequent quality analysis of the different components is performed. This quality analysis is based on components test and on analysis of the data stored in the battery management software. From an economic standpoint, disassemble the battery into cells and analysing them separately is not economically feasible, as they increase the workload. Thus, some battery components as the battery management system, sensors, among others, can be reused and remanufacturing costs can be reduced.

A scarcity of remanufacturing processes for retired Li-ion batteries from electric vehicles is verified nowadays. It is still necessary to implement and deploy capable infrastructures to the remanufacturing process with all the methodological procedures required. Studies such as the conducted by S. Martínez [26], aiming the implementation of these plants, report that remanufacturing is feasible to be carried out obtaining savings of 45% less than the cost of a new battery.

According to pilot projects conducted by NREL, remanufacturing costs lie between 25-50 €/kWh and are highly dependent on the type and state of the battery, the scale effects and the remanufacturing process [11].

2.3.2.2. Repurposing

The concept of repurposing electric vehicles batteries after their automotive use is relatively recent as it as has been addressed throughout the present review and the most common application for those retired batteries is for energy storage systems. Repurposing batteries offers several advantages and has potential to decrease battery lifecycle costs.

The repurposing process may be complex given that a dismantling of the batteries into individual cells is required. Then, a new assembly is needed, putting the cells into configurations nothing similar compared with a vehicle application, emphasizing that each different configuration requires a new and specific design. A study in this field, carried out by Gaines and Cuenca [27] computed that the development of a repurposed lithium-ion based storage system could vary between 42 and 129 €/kWh.

More recently, in 2012, Neubauer and Pesaran [28] have published a more in-depth study allowing a more accurate calculation of second-life batteries purchase. The methodology proposed by the authors allows the battery salvage value estimation when retired from the vehicle. This parameter represents the maximum possible value to the batteries when used for second-life or to recycling applications. Therefore, the following equation (1) represents the calculation of S[€], the salvage value of the retired battery as a function of the acquisition cost of a new battery, C_n[€], a health factor, K_h, a used product discount factor, k_U, and the refurbishment cost, C_{rp}[€].

$$S = \max\left(K_u K_h C_n - C_{rp}\right) \quad (1)$$

The health coefficient above-mentioned expresses a ratio between the provided energy in a used battery, PVT_U [kWh], and in a new battery, PVT_N [kWh], operating on similar conditions. Thus, this parameter is defined as follows Equation (2):

$$K_h = \frac{PVT_U}{PVT_N} \quad (2)$$

According to the calculations performed by Neubauer et al., the estimated market price for second-life Li-ion batteries varies between 38 and 154 €/kWh. The authors also verified that DoD small differences can have a significant impact in the health factor, diminishing the second-life battery lifespan and therefore, decreasing the market price. In economic profitability terms, the integration of second-life batteries in stationary applications, according to a new study of Neubauer et al. [29], verified that the use of second life batteries replacing peak plants, as natural gas based, is a viable application.

Assunção et al. [30], established a technical and economic assessment of the reuse of electric vehicles batteries for storage applications in the residential sector with electric production assured by PV. To perform this study, a typical Portuguese household was considered with an average consumption of 10 kWh/day. Thus, to make sure the production level is sufficient to reach the consumption needs, a PV system with 2,4 kW_p capacity was considered. One of the models analysed was the battery of a Nissan Leaf vehicle, given that it holds the biggest market share and offering an output power of 90 kW. In a typical residential building in Portugal, the peak power is normally below 6.9 kVA. Therefore, the battery pack can fulfil the storage needs for the average household even when considering the 80% loss in capacity.

According to the estimations performed by the authors, after 10 years of second-life use, the Nissan Leaf battery, contains 10,92 kWh of its initial capacity of 24 kWh, a value still above the daily consumption above-mentioned.

The results showed a reduction of 82,1% in the energy injection in the first year. For the fifth year of operation, a reduction of 82,8% and for the tenth, a reduction of 79,7% was verified. Thus, the use of these battery packs can offer technical and operational benefits in terms of energy exchange with the grid, even after 10 years of usage. From an economic profitability point of view, the payback period for reusing the Nissan Leaf battery showed a value of 9,53 years. The conclusions drawn by the authors for reusing electric vehicle batteries point out the technical and economic benefits for the end user, showing and supporting the batteries repurposing for residential energy storage with a PV generating system. Results showed the cost-effectiveness of this system when compared with new battery packs, emphasizing the advantages of reusing batteries for residential storage applications.

When the packs are being used to store and shift electrical energy, the charge and discharge efficiency critically determines whether energy storage will be cost-effective. Additionally, as energy prices vary geographically and by time of day, the usefulness of repurposed packs for energy storage also varies. There is scant information about the performance of electric vehicle battery packs at the end of their life in vehicles. This means that the reliability and future performance of the repurposed batteries is uncertain. It is important to consider the risk of fire and explosion associated with the use of Li-ion batteries for energy storage systems. Given that in large stationary applications there will exist more battery packs, this risk must be taken in consideration.

There is still some uncertainty regarding the demand for Li-ion batteries and as such, the cost-benefit analysis and forecasts have a significant degree of errors associated. None the less, and although these applications are not completely matured, they offer a window of opportunity to diminish battery costs and to reuse them after the end of their vehicle useful life.

Several studies were analysed regarding this topic and some factors were identified as main sources of error in cost-benefit analysis. Cost structures (second life battery acquisition costs and market prize, refurbishment costs), revenue streams (electricity prices, rate structures), technical parameters (second-life battery lifespan, power, capacity, efficiency), policies and market conditions (environmental initiatives, governmental subsidies) are the most relevant causes for uncertainties in the calculations performed so far [31].

2.3.2.3. Recycling

The environmental benefits from recycling batteries are evident given that less raw material is needed, as well as the economic benefits that it entails. It is important to note that the advantages can vary with the recycling method and even with the battery type.

Regarding Li-ion batteries, the arising question is addressed to the procedure and it is still in a development status. Although, recycling processes for lead-acid batteries and Nickel–metal-hydride present a favourable state of maturity and thus, some similarities and procedures may be transposed to Li-ion batteries recycling. After 10 to 15 years of second use, batteries can be collected and recycled.

To make the recycling process economically viable, an increase in the lithium salts to about 85€ per kg due to a scarcity of new lithium is needed [25]. Recycled lithium is about five times the cost of lithium produced from the least costly brine-based process. As lithium prices are currently low (rounding 25 €/kg) [32] [33], almost none of the lithium used in consumer batteries is completely recycled. However, with the EV market growing so meaningly, recycling is expected to be an important factor for consideration in material supply for battery production [11].

2.3.3 Environmental impact of battery repurposing

Taking in consideration the environmental awareness, an analysis of the environmental impact is essential to assess and emphasize the feasibility of reusing electric vehicles depleted batteries. Therefore, one of the most relevant factors to consider battery repurposing is precisely the environmental benefits it offers.

The reuse of EV batteries in second life applications can avoid the manufacture of new batteries and the use of polluting power plants as coal or natural gas. The life cycle of second-life batteries is schematized in Figure 2 [34].

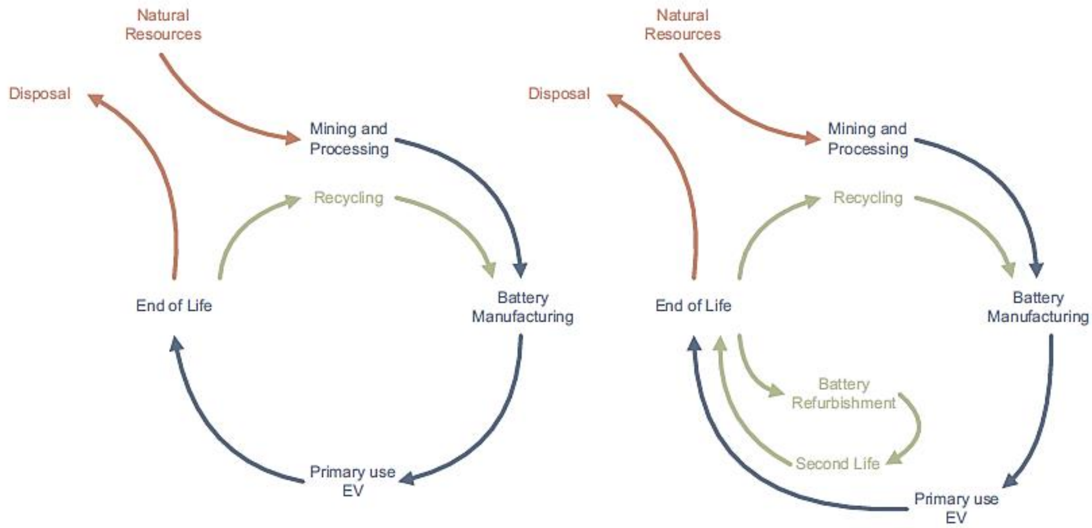


Figure 2: Life cycle of a EV battery (left); Life cycle of EV second-life batteries (right) [34].

Within the scope of this topic, several studies were performed in order to assess the environmental impact of second-life batteries. Cicconi et al. [35], compared the technical performance and environmental impact of a new battery pack and a reused battery pack in a smart grid application responding to peak demand requirements. In this work, a Life Cycle Analysis (LCA) of both an EV and PHEV battery packs was designed considering the complete lifecycle since raw material extraction to final disposal, including the manufacturing phase, transportation phases, the whole use phase and finally, the disposal. Authors evaluated the environmental impact in terms of global warming indicators [CO_2 eq.], acidification [SO_2 eq.] and eutrophication [PO_4 eq. or N eq.].

The results from this LCA evidenced a reduction of environmental damage of 25% in the second-life (Smart Grid) application compared to the normal EV/PHEV lifecycle. The conclusions of the study highlighted that second-life use for EV/PHEV retired batteries is technically and environmentally feasible.

Sathre at al. [36] developed a parametric life cycle model to describe the interrelation flows of a EV battery system in California. The authors focused their study in second-life batteries potential to increase the grid penetration of intermittent renewable energy sources and its impact in greenhouse gases emissions. One of the assumptions made considered the batteries were solely charged by renewable sources. The evaluation of GHG emissions accounted three essential factors: battery charging, cooling and transportation. The results showed a decrease in emissions of about 7 $MtCO_2$ eq. per year only in California, corresponding to 1,5% of the total emissions registered currently. Other relevant conclusion from this study points out that the cell failure and first life EOL criteria represent the principal factors influencing the environmental impact mitigation.

According to several publications and experienced methodologies, the reuse of EV retired batteries for energy storage systems showed a notorious environmental benefit in a vast set of applications, evidencing significant GHG emissions reduction. Also, when focusing in avoidance of new Li-ion batteries manufacture, natural gas or coal-based plants, this usage of second life batteries assumes an important role in environmental impact mitigation.

2.3.4 R&D projects and success cases

In section 2.2, some successful cases using new Li-ion battery-based storage systems were presented, showing the main benefits of this technology for storage applications. In this section, future projects and concrete second life battery systems already in operation will be introduced.

In 2015, five retired battery packs from Chevrolet Volts were placed in General Motors new Enterprise Data Centre in Michigan, providing enough electricity to keep the facility lights. Along with the storage system, two wind turbines with 2 kW and a 74 kW photovoltaic array were installed, achieving a 100 MWh/year electricity production, enough to supply the whole building. The used Chevrolet Volt batteries, wired in parallel, have the capacity to supply the office building for more than four hours in case of energy failure [37].

In the same year, Renault together with Connected Energy Ltd, created the E-STOR application, using retired EV batteries from the car manufacturer for second-life energy storage. E-STOR was launched and it is available in UK since 2016 and presented a 50kW/50kWh capacity. This new energy management system presents several applications to store energy generated from solar panels and wind turbines, being released later when necessary. The new system also allows the users to reduce their energy bills since batteries can be charged in low-cost off-peak tariffs. Emphasizing the project relevance, in June 2015, E-STOR won the innovation category in British Renewable Energy Awards [38].

BMW is also using vehicle battery packs for energy storage projects. Half way through 2016, a BMW and Vattenfall partnership created and developed a residential 26,4 kWh second-life battery storage system, made with BMW i3 used batteries to store the excess PV production from households. The developed system was oversized to a 27 kW rated power to fulfil customer needs and optimize own consumption. It also allows to decrease grid impact and contributes to grid stabilization in terms of primary frequency control aiming a better balance between production and consumption [39]. In 2018, a new project also using i3 battery packs is connecting to the UK National Grid and has become one of the largest to date. The storage system consists of six containers with about 33 kWh 500 battery packs each. The 22 MW facility was installed at onshore wind farm Pen y Cymoedd and it allows a hybrid renewable energy and storage asset creation [40].

Recently, at the end of June 2018, a 3MW battery storage unit was opened at the Amsterdam Arena aiming to turn the building more energy efficient. This unit is constituted by 4.200 solar panels placed on the stadium roof and the project belongs to Nissan and Eaton counting with the equivalent to 148 Nissan LEAF batteries between second-life and new electric vehicle batteries. The Amsterdam Arena represents the largest storage system using retired EV batteries in Europe, being able to power thousands of households in the city. This initiative has clearly made the stadium more sustainable representing an example to follow in introducing smart energy strategies [41].

Also in June 2018, Hyundai announced a project to build energy storage systems with used EV battery packs. The Korean automaker is already developing a demonstration project, a 1 MWh second-life battery storage system using Hyundai IONIQ and KIA Soul retired battery packs [42].

Chapter 3 – Methodology

This chapter presents all the approach followed in this work as well as the simulation tool used, the EnergyPLAN. It is composed of two main parts: (1) the model basis, which presents essentially the system characterization and simulation procedures, and (2) the scenarization.

3.1. General model setup

The foundation of the methodology followed in this thesis is based on the work developed by Nunes et al. [43], whose aim was to explore the possible complementarities between wind and solar power and electric vehicles charging, based on 2050 scenarios for Portugal, where EnergyPLAN [44] was used as simulation tool. The power system scenarios for the previous years were based on the projections in Ref. [45], based on the same approach. These scenarios were created based on a calibrated simulation model of the Portuguese power system also by Ref [45].

In Ref. [45] the year 2014 was considered as the reference year, as it was at the time the most recent year with the detailed data needed from REN (Rede Elétrica Nacional), the TSO, and DGEG (Direção Geral de Energia e Geologia), the national energy authority. The reference year corresponds to a year whose data allows to describe and represent the current panorama of the Portuguese electricity system, as well as verify the validity of the model.

This work is built upon this, mainly differing as it additionally incorporates a detailed stationary battery storage modelling. In order to evaluate the availability of batteries for storage applications it was need to, firstly, based in a set of assumptions, project the market penetration of electric vehicles in Portugal for the considered period, and, secondly, to obtain the scrappage curves to assess the effective number of available batteries to repurpose. Therefore, a battery availability scenario was created, and several changes were made to the pre-existing models in order to simulate the integration and use of the batteries in the system.

A summary of the general approach applied in this work is further presented below; additional details are given in the sources mentioned above. As for the stationary battery storage modelling, it is fully detailed.

3.1.1. EnergyPLAN

The simulation tool adopted, EnergyPLAN, was developed and is maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. Currently, it is widely used by researchers and policymakers worldwide. It is based on analytical programming, allowing a fast performance. It simulates the energy system as a single node.

The program is able to simulate the operation of the entire national energy systems on an hourly basis, including the sectors electricity, heating, cooling, industry and transport.

The key purpose consists in modelling a wide variety of options so a comparison with one another may be performed, instead of modelling an optimum solution. The use of such methodology allows to analyse the energy, environmental and economic impact of various energy strategies and to demonstrate a set of options for the energy system.

The model provides a choice between different regulation and merit order strategies for a given system, allowing two types of analysis: technical and market based. The modelling in the previous work and also in this one was made using the technical analysis. Such approach was chosen because the objective is to analyse the evolution of the Portuguese power system from the technical viewpoint and the role of batteries in the grid dynamics.

In the technical mode, EnergyPLAN optimizes the energy balances according the following merit order: 1. - non-dispatchable renewables; 2. – dispatchable renewables, e.g. large hydro; 3. - thermal power plants, with priority to the less carbon intensive ones. The model allows to set minimum capacities for dispatchable plants to compensate fluctuations by renewable production. [46].

In this thesis, only the electricity and transport sector modules were used.

The model approach is schematized in Figure 3.

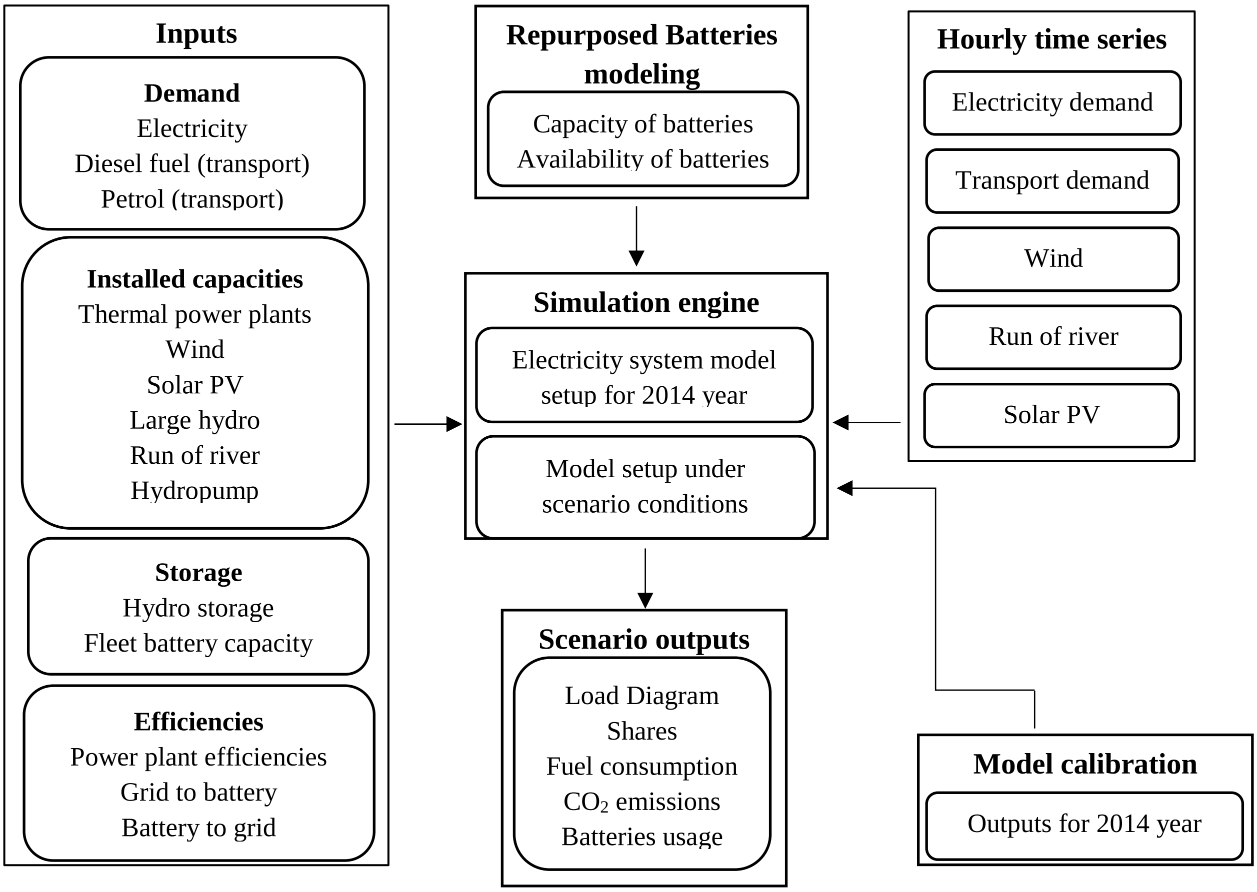


Figure 3: Model approach.

3.1.2. Base model

As mentioned above (c.f. Section 3.1), the year 2014 was considered as the reference year. This section describes the 2014 Portuguese EnergyPLAN power system model, built upon historical data respecting that period.

In 2014 the electricity consumption was of of 48,8 TWh. The power peak, 8.313 MW, was recorded on February 4th, about 1.000 MW less than the all-time high, recorded in 2010.

The total installed capacity in the Portuguese power fleet was, at the end of 2014, 17.8 GW. Renewable generation supplied 62% of the consumption. Hydro generation was 27% above the average, due to plentiful of rain, supplying 31% of demand. Wind generation also presented exceptional conditions,11% above average, supplying 24% of consumption. Biomass supplied 6% and solar photovoltaic power supplied 1% [47]. Figure 4 shows the production distribution per source.

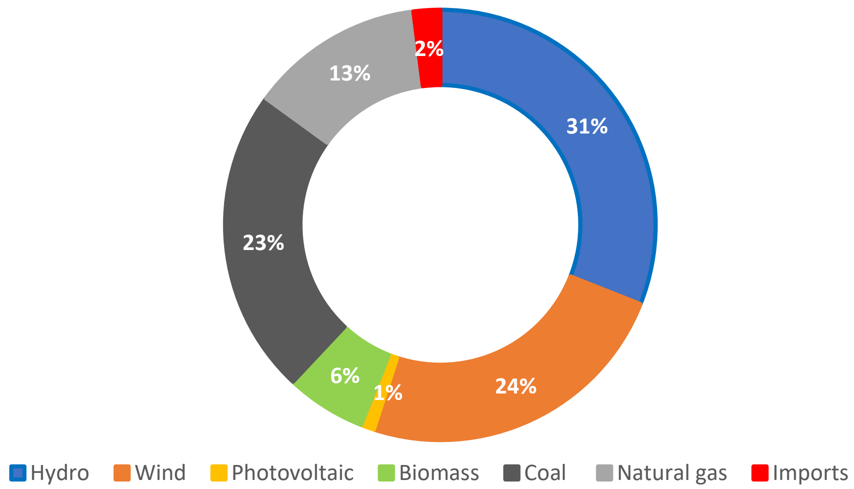


Figure 4: Portuguese 2014 electricity mix.

Along with the installed capacity of each power plant, the EnergyPLAN also requires data from annual primary energy consumption per source. In 2014 it was 13,16 TWh for natural gas, 6,95 TWh for biomass and 32,33 TWh for coal. The annual water inflow to the large hydro reservoirs, a key parameter, was of 7,13 TWh.

For each of the above-mentioned production units, the corresponding input efficiencies are shown in Table 1.

Table 1: Efficiencies of each dispatchable production unit.

Production Units	Efficiency [%]
Thermal Power Plants	40,0
Natural Gas	43,0
Biomass	40,0
Hydro with reservoir	80,0

As for non-dispatchable power plants, EnergyPLAN also needs the hourly distribution that represents production for each of these units. In the reference year, only run of river, onshore wind and solar photovoltaic plants represent non-dispatchable plants. Hourly distributions were created upscaling 15' time-step data from REN [47]. Again, each distribution was normalized.

The installed capacities per technology, both dispatchable and non-dispatchable, are presented in Table 2.

Table 2: 2014 base model: installed capacities per technology.

	2014
Total [MW]	17.776
Renewable	11.230
Hydro	5.693
Wind	4.541
Biomass	600
Cogeneration	342
Solar	396
Non-Renewable	6.546

Coal	1.756
Natural Gas	4.702
Cogeneration	873
Others	88
Cogeneration	75
Pumps	1.253
Dispatchable Power Stations	10.856
Non-Dispatchable Power Stations	6.920

EnergyPLAN allows the user to choose between several energy storage systems. For 2014, only hydroelectric plants with pumping were considered to provide storage. Thus, the model requires the reservoirs storage capacity, including their pumping power and efficiencies. Based on Ref. [47] and Ref. [49], at the end of 2014 Portugal registered a storage capacity of 3.093 GWh. The pumping power was 1.463 MW at the end of th year and the pumping efficiency around 80%.

3.1.3. Calibration

The calibration procedure validates the energy model. This process, iterative, is made referring to a past period (2014) in which some adjustments take place and whose goal is to obtain similar outputs to the historical parameters. The main variables to be calibrated include the annual electricity consumption, annual net production by technology, renewable energy sources penetration, annual consumption by primary source, average monthly electricity consumption load and CO_2 emssions.

The model is assumed as valid when the monthly and annual differences between real data and the model do not exceed 10%. In this case, the average annual errors were: 0,12% in electricity consumption; 3,09% for electricity production from all energy sources; 0,44% in the primary fuel consumption; and 0,30% in GHG emissions [45].

3.1.4. General inputs

As Figure 3 showed, a set of inputs must be included in the model, as follows: (1) annual energy production by source; (2) final energy demand; (3) primary energy demand; (3) installed capacities per technology in the power fleet; (4) large hydro energy storage; (5) water inflow to the dams; stationary energy storage; efficiency of each technology; (6) time distribution of power demand, generation and transport needs.

The time distribution is composed by 8.784 data elements representing a typical leap year. Each distribution element varies between 0 and 1, i.e., it corresponds to an adimensional value that represents the quotient between the instantaneous value (hourly) and the maximum value of the distribution.

3.1.5. Grid stabilization and flexibility requirements

The model conducts hourly calculations and assumes that all dispatchable production units can change production from one hour to the other according to some constraints.

The EnergyPLAN needs specifications about the regulation and stabilization of the power system, with implication in the energy balances. These parameters affect the predetermined order of merit of the model.

These parameters are: (1) the minimum grid stabilization share, and (2) the minimum power plant level. They are described below.

3.1.5.1. Minimum grid stabilization share

Concerning grid stabilization, it was assumed that a percentage of electricity generation must be provided by load following capable power plants, to avoid any energy supply interruption. Those power in the present study are thermal and hydro power plants with storage. Thus, the minimum grid stabilization share represents the least power share that must come from the above-mentioned dispatchable power plants, relative to the consumption, at any given time.

This parameter represents the degree to which the grid stabilization requirements have been fulfilled. The grid stabilization demand, d_{stab}, can be identified by the total power generated and the dispatchable stabilization capable power, P_{total} and P_{stab}, respectively, as in Equation (3).

$$d_{stab} = \min\left[\left(\frac{P_{stab}}{P_{total}}\right)_1, \dots, \left(\frac{P_{stab}}{P_{total}}\right)_i, \dots, \left(\frac{P_{stab}}{P_{total}}\right)_{8784}\right] \quad (3)$$

The model makes sure that the grid stability requirements are fulfilled by increasing the power plants production accordingly. The share of generation capable to stabilize the grid in 2014 was found to be 56,3% on average, with a minimum of 17,9%. The latter was the value adopted in the present work.

3.1.5.2. Thermal power plants flexibility

The minimum power plant parameter represents the minimum capacity that the thermal power plants are able to operate with.

Conventional thermal power plants have limited flexibility to change power output levels due to their technical and operational limitations. These are mainly due to the fact that these plants have long cold start times until their capacity reaches the required load level, with coal power plants representing the slowest ones, presenting cold starts from thirty minutes to several hours [45]. These power plants generally operate at a given minimum level, in order to avoid long initialization and, consequently, operational and economic penalties to the operator of these plants.

The parameter that reflects the comfortable limit of operation of these plants representing the grid flexibility, d_{flex}, given by Equation (4), is a function of the quotient between the maximum and minimum injected power in the grid by those plants, P_{th} at any instant of time i. during the year.

$$d_{flex} = \frac{\min[(P_{th})_1, \dots, (P_{th})_i, \dots, (P_{th})_{8784}]}{\max[(P_{th})_1, \dots, (P_{th})_i, \dots, (P_{th})_{8784}]} \quad (4)$$

By applying Equation (4), the minimum power plant level was found to be 822 MW [45].

3.1.6. Interconnection

EnergyPLAN simulates the grid interconnection transit by performing an hourly balance between imports and exports needs over the considered year. The model allows the user to set the available value of interconnection capacity according to the existent data.

The transmission grid is interconnected with the Spanish grid at various points, which allows the two countries to carry out bilateral exchanges of electricity. The foreign trade balance in 2014 was negative, with net imports corresponding to 6% of national consumption. The imports amounted to 4.084 GWh, whereas exports amounted to 3.184 GWh, implying a balance of -902 GWh [47].

In 2014, the year considered as basis for this study, a minimum interconnection capacity of 2.000 MW in Portugal was observed [45]. Nevertheless, this value was not adopted, and the grid connection capacity was established as 0 MW. The reason for this procedure is to be able to assess the amount of interconnection power that is necessary in each scenario tested.

3.1.7. Electric mobility modelling

To model the electric fleet, it is need to compute when the vehicles are available to supply the grid and are not in circulation, based on statistical mobility patterns [45].

To compute when electric vehicles are available for that purpose, specific inputs are needed for the electric vehicles modelling:

- D_{V2G}: transport demand of electric cars in TWh/year – depends on the scenario (c.f. Section 3.2.2)
- δ_{V2G}: hourly annual distribution of transport demand – derived from data published by Instituto Nacional de Estatística [43]
- $C_{Charger}$: total capacity of grid connection in MW – depends on the scenario (c.f. Section 3.2.2)
- $V2G_{Max\text{-}Share}$: maximum share of V2G cars which are driving during peak demand hour – derived from data published by Instituto Nacional de Estatística [43]
- $\mu_{Charger}$: efficiency of the grid to battery connection – considered 0,9 [43] [45]
- $\mu_{Inverter}$: efficiency of the battery to grid connection – considered 0,9 [43] [45]
- $S_{V2G\text{-}Battery}$: capacity of the cumulated battery storage in GWh – depends on the scenario (c.f. Section 3.2.2)
- $V2G_{Connection\text{-}Share}$: share of parked V2G cars connected to the grid – considered as 0,7 [43]

All inputs are expressed for the entire vehicle fleet. Thus, for example, the maximum system capacity, $C_{Charger}$, is calculated by multiplying each car charging power by the maximum number of vehicles plugged in at any given time.

It is important to note that in the scope of this dissertation the capacity of battery to grid connection was set to zero, with the purpose to simulate a unidirectional V2G system.

A relevant input is the distribution of the transport demand which is used for two main purposes. One is to determine how many cars are driving at a given time and consequently are not connected to the grid. This, together with the $V2G_{Max\text{-}Share}$ and the $V2G_{Connection\text{-}Share}$, determines the fraction of the V2G fleet that is connected to the power system at any given hour. The other purpose of defining δ_{V2G} is to determine the discharging of the battery storage caused by driving [44].

After that, it is necessary to assess how the charging process is made. Section 3.1.7.1 describes in detail the charging alternatives the EnergyPLAN model allows the user to opt to.

3.1.7.1. Charging strategies

The model allows to choose between two charging alternatives: dump charge and smart charge.

In a dump charge characterization, it is assumed that users freely charge the vehicles based on their schedules and personal needs. The vehicles are connected to the grid when parked and the battery is fully charged. This typology of charging may induce some instability and lack of control in electricity consumption if a management system is not present.

In the smart charging strategy approach the charging process is based on a correlation between the grid operator and the EV user. This grid operator works as a manager controlling all EVs connected to the grid at any instant. In general, the batteries are loaded during periods of excess electricity production. When there is no energy in excess, the model ensures the batteries are charged prior to driving periods. The grid operator prioritises charging the cars that will drive within the next few hours. That means, during each hour, the model inspects the next hours of driving needs, and if the battery pack is not sufficiently loaded the charging process is forced even in the case of non-existent energy super avit. The inputs required for the model include electricity demand and hourly distribution, max share of parked cars, share of cars connected, charge efficiency, battery capacity and capacity of grid to battery.

A V2G system allows a uni- or bi-directional energy flow; the unidirectional is especially attractive because it requires little, if any, additional infrastructure other than communication between the EVs and the aggregators, not implying interconnection issues or battery degradation, having more customer acceptance. For this reason, to make the analysis conservative, the V2G mode adopted in this work is considered to not provide for base load or peak power.

For simulation purposes in EnergyPLAN, 20% of the electric vehicles stock is assumed to be in circulation during rush periods, as well as that 70% of vehicles are connected to the grid when parked. The smart charging system is assumed to cover all vehicles onwards 2040 [50].

In terms of grid connection, it was assumed that the charging process is made at a standard 6 kW power [51]. To turn the analysis simpler, the model assumes the totality of batteries as one big battery. The available battery capacity corresponds to the maximum capacity, although it is not always available, since some of the cars will be driving and can neither discharge to the grid nor charge from it. The model assumes that the car batteries are fully loaded when the cars disconnect and start driving. The modelling of the batteries capacity is presented in Section 3.2.

3.1.8. Second-life storage modelling

The program allows to model energy storage systems according to the typologies of: hydro storage and on-board car batteries. The hydro storage typology can, in fact, be used for modelling any kind of electricity storage, for example stationary batteries.

The hydro storage typology is represented by three inputs:

- Pump capacity, that defines capacity to convert electricity to potential energy;
- Turbine capacity, that defines capacity to convert potential energy to electricity;
- Storage capacity, i.e., the amount of energy that can be stored.

It is important to note that the simulation of stationary storage is used to avoid critical excess electricity production (CEEP) and replace fossil thermal power plants. In the scope of this dissertation, storage plays the main role and, as such, it was carefully computed and defined.

The storage power facility is operated by charging, in the case of critical excess production, $e_{CEEP} > 0$, and discharging, first by replacing imports and then power plant (PP) production, i.e., if $e_{PP} > 0$.

The model was set to allow simultaneous operation of charging and discharging, given that from the grid stabilization point of view it may be necessary for the batteries, which are considered as able to contribute to it, to simultaneously receive and supply power. The considered efficiencies of charging and discharging the batteries were considered as 80 and 90%, repectively [44] [52].

3.2. Scenarization

For the purpose of this study, it was necessary to characterize the national electricity system evolution during the period 2030-2050 and model it, as well as the passenger vehicles sector.

The scenarios tested were from 2030 to 2050 comprehending increasing storage capacity; for 2050, two additional sub-scenarios were created: (1) one with an additional photovoltaic deployment and (2) another one corresponding to a dry year case. For each one of those scenarios, the situations with and without second-life battery storage were tested.

These future scenarios intend to represent the panorama of the Portuguese electrical system until 2050. Several scenarios were created based on targets and projections analysis available in the literature in order to obtain the inputs needed to the model. The changes performed to the pre-existing scenarios [43] [45] will be addressed, as well as their reasons.

3.2.1. Power system

The projections adopted are from Ref. [45], where they can be consulted in detail. They were based on proposed targets and objectives by the EU and the Portuguese government for climate and energy. These targets are usually modelled in top-down models such MARKAL or TIMES [48].

3.2.1.1. Electricity consumption

The simple consumption profile until 2050 was modelled disregarding grid losses [53]. Electricity consumed by electric vehicles is considered separately

Figure 5 shows the adopted consumption evolution in the years covered by this study (2030-2050), based on the above-mentioned projections.

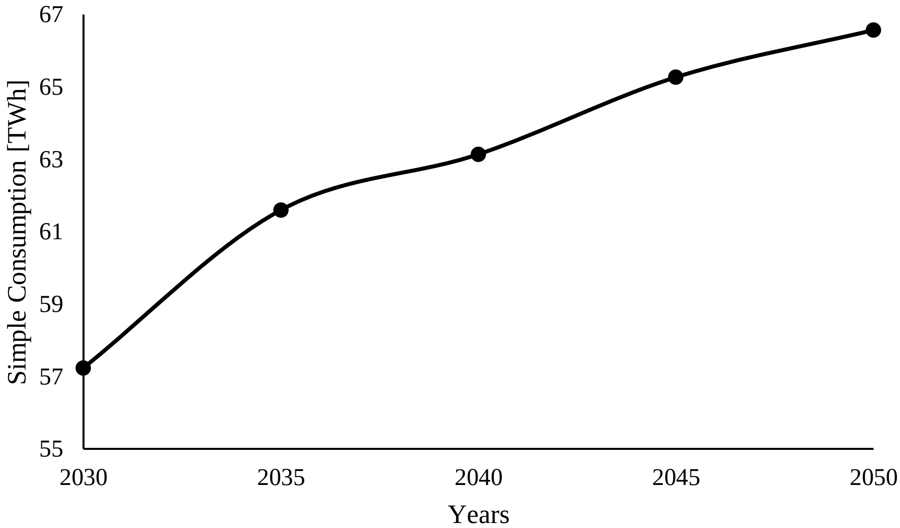


Figure 5: Electricity consumption evolution between 2030 and 2050.

3.2.1.2. Electricity production

3.2.1.2.1. Thermal power plants

Coal power plants installed capacity will show a gradual decrease as a result of dismantling this type of generation units over the years, mostly for environmental reasons. Given that scenarios start in 2030, electricity production from coal was not considered [48]. Therefore, only gas and biomass powerplants were modelled in each simulation until 2050, including cogeneration (natural gas or biomass). In the model interface, the biomass production was set as fixed and natural gas as variable. This option allowed the model to prioritize biomass in thermal power plants instead of gas, using the latter only when strictly necessary. It is considered that the installed capacity of natural gas power plants stabilizes around the present value. Concerning biomass plants, a gradual increase is expected, from 970 MW in 2030 to 1.880 MW in 2050 [48].

3.2.1.2.2.Dispatchable Hydro

Portugal has low potential to increase hydroelectric production. The capacity growth in hydroelectric power plants assumed is based on the *Programa Nacional de Barragens com Elevado Potencial Hidroeléctrico* (PNBEPH) [49], which considers a new installed capacity until 2025 of large hydro of 2.900 MW and of run-of-river of 78 MW.

As in this study the focus is storage, it is not relevant to present detailed information on all hydro plants but only their total storage capacity (for additional insights on this topic, see Ref. [49]). To model the hydro productivity through the years, the hydroelectric capability factor for 2014, 1,27, was adopted. The storage capacity was modelled as proportional to the capacity installed.

3.2.1.2.3. Non-dispatchable renewable sources

Amongst the non-dispatchable renewable sources, onshore wind is the most significant in Portugal, representing 23% of energy mix in 2017 [54]. According to some projections, 5.099 MW capacity is expected by 2020, reaching 7.300 MW by 2050, when the potential is already deplected [55] [56].

The offshore technology is still non mature, and is considered to start to have expression in the system from the end of the 2020 decade.

Although mass scale solar photovoltaics is still at an early stage in Portugal, a significant growth is expected within the next decades. From 2020 is expected a large deployment, reaching by 2050 8 GW [48].

The study performed in Ref. [45] considered also wave energy. However, in the present study this renewable energy source was not considered given the few demonstration projects and the lack of implementation projects in a medium-term horizon in Portugal.

The installed capacities per technology considered are shown in Table 3.

Table 3: Installed capacities per technology between 2030 and 2050.

Installed capacity [MW]	2030	2035	2040	2045	2050	2050[1]
Onshore wind	6.010	6.100	7.000	7.100	7.300	7.674
Offshore wind	280	424	604	820	1.067	1.400
Solar photovoltaics	5.613	6.309	6.698	7.491	8.214	16.669

[1]An alternative projection was considered with a less conservative approach allowing a better model performance. So, these values with higher renewable penetration were used to obtain a better simulation for the most relevant scenario (2050).

3.2.2. Car fleet

To evaluate the batteries availability is necessary to model the Portuguese passenger car fleet. The Portuguese fleet constitution was studied starting in 2020 until 2050 with greater focus in passenger electric vehicles. The current Portuguese fleet is essentially composed by vehicles with internal combustion engines (ICE).

The electric vehicle penetration in Portugal was simulated having Ref. [43] as a basis. Figure 6 shows the projected evolution of the fleet considering the five types of expected vehicles. Based on these projections for car stock, the fleet by 2050 will be constituted by 4.175.443 vehicles, following a distribution of 38,63% ICEs, 27,63% PHEVs and 33,74% EVs.

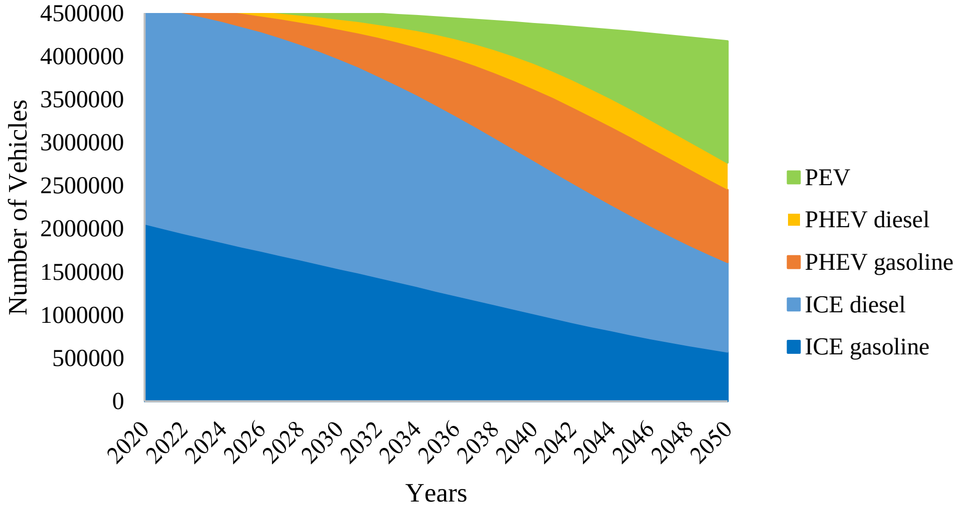


Figure 6: Portuguese fleet evolution between 2020 and 2050.

By 2030, a V2G charging system is assumed to be deployed in Portugal, and so EVs may function as energy storage units to help the grid, as they are parked 90% of the time. This makes the system more flexible, since electric vehicles can work as distributed controllable electric loads [45].

In terms of technical simulation, electric vehicles unidirectional charging is used aiming at decreasing excess electricity production and the share of non-renewable power in the system.

To assess the V2G charge demand, the model requires the distribution of transport demand and considerer the batteries as one single battery. Indeed, the total capacity of this large battery fluctuates since some of the cars will be driving. To a simpler analysis, the model assumes the batteries are fully loaded when the cars disconnect from the grid and start driving.

3.2.2.1. Onboard EVs battery capacity

The 2020 average individual batteries capacity was considered to be 40 kWh [57], although there may be batteries with capacities considerably higher, such as in Tesla models [58]. In order to estimate the batteries capacity up to 2050, an increase of 2% per year was adopted [59], as Figure 7 shows. It is important to note that the absence of detailed data and the large time frame of the analysis could lead to errors in this projection. It is expected that the capacity evolution will reach a point where it will slow down and stabilize with the respective curve presenting an S-shape. However, it is not possible yet to project accurately when it will occur.

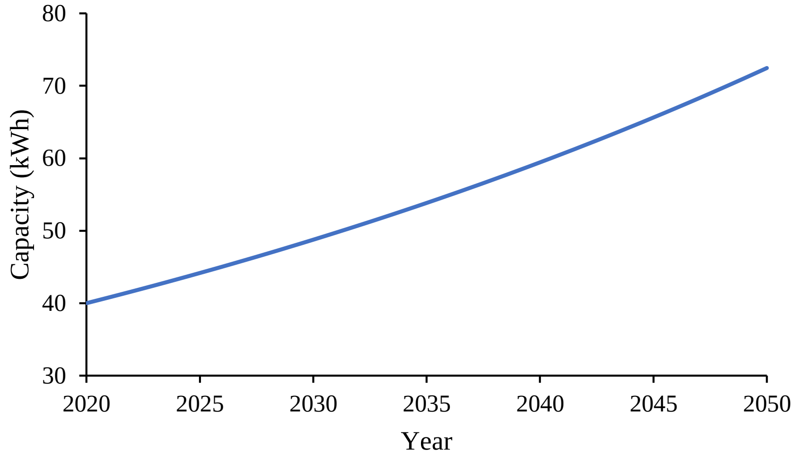


Figure 7: Expected individual average batteries capacity evolution (2020-2050).

It was also necessary to compute the degradation rate of those batteries as storage systems. For that, the assumption was made based on the depth of discharge loss while in automotive service. Considering a linear approach, it was considered that if in 8 years the battery loses 20% of charge capacity, then per year it will lose approximately 2.5%.

Thus, the available capacity and the capacity of batteries on-board regarding the degradation rate in each year, i, was calculated as shown in Equation (5).

$$C_{2020+n} =$$

$$= \sum_{i=0}^{n} [Sales_{2020+i} \times c_{2020} \times R^{i} \times (d \times i)\,] - \sum_{i=0}^{n} [Scrappage_{2020+i} \times\ c_{2020} \times R^{i-20} \times \big(d \times (i-20)\big)] \quad (5)$$

Where:
C_{2020+n} represents the total batteries capacity in a given year, i;
$Sales_{2020+i}$ represents the sales numbers in any given year i;
c_{2020} represents the individual onboard battery initial capacity;
R represents the increased rate of capacity, having a constant value of 1,02;
d represents the 2,5% fixed degradation rate, having a value of 0,975;
$Scrappage_{2020+i}$ represents the car scrappage in any given year i.

3.2.3. Second-life storage availability

The batteries availability scenarios were created taking into account the market penetration of electric vehicles. Having the values up to the present, a projection was made up to 2050 based on the number of sales and number of electric vehicles in circulation in Portugal [43].

Considering only the projected electric vehicles sales from 2020, given that before they are residual, a simulation of the availability of batteries was performed. A range of approximately 160.000 km, representing about 8 years of automotive service, was considered for the batteries [60] [61]. Thus, batteries to repurpose will start to be available in significant numbers from 2028.

To assess the storage capacity by 2050 and generally in any year, the remaining 80% of discharge capacity were considered in the calculations given that the batteries will not present the entire initial capacity. Therefore, this parameter, *SC*, was calculated using Equation (6).

$$SC_{2020+n} = \sum_{i=0}^{n} (Sales_{2020+i-8} \times c_{2020+i-8} \times 0{,}8) \quad (6)$$

As mentioned in this section, the availability of batteries assessment was the starting point, allowing a calculation of the storage capacity to repurpose. Table 4 summarizes the values serving as inputs in EnergyPLAN model for the case study when batteries are repurposed after 8 years of automotive use, beginning with sales numbers for 2020. The values presented respect to the total storage capacity of second-life batteries.

Table 4: Batteries available, respective capacity and cumulative storage capacity (2020-2050) for a 8 years time-line.

	Number of available batteries	**Individual capacity (kWh)**	**Batteries in circulation (GWh)**	**Total storage Capacity (GWh)**
2020	0	40,00	0,97	0,00
2025	0	43,06	2,13	0,00
2030	14.688	47,54	4,28	0,56
2035	47.618	52,49	10,43	2,00
2040	116.470	57,95	26,90	5,40
2045	295.281	63,98	58,39	15,11
2050	678.045	70,64	102,08	38,32

In terms of grid connection, a two-way 10 kW power capacity was considered for each second-life car battery [44]. Thus, considering the available amount of batteries and vehicles in circulation in each year, the total power connected to the grid was obtained as synthetized in Table 5, contrasting both on-board storage capacity for unidirectional V2G and second-life batteries capacity. Degradation of the batteries with use was not considered, since in stationary storage systems the stress to which the batteries are subjected is much lower than that of charging and discharging in a vehicle [59].

Table 5: Storage capacity and Grid connection in both EVs in circulation and second-life storage (2020-2050).

	Electric vehicles in circulation		**Second-life batteries**	
Scenario	Storage Capacity [GWh]	Grid Connection [MW]	Storage Capacity [GWh]	Grid Connection [MW]
2020	0,97	145,42	0	0
2025	2,13	289,61	0	0
2030	4,28	526,65	0,56	146,88
2035	10,43	1.162,65	2,00	476,18
2040	26,90	2.715,73	5,40	1.164,70
2045	58,39	5.338,67	15,11	2.952,81
2050	102,08	8.453,55	38,32	6.780,45

3.2.4. Tested scenarios

As previously mentioned in this section, the scenarios tested were from 2030 to 2050 in 5-year intervals, comprehending increasing storage capacity. Subsequently, two sub-scenarios for 2050 were tested: an additional PV deployment case and a dry year case scenario.

The scenarios presented below will briefly describe the main assumptions for each scenario in terms of energy storage systems and in section 3.2.4.8, a summary of each one is shown aiming a better understanding, gathering all the relevant given information throughout the chapter.

3.2.4.1. Scenario 1: 2030

In this scenario EV charging includes 50% smart charge and 50% dumb charge. From this year, hydro production reaches a saturation point. Storage systems can count with V2G model along with hydro pumping and second-life batteries with a 0,56 GWh storage capacity.

3.2.4.2. Scenario 2: 2035

In Scenario 2, the EV fleet keeps growing assuming an important role in electrical Portuguese system. EV charging is made 75% in smart mode and 25% in dumb mode. Second-life batteries storage capacity increases to 2,00 GWh.

3.2.4.3. Scenario 3: 2040

In this scenario, EV charging is entirely ensured by smart mode and it continues until 2050. V2G system provides a 26,90 GWh storage capacity. Concerning second-life storage capacity, it continues to grow, and this year counts with 5,4 GWh.

3.2.4.4. Scenario 4: 2045

V2G system is able to provide a 58,4 GWh storage capacity and second-life batteries 15,11 GWh.

3.2.4.5. Scenario 5: 2050

Second-life storage reaches its maximum value, 38,3 GWh, along with 102,08 GWh from V2G and 6.900 GWh from dammed hydro.

3.2.4.6. Scenario 6: Additional solar photovoltaic deployment

As the Results section will detail, the battery storage allows to diminish in the system the energy in excess, i.e., energy that needs to be curtailed or exported. This means that the storage solution allows additional deployment of renewable energy, which was considered to be photovoltaics. The additional capacity that it allows was considered to be the one that gives rise to a value of energy in excess equal to the one that the system presented without the use of battery storage. That is, it is feasible to see how the batteries facilitate the installation of solar photovoltaic power plants. In order to determine these values, several simulations were performed until the same excess of energy production was obtained. The values were tested for all the increasing storage capacities available over the years, i.e, for each year of the study, an additional deployable value for PV capacity was identified.

Following the above, Figure 8 shows the additional installed capacity for each year. A simulation of the power system operation with the 'extra' PV was performed only for 2050 as it is the study's most relevant year. The PV installed capacity value considered was 20.250 MW, a 3.581 MW extra relative to 2050 base case scenario.

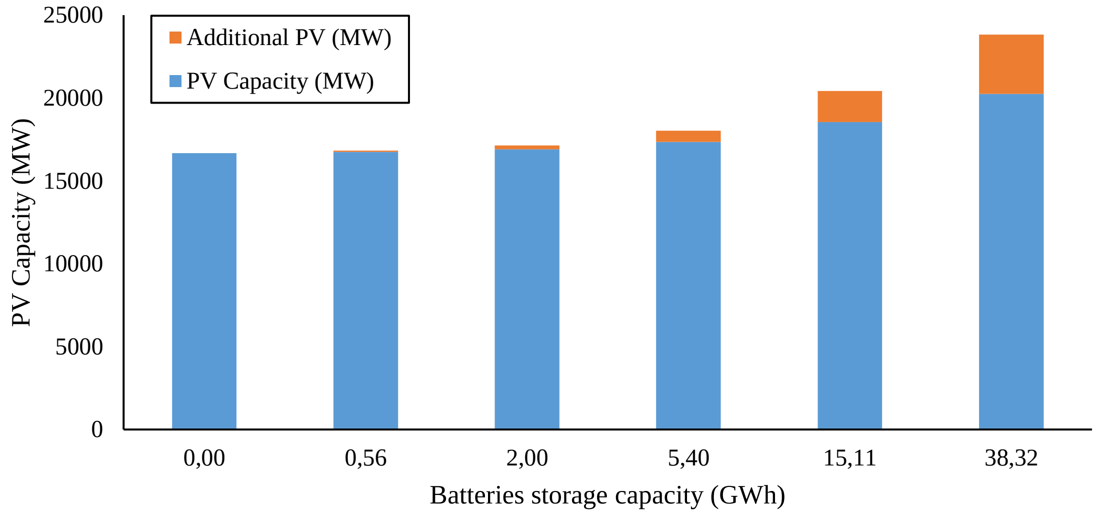


Figure 8: PV capacity growth as a function of second-life storage capacity.

3.2.4.7. Scenario 7: Dry year

The hydrological index of 2017 was 0,47 (it translates water availability – a value of 1 corresponds to the average), which was reflected in the hydroelectric productivity that was significantly reduced. This low productivity value was one of the weakest ever [62]. Thus, the dry year scenario is correspondent to an index of 0,47, and it was tested only the year 2050. The correspondent water inflow to the dams and run-of-river was corrected applying a direct regression to reflect this, resulting in 2,67 TWh of water availability (compared to 5,26 TWh in the normal scenario). River hydro had a 1.342 MW installed capacity instead of 2.855 MW considered for 2050 base case scenario.

3.2.4.8. Summary

To a simpler analysis for the sub-scenarios with and without second-life storage by 2050, abbreviations for each one were created as shown in Table 6.

Table 6: Scenario Abreviations.

Scenario	Abbreviation
Base Case 2050 (Normal Year without second-life storage)	BC-NY
Repurposed batteries storage 2050 (Normal Year)	RB-NY
Repurposed Batteries Additional PV Deployment (Normal Year)	RB-NY-PV
Base Case Additional PV Deployment (Normal year)	BC-NY-PV
Repurposed Batteries (Dry Year)	RB-DY
Base Case (Dry Year)	BC-DY

As previously mentioned, the scenarios construction was performed based on assumptions made by Ref. [43] and Ref. [45] along with the Portuguese power system and car fleet evolution until 2050. Second-life batteries were the new variable in the system.

Therefore, for a better understanding and system characterization, the study was divided in 5-year intervals starting in 2030 and ending in 2050. For 2050, two additional scenarios were created: the additional solar photovoltaic deployment and the dry year case scenarios with and without storage.

Table 7 briefly describes each scenario assumptions based on present section projections and inputs for EnergyPLAN model.

Table 7: Future Scenarios Description.

Scenario 1: 2030	In this scenario, the electrical power system faces a transition stage. Coal power plants are no long an option for electricity production under a GHGs reduction perspective. A significant investment in renewable energy sources was made, namely in solar photovoltaic with an expected installed capacity of 5.613 MW, onshore wind with 6.010 MW and the implementation of a new technology: offshore wind with a 280 MW power. EV charging includes 50% smart charge and 50% dumb charge. From this year, hydro production faces a saturation point. Storage systems can count with V2G model along with hydro pumping and second-life batteries with a 0,56 GWh storage capacity.
Scenario 2: 2035	Renewable energy sources keep presenting an increase with solar photovoltaics reaching 6.309 MW, onshore wind 6.100 MW and offshore wind 424 MW. The EV fleet keeps growing assuming an important role in electrical Portuguese system. EV charging is made 75% in smart mode and 25% in dumb mode. Second-life batteries storage capacity increases about 1,5 GWh comparing with scenario 1.
Scenario 3: 2040	The trend in comparison to the previous scenarios is maintained, with a considerable increase in renewable energy sources penetration. EV charging is entirely ensured by smart mode and it continues until 2050. Concerning second-life storage capacity, this year counts with 5,4 GWh.
Scenario 4: 2045	In this scenario, offshore wind keeps growing meaningly to an installed power of 820 MW, along with onshore wind and solar photovoltaic. V2G system is able to provide a 58,4 GWh storage capacity and second-life batteries 15,11 GWh.
Scenario 5: Repurposed batteries storage 2050 (RB-NY)	The installed capacity of Portuguese power system presents a value of 34,3 GW. A 73,8 TWh/year consumption is expected with EV representing 7,21 TWh/year. Second-life storage reaches its maximum value, 38,3 GWh, along with 102,08 GWh from V2G and 6.900 GWh from dammed hydro.
Scenario 6: Additional PV (RB-NY-PV) (BC-NY-PV)	This scenario differs from the previous one only in the installed solar photovoltaic capacity, which becomes 20.250 MW.
Scenario 7: Dry year (RB-DY) (BC-DY)	This scenario, illustrating a dry year, differs from 2050 scenario only in hydro production which takes a value of 2,667 TWh/year, contrasting with 5,26 TWh/year considered for scenario 5.

Chapter 4 – Results and Discussion

To perform a better characterization of the Portuguese power system, load diagrams were made for all the considered years in the study: 2030, 2035, 2040, 2045, 2050 and a base scenario which disregard second-life battery storage. Along with this characterization, an excess solar-photovoltaic installation and a dry year case scenarios were created.

For each year, a broader and less detailed insight was performed by an annual load diagram and in detail, three representative diagrams of typical winter, spring and summer weeks to allow a better visualization and characterization of the system as well as its variabilities.

4.1. Batteries availability

Following the mentioned procedures in Section 3, the following results concerning batteries introduction in the Portuguese power system were obtained. Only results for the 8 years repurposing case scenario will be presented, given its bigger relevance.

Figure 9 shows the assumed EV's evolution in the Portuguese fleet until 2050, the correspondent total capacity of batteries on-board and cumulative storage capacity from retired batteries. A logistic S-shaped growth for the electric vehicles penetration was assumed between 2020 and 2050. About 1,4 million of electric vehicles are expected to be in circulation by 2050, accompanied by almost 700.000 batteries for second-life applications. The storage capacity curves also show a logistic behaviour.

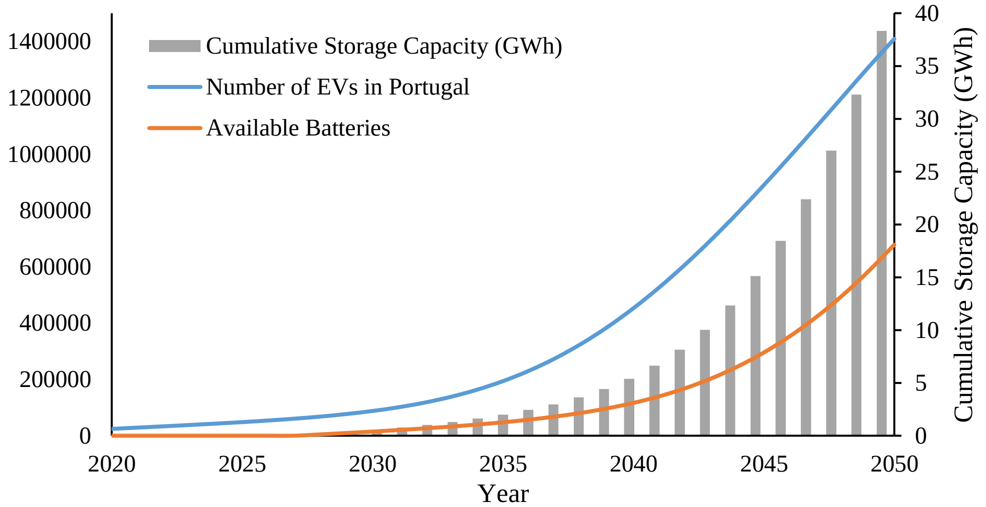


Figure 9: Electric vehicles in circulation, availability of batteries and cumulative storage capacity from 2020-2050.

4.2. Load diagrams impacts

A broader insight will be given by showing an annual load diagram and, in more detail, by showing three representative diagrams of winter, spring and summer weeks, to allow a better visualization and characterization of the system, as well as its variabilities.

The representative weeks dates are detailed below and were chosen on the basis of being illustrative seasonal weeks of the system operation.

- Winter: 3 to 9th January
- Spring: 2 to 8th May

- Summer: 1 to 7th August

It was found that the energy storage solution starts to have relevance in the system only by 2050, given that the system has already a considerable energy storage capacity using hydro-pump, which the model assumes to have priority over the battery storage. In face of this, results for the period 2030-2045 will not be presented – from the standpoint of this thesis, they are not relevant.

Each diagram shows disaggregated data of energy production, consumption, the excess electricity (represented as export needs), V2G demand and the charging and discharging of the battery banks. Consumption is divided into three variables: simple load, as a continuous black line, EVs charging, as a dashed red line, and combined load, as a continuous dark blue line, which includes the simple load, EVs charging, hydro pumping and battery banks charging. All diagrams represent one year (monthly results) or one week (hourly results, totalling 168 hours).

4.2.1. Scenario 5: 2050

4.2.1.1. Baseline Scenario 2050 (BC-NY)

Figure 10 shows the monthly average load values for each technology. It can be seen that there is some excess electricity, represented as export needs. The hourly peak value for this excess was verified during the summer, 8.270 MW. As storage capacity in second-life batteries is absent, all the production surplus above the total load (which includes the hydro-pumping load), is considered an export need rather than storable energy. The average total annual production is about 9.868 MW, totalling 86,67 TWh in the entire year.

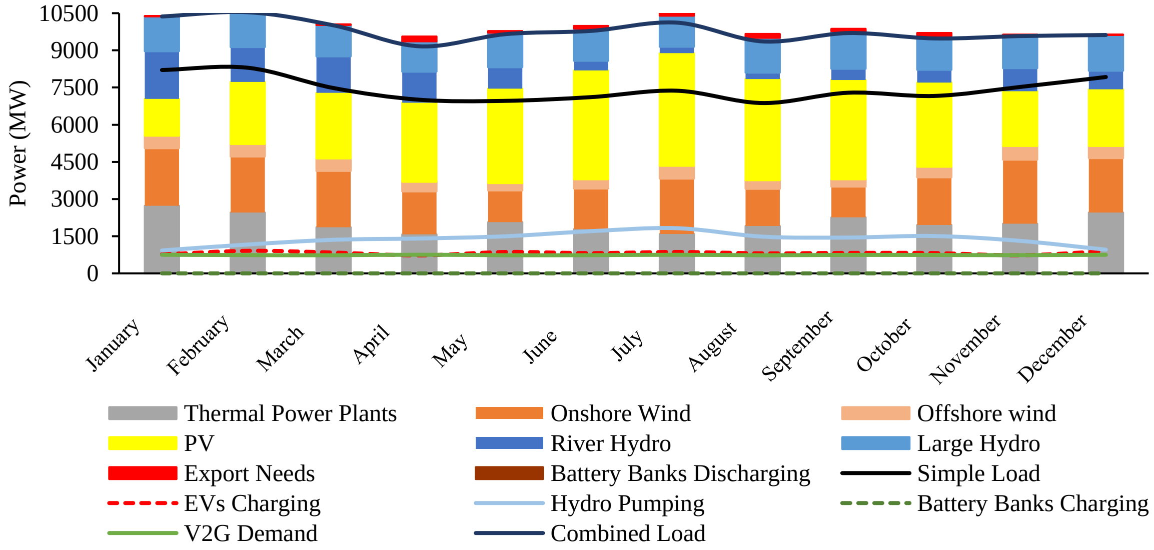


Figure 10: Yearly Load Diagram for Baseline Scenario 2050.

The winter week, Figure 11, is characterized by an atypical wind production, since there was practically no production during the three consecutive days period of Monday to Wednesday. Given this, during that period it is necessary to resort to thermal based energy, and the smart EV charging is almost absent, given the vehicles autonomy. V2G demand shows a consistent behaviour every day, with a747 MW of average value. Given the large wind power generation from Thursday to Sunday, hydro pumping is requested during this period. There is never excess of energy production during this week.

Spring week, Figure 12, is characterized by a more regular production profile, showing a slight contribution by wind. Hydro pumping works several times at its maximum capacity, 4.004 MW, because in every day there is potential excess of renewable production, which is used as a buffer of electricity, particularly of solar photovoltaic. Electric vehicles charging is higher during the weekend, presenting a peak of 6.175 MW on Sunday. Critical excess electricity production is only verified on Saturday, with an average of 2.288 MW, a significant value representing 12% of the production during that day.

During the summer, Figure 13, energy generation is mostly assured by solar photovoltaics, presenting weekly peaks of c.a. 10 GW. In this scenario electricity in excess in the middle of the day is verified for several days in a row – Thursday, Friday, Saturday and Sunday; on Thursday it presents a residual value (peaking at 1.304 MW) comparing with the other days, whose values reach 6.058 MW (on Saturday). Thus, one can see that the energy in surplus is considerable, with emphasis for solar energy, representing 44,3% of the weekly production.

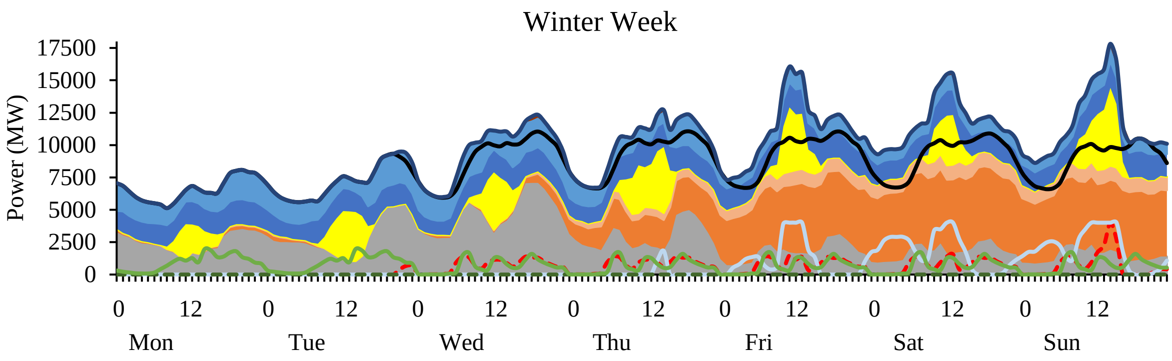


Figure 11: Representative Winter Week Diagram for the BC-NY scenario.

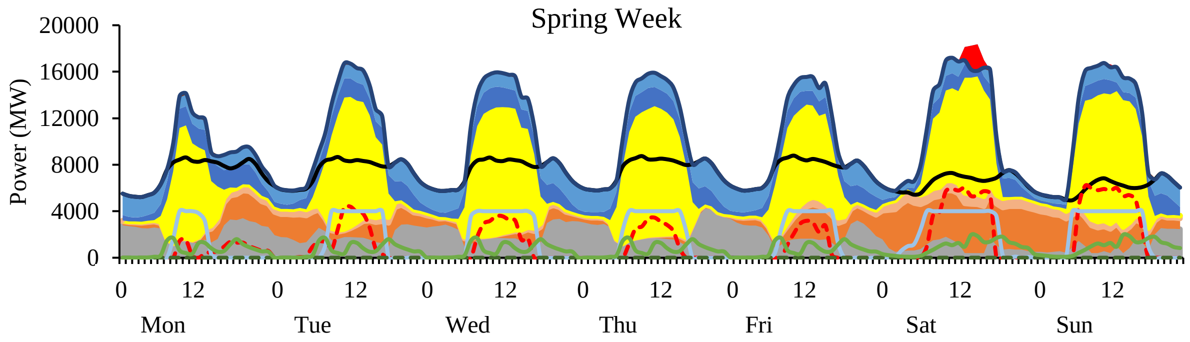


Figure 12: Representative Spring Week Diagram for the BC-NY scenario.

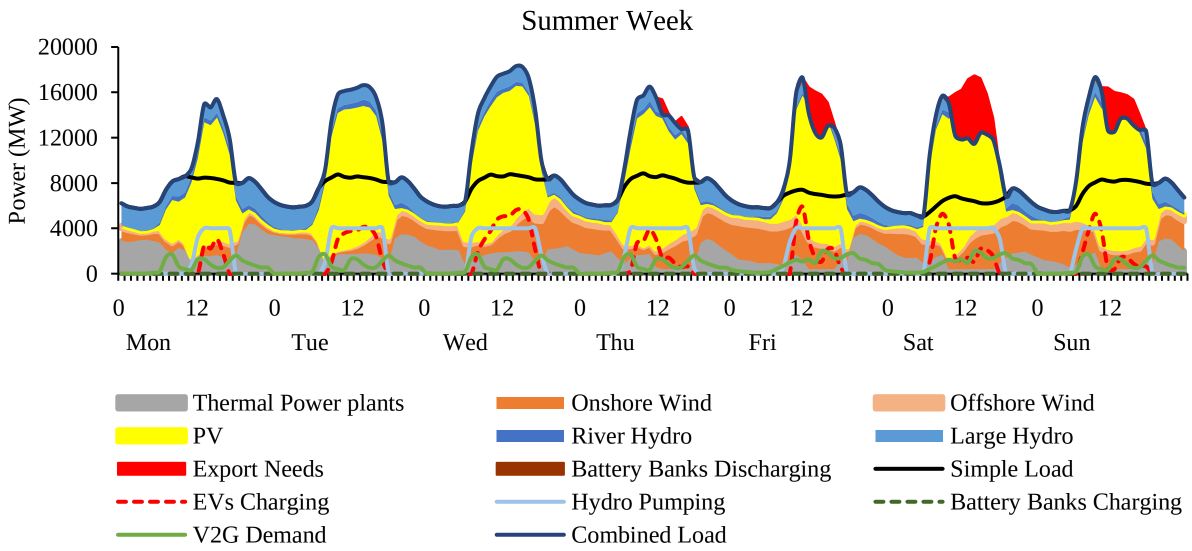


Figure 13: Representative Summer Week Diagram for the BC-NY scenario.

4.2.1.2. Second-life storage (RB-NY)

This scenario differs from the previous on because it includes additionally 38,3 GWh of energy storage capacity in battery banks. For the entire year, Figure 14, the results show that batteries should allow to reduce the amount of energy in excess from 0,77 to 0,03 TWh, and mostly they are operated during the summer at an average charging and discharging rates of 251 and 181 MW, respectively. The peak charging value, 6.780 MW, corresponding to the maximum charging rate, occurred several times between August and September, suggesting potential energy in excess during those occasions. The highest discharging value, 4.301 MW, occurred in late September and in October.

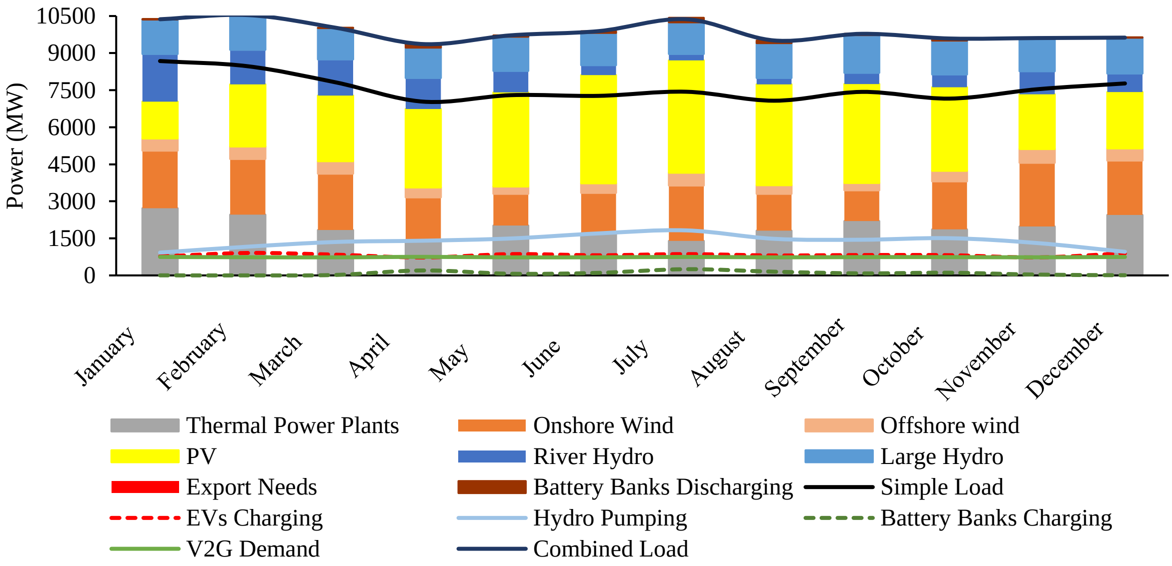


Figure 14: Yearly Load Diagram for Second-life Storage Scenario 2050 (RB-NY).

In the Winter week, Figure 15, as there was no energy in excess given the higher consumption level, charging and discharging of battery banks was not verified. Thus, this weekly diagram does not differ from the corresponding one in the BC-NY.

Spring week, Figure 16, is characterized by a slight use of second-life batteries on Saturday. This use represents a charging value around 2.280 MW, which represent the export needs identified in the previous BC-NY scenario. Regarding the discharging to the grid of the battery banks, it occurred between 5 and 9 p.m. on Saturday, peaking at 1.323 MW.

During the summer week, Figure 17, storage by the battery banks was used in every previously mentioned day with energy in excess (c.f. Section 4.2.1.1), i.e., from Thursday to Sunday. The highest charging value, 6.058 MW, was obtained on Friday around 2 p.m., the day with most production surplus, mostly from PV. The weekly average showed charging and discharging values of 363 and 228 MW, respectively. In both Spring and Summer weeks, battery banks charging was always higher than in Winter, given the surplus potential and the lower demand.

It is important to note that the dashed green line, representing battery banks charging, corresponds, in every diagram, to the energy in excess, i.e., the production surplus area relative to the combined demand, evidencing the proper model operation.

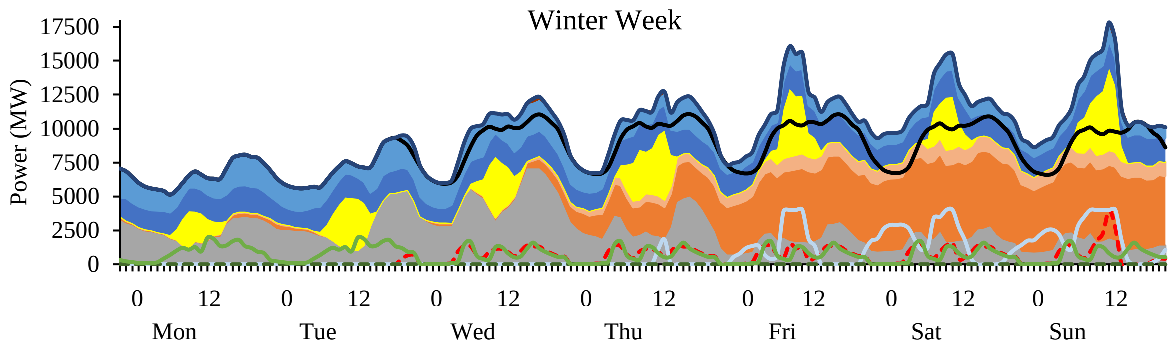
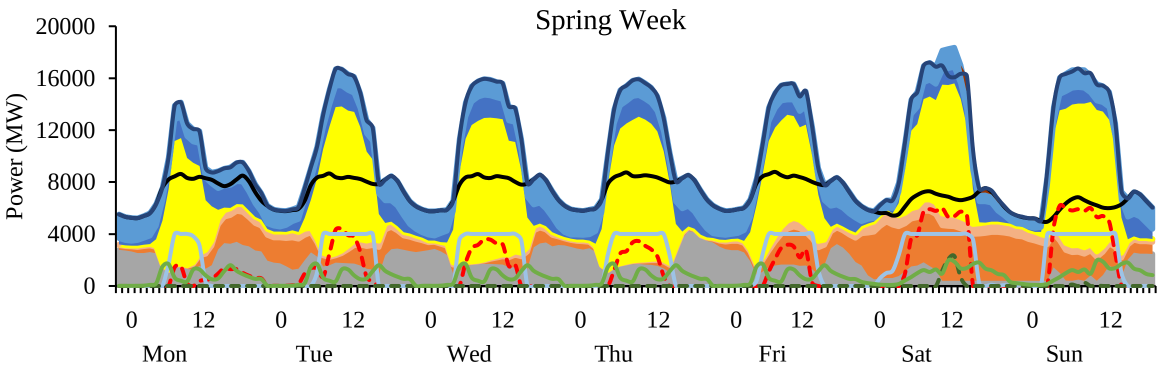


Figure 15: Representative Winter Week Diagram for the RB-NY scenario.



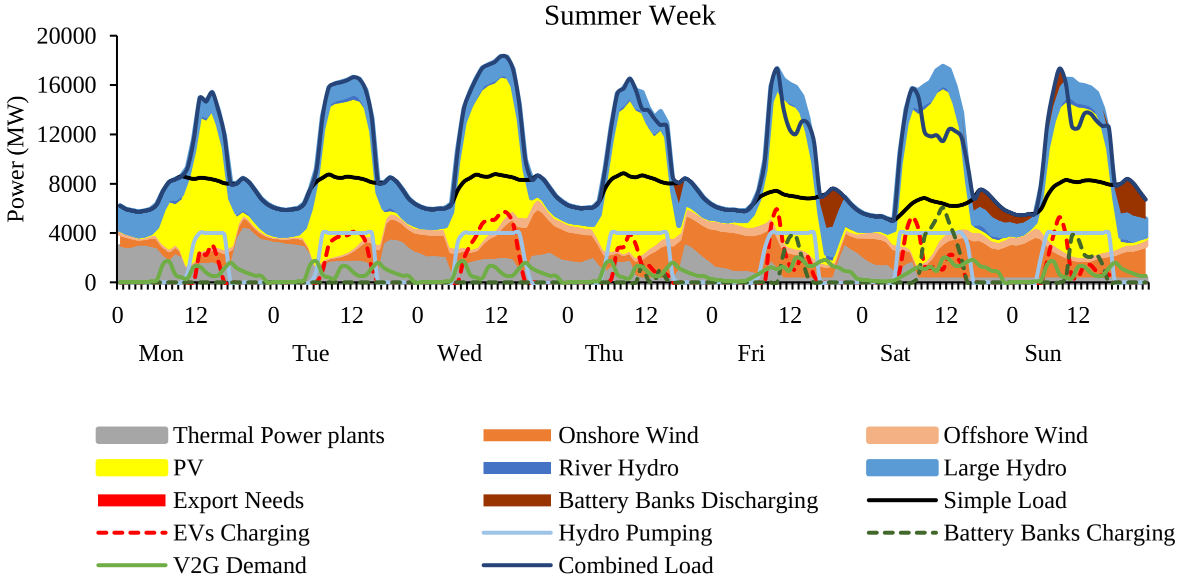


Figure 17: Representative Summer Week Diagram for the RB-NY scenario.

Figure 16: Representative Spring Week Diagram for the RB-NY scenario.

4.2.2. Scenario 6: Additional PV deployment

4.2.2.1. Base Case Additional PV Deployment (BC-NY-PV)

Figure 18 shows the monthly average values. In terms of hourly solar photovoltaic production, the peak value, 15.633 MW, was obtained in July, considerably below the 20.250 MW of installed power. The average annual production is 10.408 MW, totalling 91,41 TWh for the entire year.

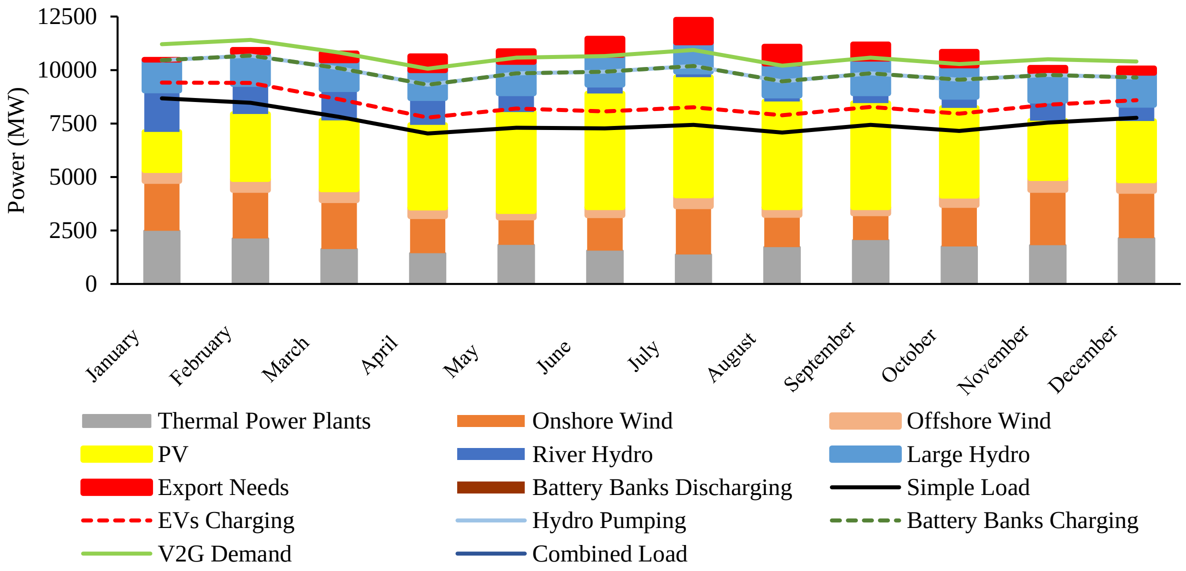


Figure 18: Yearly Load Diagram for Base Case Extra PV Scenario 2050 (BC-NY-PV)

Winter week, Figure 19, in this scenario only differs from the correspondent one in the BC-NYscenario in what matters photovoltaic energy production, which increases on average 18%. Even so, excess electricity production is never obtained during this week.

The Spring week is shown in Figure 20. Here, hydro pumping works at its maximum capacity, 4.004 MW, every day, as in the BC-NY scenario. Comparing to the homologous week in BC-NY, EV charging is slightly higher, about 4%. Such happens due to the smart charging strategy, through which the vehicles are primarily charged with energy in surplus. Excess electricity production occurs in four consecutive days, from Thursday to Sunday. Saturday presents highest surplus, peaking at 8.698 MW, which represents 41% of energy production in that day.

During the Summer week, Figure 21, production is mostly assured by solar photovoltaics, presenting weekly peaks of c.a. 14 GW. Power in excess occurs every day except on Monday, always in the middle of the day. It peaks at 8.824 MW on Saturday.

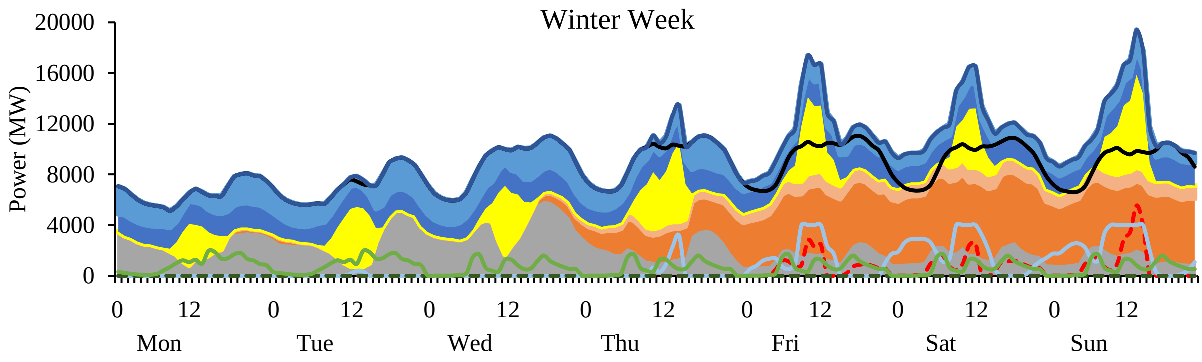


Figure 19: Representative Winter Week Diagram for the BC-NY-PV scenario.

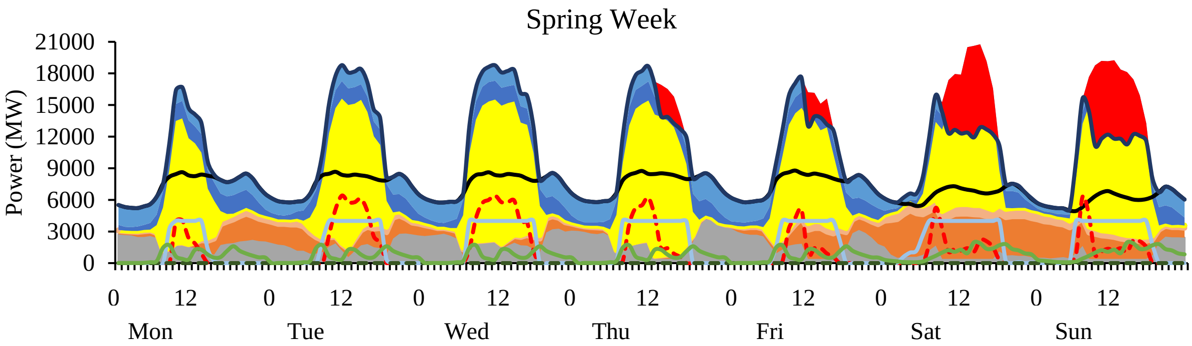


Figure 20: Representative Spring Week Diagram for the BC-NY-PV scenario.

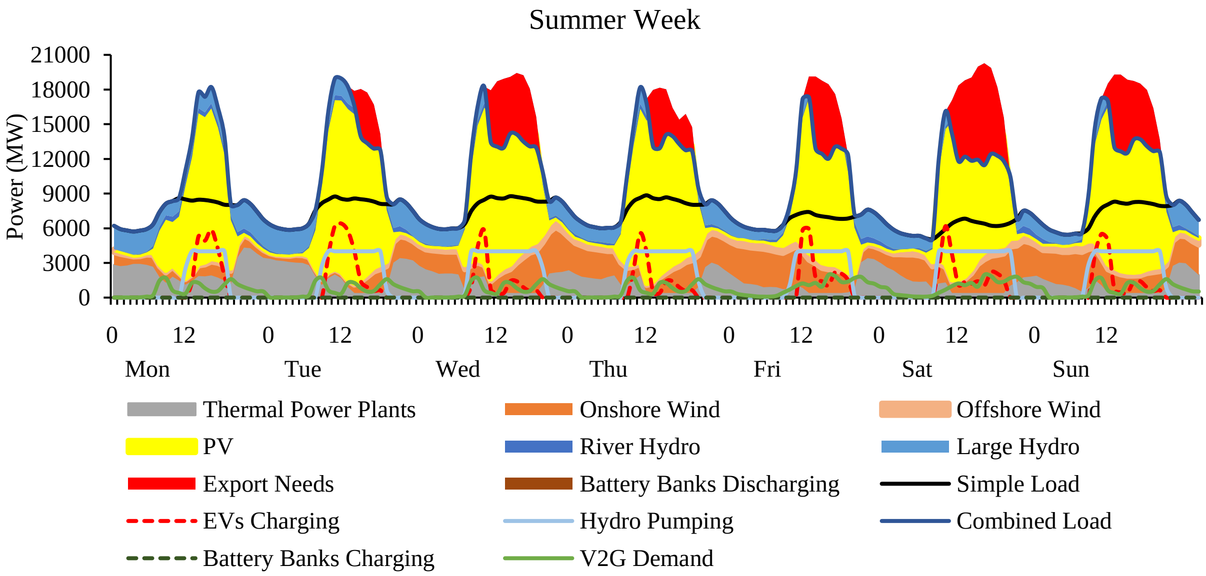


Figure 21: Representative Summer Week Diagram for the BC-NY-PV scenario.

4.2.2.2. Repurposed Batteries Additional PV Deployment (RB-NY-PV)

An additional 3.581 MW capacity of solar photovoltaics is considered to be installed in this scenario, resulting in a total installed capacity of 20.250 MW. As expected, compared to the previous second-life storage scenario, the annual excess energy and the use of the battery banks storage increase, on average 500% (charging increases on average from 85 to 425 MW and discharging from 61 to 306 MW). However, it is noted again, that relative to the BC-NY scenario energy in excess is maintained, given that this is a premise of the current scenario. These values allow to assess how an increase in storage capacity by the repurposed batteries facilitates renewable energy penetration in the power system. Figure 22 shows the average annual values, demonstrating the system operation for this case scenario.

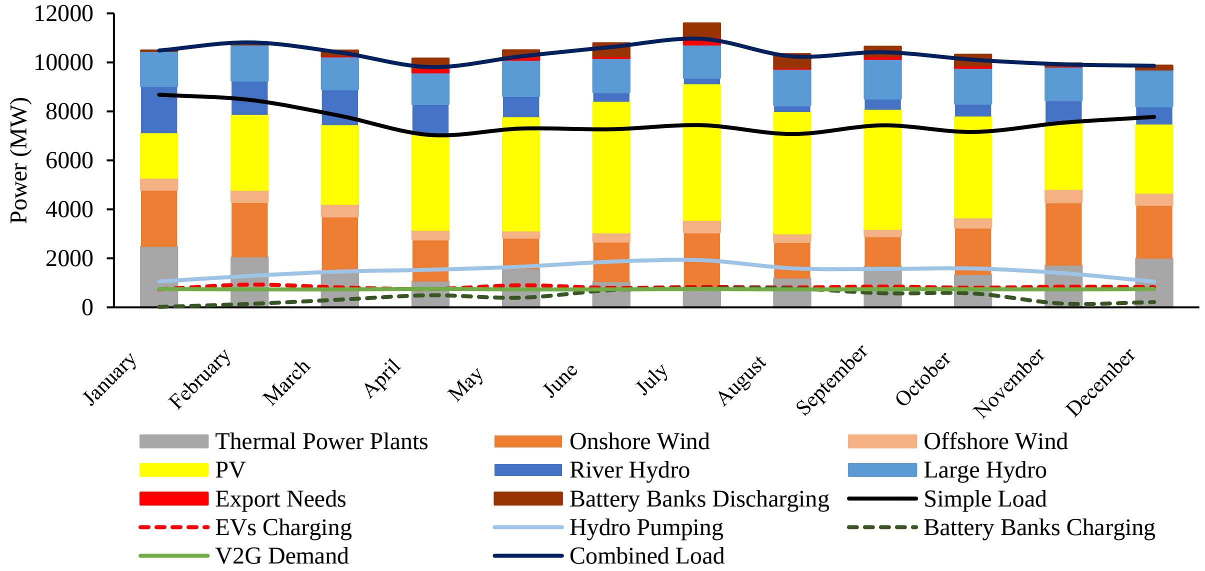


Figure 22: Yearly Load Diagram for 2ndLife Storage Extra PV Scenario 2050 (RB-NY-PV).

In the Winter week, Figure 23, again as there was no energy in excess given the higher load, the battery banks are not operated. Thus, this weekly diagram does not differ from the corresponding one in the BC-NY-PV.

The Spring week, Figure 24, is characterized by the use of battery banks charging from Thursday to Sunday. The peak charging value, 6.780 MW, occurred on Saturday. It is important to note that this value corresponds to the maximum grid capacity to connect with the battery banks, so they were charging full load. Even so, export needs were verified on Saturday, at the same time, and Sunday, indicating that if a larger energy capacity was available, the battery banks would be able to continue charging. The export needs peak at 7.457 MW on Sunday. Regarding the discharging to the grid, it occurred on Thursday and Friday between 5 and 9 p.m., and on Sunday between 7 p.m. and 12 p.m, peaking at 3.162 MW. It shows that the batteries are particularly useful during the evening load peak periods. On Saturday, battery banks discharging was not needed, due to a higher wind power generation.

During Summer, Figure 25, the battery banks are typically filled up during the day with potential excess of PV power and drained out at evening, confirming what was said above. The highest charging value, 6.780 MW, i.e. nominal capacity, was on Saturday. Battery banks discharging had a peak of 3.022 MW on Friday. The weekly charging and discharging average is of 770 and 555 MW, respectively.

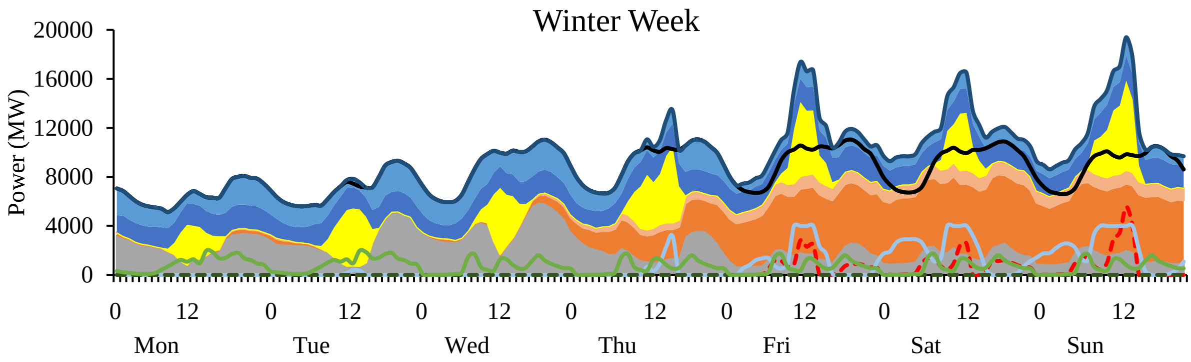


Figure 23: Representative Winter Week Diagram for the RB-NY-PV scenario.

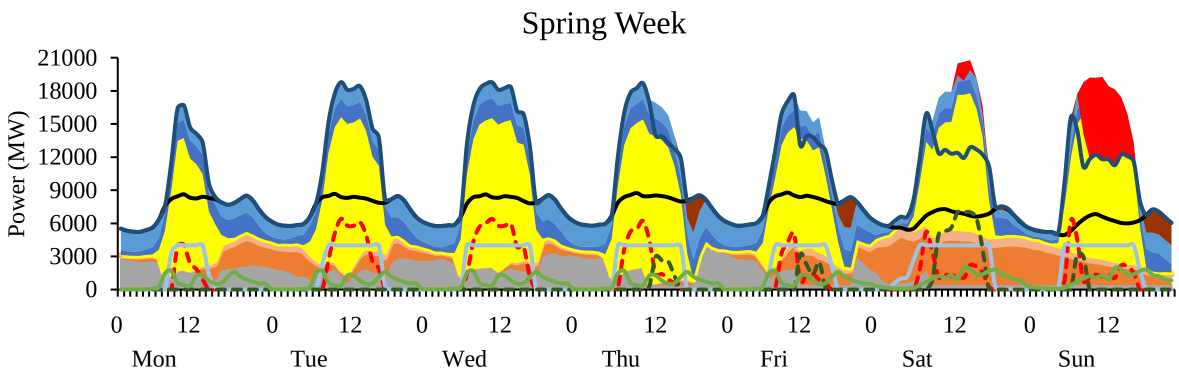


Figure 24: Representative Spring Week Diagram for the RB-NY-PV scenario.

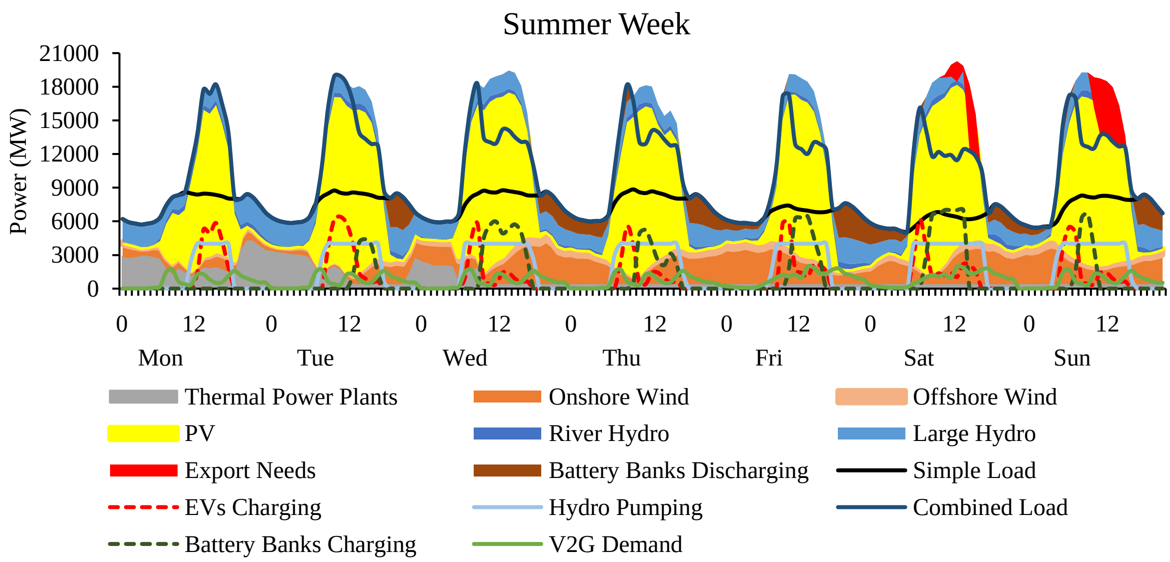


Figure 25: Representative Summer Week Diagram for the RB-NY-PV scenario.

4.2.3. Scenario 7: Dry Year

4.2.3.1. Base Case Dry Year (BC-DY)

The present scenario corresponds to the Base scenario (without battery storage) tested under conditions of less hydro resource availability. Comparing with the base BC-NYscenario, the total energy excess decreases from 0,77 to 0,32 TWh. The import needs are maintained, which suggests that repurposed batteries might be capable to fully compensate the lower stored energy in the dams, supplying the grid when requested. However, if the grid interconnection was not disabled in model interface, the imports would increase by 72,56% comparing to BC-NY scenario. The annual average values are presented in Figure 26.

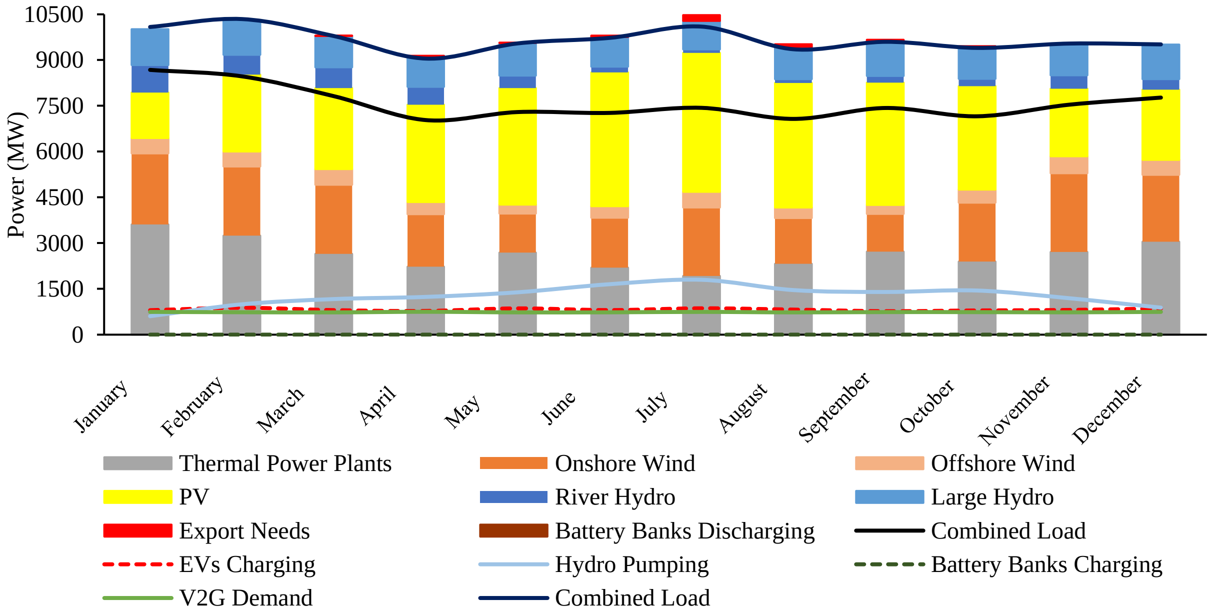


Figure 26: Yearly Load Diagram for Base Case Dry Year Scenario 2050 (BC-DY).

The Winter week, Figure 27, is characterized by production deficits on Tuesday and Wednesday due to the lack of hydro production, representing import needs that peak at 1.357 MW and 1.732 MW, respectively. Hydro pumping only works from Friday to Sunday, showing an irregular profile, reaching however its nominal power. There is never power in excess during this week.

The Spring week, Figure 28, presents a slight energy surplus on Saturday, peaking at 1.202 MW, about 7% the production of that day. Hydro pumping is requested every day in the middle of the day, always reaching full capacity.

During Summer, Figure 29, production is mostly assured by solar photovoltaics, peaking at c.a. 12 GW. Hydroelectric production represents 11,2% of the weekly production – in the BC-NY scenario it represented almost 15%. Power in excess occurs from Friday to Sunday, although residually on the former. The highest value of energy in surplus occurs on Saturday, peaking at 5.458 MW, 600 MW below the value on BC-NY scenario).

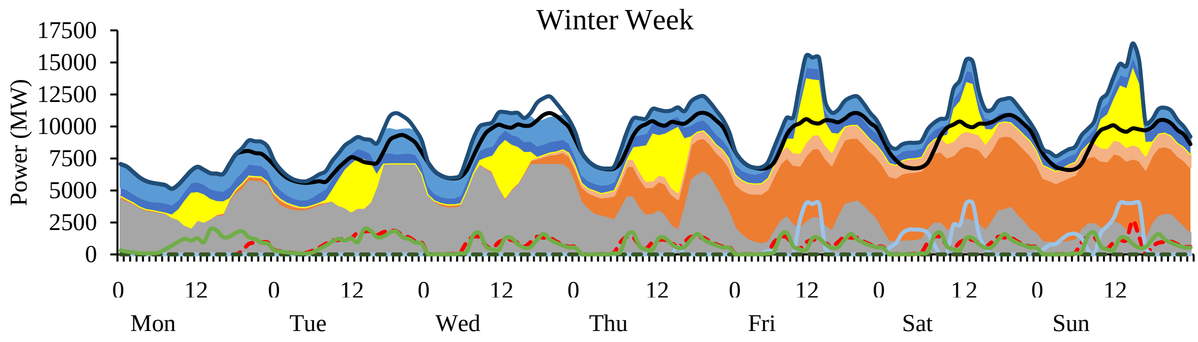


Figure 27: Representative Winter Week Diagram for the BC-DY scenario.

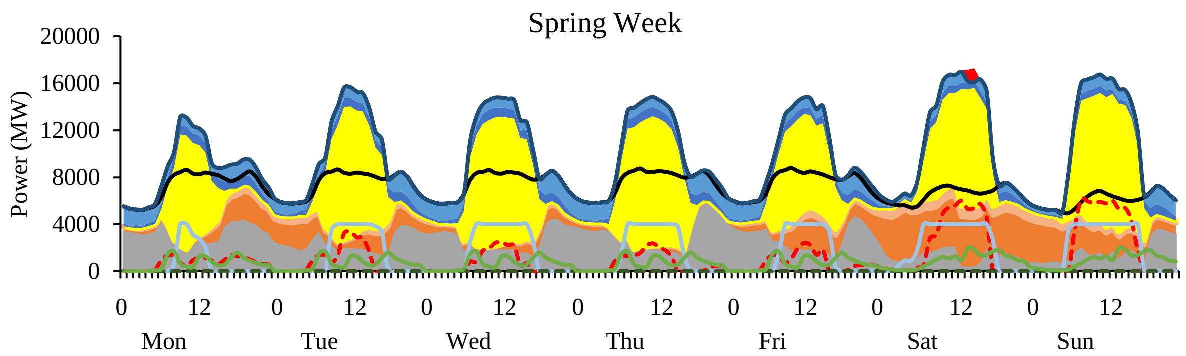


Figure 28: Representative Spring Week Diagram for the BC-DY scenario.

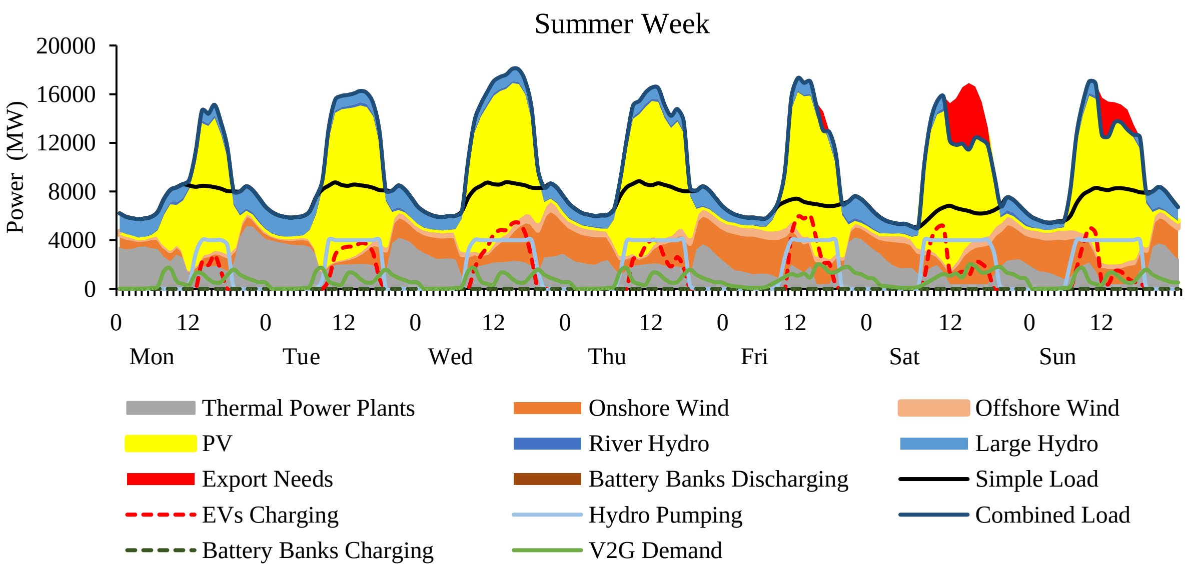


Figure 29: Representative Summer Week Diagram for the BC-DY scenario.

4.2.3.2. Repurposed Batteries Dry year (RB-DY)

In annual terms, Figure 30, batteries work at an average charging and discharging values of 36 and 26 MW, respectively. These values are about 57% lower than those obtained for the annual average for RB-NY scenario – given the smaller hydroelectric production there is less potential for excess energy. In fact, in this scenario there is never energy in excess, while in the BC-DY scenario the excess is of of 0,32 TWh. The highest charging and discharging values occurred during July, at 188 and 135 MW, respectively. Battery banks are mostly operated during the summer, peaking at 6.334 and 3.247 MW of charging and discharging.

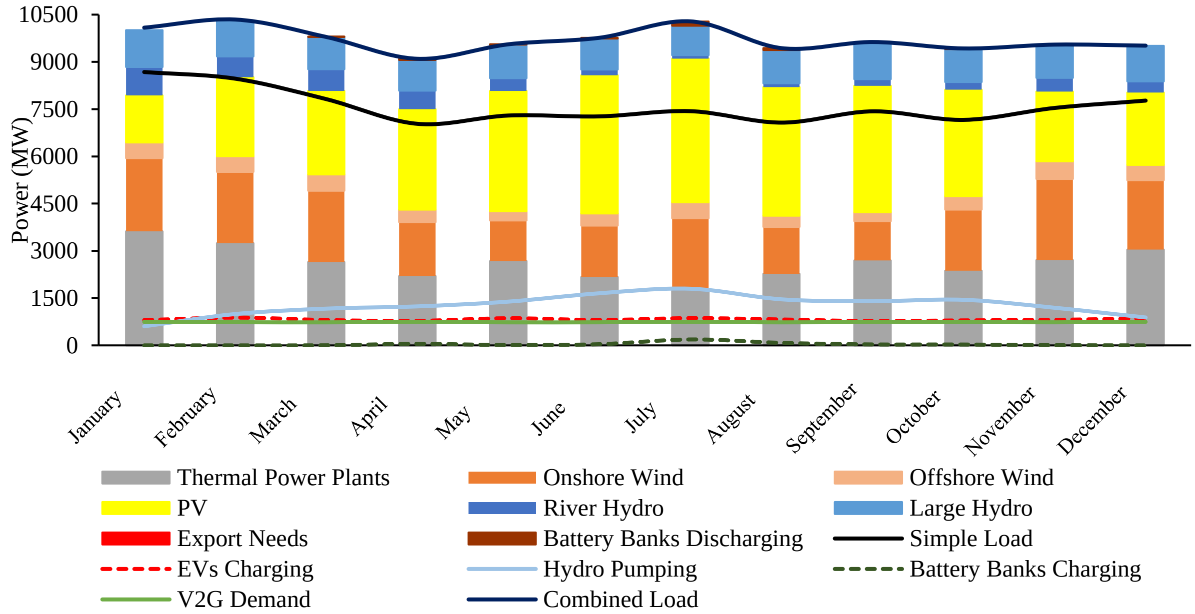


Figure 30: Yearly Load Diagram for 2ndLife Dry year Scenario 2050 (RB-DY).

In the Winter week, Figure 31, as there was no energy in excess given the higher consumption levels and the lack of hydro production, charging and discharging of battery banks was not verified. Thus, this weekly diagram does not differ from the corresponding one in the BC-DY scenario.

Spring week, Figure 32, is characterized by a small charging and discharging of batteries only on Saturday, peaking at 1.202 MW and 1.295 MW, respectively – again, charging occurs during the day and discharging occurs at evening.

During the summer week, Figure 33, storage by the battery banks was called both on Saturday and Sunday. On Sunday, battery banks discharging was requested in two periods: on a very minor scale from 0 to 9 a.m., when wind power decreases, and on a larger scale from 6 to 9 p.m. The highest charging value was on Saturday, the day with more energy in excess, peaking at 5.458 MW. Regarding battery banks discharging, it peaked at 2.008 MW on Sunday.

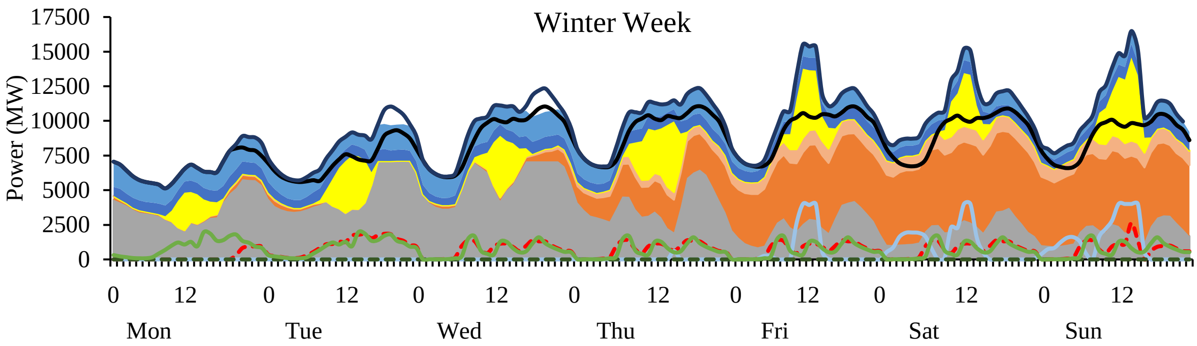


Figure 31: Representative Winter Week Diagram for the RB-DY scenario.

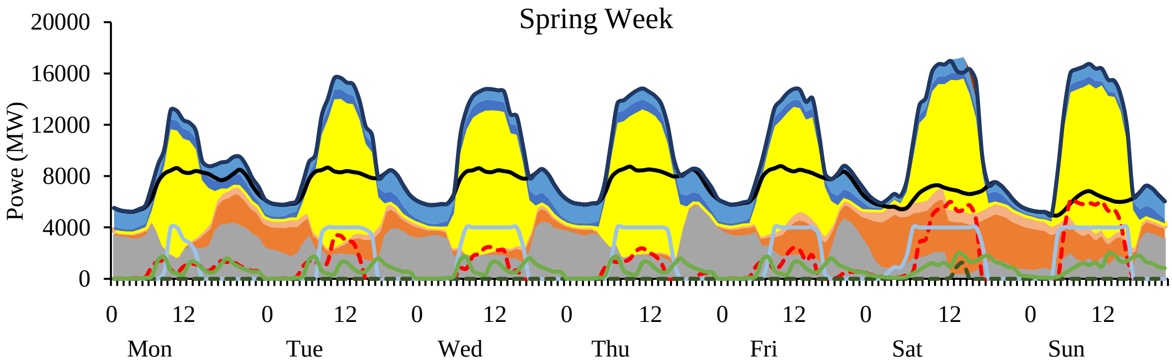


Figure 32: Representative Spring Week Diagram for the RB-DY scenario.

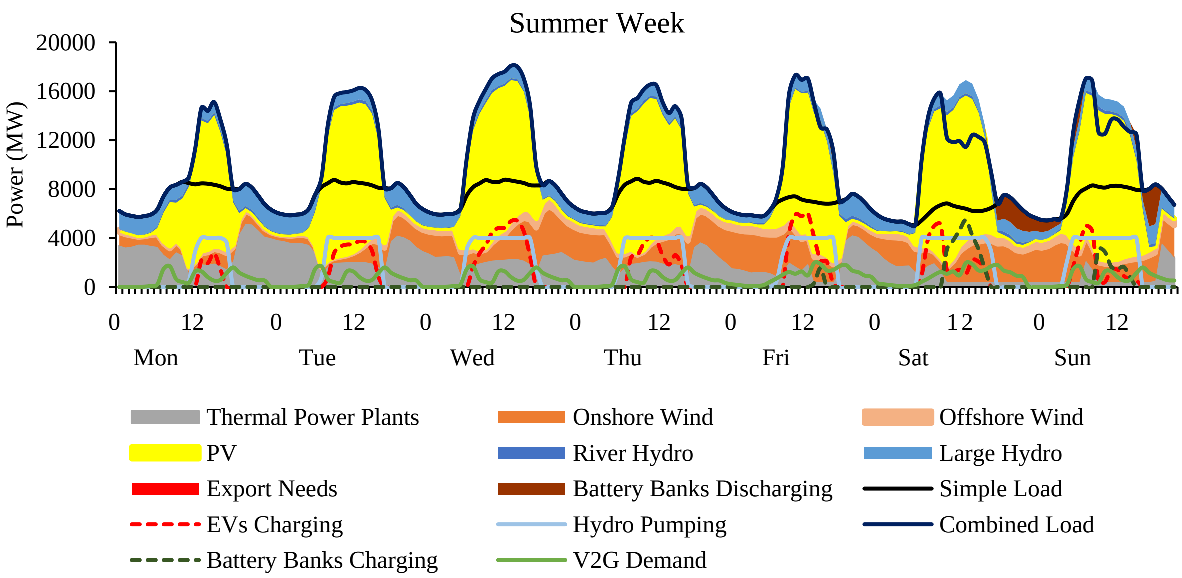


Figure 33: Representative Summer Week Diagram for the RB-DY scenario.

4.3. Grid interconnection needs

Table 8 summarizes for each scenario the maximum capacity needs for imports, corresponding to an internal production deficit, after the use of energy storage, and exports, when there is production surplus, after the use of energy storage, assuming that there is no power curtailment. In the 2050 normal scenario, a 8.270 MW export connection is needed, given the large solar photovoltaic production and the absence of second-life storage, and the energy to export is 0,77 TWh. Contrasting, with batteries in operation, these values substantially decrease to 3.810 MW and 0,03 TWh, respectively. It is thus possible to say that battery banks assume a relevant role in grid balance.

Concerning the Extra PV scenario, even with storage, a greater export capacity is needed (11.103 MW); however, the energy exchanged is approximately the same (a premise of the scenario, as detailed above). In the Dry Year scenario, there are any needs to export, because all energy surplus is stored in the batteries. However, import capacity is of 2.168 MW and energy exchanged is 0,11 TWh, given the weak hydro energy production during Winter.

Table 8: Import and Export Needs for each scenario.

Scenarios		2030	2035	2040	2045	BC-NY	RB-NY	BC-NY PV	RB-NY PV	BC-DY	RB-DY
Maximum capacity needed [MW]	Import	0	0	0	0	595	595	373	373	2.168	2.168
	Export	0	0	0	0	8.270	3.810	11.103	11.103	6.334	0
Annual energy exchanged [TWh]	Import	0	0	0	0	0	0	0	0	0,11	0,11
	Export	0	0	0	0	0,77	0,03	4,49	0,75	0,32	0

Concerning the two main scenarios (BC-NY and RB-NY), the annual needs for imports and exports are shown in Figures 34 and 35, respectively. One can see a prominent difference between these two situations: in the BC-NY scenario the import needs are residual throughout the year and the export needs are considerable, happening for 350 hours along the year, as already confirmed by the values presented in Table 8. In the RB-NY case scenario, there is a sharp decrease in these needs, where exports should be needed only for 16 hours along the year.

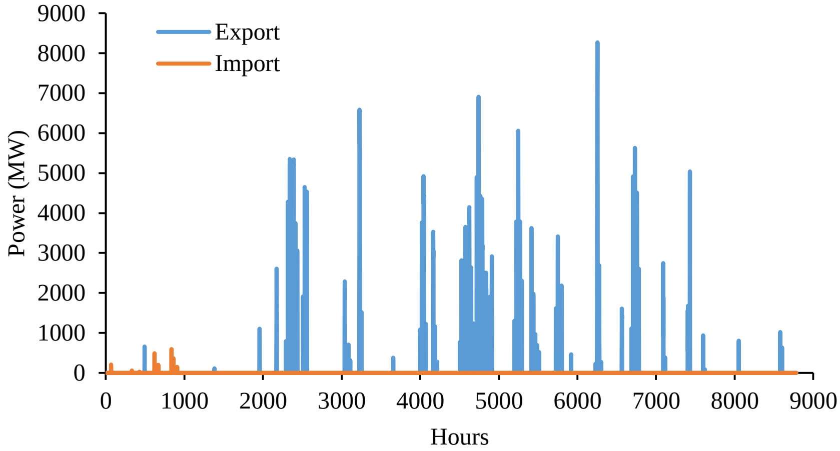


Figure 34: Import and Export need for the Base Case Scenario (BC-NY).

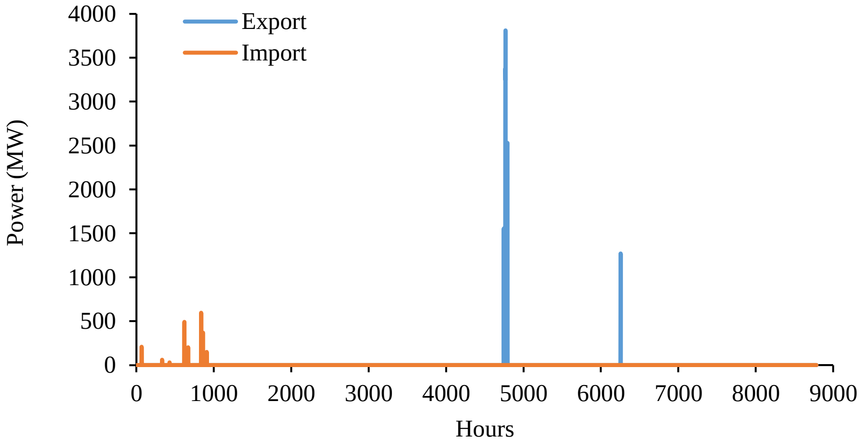


Figure 35: Import and Export need for the 2nd Life Storage Scenario (RB-NY).

Regarding the use of the battery banks during the year for the RB-NY scenario showed in Figure 36, it is possible to verify that they are discharging more often than charging, as the smoother and more prolonged discharging curve indicates. However, charging of the batteries occur generally more intensely. It was found that the capacity factor of using the second-life batteries is low (about 5%), since the Portuguese power system already comprises a large hydro-pumping capacity to store energy.

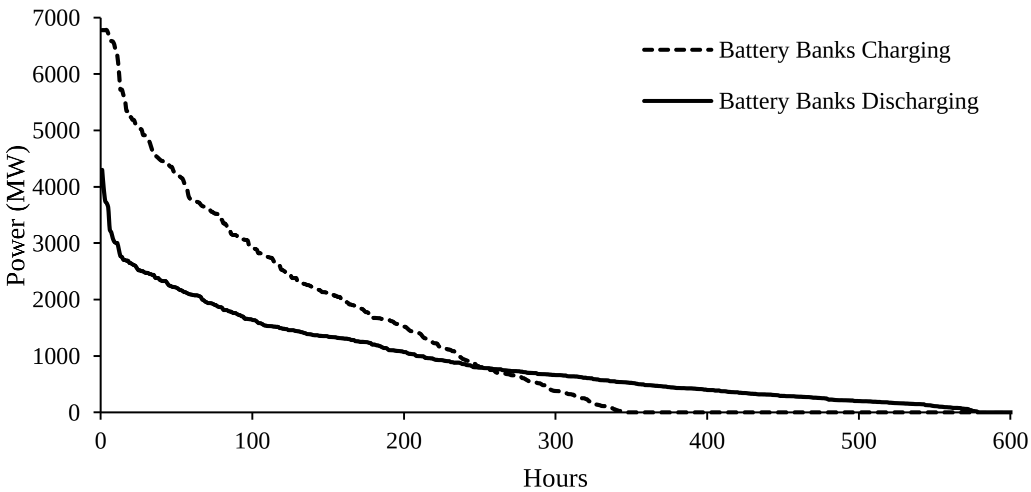


Figure 36: Battery banks usage during the year.

Figures 36 and 37 together allow a complete understanding of the power system operation with second-life batteries working, in which it is possible to verify how often batteries were charged to their maximum storage capacity. One can verify that this maximum value (38,3 GWh represented in the dashed line) was reached between mid June and beginning of July, and at the end of September a value of around 35 GWh, 92% of the capacity, was reached. Again, it is possible to see the absence of use of battery banks during the winter and a more substantial prevalence during the Spring and Summer.

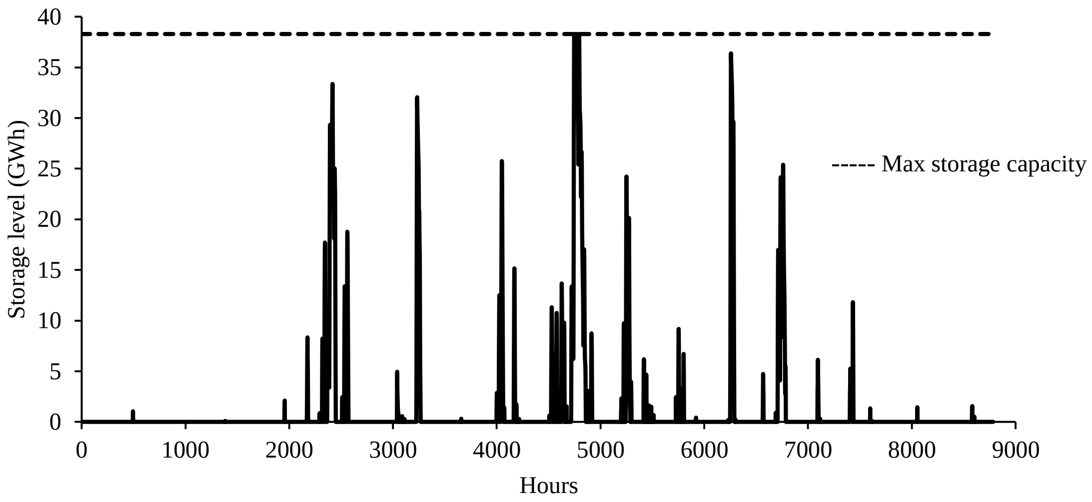


Figure 37: Storage level during the year (RB-NY).

Figure 38 shows the average daily charging/discharging profile of the batteries for the summer week. One can see that the charging values reach their peak (around 3.800 MW) next to the hours of high photovoltaic production, that is, from 1 p.m. to 4 p.m. That charging values represent the energy surplus channelled to the batteries. Regarding batteries discharging, it occurs in the evening (peaking around 10-11 p.m. at 2.691 MW), when there is no photovoltaic production and, thus, the energy stored in the batteries is requested to supply the grid.

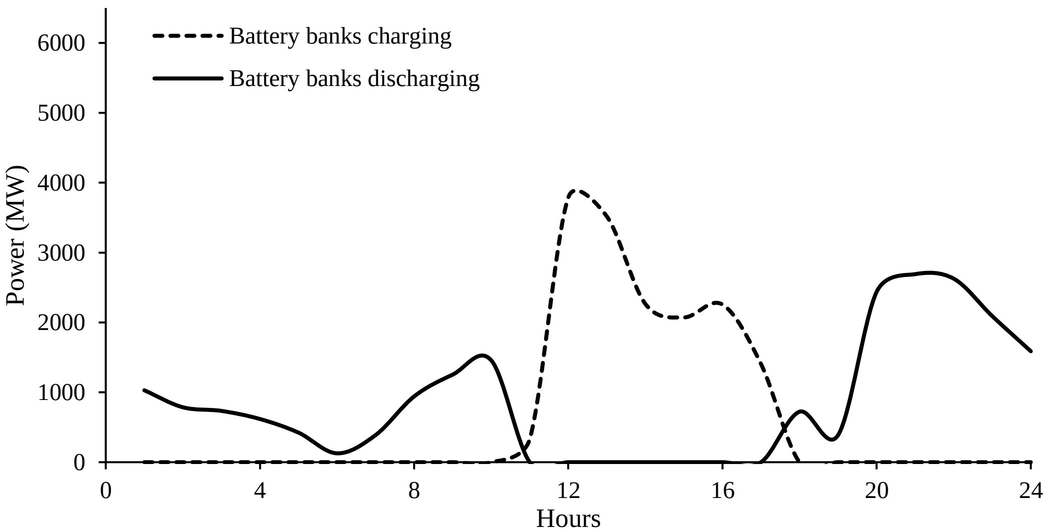


Figure 38: Daily average charging/discharging profile for the summer week.

4.4. CO_2 emissions

Figure 39 summarizes the simulated values for the total annual CO_2 emissions of the power system and the passenger vehicles fleet.

In each scenario including second-life battery storage, the emissions are always lower when comparing to the corresponding scenario disregarding this solution. Such results quantify how the system benefits environmentally with second-life battery storage inclusion.

If one focuses in the comparison between the scenarios without and with storage under normal climatic conditions, i.e., scenarios without second-life storage (BC-NY) and with second-life storage (RB-NY), respectively, the batteries allow to decrease CO_2 emissions by 0,2 Mton, which represent 3,4% of total emissions from the power system.

Regarding the Extra Photovoltaic and Dry Year scenarios, the figure also shows the CO_2 emissions for the cases without and with battery storage.

From the graph analysis, it is possible to verify that the total emissions from the power system are higher in the dry year scenarios, given the lower penetration of renewables due to the lack of hydro contribution.

The RB-NY-PV scenario allows emissions to reduce by about 1 Mton, comparing to the BC-NY-PV. In the RB-DY scenario, emissions are also lower than in the BC-DY scenario due to the battery storage, although the difference is small (about 0,1 Mton). Comparing the BC-DY scenario to the BC-NY one, emissions are 2 Mton higher, given the need for assistance by thermal power plants.

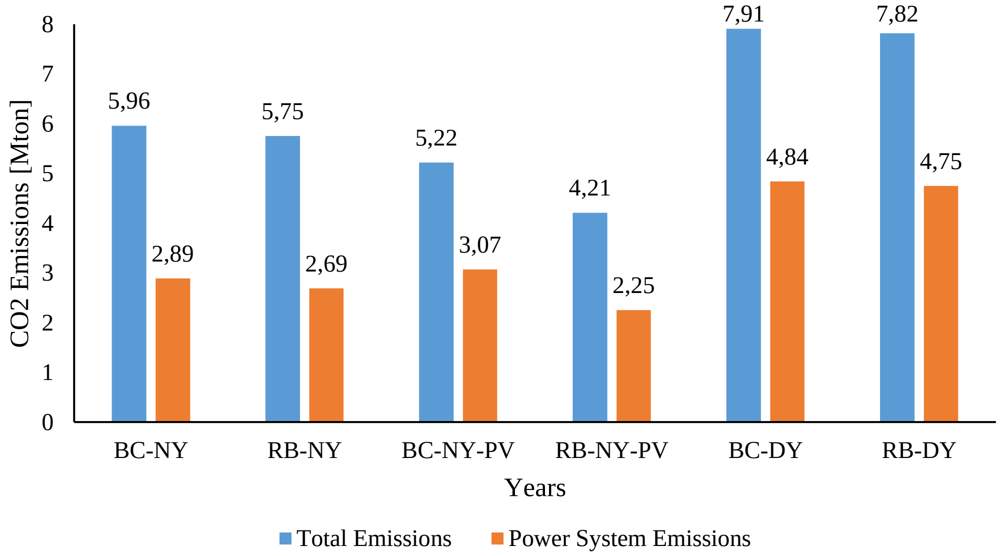


Figure 39: CO_2 emissions (Comparison between main scenarios with and without battery storage).

Figure 40 shows how CO_2 emissions evolve in the system as a function of photovoltaics installed capacity for three different cases of storage: 38,3 GWh of second-life storage capacity, half storage capacity (19 GWh) and no storage capacity at all. It can be seen that the second-life storage solution is most effective at decreasing emissions at higher levels of PV installed capacity. Particular emphasis is given to the difference verified between the cases with and without storage. In the absence of storage emissions decrease with increasing PV is flatter, and there are more pronounced diminished returns of adding PV.

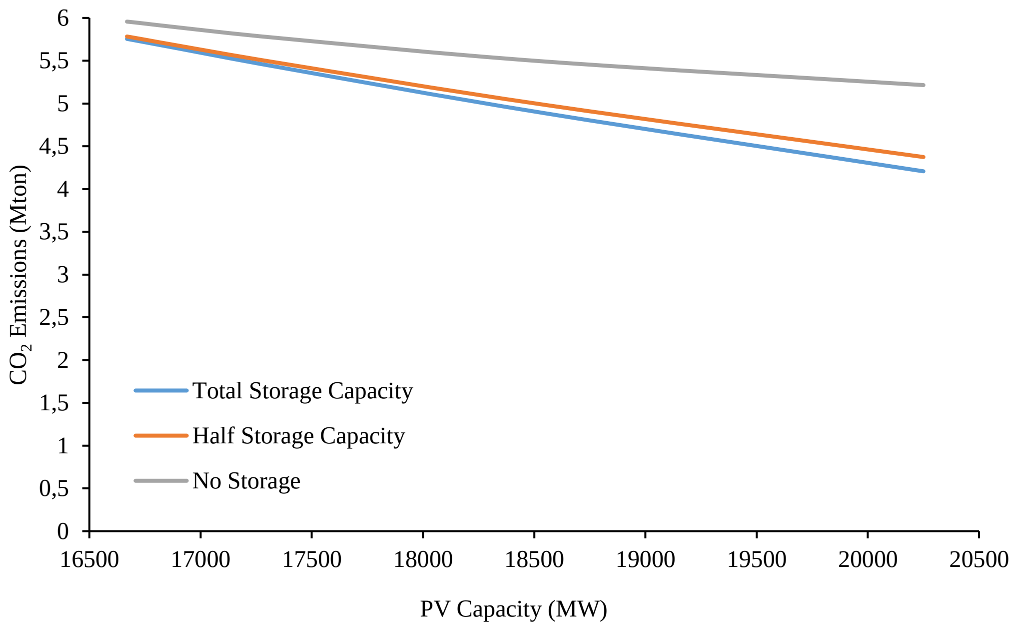


Figure 40: CO_2 emissions (Comparison between main scenarios with and without second-life battery storage).

Chapter 5 - Conclusions and Future Prospects

This study analysed how a large power system can profit from electric cars second-life batteries to store excess of non-controllable renewable energy.

The literature review has shown that the insertion of energy storage systems for renewable sources may transform the EV technology and markets in terms of cleanliness of charging source, by repurposing the batteries in an end of life condition. Several factors will determine the feasibility of second life batteries usage, such as the cost of acquisition and the repurposing process. Nevertheless, the most relevant factor is battery degradation. According to the literature, the reuse of electric vehicles retired batteries for energy storage systems shows notorious environmental benefits, allowing significant GHG emissions reduction, by means of avoiding new batteries manufacture, and replacing of natural gas or coal-based plants backing up the power grid.

To analyse the system operation with the second life storage solution, the evolution of the Portuguese power system and the passenger cars sector was simulated hourly for the period 2030 to 2050, at each 5-year interval. For 2050 two sub-scenarios were designed: one considering additional PV deployment and another one simulating the case of a dry year, wherein hydro availability is low. Each one was compared against the case of the system not including second-life storage.

The results were evaluated by: the annual balance between consumption and production of electricity by technology; the international interconnection needs; the amount of CO_2 emissions of transportation the power system; the load diagrams.

Results showed that by 2050 the second-life batteries market should represent in Portugal about 38 GWh of storage capacity, allowing, in a normal year, a decrease in energy surplus from 0,77 to 0,03 TWh. The battery banks are mostly operated during the summer to store photovoltaic production. Regarding renewables integration, the batteries should allow an additional 3.581 MW photovoltaics deployment. For a dry year scenario, results suggest that the repurposed batteries are capable to fully compensate the lower stored energy in the dams, supplying the grid when requested.

Regarding controllable energy storage by 2050, it is achieved essentially by hydroelectric pumping and by the on-board batteries of the electric vehicles (V2G). Given that the round-trip combined efficiency of hydro pumping is c.a. 60%, which has priority over storing the same energy in electric car batteries, a process much more efficient, as its efficiency is of c.a. 85%, it would be interesting to test the system inverting this priority.

Concerning needs for imports/exports, consequentially international interconnection capacity, in 2050 for the case without energy storage scenario, a 8.270 MW export connection is required and the energy to export is 0,77 TWh. Having the battery banks in operation, these values decrease to 3.810 MW and 0,03 TWh, respectively. It is thus possible to say the second-life batteries assume a relevant role balancing the grid. In a dry year scenario, export needs are not verified given that the batteries are capable to store all the potential energy surplus. Nevertheless, a 2.168 MW import capacity is needed given the weak hydro winter production.

Regarding environmental benefits, the second-life storage batteries allow a decrease of 0,2 Mton in CO_2 emissions, representing 3,4% of total emissions from the power system. In the additional PV deployment case, one can see an improvement of this reduction to 32%, i.e., the second-life storage solution is most effective at decreasing emissions at higher levels of photovoltaic installed capacity.

In spite of these results, it was found that the annual capacity factor of the second-life batteries should be low (about 5%), since the Portuguese power system already comprises a large hydro-pumping capacity to store energy, suggesting that in systems where this is not the case the batteries should become more relevant.

5.1. Limitations and future work

Simulation models, intrinsically, no matter their complexity, are approximations of reality, more or less accurate according to the robustness of their equations and the reandomness of what they seek to explain and of the data they rely on.

The model used in this work is no exception. From its limitations, two stand out: (1) it relies on scarce data about the evolution of batteries capacity, their degradation rate under electric vehicles use and the process for their modification for stationary storage applications; (2) the model does not allow the user to choose how the electricity in excess is channelled between hydroelectric pumping and electric vehicle charging, prioritizing the former over the latter. If this was possible, it would be possible to evaluate better the value of the second-life batteries storage solution.

As future work, as the second-life storage capacity only begins to be useful by 2050, in future simulations of scenarios respecting the period before 2050 it would be interesting to consider higher values of photovoltaics penetration than the ones evaluated by this study, to see how the batteries would help to deploy extra PV before 2050. Additionally, further scenarios could be tested, for instance, an extra PV scenario in a dry year case, with and without second-life batteries storage.

Since there is not much data on how these batteries degrade in stationary storage applications, more R&D in this area is needed to allow better modeling of second-life storage applications. The number of studies of economic scope should also increase in order to assess the real feasibility of the solution and the business models it can rely on.

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Appendix A – Conference Article

SDEWES2018.0571

The Role of Second-Life Batteries on Renewable Based Power Systems

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Abstract

Electric mobility is taking of, and it will represent a large share of the global automobile market in the next decades. The batteries of these vehicles are typically replaced while still having a significant remaining capacity, thus they are suitable for alternative uses, creating in the medium-long term opportunities for their repurpose to domestic applications or to direct coupling to renewable energy systems. This study analyses from a technical and energy balances viewpoint how a large power system can take advantage of second-life batteries to store potential excess of non-controllable renewable energy.

For that, it uses the future Portuguese power system as case study. It couples a model of electric mobility diffusion and second-life batteries availability with various EnergyPlan simulation models of the power system for the period 2030-2050, comprising sub-models of unidirectional smart charging of electric vehicles. The results are illustrated and quantified against a base case scenario, which disregard second-life battery storage. Load diagrams of the power system are shown, and it is quantified to what extent this solution may facilitate the deployment of solar-photovoltaics and reduce the needs for imports and exports and abroad interconnection capacity. Since the Portuguese power system is largely based on hydro energy, the results are shown both for the cases of a normal and a dry year.

The results show that by 2050 the second-life batteries market should represent about 38 GWh of storage capacity. On a normal year, they allow to reduce the amount of energy in excess from 0.77 to 0.03 TWh, and mostly they are operated during the summer at an average charging and discharging rates of 251 and 181 MW, respectively. In terms of renewables integration, the batteries should allow an additional 3,581 MW of photovoltaics deployment, which allow to increase the electricity renewable share by 4%. Concerning environmental benefits, the batteries allow to decrease CO_2 emissions by 0.2 Mton, which represent 3,4% of total emissions from the power system. If one considers the scenario with increased photovoltaics deployment that they allow, the reduction of CO_2 emissions ascends to 32%. For the dry year scenario, the results are that the repurposed batteries are capable to fully compensate the lower storage capacity in the dams, supplying the grid when requested. In spite of these results, it was found that the capacity factor of the second-life batteries should be low (about 5%), since the Portuguese power system already comprises a large hydro-pumping capacity to store energy, suggesting that in systems where this is not the case the batteries should become more relevant.

The role of second-life batteries on renewable based power systems

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ABSTRACT

Electric mobility is taking off, and it will represent a large share of the global automobile market in the next decades. The batteries of these vehicles are typically replaced while still having a significant remaining capacity, creating opportunities for their repurpose to domestic applications or to direct coupling to renewable energy systems. This study analyses from a technical and energy balances viewpoint how a large power system can take advantage of second-life batteries to store potential excess of non-controllable renewable energy. For that, it uses the future Portuguese power system as case study. It couples a model of electric mobility diffusion and second-life batteries availability with various EnergyPlan simulation models for the period 2030-2050. By 2050 second-life batteries market should represent about 38 GWh of storage capacity. They allow to reduce the amount of energy in excess from 0,77 to 0,03 TWh, and mostly they are operated during the summer. In terms of renewables integration, the batteries should allow an additional 3.581 MW of photovoltaics deployment. Batteries allow to decrease CO_2 emissions by 0,2 Mton, which represent 3,4% of total emissions from the power system.

KEYWORDS

Second-life batteries, power systems analysis, electric vehicles, smart charging, battery storage, CO_2 emissions

1. INTRODUCTION

Despite representing a viable promising alternative for a more sustainable transport sector, electric vehicles carry an arduous environmental issue related with the end-of-life of the batteries. Logically, the fast growth of their market share will lead to an emergence of battery disposal in the medium-long term. This issue has been proposed to be addressed by repurposing used batteries to provide stationary low-cost energy storage.

Retrieving value from those batteries with no more use in automotive service could soften the problems related to battery disposal. Given that these batteries, in most cases still hold approximately 80% of their energy capacity after automotive use, it may be achievable to repurpose them to energy storage and peak-shifting/shaving applications [1]. The repurposed batteries could be employed in single homes, office buildings, factories or in power plants. To enable a market of retired Electric Vehicles (EVs) batteries, the

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development of effective business models is imperative. A fast market penetration of EV's is hugely restricted by the cost of batteries. Likewise, the development of grid-connected battery energy storage systems, which could increase the grid reliability and renewable energy use, is similarly conditioned by the cost of batteries. This issue has been mitigated by lower material costs, enhanced process efficiencies and by a significant increase in production volumes, leading to economies of scale.

Repurposing batteries offers several advantages and has potential to decrease battery lifecycle costs. The repurposing process may be complex given that a dismantling of the batteries into individual cells is required. In 2012, Neubauer and Pesaran [2] have published an in-depth study allowing an accurate calculation of second-life batteries purchase. According to the calculations performed by them, the estimated market price for second life Li-ion batteries varies between 38 and 154EUR/kWh. Several studies were reviewed, and some factors were identified as main sources of error in the cost-benefit analysis. Cost structures (second life battery acquisition costs and market prize, refurbishment costs), revenue streams (electricity prices, rate structures), technical parameters (second life battery lifespan, power, capacity, efficiency), policies and market conditions (environmental initiatives, governmental subsidies) are the most relevant causes for uncertainties in the calculations performed so far [3].

Concerning the environmental impacts of second-life batteries, several studies were carried. Cicconi et al., [4] compared the technical performance and environmental impact of a new and a reused battery packs in a smart grid application responding to peak demand requirements. In this work, a Life cycle analysis (LCA) of both an EV and plug-in hybrid electric vehicle (PHEV) battery packs was designed considering the complete lifecycle since raw material extraction to final disposal, including the manufacturing, transportation phases, whole use phases and, finally, the disposal. The results from this LCA evidenced CO_2 emissions reduction of 25% in the second life application compared to the normal EV/PHEV lifecycle. The conclusions of the study highlighted that second life use for retired batteries is technically and environmentally beneficial. For additional insights on this topic, see Refs. [5] and [6].

1.1. Motivation and Objectives

In the context of the growing need for energy storage systems, more and more energy-efficient and economically viable alternatives are needed. Thus, used batteries of electric vehicles may represent an alternative given the significant growth of electric mobility, creating opportunities for their reuse for energy storage either in domestic use or by direct coupling with systems of renewable energy generation. Therefore, the interest in this topic arises essentially from the imperative need of creating alternatives and the fact that it may represent a solution to make the batteries lifespan longer, whose end-of-life still represents an environmental problem yet to be addressed.

The purpose of this work is to analyse and simulate energetically and environmentally the reuse of electric vehicles batteries as stationary energy storage applications. The Portuguese power system is used as case study; it already presents a significant share of renewable energy – c.a. 50% –, mostly hydro and wind. Still, the export capacity is limited due to the similarity with the Spanish energy production, leading to the need to create alternative large-scale storage systems alongside with hydro-pumping. This study couples a model of electric mobility diffusion and second-life batteries availability with various EnergyPlan simulation models for the period 2030-2050. This model allows to identify the role that the repurposed batteries may have in the system operation, and in what way they may represent a benefit by enabling a larger share of renewable energy in the system.

2. METHODOLOGY

For the simulation, it was necessary to characterize the national electricity system over the years covered by the study, 2030-2050, as well as to incorporate the transport sector with a focus only on the passenger vehicles.

The methodology followed here is based on the work developed by Nunes et al. [7] whose aim was to explore the possible complementarities between wind and solar power and electric vehicles charging, based on 2050 scenarios for Portugal, using EnergyPLAN [8] as simulation tool. The scenarios used here to model and analyse the electrical system are derived from the projections on that study. These scenarios were created based on a calibrated model of the Portuguese electricity system from a reference year (2014), that served as the basis to design the different case scenarios.

The developed model in this work mainly differs from the previous one in the battery storage modelling. In order to evaluate the availability of batteries for storage applications it was need to, firstly, based in a set of assumptions, project the market penetration of electric vehicles in Portugal for the considered period, and secondly, to obtain the scrappage curves to assess the effective number of available batteries to repurpose. Therefore, a battery availability scenario was created, and several changes were made to the pre-existing scenarios in order to model the integration and use of the batteries in the system.

The modelling of each of the scenarios was done using the EnergyPLAN technical analysis. Such approach was chosen mainly due to the objective of the study being to model and analyse the evolution of the Portuguese electrical system from the technical viewpoint and the role of batteries in the grid dynamics. The model approach is schematized in Figure 1.

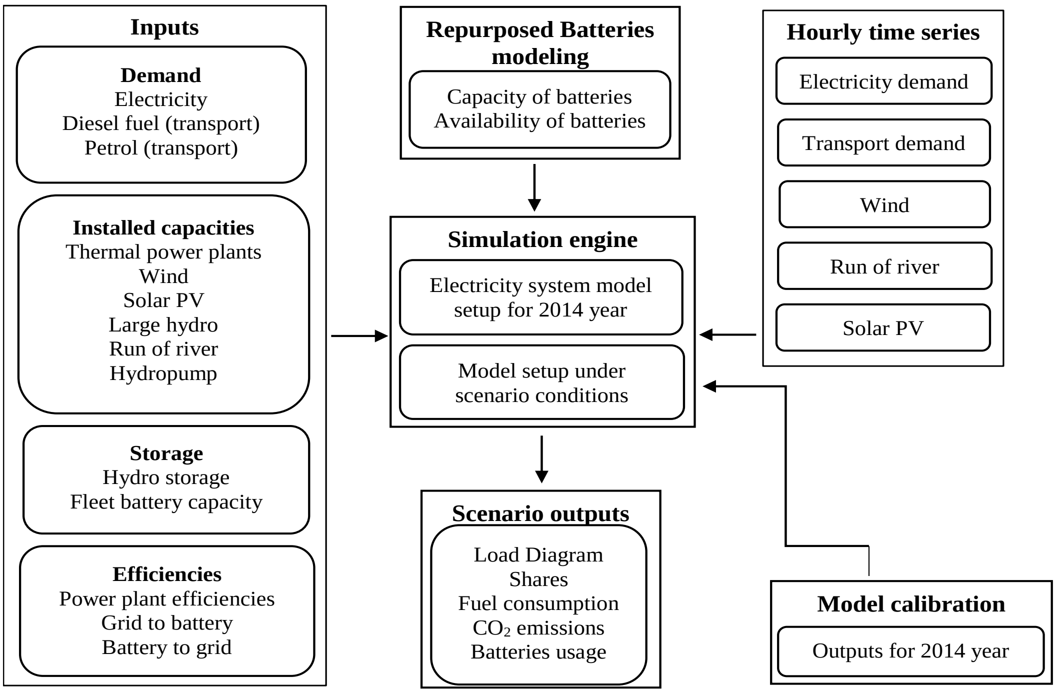

Figure 1. Model Approach

2.1. Battery Storage Modelling

2.1.1 Availability of batteries. The battery availability scenarios were created taking into account the projected market penetration of electric vehicles. Having the values up to the present, a projection was made up to 2050 using the sales and number of electric vehicles in circulation in Portugal [7].

Assuming electric vehicles sales from 2020, a simulation of the availability of batteries was performed. A range of approximately 160.000 km, representing about 8 years of automotive service was considered for the batteries [9] [10]. Thus, batteries to repurpose will start to be available in significant numbers from 2028.

2.1.2 Onboard Battery Capacity. The 2020 average individual batteries capacity was considered to be 40kWh [11], although there may be batteries with capacities considerably higher, such as in Tesla models [12]. In order to estimate the batteries capacity up to 2050, an increase of 2% per year was adopted [13]. It was also necessary to compute the degradation rate of those batteries as storage systems. For that, the assumption was made based on depth of discharge loss while in automotive service. Considering a linear approach, it was considered that if in 8 years the battery loses 20% of charge capacity, then per year it will lose approximately 2,5%. It is important to note that in stationary storage systems the stress to which the batteries are subjected is much lower than that of charging and discharging in a vehicle [13].

Thus, the capacity of batteries in circulation regarding the degradation rate in each year, i, was calculated as shown in Equation (1).

$$C_{2020+n} = \sum_{i=0}^{n}\left[Sales_{2020+i} \times c_{2020} \times R^{i} \times (d \times i)\right] - \sum_{i=0}^{n}(Scrappage_{2020+i} \times c_{2020+i}) \quad (1)$$

Where:
C_{2020+n} represents the total batteries capacity in a given year, i;
$Sales_{2020+i}$ represents the sales numbers in any given year i;
c_{2020} represents the individual onboard battery initial capacity;
R represents the increased rate of capacity, having a constant value of 1,02;
d represents the 2,5% fixed degradation rate, having a value of 0,975;
$Scrappage_{2020+i}$ represents the car scrappage in any given year i.

2.1.3 Stationary Battery Storage Capacity. To assess the storage capacity by 2050 and generally in any year, the remaining 80% of discharge capacity were considered in the calculations given that the batteries will not present the entire initial capacity. Therefore, this parameter, SC, was calculated using Equation (2).

$$SC_{2020+n} = \sum_{i=0}^{n}(Sales_{2020+i-8} \times c_{2020+i-8} \times 0{,}8) \quad (2)$$

2.2. Simulation procedures

To perform a better characterization of the Portuguese power system, load diagrams were analysed for all the considered years in the study: 2030, 2035, 2040, 2045, 2050 for a base scenario, which disregard second-life battery storage, and for the scenarios with stationary storage. Along with these characterization, an excess solar-photovoltaic installation and a dry year case scenarios were created.

2.2.1 Additional PV deployment. As the Results section will detail, the battery storage allows to diminish in the system potential energy in excess, i.e., energy that needs to be curtailed or exported. This means that the storage solution allows additional deployment of renewable energy, which we considered to be photovoltaics. This additional capacity was considered to be the one that gives rise to a value of energy in excess equal to the one that the system presented without the use of battery storage. That is, it is feasible to see how the batteries facilitate the installation of solar photovoltaic power plants. In order to determine these values, several simulations were performed until the same excess of energy production was obtained. The values were tested for all the increasing storage capacities available over the years, i.e, for each year of the study, an additional deployable value for PV capacity was identified.

2.2.2 Dry year. A scenario of reduced water flow to the dams and in the rivers was considered in order to analyse how a hypothetical year of drought would adversely affect the system operation and what could be the role of battery storage in that situation. It should be recalled that Iberia is a territory especially vulnerable to climate change, and longer and more frequent droughts are expected in the future [14][15]. To base this scenario, the year 2017 was selected given that it was extremely dry and hot - in fact, 2017 is among the four warmest years in Portugal since 1931 [16].

The hydrological index of 2017 was 0,47 (it translates water availability – a value of 1 corresponds to the long-term average), which was reflected in the hydroelectric productivity that was significantly reduced. This low productivity value was one of the weakest ever [16]. Thus, the dry year scenario is correspondent to an index of 0,47 and it was tested only for the year 2050. The correspondent water inflow to the dams and run-of-river was corrected applying a direct regression to reflect this, resulting in 2,67 TWh of water availability (compared to 5,26 TWh in the normal scenario).

To a simpler analysis, abbreviations for each scenario were created as shown in Table 1.

Table 1. Scenario Abbreviations

Scenario	Abbreviation
Base Case 2050 (Normal Year without second-life storage)	BC-NY
Repurposed batteries storage 2050 (Normal Year)	RB-NY
Repurposed Batteries Additional PV Deployment (Normal Year)	RB-NY-PV
Base Case Additional PV Deployment (Normal year)	BC-NY-PV
Repurposed Batteries (Dry Year)	RB-DY
Base Case (Dry Year)	BC-DY

2.3. Model Inputs

Table 1 summarizes the values serving as inputs in EnergyPLAN model for the case study when batteries are repurposed after 8 years of automotive use. The values presented respect to the total storage capacity of second-life batteries.

Table 2. Batteries available, respective capacity and cumulative storage capacity (2020-2050)

	Number of available batteries	Individual capacity (kWh)	Batteries in circulation (GWh)	Total storage capacity (GWh)
2020	0	40,00	0,97	0,00
2025	0	43,06	2,13	0,00
2030	14.688	47,54	4,28	0,56
2035	47.618	52,49	10,43	2,00
2040	116.470	57,95	26,90	5,40
2045	295.281	63,98	58,39	15,11
2050	678.045	70,64	102,08	38,32

Figure 2 shows the assumed EV's evolution in the Portuguese fleet until 2050, the correspondent availability of batteries and cumulative storage capacities from retired batteries. A logistic growth for both electric vehicles penetration and available batteries was assumed between 2020 and 2050. About 1,4 million of electric vehicles are expected to be in circulation by 2050, accompanied by almost 700.000 batteries for second-life applications. The storage capacity curves also show a logistic behaviour.

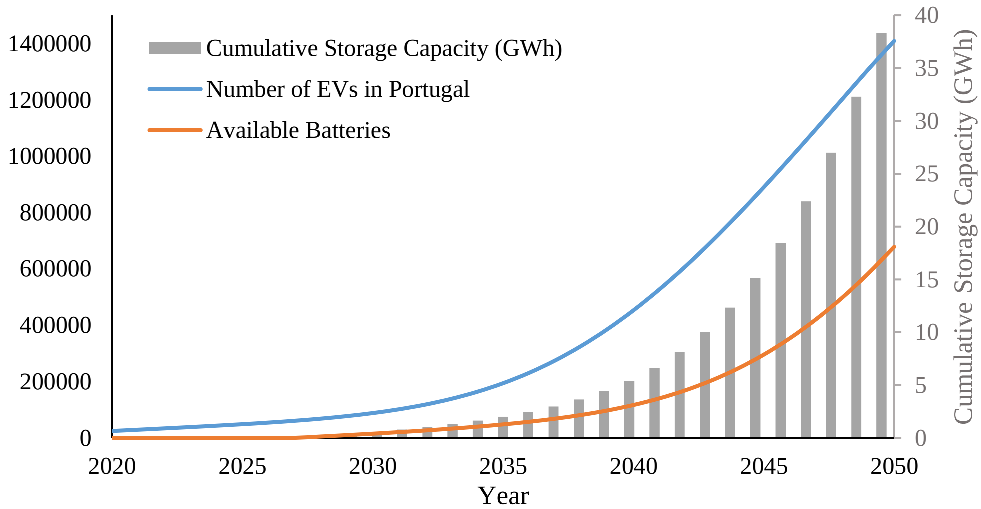

Figure 2. Electric vehicles in circulation, availability of batteries and cumulative storage capacity from 2020-2050

In terms of grid connection, a two-way 10kW power capacity was considered for each second-life battery [8]. Thus, considering the available amount of batteries and vehicles in circulation in each year, the total power connected to the grid was obtained as synthetized in Table 2, contrasting both on-board storage capacity for unidirectional V2G and second-life batteries capacity.

Table 3. Storage capacity and Grid connection in both EVs in circulation and second-life storage (2020-2050)

	Electric vehicles in circulation		**Second-life batteries**	
Years	Storage Capacity [GWh]	Grid Connection [MW]	Storage Capacity [GWh]	Grid Connection [MW]
2020	0,97	242,37	0	0
2025	2,13	482,69	0	0
2030	4,28	877,75	0,56	146,88
2035	10,43	1.937,74	2,00	476,18
2040	26,90	4.526,21	5,40	1.164,70
2045	58,39	8.897,78	15,11	2.952,81
2050	102,08	14.089,24	38,32	6.780,45

Table 3 briefly describes the most relevant scenario assumptions based on performed projections and inputs for EnergyPLAN model.

Table 4. Inputs summary for the most relevant scenarios (2050)

Repurposed batteries storage 2050 (RB-NY)	The installed capacity of Portuguese power system presents a value of 34,3 GW. Solar PV presents an installed capacity of 16.669 MW, being the renewable energy source with the highest contribution, followed by onshore wind with 7.674 MW. A 73,8 TWh/year consumption is expected with EV representing 7,21 TWh/year. Second-life storage reaches its maximum value, 38,3 GWh, along with 102,08 GWh from V2G and 6.900 GWh from dammed hydro. Hydro-pump represents 4.004 MW.
Additional PV (RB-NY-PV) (BC-NY-PV)	This scenario differs from the previous one only in the installed solar photovoltaic capacity, which becomes 20.250 MW.
Dry year (RB-DY) (BC-DY)	This scenario, illustrating a dry year, differs from 2050 scenario only in hydro production which takes a value of 2,667 TWh/year, contrasting with 5,26 TWh/year considered for the normal scenario 2050.

3. RESULTS

3.1. Load Diagrams

For each year, a broad insight is given by an annual load diagram and, in more detail, by three representative diagrams of winter, spring and summer weeks, to allow a better visualization and characterization of the system, as well as its variabilities.

We found that the energy storage solution starts to have relevance in the system only by 2050, given that the system has already a considerable energy storage capacity using hydro-pump, which the model assumes to have priority over the battery storage. In face of this, load diagrams for the period 2030-2045 will not be presented.

As mentioned in Section 2, it will be shown for each year an annual diagram and three exemplary diagrams of seasonal weeks.

Each diagram shows disaggregated data of energy production, consumption, the excess electricity (represented as export needs), V2G demand and the charging and discharging of the battery banks. Consumption is divided into three variables: simple load, as a continuous black line, EVs charging, as a dashed red line, and combined load, as a continuous dark blue line, which includes the simple load, EVs charging, hydro pumping and battery banks charging. All diagrams represent one year (monthly results) or one week (hourly results, totalling 168 hours).

3.1.1 Baseline Scenario 2050 (BC-NY). Figure 3 illustrates the load diagram showing the monthly average values where the excess electricity represented as export needs is noticeable. The peak value for this excess was verified in the summer, 8.270 MW. As storage capacity in second-life batteries is absent, in every month, the production surplus was considered an export need rather than storable energy. The average total annual production is about 9.868 MW, totalling 86,67 TWh for the entire year.

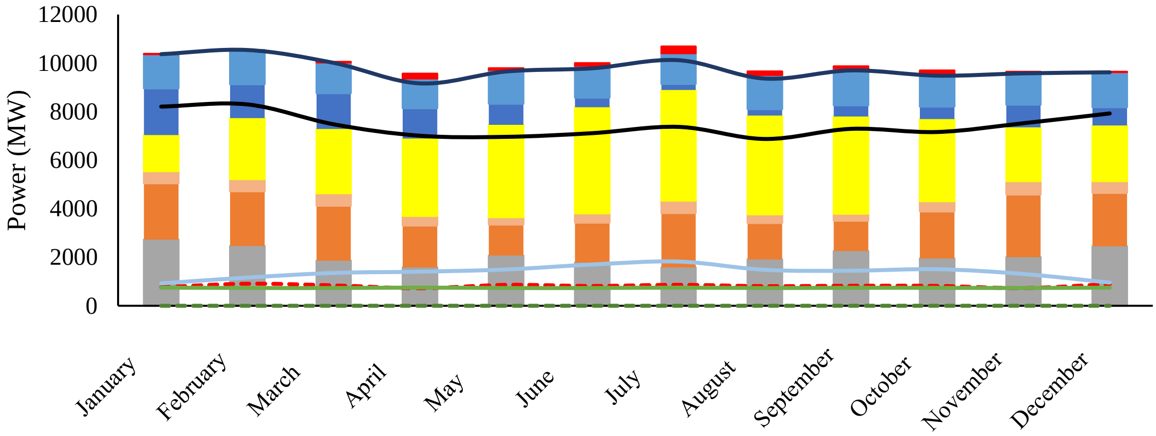

Figure 3. Yearly Load Diagram for Normal Scenario 2050

In the summer (Figure 4) production is mostly assured by solar photovoltaics, presenting weekly peaks of c.a. 10 GW. The figure shows energy in excess in the middle of the day in in several consecutive days (Thursday, Friday, Saturday and Sunday). Thus, one can see that the energy in surplus is considerable, with emphasis for solar energy.

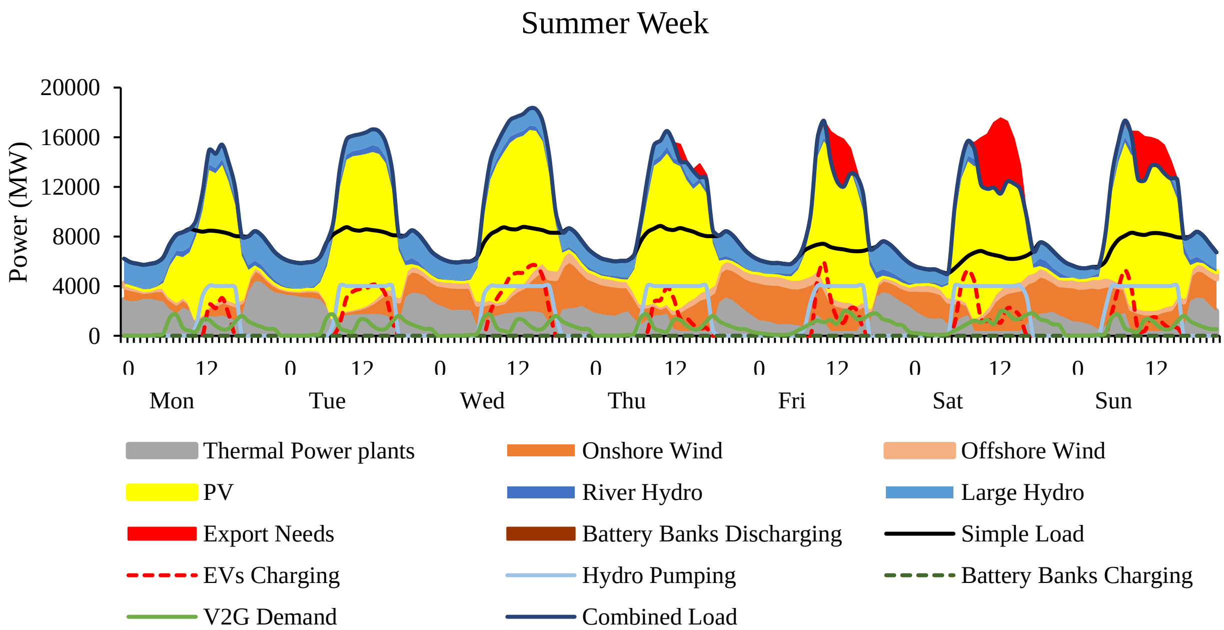

Figure 4. Representative Summer Week Diagram for the BC-NY scenario

3.1.2 Second-life storage 2050 (RB-NY). Results showed that batteries should allow to reduce the amount of energy in excess from 0,77 to 0,03 TWh, and mostly they are operated during the summer at an average charging and discharging rates of 251 and 181 MW, respectively. The peak charging value, 6.780 MW, corresponding to the maximum charging rate, occurred several times between August and September, suggesting potential energy in excess during those occasions. The highest discharging value, 4.301 MW, occurred in late September and in October.

In the Winter week (Figure 5), as there was no energy in excess given the higher consumption levels, charging and discharging of battery banks was not verified. Thus, this weekly diagram does not differ from the corresponding one in the normal scenario.

Spring week (Figure 6) is characterized by a slight use of batteries on Saturday. This usage represents a charging value around 2.280 MW, which represent the export needs identified in the previous scenario. Regarding the discharging to the grid of the battery banks, it occurred between 5 and 9 p.m.of Saturday, registering a peak of 1.323 MW.

During the summer week (Figure 7), storage by the battery banks was used in every mentioned day with energy excess, i.e., from Thursday to Sunday. The highest charging value was obtained on Friday, the day with most production surplus. This charging value is of 6.058 MW at 2 p.m, the period when solar photovoltaics production peaks. The weekly average showed charging and discharging rates of 363 and 228 MW, respectively. In both Spring and Summer scenarios, battery banks charging was always higher given the production surplus and the less need to suppress consumption.

It is important to note that the dashed green line representing battery banks charging corresponds, in every diagram, to the energy in excess, i.e., the production surplus area, evidencing the proper model operation.

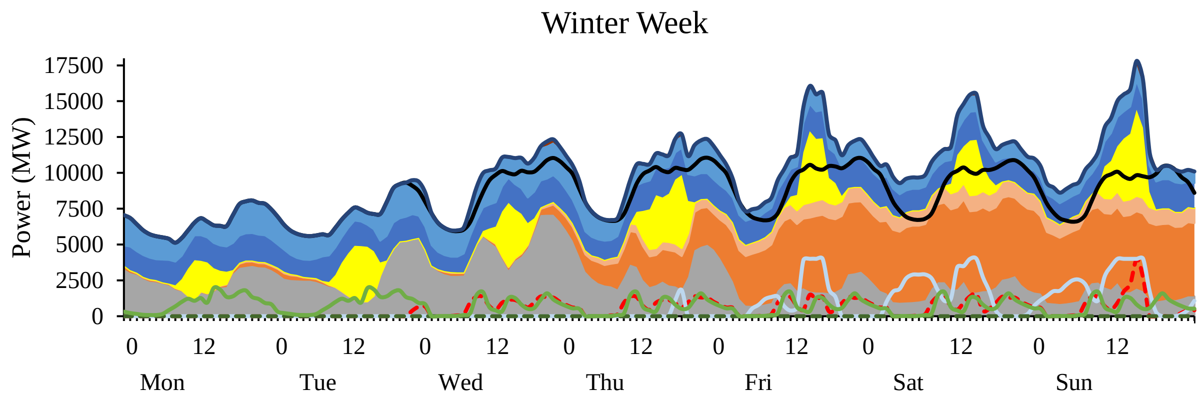

Figure 5. Representative Winter Week Diagram for the RB-NY scenario

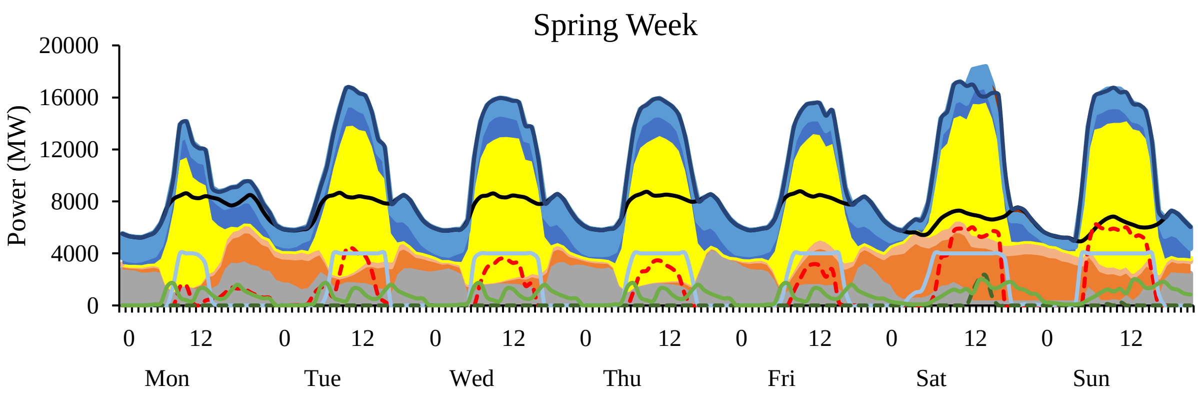

Figure 6. Representative Spring Week Diagram for the RB-NY scenario

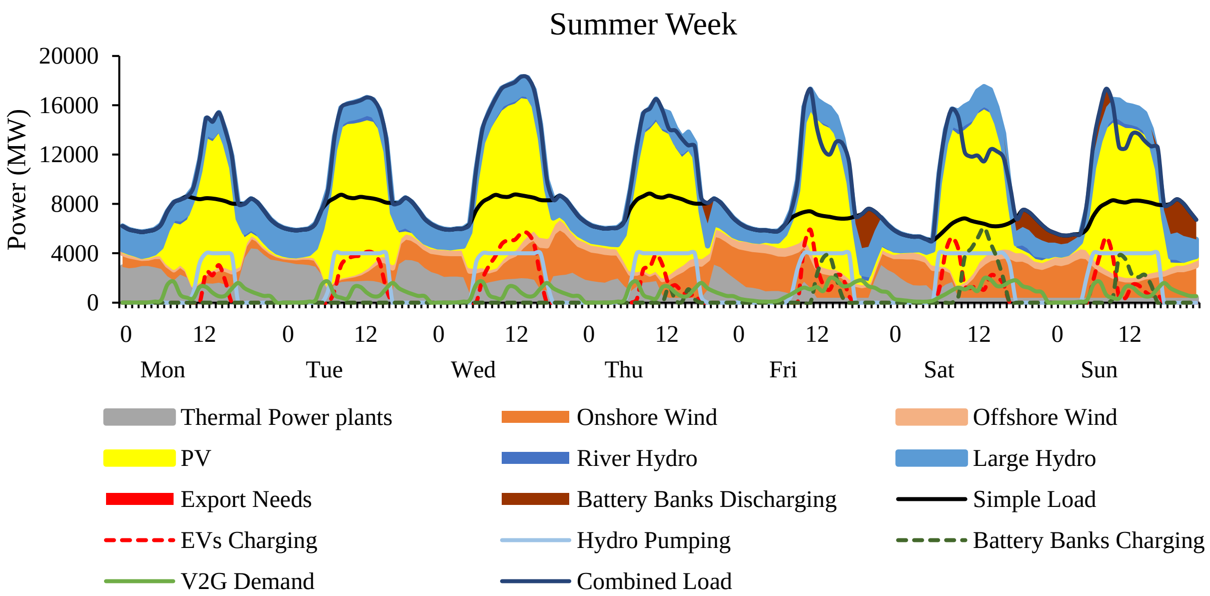

Figure 7. Representative Summer Week Diagram for the RB-NY scenario

3.1.3 Additional PV deployment scenario (RB-NY-PV). In this scenario, an additional 3.581 MW capacity of solar photovoltaics is considered to be installed, resulting in a total installed capacity of 20.250 MW. As expected, compared to the previous scenario, (RB-NY) annual excess energy and the use of the battery banks storage increase, on average 500% (from 85 to 425 MW charging and from 61 to 306 MW discharging). These values allow the assessment on how an increase in storage capacity by the repurposed batteries facilitates renewable energy penetration in the national electrical system.

3.1.4 Dry Year Scenario (RB-DY). Comparing with the base scenario for 2050, in a dry year (BC-DY), disregarding second-life battery storage, the total energy excess would present an annual value of 0,32 TWh. Having the battery banks working, this value is null. Since the import need are maintained, the results suggest that repurposed batteries are capable to fully compensate the lower storage capacity in the dams, supplying the grid when requested.

Battery banks are mostly operated during the summer, reaching a maximum charging value of 6.334 MW and a discharging of 3.247 MW. In annual terms, batteries work at an average charging and discharging rates of 36 and 26 MW, respectively. These values are about 57% lower than those obtained for the annual average rates for RB scenario, given the hydroelectric production deficit, thereby reducing excess energy.

3.2. Grid Interconnection

Table 4 summarizes the power grid needs for imports (production deficit) and exports (production surplus, after the use energy storage) in each scenario. One can see an absence of import/export needs from 2030 to 2045. Such occurs given the existence of EVs and hydro pumping serving as energy buffer to the grid. In the 2050 normal scenario, a 8.270 MW export connection is needed, given the high solar photovoltaic production and the absence of second-life storage, and the energy to export is 0,77 TWh. Contrasting, with batteries in operation, these values substantially decrease to 3.810 MW and 0,03 TWh, respectively. It is thus possible to say that battery banks assume a relevant role in grid balance. Concerning the Additional PV scenario, even with storage (RB-NY-PV), a greater export needs are verified (11.103 MW), however, the energy exchanged is approximately the same (a premise of the scenario, as detailed above). In the Dry Year scenario, there any needs to export, because all energy surplus is stored in the batteries. However, import capacity is of 2.168 MW and energy exchanged 0,11 TWh, given the weak hydro winter energy production.

Table 5. Import and Export Needs for each scenario

Scenarios	2030	2035	2040	2045	2050	2050 (RB-NY)	RB-NY-PV	RB-DY
Maximum capacity needed [MW]								
Import	0	0	0	0	595	595	373	2168
Export	0	0	0	0	8.270	3.810	11.103	0
Annual energy exchanged [TWh]								
Import	0	0	0	0	0	0	0	0,11
Export	0	0	0	0	0,77	0,03	0,75	0

Regarding the use of the battery banks during the year (Figure 8), it is possible to verify that they are discharging more often than charging, evidenced by the smoother and more prolonged discharging curve. However, charging of the batteries occur generally more intensely. It was found that the capacity factor of using the second-life batteries is low (about 5%), since the Portuguese power system already comprises a large hydro-pumping capacity to store energy.

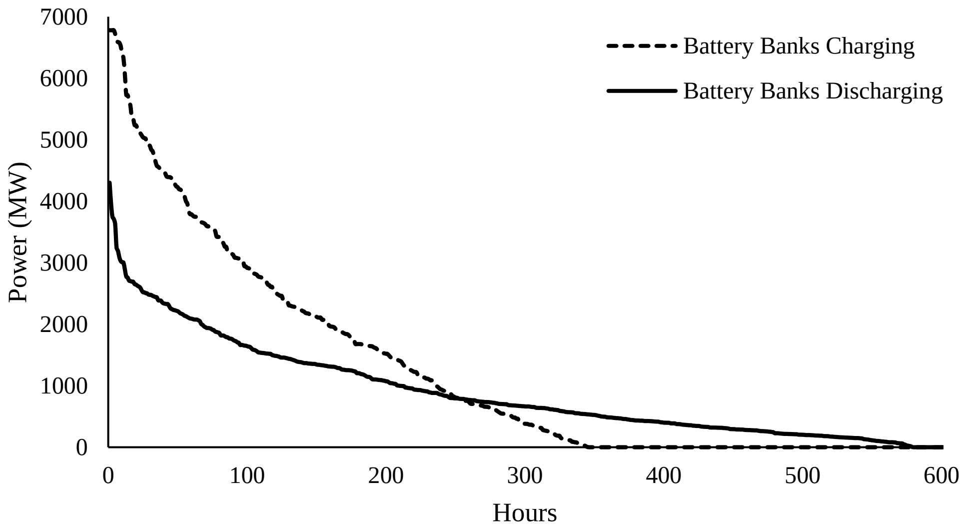

Figure 8. Battery banks usage during the year

3.3. CO_2 Emissions

Figure 9 summarizes the calculated values for the total annual CO_2 emissions of the power system and the passenger vehicles fleet.

If one focuses in the comparison between the base case scenario for 2050 with and without storage (BC-NY and RB-NY scenarios, respectively), the batteries allow to decrease CO_2 emissions by 0,2 Mton, which represent 3,4% of total emissions from the power system.

Regarding the additional solar photovoltaic and dry year case scenarios, the figure also shows the calculated CO_2 emissions for the cases without and with battery storage (BC-DY and RB-DY). From the graph analysis, it is possible to verify that the total emissions from the power system are always higher in the dry year scenario given the lower penetration of renewables due to the lack of hydro contribution.

The RB-NY-PV scenario allows emissions to reduce to about 1 Mton, comparing to the BC-NY-PV. In the RB-DY scenario, emissions are also lower due to the battery storage, although the difference is small (about 0,1 Mton). Also compared to the BC-NY scenario, emissions are 2 Mton higher, given the need for assistance by thermal power plants.

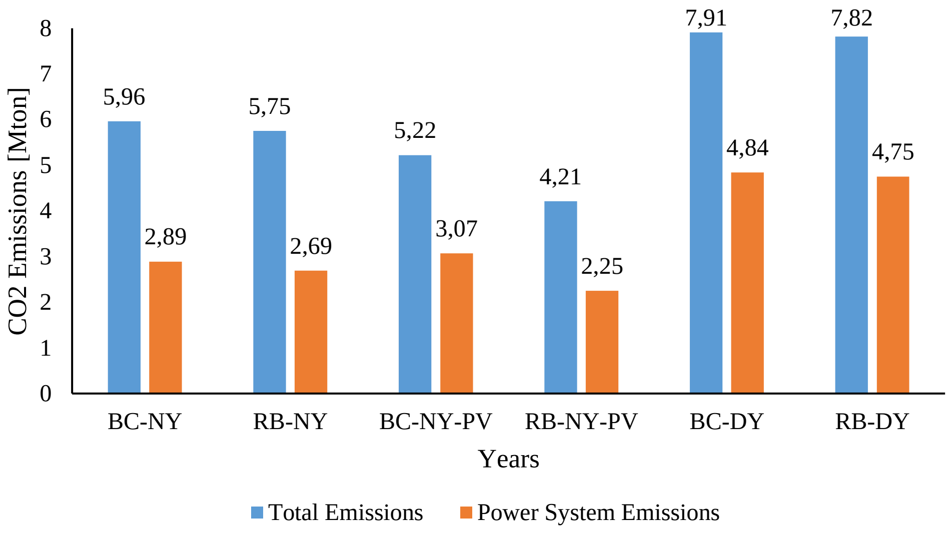

Figure 9. CO_2 emissions (Comparison between main scenarios with and without battery storage)

4. CONCLUSIONS

This study analysed how a large power system can profit from second-life batteries to store potential excess of non-controllable renewable energy. By 2050, the second-life batteries market should represent about 38 GWh of storage capacity, allowing, on a normal year, a decrease in energy surplus from 0,77 to 0,03 TWh. The battery banks are mostly operated during the summer to store photovoltaic production. Regarding renewables integration, the batteries should allow an additional 3.581 MW photovoltaics deployment. For a dry year scenario, results suggest that the repurposed batteries are capable to fully compensate the lower storage capacity in the dams, supplying the grid when requested.

Concerning the requirements for imports/exports, consequentially the requirements for abroad interconnection capacity, in 2050 for the case without energy storage scenario, a 8.270 MW export connection is required and the energy to export is 0,77 TWh. Having the battery banks in operation, these values decrease to 3.810 MW and 0,03 TWh, respectively. It is thus possible to say the second-life batteries assume a relevant role balancing the grid. In a dry year scenario, export needs are not verified given that the batteries are capable to store all the potential energy surplus. Nevertheless, a 2.168 MW import capacity is needed given the weak hydro winter production.

Regarding environmental benefits, the second-life storage batteries allow a decrease of 0,2 Mton in CO_2 emissions, representing 3,4% of total emissions from the power system. In th additional PV deployment scenario, one can see an ascension of this reduction to 32%.

In spite of these results, it was found that the annual capacity factor of the second-life batteries should be low (about 5%), since the Portuguese power system already comprises a large hydro-pumping capacity to store energy, suggesting that in systems where this is not the case the batteries should become more relevant.

ACKOWLEGMENTS

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