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MASTER THESIS

Master Level Thesis

European Solar Engineering School

No.308, September 2022

Techno-economic study of second-life EV batteries as alternative energy storage and comparison with lead-acid and new Li-ion batteries in off-grid PV systems

Master thesis 30 credits, 2022
Solar Energy Engineering

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Course Code: EG3011

Examination date:15 September 2022

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Abstract

The global EV stock is expected to increase from 7.2 million in 2019 to nearly 140 million vehicles by 2030. So, the demand for the battery also increases due to the increase in the number of EVs. In any EV, battery degradation is an unavoidable phenomenon and EV batteries are assumed to arrive at their end-of-life in EV application when the state of health reaches 80 %, repurposing the eligible EV batteries after end of first life is expected to extend their lifetime by another 5-15 years in the second life applications.

This thesis aims to conduct a techno-economic study on the usage of second life EV batteries as an alternative storage option in off-grid PV systems compared to lead-acid batteries and new Li-ion batteries. A single-family house with an annual demand of 2245 kWh/year located in Athens was chosen as the primary location, the off-grid PV system is pre-sized for Athens and based on the pre-sizing results and what is state of art in the market. The system components were chosen for system design (4 kW bi-directional inverter, 2.9 kW PV array, 7.2 kW genset and three battery bank options i.e., 16.5 kWh of lead-acid, 8 kWh new Li-ion and 12.6 kWh of second life EV battery). PV off-grid system with different storage options is simulated using HOMER for both locations and the results are compared.

The simulation results show that the designed off-grid PV system can reach a solar fraction of 90 % in Athens and 73 % in Gotland when 16.5 kWh of lead-acid batteries are used with an allowed depth of discharge of 50 %. When a new Li-ion battery of 8 kWh with an allowed depth of discharge of 80 % is used then the achievable solar fraction is 84 % in Athens and 71 % in Gotland, When the second life EV battery of 12.6 kWh with an allowed depth of discharge of 60 % is used then the achievable solar fraction is 90 % in Athens and 74 % in Gotland. Sensitivity analysis is performed on the depth of discharge and results showed that the solar fraction can be increased by allowing the battery to discharge more, but it also decreases the battery lifetime.

The simulation results also show that the net present cost was lower in Athens for all the reference cases compared to Gotland. Net present cost and levelized cost of electricity for the off-grid system are 25.3 k€, 0.9 €/kWh in Athens and 29.2 k€, 1.0 €/kWh in Gotland when a lead-acid battery is used. When a new Li-ion battery is used then 26.2 k€, 0.9 €/kWh in Athens and 29.3 k€, 1.0 €/kWh in Gotland, when the second life EV battery is used then 26.7 k€, 0.9 €/kWh in Athens and 30.7 k€, 1.1 €/kWh in Gotland.

Overall, the net present cost and levelized cost of electricity are lower in Athens in all cases compared to Gotland. For the reference house in Athens, lead acid battery system has shown slightly lower net present cost than new Li-ion battery and second life EV battery. For the reference house in Gotland, both lead acid battery and new Li-ion battery system have shown similar net present cost and they are slightly lower than second life EV battery.

Also, the second life EV battery levelized cost of electricity is fairly comparable to the new Li-ion and lead acid battery system. In future, the massive inflow of used batteries from EV are expected to be available on the market for the second life application at a lower price than today. Thus, in future, second life EV batteries can become economically viable.

Acknowledgement

I would like to thank my supervisor **Emmanouil Psimopoulos** (Manos) for being a great support throughout the thesis period, he has been kind and helped me with all the necessary details during stressful hours, and whenever I needed time to discuss he always said yes and made time available for me in his busy schedule.

I would like to thank my wife **Abi** for the support at home and for sacrificing her free time for my studies, also thank **Jacob** from the Volvo family for the continued support, had any one of them said No at any point in time during my studies I could not have continued and finished it.

I would like to express my gratitude to **Desiree** for her support during the first semester.

Finally, I would like to thank **my daughter** for **un-happily sacrificing** some of the play & care time from me.

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Abbreviations

Abbreviation	Description
BESS	Battery energy storage system
BMS	Battery management unit
CAN	Controller Area Network
CRF	Capital recovery factor
DG	Diesel generator
DoD	Depth of discharge
EoL	End of Life
EV	Electric vehicle
KPI	Key performance indicator
LA	Lead-Acid
LCOE	Levelized Cost of Electricity
LCPA	Life-cycle performance analysis
LFP	Lithium iron phosphate
Li-ion	Lithium-ion
LMO	Lithium-ion manganese oxide
MPPT	Maximum power point tracking
NASA	National Aeronautics and Space Administration
NMC	Nickel Manganese Cobalt
O&M	Operation and maintenance
OEM	Original equipment manufacturers
PCB	Printed circuit board
PERC	Passivated emitter and rear contact
PV	Photovoltaic
SLB	Second life battery
SoC	State of charge
SoH	State of health

Nomenclature

Symbol	Description	Unit
A_{batt}	Number of autonomy hours	h
C_{batt_rep}	Replacement cost for the battery	€
C_{batt_wear}	Storage wear cost	€/kWh
C_{NPC_tot}	Total new present cost	€
$Cost_{ann\_total}$	Total annualised cost	€
CRF()	Capital recovery factor	-
EE_f	Excess electricity fraction	%
E_{bat}	Battery bank size	kWh
E_{day_demand}	Total energy demand of the house per day	kWh
E_{excess}	Excess electricity produced or curtailed by PV	kWh
E_{load}	Total daily load before losses	kWh
E_{nonren}	Energy produced by non-renewable sources	kWh
E_{served}	Total energy served	kWh
E_{total}	Amount of electricity produced by all the sources	kWh
$L_{prim,avg}$	Average primary load	kWh/day
n	Number of autonomy hours	h
N_{batt}	Number of batteries in the battery bank	-
PSH	Peak sun hour	kWh/kW/day
PV_{Array}	PV array size	kW
$Q_{lifetime}$	Lifetime throughput of the battery	kWh
$Q_{lifetime}$	Lifetime throughput of a single battery	kWh
q_{min}	Minimum state of charge allowed for the battery bank	%
Q_{nom}	Nominal capacity of the battery	Ah
Q_{thrpt}	Annual throughput of the battery	kWh
R_{batt}	Estimated lifetime for the battery bank	kWh
$R_{batt,f}$	Storage float life	year
S	Salvage value	€
S_f	Solar fraction	%
V_{nom}	Nominal voltage of the battery	V
η_{BOS}	System efficiency (Balance of system)	-
η_{BOSb}	System efficiency after battery (Balance of system after battery)	-
η_{rt}	Round trip efficiency of the battery	%
η_{STC}	Non-standard test condition	-

1 Introduction

In transport sector, oil was the major energy source for supplying nearly 92 % of the energy over the past decade, today the transportation sector is contribution nearly one quarter of the global energy related direct CO_2 emissions[1]. Until 2019, there are about 7.2 million passenger electric cars being used on road, majority of them are in Europe, United States and China [1]. The vital part of any electric vehicle is it's battery and lithium-ion (Li-ion) batteries are most widely used in Electric Vehicles (EV) today [1].

The global EV stock is expected to increase from 7.2 million in 2019 to 50 million by the year 2025, and nearly 140 million vehicles by 2030 [1]. So, the demand for the battery also increases due to the increase in number of cars and the EV's range (i.e., battery pack size inside a car defines the range it can drive in one charge) is also increasing [1].

Battery degradation is a unavoidable phenomenon and it can reduce the range that the EV can travel on a single charge, the three major factors that can accelerate the battery degradation are temperature, charge and discharge pattern and time [1]. EV batteries are assumed to arrive to its end-of-life when the state of health (SoH) reaches 80 % (i.e., they can retain only 80 % of their total initial capacity), such batterie's lifetime can be varying depending on customer's driving patterns, maintenance and preferences [1]. The estimated / expected lifetime is between 8-15 years depending on the original equipment manufacturers (OEM) and model [1].

In most cases, several components from the used vehicles' battery systems will be still in good conditions particularly if the vehicle was taken out of road due to accidents or mechanical defect (i.e., SoH > 80 %), such components can be refurbished and reused again in EV [1]. Also, batteries with SoH between 70 % to 80 % can be used again in stationary storage applications with less demands, to deliver ancillary services to grid for example, peak shaving, balance the renewables-based sources' intermittency [1].

Repurposing the eligible EV batteries after end of first life is expected to extend theirs lifetime by another 5-15 years depending on their initial SoH in second life [1]. There are wide range of applications where the second-life batteries can potentially be used and provide various services to grid operators, electric utilities and commercial/residential customers, key examples are increased consumption of onsite renewables, frequency regulation, peak shaving and telecom towers [1]. Another example for potential second life applications is using them for off-grid solar powered systems [2].

From the market perspective, it is estimated that the amount of EV batteries taken out from automotive applications will be approximately 20 GWh by 2025 and up to 100 GWh by 2030, which is roughly the same amount of current yearly battery production [1]. These vast number of used batteries should be directed to either for recycling or for second life applications, it is crucial to have the effective measures and plans to manage the upcoming volumes of used batteries otherwise it can be a significant liability to the environment.

1.1 Aims

The aim of this thesis is to examine the alternative sustainable storage solutions for off-grid Photovoltaic (PV) system such as, second life batteries from an EV instead of a traditional lead-acid batteries and Li-ion batteries designed for stationary solar applications.

Moreover, the thesis also includes study of system performance and economic analysis of the system of second life batteries and compare with new Li-ion battery and new lead acid battery performance. The simulation study will be realized in HOMER Pro.

1.2 Method

Overview of the methodology that will be followed in this thesis work is presented in Figure 1.1.

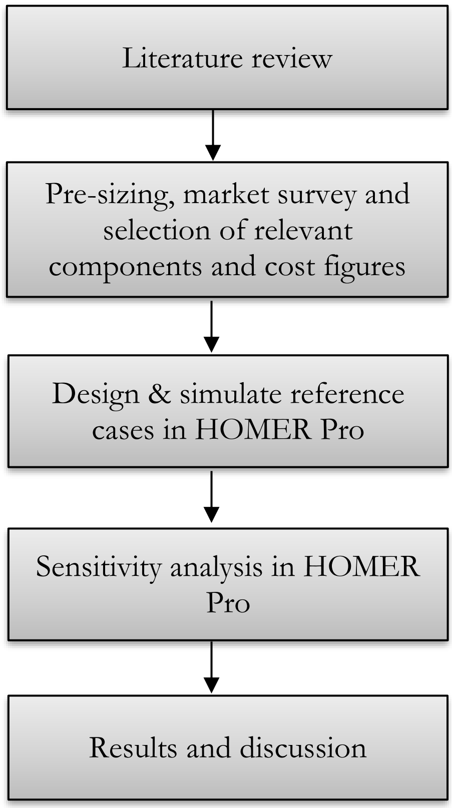

Figure 1.1 An overview of the methodology

The thesis includes the following steps:

- **Literature review:** A broad literature review is performed about the feasibility and different options for used EV batteries in the second life applications, second life batteries in PV applications, EV battery degradation, suitable state of health (SoH) and charge/discharge state of charge (SoC) for second life application, useful life remaining in the used EV battery in second life application, lifetime estimation of lead acid battery and new Li-ion battery.

- **Pre-sizing and market survey of system components:**

  Preliminary sizing of the system with average peak sun hour for the location Athens will be performed, based on pre-sizing result, market survey will be performed to find suitable components such as a bi-directional inverter that shall work with the second life battery bank of electric vehicles and should also work with other traditional off-grid batteries i.e., lead-acid (LA) and Li-ion batteries in order to compare the different batteries options economically in the off-grid PV system.

  Same set of system component will be used in Gotland, so that the effect of location on the system performance can be studied and compared.

- **Design & simulation in HOMER Pro:** A single family house with an off-grid roof top PV system for year around use, the house is equipped with PV system and a diesel generator (DG) as auxiliary power source. Electricity for cooking, heating and hot water is not considered in simulation study.

HOMER Pro is chosen for simulations since this software allows sensitivity analysis, similar tools such as PVSyst can be used for off-grid PV system simulations but it does not support sensitivity analysis [3]. So, HOMER Pro will be used for simulations, for simplicity HOMER Pro will be named as HOMER in advance.

Two references locations will be used for simulation study in HOMER, both reference locations are in Europe, one located in north of Europe (Gotland) and another in south of Europe (Athens). However, the main sizing will be for reference location Athens, and the same set of components will be evaluated in the other reference location Gotland to analyse the effect of location change on the same system.

Reference location: in Athens, Greece [37°59.0`N, 23°43.7`E]
- **Reference case 1:** Off-grid application with lead-acid battery
- **Reference case 2:** Off-grid application with Li-ion battery
- **Reference case 3:** Off-grid application with second life EV battery

Reference location 2: in Gotland, Sweden [57°28.1`N, 18°29.2`E]
- **Simulation case 1:** Off-grid application with lead-acid battery
- **Simulation case 2:** Off-grid application with Li-ion battery
- **Simulation case 3:** Off-grid application with second life EV battery

- **Sensitivity analysis:** A sensitivity analysis shall be performed on battery's lifetime, on battery replacement price, on inverter replacement price, on allowed depth of discharge (DoD), on nominal discount rate and on expected inflation rate.

- **Results and conclusion:** The study shall analyse and evaluate with the help of literature review and simulation results whether the second life EV battery is suitable and cost-efficient or not for the chosen locations compared to lead acid battery and new Li-ion battery, also future work shall be presented where it is applicable.

1.3 Previous work

Zhu et al. [4] evaluates the feasibility of second life application for EV batteries from economic and technological perspective based on several latest industrial reports and technical publications. EV is a challenging environment for the batteries where they typically put under a wide range of operating temperatures, high charge/discharge rate and a high depth of discharge [4]. In 1996, United States advanced battery consortium (USABC) say that the battery pack from EV has to retire when the SoH reaches 80 %, however this level comes from 20 years ago, currently, the maximum capacity of the EV batteries increases significantly (e.g., Tesla Model S offers a long rage plus) thus now a days the user can accept a higher loss in capacity [4].

Five options for the used EV batteries are restoring, recycling, incineration, disposal and reuse [4]. Disposal is the energy efficient option compared to other options but it becomes necessary in some circumstances, incineration refers to using the battery material as fuel for other processes that comes with a risk of producing toxic gases into the atmosphere, recycling refers to extracting valuable raw material from the used battery cells, restoring refers to process in which the used batteries are disassembled and the cathode material is reused in battery manufacturing directly without further processing [4]. The fifth option reuse refers to process in which the used batteries with or without refurbishment be placed in another vehicle or different applications such as stationary energy storage system [4].

Falk et al. [2], in 2020 presented the use of photovoltaic panels together with a 85 kWh of 2nd life battery from EV as an off-grid system for electrifying (mini-grid) an Island in Tanzania, the system has been running since 2017 and was able to supply an average load of 42.31 kWh, theirs economic and ecological evaluations so far demonstrated the results of this approach to use the 2nd life EV battery as an alternate to conventional diesel generator.

Reid and Julve [5], presented an example use case where the second life battery can be used at residential together with PV, the advantages and potential market size for second use are discussed. The article also covers the German market. The authors conclude that, the EV battery storage should be embraced as an important part of the power system, the development of flexible market should be accelerated, the rollout of EV, aggregators and second life batteries(SLB) should be supported [5].

Haram et al. [6], reviewed many projects and research work that involves second life battery for realizing the state of the art, technical and economic feasibility and the impact on the environment. The article concludes that utilizing SLB provide opportunities to generate revenue and also addresses the environmental concerns, however there are challenges do exist such as the lack of standardised assessment procedure and lack of trustworthy information due to low number of studies related to SLB, further studies of SLB are recommended [7].

Cusenza et al. [8] examined a grid connected PV system consists of a battery energy storage system (BESS) made of second life EV batteries that provides required electricity for a nearly zero residential building (250 MWh/year), the installation of different BESS sizes were analysed and an optimal BESS size of around 46 kWh of energy capacity allowed to achieve significant load match increase for that building.

Casals et al. [9] analysed the rest of useful life of a second life EV batteries in stationary applications such as support to EV fast chargers, self-consumption, area regulation and transmission deferral. An electric battery aging model that runs on MatLab includes several ageing mechanisms such as calendar aging, c-rate, depth of discharge, temperature and voltage. The results of the study showed that the second life application lifespan clearly affected by the usage, the lifespan varied from 30 years to 6 years depending on the application and usage [9]. Li-ion batteries are considered not suitable for EV when they reach 80-70 % if its initial capacity (i.e., when the state of health reaches 80-70 %, at this moment they are taken out from the EV and recycled (i.e., adding cost and waste and environmental burdens to its life cycle), the end of life (EoL) for the second life application is considered as rest of useful life of the battery, normally, for second life EV batteries the common end of life is at 60 % SoH, fixing end of life at 40 % could expand the lifespan of the second life application [9]. The system seemed to be capable to working even at lower EoL, but with a risk of running into sudden failure of the battery [9]. As a result of this study, a lifetime of 5.9 years is expected in the second life application if the EoL is assumed to be 60 % SoH and the lifetime reaches to 11.6 years if the EoL is assumed to be 40 % SoH.

Reinhard et al. [10] examined the economic viability of second use of EV batteries as storage option for grid connected PV residential applications, the batteries were used for load shifting and peak shaving. Simulations were performed to figure out the economically viable battery price compared to changes in the assumed electricity price [10]. The batteries can be used in the second life application in residential building for about 7 years before the end of life of 60 % SoH is reached, at the same time the internal resistance of the battery also increases from 150 % to 320 % of its beginning value in the second life [10].

Broussely et al. [11] address the main again mechanisms in Li-ion batteries. Basically, battery capacity loss is directly related to the increase in the batteries increase in internal resistance that is caused by active material transformation during batteries' lifetime. Battery degradation can be classified into two types based on the status of the battery i.e., during charge/discharge and while on storage. The aging happens on storage (standby) due to side reactions resulting from thermodynamic instability of materials in the battery, cycling process includes kinetically induced aging effects such as volume changes or concentration gradients [11].

Huang et al. [12] proposed a life-cycle performance analysis (LCPA) method in which degradation was also investigated. Degradation is usual in energy components and neglecting this effect during the system design may lead to a unstable system after several years of operation [12]. The proposed two step LCPA method integrates the uncertainties in the thermal load and climatic condition prediction and considers the degradation of energy components in the system.

Jiang et al. [13] investigated the long term cycling performance of Li-ion (lithium iron phosphate-LFP) batteries in different cycling SoC ranges. It was found that batteries that were cycled in medium SoC (20 % to 80 %) range exhibited improved cycling stability compared to the batteries that were cycled at both ends of the SoC ranges (0 % to 100 %)[13]. The results reveal that the batteries that were cycled at the end of SoC (0-20 %, 80-100 %) exhibit higher polarization impedance , caused significant structural change to anode and cathode material than those batteries cycled in mid-range SoC (20-80 %), thus, identifying the best operating SoC range and other operating condition can significantly extend the batteries cycle life [13].

According to BloombergNEF article [14], the Li-ion battery pack prices are expected to continue to fall in future, it was 1200 $/kWh in 2010, 140 $/kWh in 2020, 132 $/kWh in 2021, it is predicted that the average price should be below 100 $/kWh by 2024, automaker companies like Renault and Ford have announced a target price of 80 $/kWh by 2030.

Wikner and Thiringer [15] investigated the impact of aging when using the different SoC levels on EV batteries (Nickel Manganese Cobalt (NMC)/ Lithium ion Manganese Oxide (LMO)), an extensive test series was conducted in various SoC intervals over the period of three years during which the degradation as a function of number of cycles were established, the study concluded that that there is a huge potential to prolong the battery lifetime by avoiding high SoC values, additionally the lifetime can be prolonged further by only charging with the needed energy and use a small DoD [15].

Keshan et al. [16] PV system with lead-acid batteries and Li-ion batteries as stationary storage in off-grid applications are studied. various aspects, such as efficiency, charging characteristics life cycle and cost of the lead acid and Li-ion battery is compared [16]. Through the cost analysis Li-ion batteries are shown to be a cost effective option compared to lead acid battery when the total number of charge/discharge cycle is considered, however the upfront cost for lead-acid battery is lower compared to Li-ion battery [16].

Dufo-López et al. [17] analysed multiple models for estimating the lifetime of OPzS lead-acid battery and Li-ion battery to estimate the lifetime. Two different locations were considered: one in Spain and another in Algeria. An advanced weighted Ah-throughput model was used for OPZS lifetime estimation: 12 years was obtained for the location in spain and 5 years for the location in Argelia [17]. For Li-ion battery, both calendar and cycle aging were considered: 20 years were estimated for the location in Spain and 13 years for the location in Argelia [17]. However, the cost of $LiFePO_4$ is around twice the amount of OPzS, Li-ion can be competitive with OPzS batteries in PV standalone systems considering the expected reduction in Li-ion battery price [17].

2 System design and simulations studies

A single-family house with off-grid PV system will be studied in two reference locations i.e., Athens and Gotland, the system will be sized primarily for the reference location Athens and the same size will be used for the second location Gotland, that way the effect of location on the system performance can be studied and compared since the same set of system components will be used in both locations.

Figure 2.1 shows the intended system architecture of the off-grid system. The system consists of a bi-directional inverter, PV panels, diesel generator as a backup power source, house load and battery storage unit. Three distinct types of battery storage units will be used in the simulation study for each location, but only one of the three battery bank option is connected at a time.

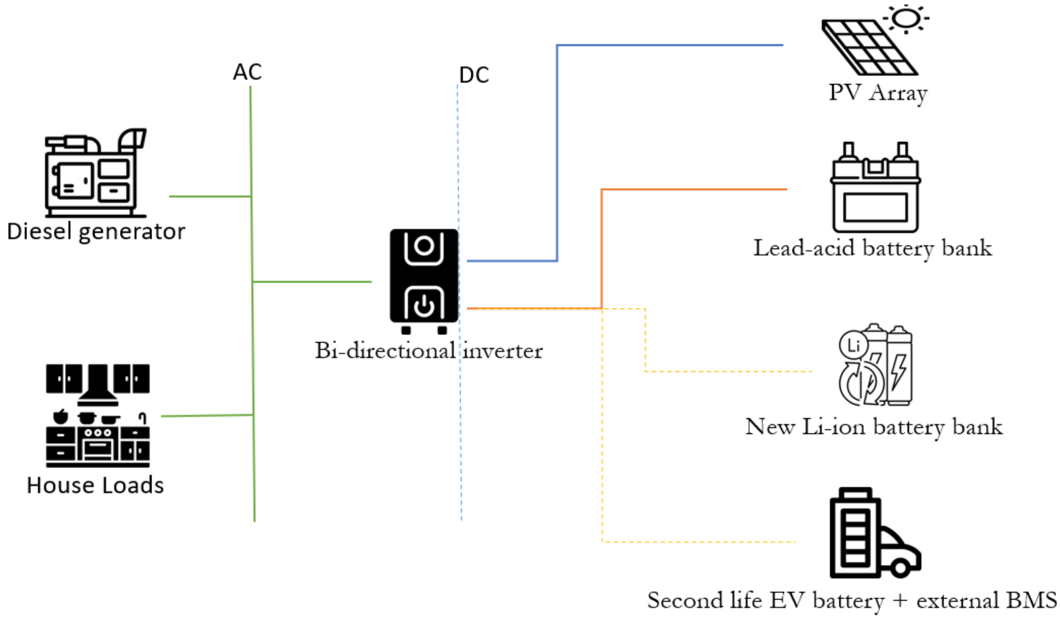

Figure 2.1 System architecture

2.1 Boundary conditions

The overall project's lifetime is 25 years, batteries need to be replaced when the float life is reached or when the maximum number of cycles is reached whichever comes first (for example, lead-acid battery bank is replaced when the float life of 15 years reached or when 2400 cycles is reached). Inverter is to be replaced after its lifetime (for example, every 10 years). The optimization result with least net present cost (NPC) is considered as economically more suitable and will be compared with other reference cases. PV and battery degradation over the years(multi-year) is not considered, capital recovery factor and total yearly electricity demand will be used for LCOE calculation. PV derating factor of 80 % will be used to cover all the PV losses due to non-optimal operating conditions. This factor accounts for non-optimal orientation, non-optimal tile of the roof, shading losses, soiling losses, and wiring losses...etc.

Heating, cooling, and cooking needs of the house is not considered as a part of the electrical load for the house[1]. The battery storage units are assumed to be placed inside the building and no additional cooling system for the storage unit is considered. For the battery lifetime calendar and cycle aging is considered, effect of temperature on the battery aging is not considered in this simulation (i.e., due to lack of data about temperature vs capacity curve, temperature vs lifetime curve). HOMER will be used with a set of chosen system

[1] Heating, cooling, and cooking needs are assumed to be covered by gas or wood or district heating. Thus, it was excluded from the daily load profile and not considered in simulation studies.

components with pre-defined size. Estimation of battery degradations and SoH is not a part of the simulation.

The solar radiation and weather data (monthly averages for global horizontal radiation over 22-year period, i.e., 1983-2005) from the National Aeronautics and Space Administration (NASA) database was used in simulation [18], HOMER optimization model is used to generate the synthetic hourly solar data using the algorithm and the monthly average data from NASA database [19]. Idealized battery module in HOMER library was used for different battery banks. The load profile that will be used for designing the systems is detailed in section 2.1.1.

2.1.1. Load profile details

For the simulations in HOMER, the house is assumed to have a PV system installed with a BESS, simulations will be performed with three different battery technologies but only one at a time and genset as the auxiliary power source (backup). The house is assumed to have a set of electrical devices as listed in Table 2.1 with theirs rated power and hours of usage.

Table 2.1 House Electric Loads

Description	More details	Quantity	Rated power [W]	Total power [W]	Usage [h]	Total energy [Wh]
Lamp 1	Garage	2	30	60	8	480
Lamp 2	House	8	7	56	8	448
Lamp 3	Yard	5	11	55	8	440
Lamp 4		10	11	110	8	880
Fridge		1	100	100	12	1200
TV	On the house	1	40	40	4	160
Mobiles		4	10	40	2	80
Computer		3	30	90	4	360
Laundry on the weekends, on the weekdays power tools such as iron box, other tools etc		1	2100	2100	1	2100
Total electricity demand						6.148 [kWh/day]
Total peak power[2]				4.75 kW		

Hourly load profile is shown in Figure 2.2, this daily load profile is given as an input to HOMER with 0 % random variability (i.e., HOMER considers the same load profile for all days with no expected changes).

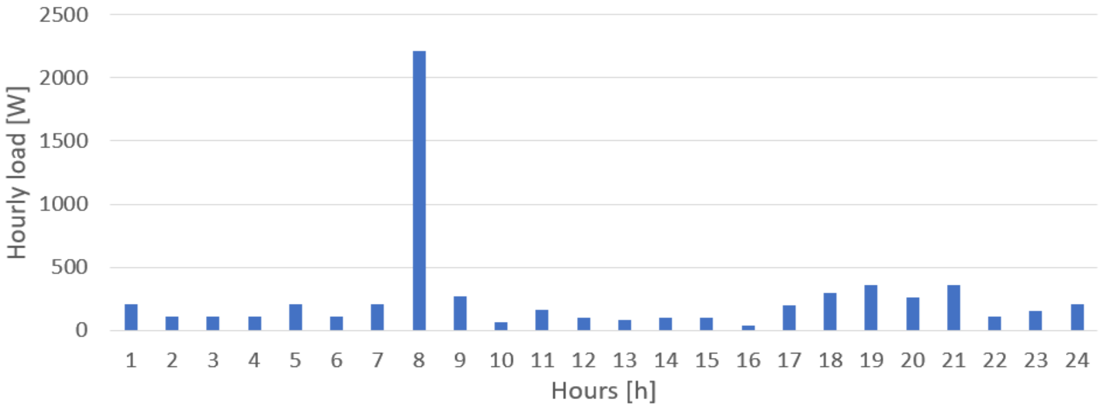

Figure 2.2 Hourly load profile of the house (for the house in Athens and Gotland)

[2] Peak power of the house when all the devices are turned On at the same time.

2.1.2. Preliminary sizing of the system

Quick three step method was used to pre-size the system for Athens which is the primary location of study.
Total daily load of the house can be expressed as

$$E_{load} = \frac{E_{day\_demand}\,[kWh]}{\eta_{BOS}} \qquad \textit{Equation 1}$$

Where E_{day_demand} is total energy demand of the house per day, η_{BOS} is efficiency of balance of system, which is assumed as 0.7, the house's daily load is 6148 Wh

So, using the equation and values given above, the estimated E_{load} is:

$E_{load} \approx 8.8$ kWh.

Estimated PV array size can be expressed as

$$PV_{Array} = \frac{E_{load}\,[kWh]}{PSH \cdot \eta_{STC}\,[\frac{kWh}{kWp}/day]} \qquad \textit{Equation 2}$$

where PSH is average yearly peak sun hour for a particular location, in this case it is Athens, Greece and it is assumed to be 4.6 hours [20] (yearly average in kWh/kW/day), losses due to non-STC conditions (η_{STC}) is assumed to be 30 %, i.e., for example, losses due to temperature, optical losses due to non-optimal tilt etc…so the assumed η_{STC} is 0.7.

So, using the equation and values given above, the required PV array size is:

PV_{Array} size ≈ 2.7 [kW]

For pre-sizing the batteries, different DoD is assumed for different battery technologies are, for lead-acid battery 50 % (usable SoC range is 50 % to 100 %), for new Li-ion battery 80 % (usable SoC range is 20 % to 100 %), for second life EV batteries 60 % (usable SoC range is 20 % to 80 %). The balance of system after the battery (η_{BOSb}) is assumed as 0.85 for lead-acid batteries and 0.9 for Li-ion batteries (i.e., losses due to charging and discharging the battery, cabling losses are 15 % for lead-acid batteries and 10 % for Li-ion batteries). Estimated battery size can be expressed as

$$E_{bat} = \frac{E_{load} \cdot n\,[kWh]}{DoD \cdot \eta_{BOSb}} \qquad \textit{Equation 3}$$

Where, n is number of autonomy days in this study it is 1 day. So, using the equation and values given above, the estimated size of the batteries E_{bat} is:

E_{bat} [for lead acid] ≈ 14.5 kWh
E_{bat} [for new Li-ion] ≈ 8.5 kWh
E_{bat} [for second life EV battery] ≈ 11.3 kWh

48 V battery system is decided to be used in this thesis since the same inverter will be analysed for all three different battery technologies.

2.1.3. System components selection

Based on the pre-sizing, market survey was performed to find suitable components for the systems that can be used in a typical off-grid system. The same set of components would be used in all simulations.

Victron EasySolar-II 5 kVA [21] was a preferred choice since this product integrated with an inverter, charger, maximum power point tracking (MPPT) charge controller. It supports 48 V battery system with an input range of 38 to 66 V and also can communicate with controller area network (CAN) based battery management system unit (BMS) system which is a requirement to communicate with EV battery's BMS. Maximum charge current for the charger is 70 A when the battery is charging from the AC source. MPPT charge controller 's maximum output current is 100 A. The inverter can support up to 5.8 kW PV string but considering the future load increase and system's stability it was decided to oversize the inverter.

For lead-acid battery, Sunlight's RES SOPzV 425 cells [22] are chosen, the valve regulated lead-acid cells are 2 V each and they are suitable for residential PV installations [23]. The float lifetime is 15 years and 2400 cycles for 50 % DoD at 20 ℃. Since our system voltage is 48 V, 24 number of cells are to be connected in series. Nominal capacity is 344 Ah for one cell, so the battery string size becomes 16.5 kWh (24 * 2 V * 355 Ah) of which usable size is 8.25 kWh since 50 % DoD is considered.

For new Li-ion battery, BYD's Battery-Box Premium LVS 8.0 [24] is chosen which comes with CAN based BMS included. Nominal battery voltage is 51.2 V. Maximum continuous discharge current is 130 A, battery pack size is 8 kWh of which usable size is 6.4 kWh since 80 % DoD is considered. Round trip efficiency of 95 % and manufacturer's warranty for 10 years. This storage unit consists of one BMS, one LVS base and cover and two premium battery modules of 4 kWh each, this unit also supports operation with Victronenergy inverter.

For second life EV battery, modules that were taken out from a Tesla model S EV [25] is chosen. The module consists of 516 number of Panasonic 18650NCR cells with 6S86P configuration (6 cells in series and 86 parallel connections) with 3.7 V nominal voltage per cell, charge and discharge cut-off voltage per cell is 4.2 V and 3.3 V, 3400 mAh nominal capacity per cell. The battery module size is 6.4 kWh (516 * 3.7 V * 3400 mAh), the rated discharge current is 580 A. Two modules are to be connected in series, so the nominal voltage of the battery string is 48 V and string size becomes 12.8 kWh (2 * 6.4) of which usable size is 7.68 kWh since 60 % DoD is considered for discharge.

This second life EV battery module comes with original BMS printed circuit board (PCB) attached, but a central battery module controller is required that acts as a master BMS for the connected modules. Bpath's BMS [29] is chosen since this BMS controller works with Victronenergy inverter. This controller can support up to 20 modules that makes it possible to increase the storage size in future if needed. This BMS controller will be connected on the positive line between the battery bank and the inverter.

However, from similar other webstore, there were other modules with same cell chemistry, but different sizes were available [26]–[28]. During the market survey for available second-hand EV batteries, it is seen that there are not many suppliers available as of today and the price varies a lot for similar size battery pack without mentioning some key details such as for example present state of health or remaining expected cycles/lifetime, they also provide a limited time warranty for 1 year. All those concerns make the components selection process complicated.

For Solar panels, Peimar's SM330M-BF [30] modules are chosen, it is a monocrystalline passivated emitter and rear contact (PERC) 60-cell solar panel with an efficiency of 19.7 % and maximum power output is 330 W under STC conditions, comes with a 30 year power output warranty. From the pre-sizing in section 2.1.2, the required PV array size is 2.7 kW for the base location Athens, hence number of modules required would be 9 modules, so the new PV array size become 2.9 kW. (It should be noted that the same PV array size will be in used for the location Gotland even though the PV array size was originally calculated for Athens. This is to keep the same set of components in all simulation cases, so the results can be compared to see how the location and battery technology affects the solar fraction and net present cost of the system.)

For diesel generator, Energy's Elverk T9000Full [31] is chosen. This unit has one 3 phase socket and two single phase sockets as outputs, however the PV system in design is a single-phase system. This generator can provide continuous output of 7.2 kW and fuel tank volume of 14 L and supports electric start.

The list of selected components for the system setup is listed in Table 2.2.

Table 2.2 Selected components list

Component category	Brand & Model name	Lifetime	Size	Unit
Bi-directional inverter	Victron Energy & Easysolar-II GX	10 years	4	kW
Lead-acid battery	Sunlight & RES SOPzV 425	15 years / 2400 cycle[1]	16.5	kWh
New Li-ion battery	BYD & Premium LVS 8.0	15 years / 6000 cycles[2]	8	kWh
Second life EV battery	Tesla & 18650 battery modules	7 years / 1000 cycle	12.8	kWh
PV panels	Peimar & SG300MBF	25 years	2.9	kW
Diesel generator	Energy & T9000Full	25 years / 15000 h	7.2	kW

[1]2400 cycles at 50 % DoD
[2]6000 cycles at 100 % DoD

2.1.4. HOMER Pro software

HOMER Pro is developed by National Renewable Energy Laboratory, enhanced and distributed by HOMER Energy [32]. HOMER Pro is a simulation software in which the user can create and simulate a bi-directional energy production with several combinations of energy related components. HOMER Pro library contains a wide variety of energy components with their properties and the user is also able to add components to the library manually. HOMER Pro runs the simulations and optimize the solution for the chosen system and provides several combinations of components with their total net present cost and also with the levelized cost of electricity (LCOE). HOMER Pro is widely used by researchers in the energy sector. HOMER Pro is chosen for simulations since this software allows sensitivity analysis, similar tool such as PVSyst, Polysun can be used for off-grid PV system simulations but it does not support sensitivity analysis[3]. Sensitivity analysis on several input parameters is a key part in this thesis so HOMER pro is suitable for this study.

2.1.5. Selected component's inclusion in HOMER Library

In order to use the selected components in simulation, the component must present in the HOMER Library, so additional components were created in library by copying existing template and the components properties are updated according to the datasheet of the corresponding component.

For Victron EasySolar-II, this product was not available in library, so a copy of generic converter is used and renamed for this chosen inverter, according to the inverter's data sheet [33] the following parameters were changed in the new inverter profile in home pro library, inverter's size is 4 kW (continuous output power at 25 ℃), maximum efficiency of 96 % for inverter and rectifier operation. Vectron's product come with a 5-year manufacturer guarantee. In the reference case a lifetime of 10 years is considered, sensitivity analysis will be performed on inverter lifetime.

Sunlight's RES SOPzV 425 [34] battery properties available in HOMER library. A copy of that profile is taken and used in the simulation with the parameters round trip efficiency is 87 %, maximum charge current of 103 A and maximum discharge current of 206 A, battery's design float life is 15 years, number of cycles vs DoD table according to the datasheet (2400 cycles at 50 % DoD), annual throughput of 825 kWh calculated by HOMER using the number of cycles vs DoD table provided. For this battery in simulation, batteries lifetime is limited by float lifetime and amount of throughput. According to the datasheet the battery can be discharged up to 80 % DoD. In the reference case a float lifetime of 15 years, 50 % DoD are considered, sensitivity analysis will be performed on float lifetime, on DoD between 20 % to 50 % and on battery replacement price.

BYD Battery-Box Premium LVS 8.0 properties was not available in library, to include then in the simulation, a copy of "Fortress Power LFP-10" template used and renamed as BYD battery-box. Both BYD and Fortress Power batteries use same battery chemistry (LFP). After copying and renaming, some properties are changed in the new BYD's profile in library. According to BYD's datasheet [35], the changed parameters in HOMER's library for the copied template are nominal voltage to 51.2 V, nominal capacity to 156 Ah (i.e., 8 kWh/51.2 V), round trip efficiency to 95 %, max charge and discharge current to 130 A, 10 years manufacturer guarantee, according to Perma Batteries [36] this battery can complete 6000 cycles at 100 % DoD i.e., a lifetime throughput of 47923 kWh according to HOMER calculation which will be used in the simulation. For this battery in simulation, battery lifetime is limited by float lifetime and amount of throughput. In the reference case a float lifetime of 15 years, 80 % DoD are considered, sensitivity analysis will be performed on float lifetime, on DoD between 0 % to 40 % and on battery replacement price.

For the second life EV batteries, a copy of the Tesla Powerwall 2.0 profile was used, Tesla Powerwall 2.0 and the chosen battery module from Tesla Model S EV use the same battery chemistry NMC, but the cell dimensions are slightly different. According to the information from the seller's website [25] the parameters are entered in library for the second life battery which was used in simulation, the modified parameters per module are, nominal voltage 22.2 V (6 series cells * 3.7 V per cell), nominal capacity is 288 Ah, max charge and discharge current is 580 A, round trip efficiency is 95 % (from Tesla Powerwall's profile). Based on the literature review [9][10], it is assumed that the lifetime will be 7 years and a minimum of 1000 cycles at 100 % DoD is expected in the second life application, however the battery intended to be operated within 20 % SoC to 80 % SoC range (i.e., the battery will not be charged more than 80 % SoC and discharged below 20 % SoC to ease the stress on the battery), however in simulation the useable SoC range used is 40 % to 100 % since HOMER doesn't allow maximum state of charge as a input. For this battery in simulation, batteries lifetime is limited by float lifetime and amount of throughput. End of Life SoH is not considered in HOMER. In the reference case a float lifetime of 7 years, 60 % DoD are considered, sensitivity analysis will be performed on float lifetime, on DoD between 50 % to 80 % and on battery replacement price.

For diesel generator, a copy of generic 10kW fixed capacity genset is used and the parameters are changed according to the chosen generator. The parameter changed are fixed generator capacity to 7.2 kW, minimum load ration of 25 % is used for simulations and linear fuel curve from the default template was used. In the reference cases a lifetime of 15000 operating hours is considered.

2.1.6. Economics

For the economic analysis, the following assumptions listed in Table 2.3 were used for both locations.

Table 2.3 Financial boundary conditions and assumptions

Description	Value
Nominal discount rate	8 %
Expected inflation	2 %
Projects lifetime	25 years
Diesel price (assumed unchanged for entire project's lifetime)	2 €/L

The list of components with their price is presented in Table 2.4. The price includes value added tax and shipping cost where it is applicable. For the Primar PV array, a total turnkey price was assumed, and it includes costs for PV modules, installation service and all necessary cabling.

Table 2.4 Price list for selected components

Brand and Model name	Size	Unit price	Price [incl.VAT & delivery]	Other details
Victronenergy - Easysolar-II GX	4 kW	3500 €/unit	3600 €	
Sunlight - RES SOPzV 425	16.5 kWh	196 €/cell	4780 €	i.e., 289[1] €/kWh
BYD – Premium LVS 8.0	8 kWh	-	5310 €	i.e., 663[2] €/kWh
Tesla – 18650 battery modules	12.8 kWh	1650 €/module	3300 €	i.e., 354[3] €/kWh (incl. BMS cost)
Peimar – SG300MBF	2.9 kWh	1000[4] € /kW	2900 €	
Energy – T9000Full	7.2 kWh	2870 €/unit	3000 €	
Bpath's BMS unit		-	1239 €	

[1] 4780 € for 16.5 kWh lead acid battery bank.
[2] 5310 € for 8 kWh Li-ion battery bank.
[3] 4539 € (3300+1239) for 12.8 kWh second life EV battery bank.
[4] Price including installation and necessary cabling

Replacement, operation & maintenance (O&M) costs are listed in Table 2.5.

Table 2.5 Replacement and O&M costs

Component	Description	Cost
Diesel generator	O&M cost for one operation hour.	0.3 €/h
	Replacement cost after 15000 hrs of operation	3000 €
PV array	Yearly O&M	100 €
Bi-directional inverter	Replacement cost every 10 years	3600 €
Lead acid battery	Replacement every 15 years **or** when 2400 cycles completed	4780 €
New Li-ion battery	Replacement every 15 years **or** when 6000 cycles completed	5310 €
Second life EV battery	Replacement every 7 years **or** when 1000 cycles completed	3300 €

2.2 Simulations studies in HOMER

In HOMER, for each component listed in Table 2.2, advance sizing option was used to set upper and lower limit to force the HOMER to use the same sizing as mentioned Table 2.2 as well as with the cost and O&M details listed in Table 2.4 and Table 2.5 are used as input for the simulations(only one battery bank technology connected at a time).

The following optimization settings are used in simulations: 60 minutes time step, system design precision of 1 %, NPC precision of 1 %, maximum annual capacity shortage of 0 % and electric load random variability of 0 %.

For the generator control, combined dispatch is chosen in which HOMER decides the best operation strategy among the cycle charging and load following (In cycle charging, the generator operates at full power and the surplus can be used to charge the batteries, so that the generator can be turned off during the future period. In load following strategy, the generator supply only the load.). Idealized storage module is used in simulations i.e., end of life for the storage is decided based on the inputs float life and lifetime throughput. Also, the maximum charge-rate (A/Ah) variable that imposes a limit on the charge rate is not used. Sensitivity analysis will be performed on all reference cases on the following attributes: on battery's lifetime, on battery replacement price, on inverter replacement price, on allowed depth of discharge (DoD), on nominal discount rate and on expected inflation rate.

The simulation cases are:

- **Athens**

  Reference case 1: With 16.5 kWh lead-acid battery (15 years / 2400 cycles, 50 % DoD), results are described in section 3.2.1

  Reference case 2: With 8 kWh new Li-ion battery (15 years / 6000 cycles, 80 % DoD), results are described in section 3.2.2

  Reference case 3: With 12.8 kWh second life EV battery (7 years / 1000 cycles, 60 % DoD), results are described in section 0

- **Gotland**
  Reference case 1: With 16.5 kWh lead-acid battery (15 years / 2400 cycles, 50 % DoD), results are described in section 3.3.1
  Reference case 2: With 8 kWh new Li-ion battery (15 years / 6000 cycles, 80 % DoD), results are described in section 3.3.2
  Reference case 3: With 12.8 kWh second life EV battery (7 years / 1000 cycles, 60 % DoD), results are described in section 3.3.3

2.3 Key performance indicators (KPIs)

Solar fraction or also known as renewable fraction is expressed as

$$S_f = 1 - \frac{E_{nonren}}{E_{served}} \qquad \textit{Equation 4}$$

where,

E_{nonren} is Electricity produced by the diesel generator in kWh/year
E_{served} is total electrical load served in kWh/year

Excess electricity is the amount of electricity that is curtailed because of lack of storage and lack of load (i.e., any surplus produced by PV, excess electric fraction can be expressed as

$$EE_f = 1 - \frac{E_{excess}}{E_{total}} \qquad \textit{Equation 5}$$

where,

E_{excess} is the amount of excess electricity produced in kWh/year
E_{total} is the amount of electricity produced by all the sources in kWh/year

In HOMER, float lifetime and throughput are the two independent factors that limit the lifetime of battery bank, i.e., batteries can reach to end of life due to old age or due to charge/discharge cycle depletion [18]. Expected life (R_{batt}) is calculated as [18]

$$R_{batt} = \begin{cases} \dfrac{N_{batt} \cdot Q_{lifetime}}{Q_{thrpt}} & \textit{if limited by throughput} \\ R_{batt,f} & \textit{if limited by time} \\ Min\left(\dfrac{N_{batt} \cdot Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) & \textit{if limited by throughput and life} \end{cases}$$

Equation 6

where,

R_{batt} is estimated lifetime for the battery bank in years.
N_{batt} is number of batteries in the battery bank.
$Q_{lifetime}$ is lifetime throughput of the battery in kWh.
Q_{thrpt} is annual throughput of the battery in kWh/year.
$R_{batt,f}$ is storage float life in years.

Storage float-life or lifetime is defined in years (i.e., lifetime if the battery remains fully charged and be standby) [37] typically by the battery manufacturers.

HOMER calculated the autonomy as [18]

$$A_{batt} = \frac{N_{batt} \cdot V_{nom} \cdot Q_{nom} \cdot \left(1 - \frac{q_{min}}{100}\right) \cdot 24h/day}{L_{prim,avg} \cdot (1000 \frac{Wh}{kWh})} \quad \textit{Equation 7}$$

where, A_{batt} is number of autonomy hours,
N_{batt} is number of batteries in the battery bank.
V_{nom} is nominal voltage of the battery.
Q_{nom} is nominal capacity of the battery in Ah.
q_{min} is minimum state of charge allowed for the battery bank.
$L_{prim,avg}$ is the average primary load in kWh/day.

LCOE is expressed as [18]

$$LCOE = \frac{Cost_{ann\_total}\,[€]}{Energy_{served}[kWh]} \quad \textit{Equation 8}$$

where,

Total annualised cost can be expressed as [18]

$$Cost_{ann\_total} = CRF(i, R_{proj}) \cdot C_{NPC\_tot} \quad \textit{Equation 9}$$

where,

i is annual real discount rate, R_{proj} is project lifetime.

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \textit{Equation 10}$$

where,

i is real discount rate, n is number of years.

C_{NPC_tot} is the total NPC. i.e., the net present value of all costs (initial investment, replacement costs, O&M costs, cost for fuel) over its lifetime minus the net present value of all revenue (salvage) over its lifetime. HOMER calculates the NPC by adding all the discounted cashflows reach year over the lifetime of the project [18].

HOMER calculates the system's salvage value as the value remaining at the end of the project. HOMER assumes the salvage value is directly proportional to its remaining life and the value depends on the replacement price [18], In this thesis, System's salvage value includes the salvage value for the components: inverter, diesel generator and battery bank. System's savage value be expressed as

$$S = C_{rep} \cdot \frac{R_{rem}}{R_{comp}} \quad \textit{Equation 11}$$

where,

C_{rep} is replacement cost, R_{comp} is component lifetime and R_{rem} is remaining life of the component at the end of projects lifetime.

3 Results

Results are presented in 4 sections, the pre-sizing and selected components size are given first (pre-sizing is done for the location Athens, but the same size will be studied in the other location Gotland), the same set of components will be used for Athens and Gotland in the following two sections afterwards, finally the comparison of NPC, LCOE and solar fraction for the two locations(Athens and Gotland) is presented since same set of components were used in both locations.

3.1 Preliminary sizing results

The result of pre-sizing and the size of selected components based on market survey & availability are presented in Table 3.1.

Table 3.1 System pre-sizing results

Components	Pre-sizing results	Selected component size	Unit
PV array size	2.7	2.9	kW
LA battery size	14.5	16.5	kWh
New Li-ion battery size	8.5	8	kWh
Second life EV battery size	12.6	12.8	kWh
Inverter size	-	4	kW

3.2 Simulation results (Location: Athens)

Results of the simulation study of an off-grid PV system located in Athens consists of 2.9 kW PV panels, 4 kW bi-directional inverter, 7.2 kW diesel generator with three different storage options but only one storage unit connected at a time (results with size of 16.5 kWh lead-acid battery bank are presented in section 3.2.1, results with size of 8 kWh new Li-ion battery bank are presented in section 3.2.2, results with size of 12.8 kWh second life EV battery bank are presented in section 0).

3.2.1. Off-grid system with lead-acid battery, Athens

Annual electricity production summary is presented in Table 3.2.

Table 3.2 Overall summary (for LA battery system, Athens)

Parameter	Value	Unit
PV electricity production	4310	kWh/year
Diesel generator electricity production	220	kWh/year
Total house demand (annual)	2245	kWh/year
Solar fraction (annual)	90	%
Excess electricity fraction (annual)	43	%
LCOE	0.9	€/kWh
NPC	25.3	k€
System’s salvage value	2.0	k€

Monthly electricity production distribution, solar fraction distribution and excess electricity fraction are shown in Figure 3.1.

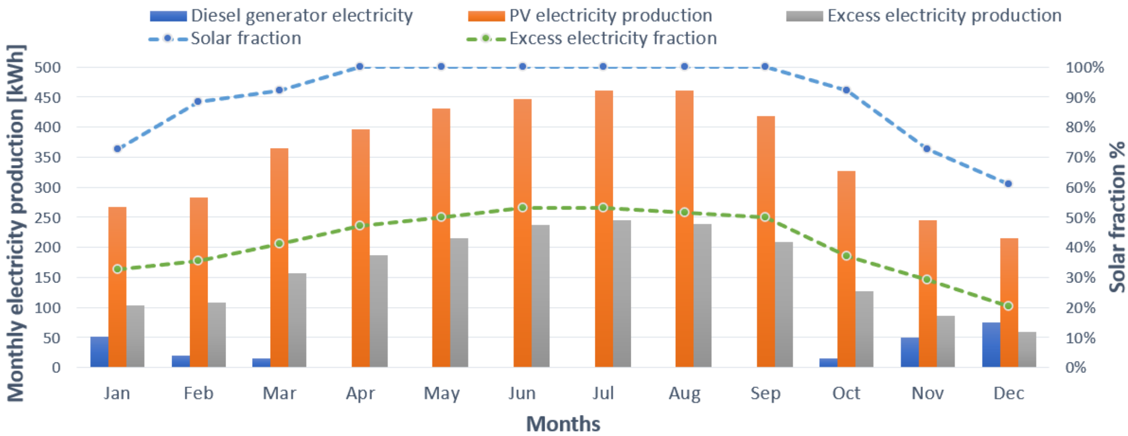

Figure 3.1 Distribution of monthly electricity production, solar fraction and excess electricity fraction

Battery performance indicators are listed in Table 3.3.

Table 3.3 Battery performance parameter (for LA battery system, Athens)

Parameter	Value	Unit
Energy input (annual)	1850	kWh/year
Energy output (annual)	1610	kWh/year
Losses (annual)	240	kWh/year
Annual throughput	1720	kWh/year
Autonomy	32	h
Battery bank's lifetime throughput	19810	kWh
Expected life	11.5	year

Sensitivity analysis was performed on the allowed depth of discharge also known as minimum SoC after which the discharge is not allowed. According to the initial assumptions the allowed DoD is 50 %, but different DoD values were used in the simulation and the key results are presented in Table 3.4.

Table 3.4 Sensitivity analysis - DoD (for LA battery system, Athens)

	80 %	70 %	60 %	50 %	40 %
NPC [k€]	24.6	25.0	25.2	25.4	26.0
LCOE [€/kWh]	0.8	0.9	0.9	0.9	0.9
Solar fraction [%]	93	92	90	90	87
Excess electricity fraction [%]	42	43	43	43	44
DG total fuel [L/year]	56	71	81	87	110
DG running time [h/year]	38	50	58	68	85
Autonomy [h]	51	45	38	32	26
Battery annual throughput [kWh/year]	1790	1770	1760	1720	1698
Battery usable nominal capacity [kWh]	13.2	11.6	10.0	8.2	6.6
Expected life [year]	11.1	11.2	11.3	11.5	11.7

Sensitivity analysis was performed on battery's float lifetime and the results are presented in Table 3.5.

Table 3.5 Sensitivity analysis – Battery float life (for LA battery system, Athens)

Battery float-life [year]	NPC [k€]	LCOE [€/kWh]	Salvage value [k€]	Expected life [year]	Initial battery capital [€]
8	27.7	0.9	1.0	8.0	4780
9	26.8	0.9	0.2	9.0	
10	26.2	0.9	0.6	10.0	
11	25.6	0.9	0.8	11.0	
12	25.4	0.9	1.0	11.5	
15	25.4	0.9	1.0	11.5	

Sensitivity analysis was performed on inverter's lifetime and the results are presented in Table 3.6.

Table 3.6 Sensitivity analysis - Inverter lifetime (for LA battery system, Athens)

Inverter Life [year]	NPC [k€]	LCOE [€/kWh]	Initial inverter capital [€]
10	25.4	0.9	3600
12	24.5	0.8	
14	24.0	0.8	
15	23.9	0.8	

Sensitivity analysis was performed on battery's replacement price and the results are presented in

Table 3.7.

Table 3.7 Sensitivity analysis – Battery replacement price (for LA battery system, Athens)

Battery replacement cost	NPC [k€]	LCOE [€/kWh]	Initial battery capital [€]
-20 %	25.6	0.9	4780
-10 %	25.9	0.9	
-	26.2	0.9	
+10 %	26.5	0.9	
+20 %	27.0	0.9	

Sensitivity analysis was performed on discount rate and inflation rate, the results are presented in Table 3.8.

Table 3.8 Sensitivity analysis – Economics inputs (for LA battery system, Athens)

Parameter	NPC [k€]	LCOE [€/kWh]
Nominal discount rate [%] at fixed inflation rate 2 %		
6	28.7	0.8
8	26.2	0.9
10	24.2	1.0
Expected inflation rate [%] at fixed discount rate 8 %		
1	25.0	0.9
2	26.2	0.9
3	27.4	0.8
4	28.9	0.8
5	30.4	0.8

3.2.2. Off-grid system with new Li-ion battery, Athens

Annual electricity production summary is presented in Table 3.9.

Table 3.9 Overall summary (for new Li-ion system, Athens)

Parameter	Value	Unit
PV electricity production	4310	kWh/year
Diesel generator electricity production	360	kWh/year
Total house demand (annual)	2245	kWh/year
Solar fraction (annual)	84	%
Excess electricity fraction (annual)	48	%
LCOE	0.9	€/kWh
NPC	26.2	k€
System's salvage value	1.5	k€

Monthly electricity production distribution, solar fraction distribution and excess electricity fraction are shown in Figure 3.2.

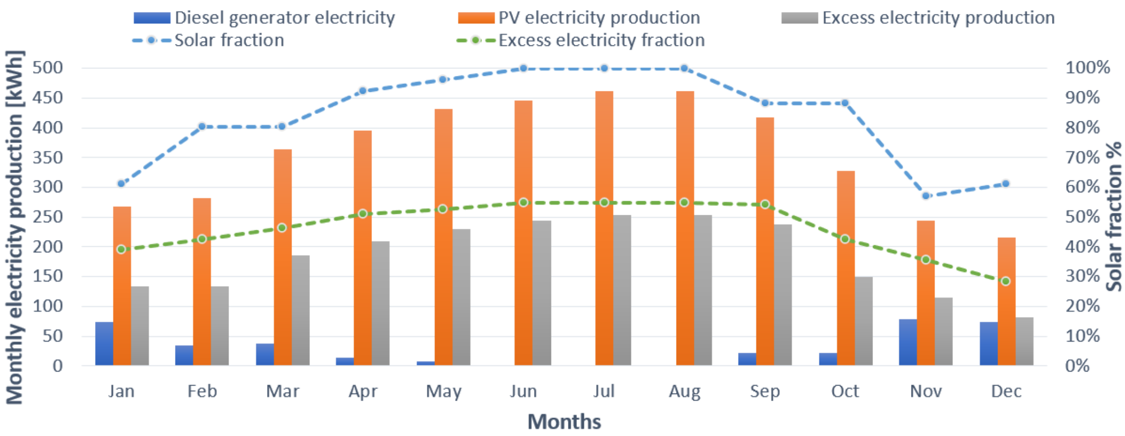

Figure 3.2 Distribution of monthly electricity production, solar fraction and excess electricity fraction

Battery performance indicators are listed in Table 3.10.

Table 3.10 Battery performance parameter (for new Li-ion system, Athens)

Parameter	Value	Unit
Energy input (annual)	1710	kWh/year
Energy output (annual)	1630	kWh/year
Losses (annual)	80	kWh/year
Annual throughput	1670	kWh/year
Autonomy	25	h
Battery bank's lifetime throughput	25076	kWh
Expected life	15	year

Sensitivity analysis was performed on the allowed depth of discharge also known as minimum SoC after which the discharge is not allowed. According to the initial assumptions the allowed DoD is 80 % , but since this battery supports 100 % DoD, different DoD values up to 100 % were used in the simulation and the results are presented in *Table 3.11*.

Table 3.11 Sensitivity analysis - DoD (for new Li-ion system, Athens)

	100 %	90 %	80 %	70 %	60 %
NPC [k€]	25.5	25.8	26.2	26.6	30.8
LCOE [€/kWh]	0.9	0.9	0.9	0.9	1.1
Solar fraction [%]	86	85	84	81	62
Excess electricity fraction [%]	47	47	48	48	53
DG total fuel [L/year]	109	117	131	144	294
DG running time [h/year]	61	69	84	81	158
Autonomy [h]	31	28	25	22	19
Battery annual throughput [kWh/year]	1660	1670	1670	1640	1380
Battery usable nominal capacity [kWh]	8.0	7.2	6.4	5.6	4.8
Expected life [year]	15	15	15	15	15

Sensitivity analysis was performed on battery's float lifetime and the results are presented in Table 3.12.

Table 3.12 Sensitivity analysis – Battery float life (for new Li-ion system, Athens)

Battery float-life [year]	NPC [k€]	LCOE [€/kWh]	Salvage value [k€]	Expected life [year]	Initial battery capital [€]
12	27.3	0.9	1.2	12	
15	26.2	0.9	0.4	15	
16	26.0	0.9	0.6	16	5310
17	25.7	0.9	0.7	17	
18	25.5	0.9	0.8	18	

Sensitivity analysis was performed on battery's replacement price and the results are presented in Table 3.13.

Table 3.13 Sensitivity analysis – Battery replacement price (for new Li-ion system, Athens)

Battery replacement cost	NPC [k€]	LCOE [€/kWh]	System Salvage value [k€]	Initial battery capital [€]
-40 %	25.5	0.9	1.3	
-30 %	25.7	0.9	1.3	
-20 %	25.9	0.9	1.4	5310
-10 %	26.0	0.9	1.4	
-	26.2	0.9	1.5	

Sensitivity analysis was performed on discount rate and inflation rate, the results are presented in Table 3.14.

Table 3.14 Sensitivity analysis – Economics inputs (for new Li-ion system, Athens)

Parameter	NPC [k€]	LCOE [€/kWh]
Nominal discount rate [%] at fixed inflation rate 2 %		
6	28.7	0.8
8	26.2	0.9
10	24.3	1.0
Expected inflation rate [%] at fixed discount rate 8 %		
1	25.2	1.0
2	26.2	0.9
3	27.4	0.8
4	28.8	0.8
5	30.2	0.8

3.2.3. Off-grid system with second life EV battery, Athens

Annual electricity production summary is presented in Table 3.15.

Table 3.15 Overall summary (for 2nd life Li-ion system, Athens)

Parameter	Value	Unit
PV electricity production	4310	kWh/year
Diesel generator electricity production	220	kWh/year
Total house demand (annual)	2245	kWh/year
Solar fraction (annual)	90	%
Excess electricity fraction (annual)	46	%
LCOE	0.9	€/kWh
NPC	26.7	k€
System's salvage value	1.4	k€

Monthly electricity production distribution, solar fraction distribution and excess electricity fraction are shown in Figure 3.3.

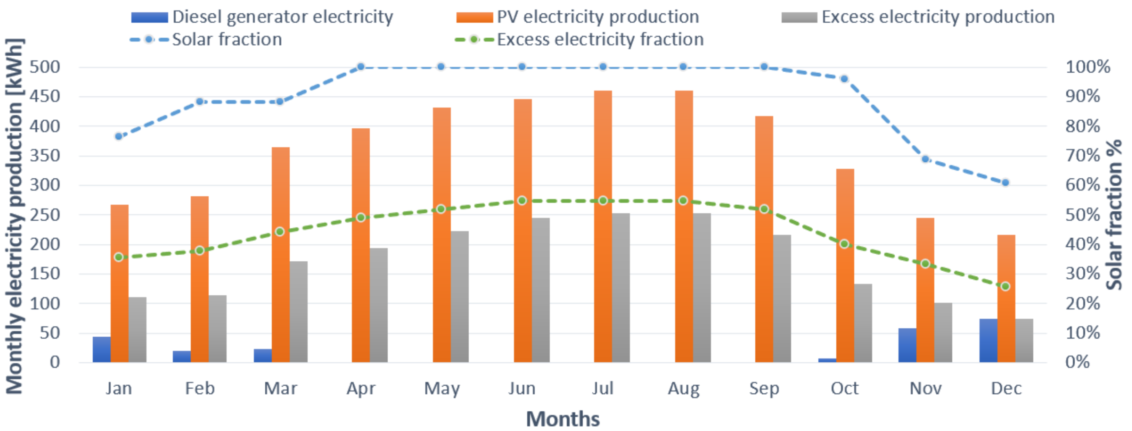

Figure 3.3 Distribution of monthly electricity production, solar fraction and excess electricity fraction

Battery performance indicators are listed in Table 3.16.

Table 3.16 Battery performance parameter (for 2nd life Li-ion system, Athens)

Parameter	Value	Unit
Energy input (annual)	1700	kWh/year
Energy output (annual)	1620	kWh/year
Losses (annual)	80	kWh/year
Annual throughput	1660	kWh/year
Autonomy	30	h
Battery bank's lifetime throughput	11620	kWh
Expected life	7	year

Sensitivity analysis was performed on the allowed depth of discharge also known as minimum SoC after which the discharge is not allowed. According to the initial assumptions the usable SoC range is 60 % (intended between 20 % to 80 %, but limits in HOMER is 40 % to 100 % due to limitations in HOMER), but different usable SoC range values were used in the simulation and the results are presented in Table 3.17.

Table 3.17 Sensitivity analysis - DoD (for 2nd life Li-ion system, Athens)

	50 %	60 %	70 %	80 %
Intended SoC range to be used [%]	20-70	20-80	20-90	10-90
SoC range used in HOMER [%]	50-100	40-100	30-100	20-100
NPC [k€]	27.0	26.7	26.3	26.0
LCOE [€/kWh]	0.9	0.9	0.9	0.9
Solar fraction [%]	88	90	92	93
Excess electricity fraction [%]	47	46	46	45
DG-total Fuel [L/year]	97	85	70	62
DG running hours [h/year]	68	64	54	46
Autonomy [h]	25	30	35	40
Battery annual throughput [kWh/year]	1660	1660	1670	1680
Battery usable nominal capacity [kWh]	6.4	7.7	8.9	10.2
Expected life [year]	7	7	7	7

Sensitivity analysis was performed on battery's float lifetime and the results are presented in Table 3.18.

Table 3.18 Sensitivity analysis – Battery float life (for 2nd life Li-ion system, Athens)

Battery float-life [year]	NPC [k€]	LCOE [€/kWh]	System salvage value [k€]	Expected life [year]	Initial battery capital [€]
5	29.1	1.0	0.0	5.0	3300
6	27.7	0.9	0.7	6.0	
7	27.0	0.9	0.3	7.0	
8	26.1	0.9	0.6	7.7	

Sensitivity analysis was performed on battery's replacement price and the results are presented in Table 3.19.

Table 3.19 Sensitivity analysis – Battery replacement price (for 2nd life Li-ion system, Athens)

Battery replacement cost	NPC [k€]	LCOE [€/kWh]	System salvage value [k€]	Initial battery capital [€]
-40 %	25.4	0.9	0.2	
-30 %	25.8	0.9	0.2	
-20 %	26.2	0.9	0.3	3300
-10 %	26.3	0.9	0.3	
-	26.7	0.9	0.4	

Sensitivity analysis was performed on discount rate and inflation rate, the results are presented in Table 3.20.

Table 3.20 Sensitivity analysis – Economics inputs (for 2nd life Li-ion system, Athens)

Parameter	NPC [k€]	LCOE [€/kWh]
Nominal discount rate [%] at fixed inflation rate 2 %		
6	29.4	0.8
8	26.7	0.9
10	24.6	1.0
Expected inflation rate [%] at fixed discount rate 8 %		
1	25.5	1.0
2	26.7	0.9
3	28.0	0.9
4	29.5	0.8
5	31.1	0.8

3.3 Simulation results (Location: Gotland)

Results of the simulation study of the off-grid PV system located in Gotland that consists of 2.9 kW PV panels, 4 kW bi-directional inverter, 7.2 kW diesel generator with three different storage options but only one storage unit connected at a time. Results with size of 16.5 kWh lead-acid battery bank are presented in section 3.3.1, also, a sensitivity analysis was realised to find the required PV array size to reach same solar fraction as in Athens. The results with size of 8kWh new Li-ion battery bank are presented in section 3.3.2, results with size of 12.8 kWh second life EV battery bank are presented in section 3.3.3.

3.3.1. Off-grid system with lead-acid battery, Gotland

Annual electricity production summary is presented in Table 3.21.

Table 3.21 Overall summary (for LA battery system, Gotland)

Parameter	Value	Unit
PV electricity production	3480	kWh/year
Diesel generator electricity production	600	kWh/year
Total house demand (annual)	2245	kWh/year
Solar fraction (annual)	73	%
Excess electricity fraction (annual)	37	%
LCOE	1.0	€/kWh
NPC	29.2	k€
System's salvage value	2.0	k€

Monthly electricity production distribution, solar fraction distribution and excess electricity fraction are shown in Figure 3.4.

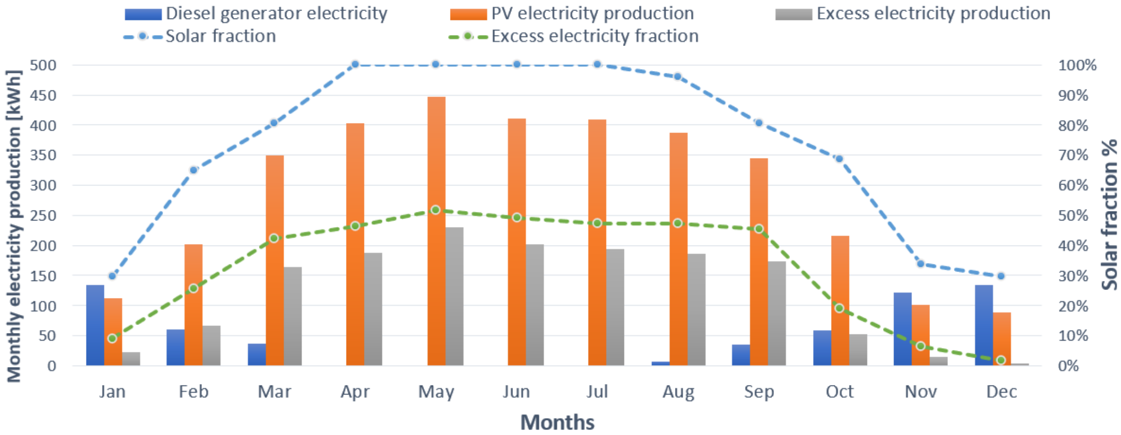

Figure 3.4 Distribution of monthly electricity production, solar fraction and excess electricity fraction

Battery performance indicators are listed in *Table 3.22.*

Table 3.22 Battery performance parameter (for LA battery system, Gotland)

Parameter	Value	Unit
Energy input (annual)	1790	kWh/year
Energy output (annual)	1570	kWh/year
Losses (annual)	230	kWh/year
Annual throughput	1680	kWh/year
Autonomy	32	h
Battery bank's lifetime throughput	19810	kWh
Expected life	11.8	year

Sensitivity analysis was performed on the allowed depth of discharge also known as minimum SoC after which the discharge is not allowed. According to the initial assumptions the allowed DoD is 50 %, but different DoD values were used in the simulation and the results are presented in *Table 3.23.*

Table 3.23 Sensitivity analysis - DoD (for LA battery system, Gotland)

	80 %	70 %	60 %	50 %	40 %
NPC [k€]	28.2	29.0	28.6	29.2	29.2
LCOE [€/kWh]	1.0	1.0	1.0	1.0	1.0
Solar fraction [%]	78	78	76	73	73
Excess electricity fraction [%]	35	36	36	37	37
DG total fuel [L/year]	186	216	204	224	230
DG running time [h/year]	125	146	143	157	172
Autonomy [h]	51	45	39	32	26
Battery annual throughput [kWh/year]	1730	1710	1680	1680	1599
Battery usable nominal capacity [kWh]	13.2	11.6	9.9	8.2	6.6
Expected life [year]	11.4	11.6	11.8	11.8	12.4

Sensitivity analysis was performed on battery's float lifetime and the results are presented in Table 3.24.

Table 3.24 Sensitivity analysis – Battery float life (for LA battery system, Gotland)

Battery float-life [year]	NPC [k€]	LCOE [€/kWh]	Salvage value [k€]	Expected life [year]	Initial battery capital [€]
8	31.7	1.1	1.0	8.0	4780
9	30.8	1.1	0.2	9.0	
10	30.2	1.0	0.6	10.0	
11	29.6	1.0	0.8	11.0	
12	29.2	1.0	1.0	11.8	
15	29.2	1.0	1.0	11.8	

Sensitivity analysis was performed on inverter's lifetime and the results are presented in Table 3.25.

Table 3.25 Sensitivity analysis - Inverter lifetime (for LA battery system, Gotland)

Inverter Life [year]	NPC [k€]	LCOE [€/kWh]	Initial inverter capital [€]
10	29.2	1.0	3600
12	28.4	1.0	
14	27.9	1.0	
15	27.7	0.9	

Sensitivity analysis was performed on battery's replacement price and the results are presented in Table 3.26.

Table 3.26 Sensitivity analysis – Battery replacement price (for LA battery system, Gotland)

Battery replacement cost	NPC [k€]	LCOE [€/kWh]	Initial battery capital [€]
-20 %	28.7	1.0	4780
-10 %	28.9	1.0	
-	29.2	1.0	
+10 %	29.5	1.0	
+20 %	29.8	1.0	

Sensitivity analysis was performed on discount rate and inflation rate, the results are presented in Table 3.27.

Table 3.27 Sensitivity analysis – Economics inputs (for LA battery system, Gotland)

Parameter	NPC [k€]	LCOE [€/kWh]
Nominal discount rate [%] at fixed inflation rate 2 %		
6	32.5	0.9
8	29.2	1.0
10	26.7	1.1
Expected inflation rate [%] at fixed discount rate 8 %		
1	27.8	1.1
2	29.2	1.0
3	30.8	1.0
4	32.6	0.9
5	34.6	0.9

Sensitivity analysis was realised on renewable fraction to see the different PV array size required for Gotland to meet the same renewable fraction as in Athens which is 90 % and listed in Table 3.2 (the off-grid system with the lead-acid battery bank). In order to do that, the PV panel sizing limitation which was set according to pre-sizing results are removed and minimum renewable fraction parameter was assigned to different values as in Table 3.28. The different PV array size required for Sweden location is presented in Table 3.28.

Table 3.28 Sensitivity analysis - Renewable fraction (for LA battery system, Gotland)

Renewable fraction [%]	PV array [kW]	LCOE [€/kWh]	NPC [k€]	Excess electricity [kWh]	Excess electricity fraction [%]
73*	2.9	1.0	29.2	1500	37
75	3.5	1.0	29.5	2110	45
80	4.1	1.0	30.0	2790	52
85	5.7	1.1	32.2	4600	64
90	11.0	1.5	42.8	10960	81

*Renewable fraction for Athens in reference case 1 presented in Table 3.21

3.3.2. Off-grid system with new Li-ion battery, Gotland

Annual electricity production summary is presented in Table 3.29.

Table 3.29 Overall summary (for new Li-ion system, Gotland)

Parameter	Value	Unit
PV electricity production	3480	kWh/year
Diesel generator electricity production	650	kWh/year
Total house demand (annual)	2250	kWh/year
Solar fraction (annual)	71	%
Excess electricity fraction (annual)	41	%
LCOE	1.0	€/kWh
NPC	29.3	k€
System's salvage value	1.4	k€

Monthly electricity production distribution, solar fraction distribution and excess electricity fraction are shown in Figure 3.5.

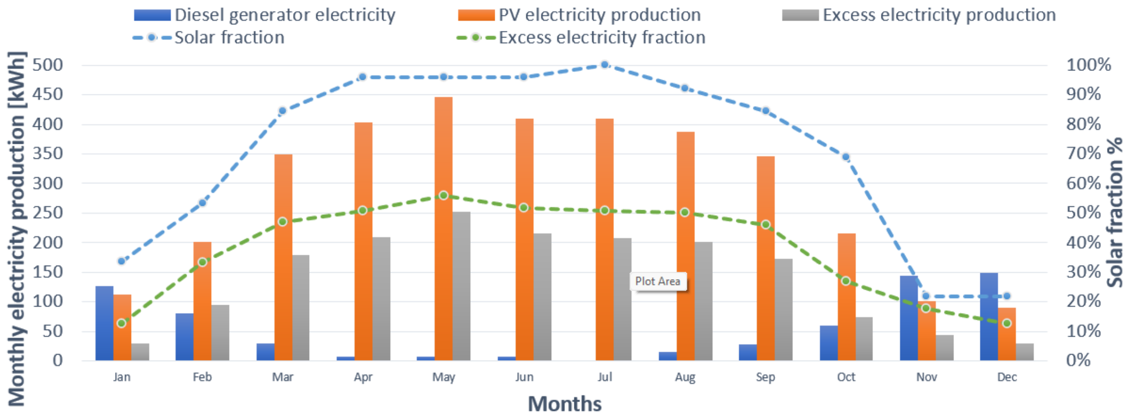

Figure 3.5 Distribution of monthly electricity production, solar fraction and excess electricity fraction

Battery performance indicators are listed in Table 3.30.

Table 3.30 Battery performance parameter (for new Li-ion system, Gotland)

Parameter	Value	Unit
Energy input (annual)	1660	kWh/year
Energy output (annual)	1580	kWh/year
Losses (annual)	80	kWh/year
Annual throughput	1620	kWh/year
Autonomy	25	h
Battery bank's lifetime throughput	24338	kWh
Expected life	15	year

Sensitivity analysis was performed on the allowed depth of discharge also known as minimum SoC after which the discharge is not allowed. According to the initial assumptions the allowed DoD is 80 %, but since this battery supports 100 % DoD, different DoD values up to 100 % were used in the simulation and the results are presented in Table 3.31.

Table 3.31 Sensitivity analysis - DoD (for new Li-ion system, Gotland)

	100 %	90 %	80 %	70 %	60 %
NPC [k€]	28.6	28.2	29.4	30.7	32.3
LCOE [€/kWh]	1.0	1.0	1.0	1.1	1.1
Solar fraction [%]	73	73	71	63	55
Excess electricity fraction [%]	40	40	41	44	46
DG total fuel [L/year]	214	221	238	289	349
DG running time [h/year]	125	136	153	154	179
Autonomy [h]	31	28	25	22	18
Battery annual throughput [kWh/year]	1630	1630	1620	1460	1340
Battery usable nominal capacity [kWh]	8.0	7.2	6.4	5.6	4.8
Expected life [year]	15	15	15	15	15

Sensitivity analysis was performed on battery's float lifetime and the results are presented in Table 3.32.

Table 3.32 Sensitivity analysis – Battery float life (for new Li-ion system, Gotland)

Battery float-life [year]	NPC [k€]	LCOE [€/kWh]	Salvage value [k€]	Expected life [year]	Initial battery capital [€]
12	30.4	1.0	1.2	12	5310
15	29.3	1.0	0.4	15	
16	29.1	1.0	0.6	16	
17	28.9	1.0	0.7	17	
18	28.6	1.0	0.8	18	

Sensitivity analysis was performed on battery's replacement price and the results are presented in Table 3.33.

Table 3.33 Sensitivity analysis – Battery replacement price (for new Li-ion system, Gotland)

Battery replacement cost	NPC [k€]	LCOE [€/kWh]	Salvage value [k€]	Initial battery capital [€]
-40 %	28.6	1.0	0.2	
-30 %	28.8	1.0	0.3	
-20 %	29.0	1.0	0.3	5310
-10 %	29.2	1.0	0.4	
-	29.3	1.0	0.4	

Sensitivity analysis was performed on discount rate and inflation rate, the results are presented in Table 3.34.

Table 3.34 Sensitivity analysis – Economics inputs (for new Li-ion system, Gotland)

Parameter	NPC [k€]	LCOE [€/kWh]
Nominal discount rate [%] at fixed inflation rate 2 %		
6	32.5	0.9
8	29.3	1.0
10	27.0	1.1
Expected inflation rate [%] at fixed discount rate 8 %		
1	28.0	1.1
2	29.5	1.0
3	30.9	1.0
4	32.6	0.9
5	34.6	0.9

3.3.3. Off-grid system with second life EV battery, Gotland

Annual electricity production summary is presented in Table 3.35.

Table 3.35 Overall summary (for 2nd life Li-ion system, Gotland)

Parameter	Value	Unit
PV electricity production	3480	kWh/year
Diesel generator electricity production	580	kWh/year
Total house demand (annual)	2245	kWh/year
Solar fraction (annual)	74	%
Excess electricity fraction (annual)	40	%
LCOE	1.1	€/kWh
NPC	30.7	k€
System's salvage value	1.3	k€

Monthly electricity production distribution, solar fraction distribution and excess electricity fraction are shown in Figure 3.6.

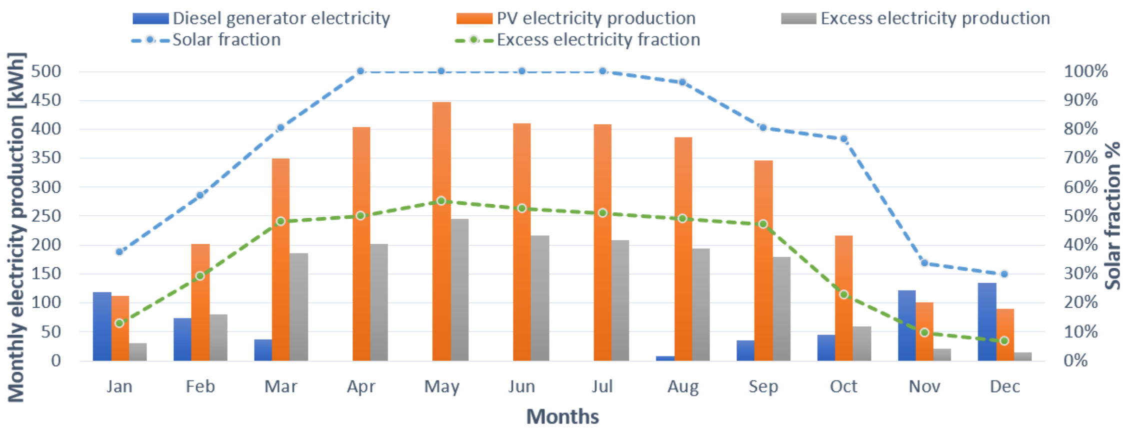

Figure 3.6 Distribution of monthly electricity production, solar fraction and excess electricity fraction

Battery performance indicators are listed in *Table 3.36*.

Table 3.36 Battery performance parameter (for 2nd life Li-ion system, Gotland)

Parameter	Value	Unit
Energy input (annual)	1650	kWh/year
Energy output (annual)	1570	kWh/year
Losses (annual)	80	kWh/year
Annual throughput	1610	kWh/year
Autonomy	30	h
Battery bank's lifetime throughput	11240	kWh
Expected life	7	year

Sensitivity analysis was performed on the allowed depth of discharge also known as minimum SoC after which the discharge is not allowed. According to the initial assumptions the usable SoC range is 60 % (intended between 20 % to 80 %, but limits in HOMER is 40 % to 100 % due to limitations in HOMER), but different usable SoC range values were used in the simulation and the results are presented in *Table 3.37*.

Table 3.37 Sensitivity analysis – DoD (for 2nd life Li-ion system, Gotland)

	50 %	60 %	70 %	80 %
Intended SoC range to be used [%]	20-70	20-80	20-90	10-90
SoC range used in HOMER [%]	50-100	40-100	30-100	20-100
NPC [k€]	30.6	30.7	29.8	29.4
LCOE [€/kWh]	1.1	1.1	1.0	1.0
Solar fraction [%]	74	74	77	79
Excess electricity fraction [%]	40	40	39	39
DG-total Fuel [L/year]	220	221	193	177
DG running hours [h/year]	157	157	135	123
Autonomy [h]	25	30	35	40
Battery annual throughput [kWh/year]	1560	1600	1610	1640
Battery usable nominal capacity [kWh]	6.4	7.7	9.0	10.0
Expected life [year]	7	7	7	7

Sensitivity analysis was performed on battery's float lifetime and the results are presented in Table 3.38.

Table 3.38 Sensitivity analysis – Battery float life (for 2nd life Li-ion system, Gotland)

Battery float-life [year]	NPC [k€]	LCOE [€/kWh]	Salvage value [k€]	Expected life [year]	Initial battery capital [€]
5	33.1	1.1	0.0	5.0	3300
6	31.7	1.1	0.7	6.0	
7	30.7	1.1	0.3	7.0	
8	29.9	1.0	0.7	7.9	

Sensitivity analysis was performed on battery's replacement price and the results are presented in Table 3.39.

Table 3.39 Sensitivity analysis – Battery replacement price (for 2nd life Li-ion system, Gotland)

Battery replacement cost	NPC [k€]	LCOE [€/kWh]	Salvage value [k€]	Initial battery capital [€]
-40 %	28.5	1.0	0.2	3300
-30 %	28.9	1.0	0.2	
-20 %	29.6	1.0	0.3	
-10 %	30.1	1.0	0.3	
-	30.5	1.0	0.3	

Sensitivity analysis was performed on discount rate and inflation rate, the results are presented in Table 3.40.

Table 3.40 Sensitivity analysis – Economics inputs (for 2nd life Li-ion system, Gotland)

Parameter	NPC [k€]	LCOE [€/kWh]
Nominal discount rate [%] at fixed inflation rate 2 %		
6	34.3	1.0
8	30.7	1.1
10	27.9	1.1
Expected inflation rate [%] at fixed discount rate 8 %		
1	29.1	1.1
2	30.7	1.1
3	32.4	1.0
4	34.4	1.0
5	36.7	0.9

3.4 Comparison of different system's results

3.4.1. Impact of DoD to NPC and Solar fraction

NPC of the different system storage options against the allowed DoDs for both locations is compared and presented in Figure 3.7.

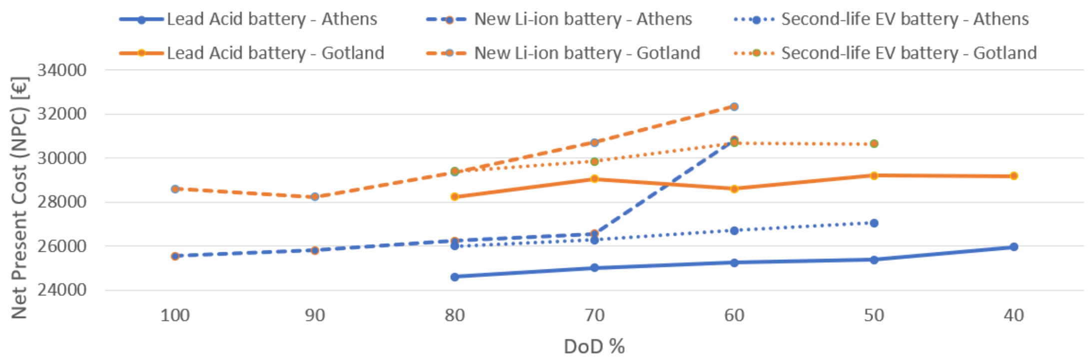

Figure 3.7 NPC compared to allowed DoDs

Solar fraction of the different system storage options against the allowed DoDs for both locations is compared and presented in Figure 3.8.

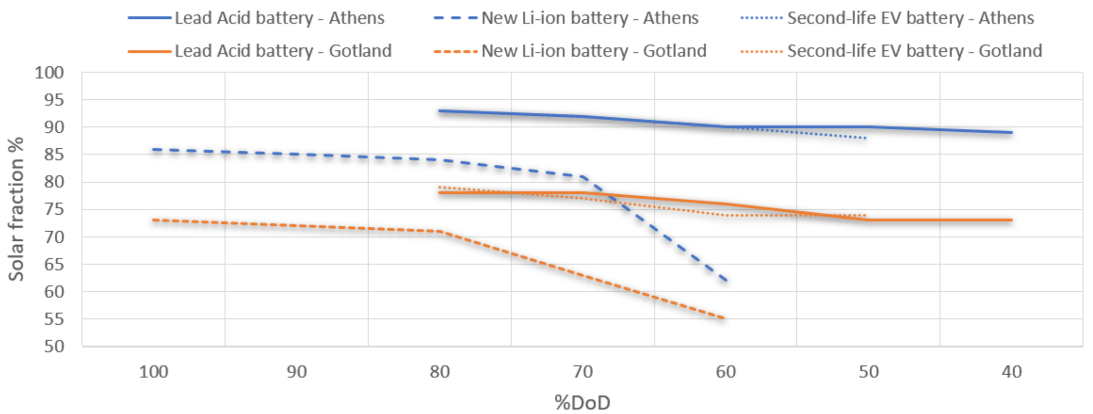

Figure 3.8 Solar fraction compared to allowed DoDs

3.4.2. Impact of Li-ion battery replacement price to NPC

Li-ion battery price is expected to decrease in future, thus there is a big uncertainty in the price for new Li-ion battery and second life EV battery. Sensitivity analysis was performed on the battery replacement price up to 40 % price reduction for new Li-ion battery and second life EV battery, a fixed price for lead-acid battery from the initial simulation is used to compare the results (i.e., price reduction is applied only for the Li-ion batteries).

NPC of the different system storage options against the battery's float lifetime for both locations is compared and presented in *Figure 3.9*.

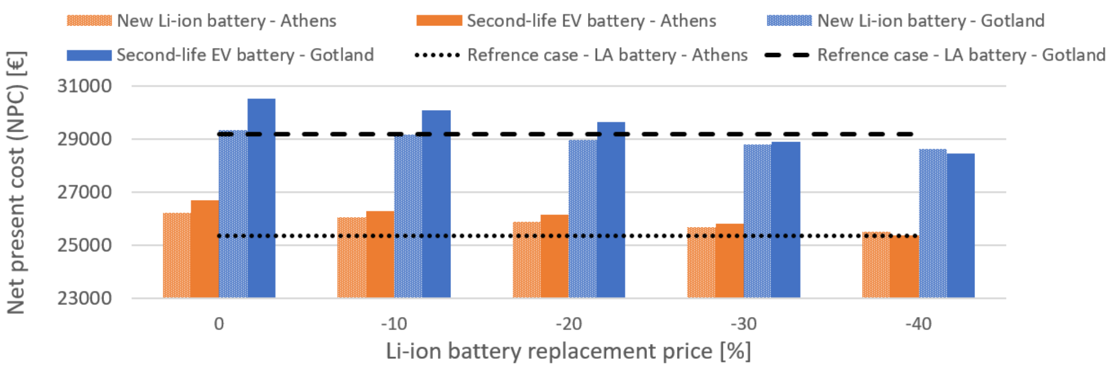

Figure 3.9 NPC compared to Battery replacement price reduction for Li-ion batteries

3.4.3. Impact of battery float life to NPC

Battery's lifetime is a key parameter in finding the cheapest storage solution for the house. Initially a lifetime of 15 years/2400 cycles was assumed for lead-acid battery and 15 years/6000 cycles for new Li-ion battery, 7 years/1000 cycles for second life EV battery. Sensitivity analysis was performed on the battery's float lifetime.

NPC of the different system storage options against the battery's float lifetime for both locations is compared and presented in Figure 3.10.

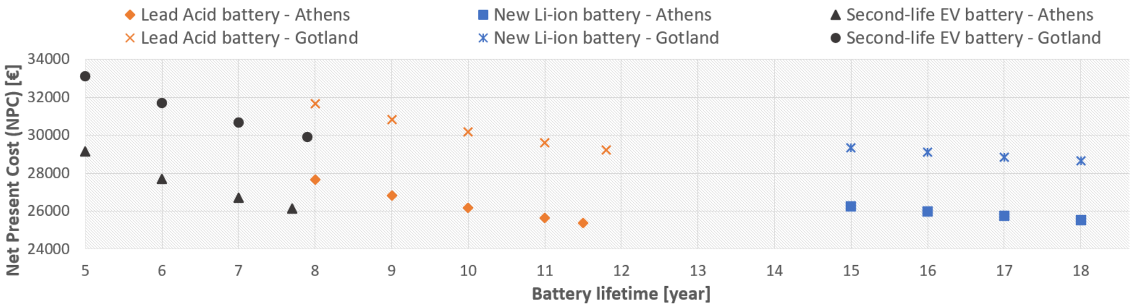

Figure 3.10 NPC (including salvage) compared to battery lifetime

NPC of the different system storage options against the battery's float lifetime for both locations is compared and presented in Figure 3.11.

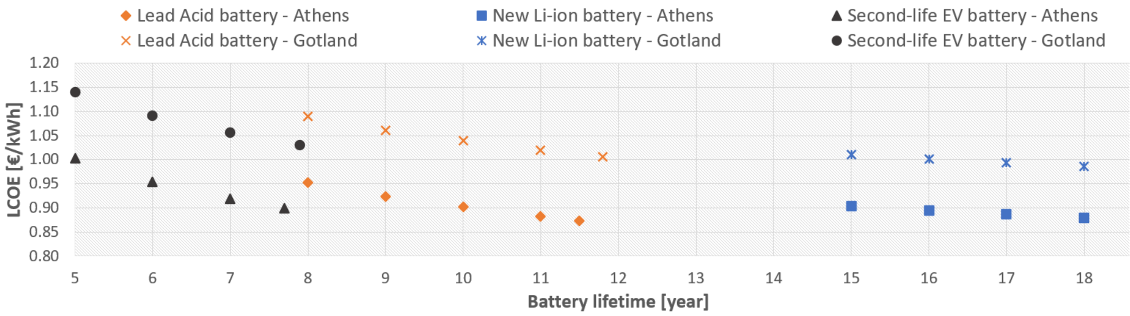

Figure 3.11 LCOE (including salvage) compared to battery lifetime

3.4.4. Impact of system's salvage value and float life to NPC and LCOE

HOMER calculated the system's salvage value as the value remaining for the components at the end of the project (i.e., inverter, diesel generator and battery bank), this salvage value is considered as revenue generated and thus it is subtracted from the total expenditures in NPC calculation. However, for an off-grid house, it is impractical to consider the salvage value, hence the salvage value is not considered as a revenue. Based on the simulation output for the reference cases, NPC and LCOE were recalculated manually excluding the salvage value and the values are presented in Table 3.41.

Table 3.41 NPC and LCOE excluding salvage for the reference cases

	Including salvage		Excluding salvage	
	NPC [k€]	LCOE [€/kWh]	NPC [k€]	LCOE [€/kWh]
Lead Acid battery - Athens	25.4	0.9	27.4	0.9
New Li-ion battery - Athens	26.2	0.9	27.7	0.9
Second-life EV battery - Athens	26.7	0.9	28.1	1.0
Lead Acid battery - Gotland	29.2	1.0	31.2	1.1
New Li-ion battery - Gotland	29.3	1.0	30.7	1.1
Second-life EV battery - Gotland	30.7	1.0	32.0	1.1

From the sensitivity analysis result, the LCOE excluding salvage are calculated and presented in Figure 3.12.

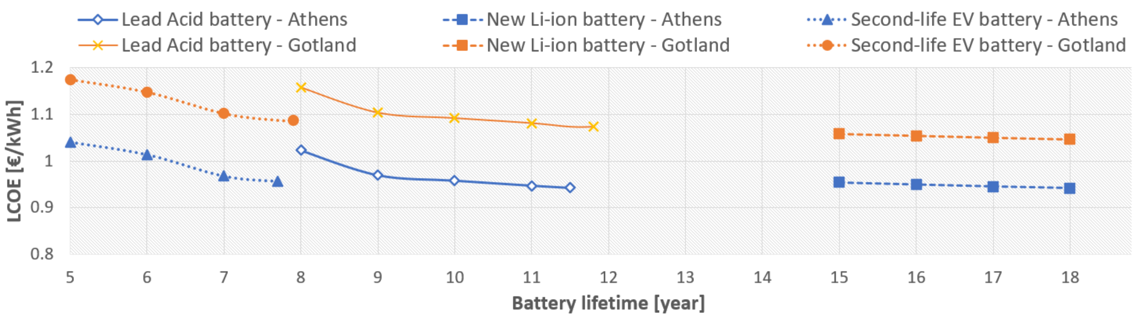

Figure 3.12 LCOE (excluding salvage) compared to battery lifetime

From the sensitivity analysis result, the NPC excluding salvage for different battery life are calculated and presented in *Figure 3.13*.

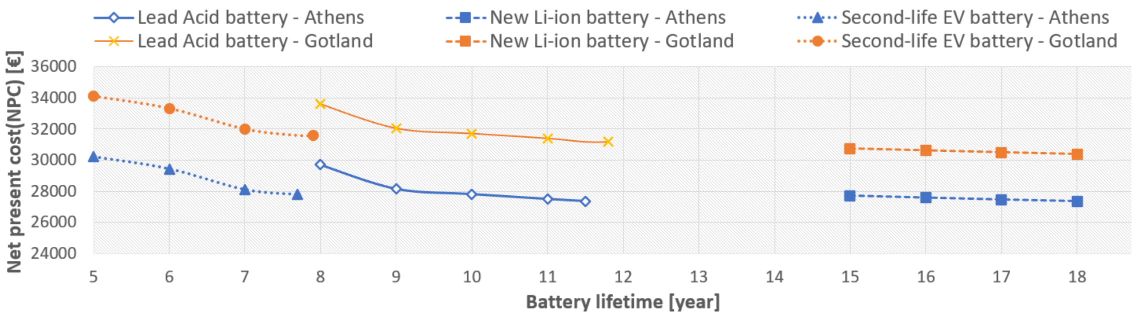

Figure 3.13 NPC (excluding salvage) compared to battery lifetime

3.4.5. Impact of battery's usable nominal capacity to NPC and LCOE

Usable nominal capacity is the storage capacity which is adjusted based on the depth of discharge of the battery, i.e., if the DoD is 50 % and the battery bank size is 8 kWh then the usable capacity is 4 kWh.

According to the pre-sizing, the estimated battery bank sizes are 14.5 kWh for lead acid, 8.5 kWh for new Li-ion and 11.3 kWh for second life EV battery, i.e., the usable battery capacity is comparable between storage options[3]. After the market survey, based on market availability slightly different size battery banks were chosen, thus the usable nominal capacity varies from 6.4 kWh to 8.2 kWh in reference cases (i.e., 8.2 vs 6.4 vs 7.7 kWh).

From the DoD sensitivity analysis, 40 % DoD for lead acid battery, 80 % DoD for new Li-ion battery and 50 % DoD for second life EV battery have nearly same usable capacity and theirs's NPC and LCOE can be compared (i.e., 6.6 vs 6.4 vs 6.4 kWh).

The DOD, battery size and usable capacity in references cases are presented in Table 3.42.

Table 3.42 NPC and LCOE compared to batteries nominal usable capacity

	DoD [%]	Battery bank size [kWh]	Usable capacity [kWh]	NPC [k€]	LCOE [€/kWh]
Reference cases list					
Lead Acid battery - Athens	50	16.5	8.2	25.4	0.9
New Li-ion battery - Athens	80	8.0	6.4	26.2	0.9
Second-life EV battery - Athens	60	12.8	7.7	26.7	0.9
Lead Acid battery - Gotland	50	16.5	8.2	29.2	1.0
New Li-ion battery - Gotland	80	8.0	6.4	28.2	1.0
Second-life EV battery - Gotland	60	12.8	7.7	30.7	1.1
Sensitivity analysis cases where usable capacity closer to range					
Lead Acid battery - Athens	40	16.5	6.6	26.0	0.9
New Li-ion battery - Athens	80	8.0	6.4	26.2	0.9
Second-life EV battery - Athens	50	12.8	6.4	27.0	0.9
Lead Acid battery - Gotland	40	16.5	6.6	29.2	1.0
New Li-ion battery - Gotland	80	8.0	6.4	28.2	1.0
Second-life EV battery - Gotland	50	12.8	6.4	30.6	1.1

From the comparison it can see that the NPC and LCOE for lead acid battery and new Li-ion battery is same within each reference location. NPC and LCOE for Second life EV battery bank option seem slightly higher compared to lead acid and new Li-ion option within each location.

[3] η_{BOSb} is assumed as 0.85 for lead-acid batteries and 0.9 for Li-ion batteries. The difference is negligible, so the usable nominal capacity can be compared.

4 Discussion

From the literature study it can concluded that the used EV batteries has the potential to be used in the residential buildings for solar applications, a lifetime of around 7 years can be expected in the second life application when the state of health at the time of end of first life is more than 80 %, the battery can be used in second life application until the SoH reaches 60 % for a stable operation and can be continued up to SoH of 40 % with a risk of sudden death of the battery causing the system unstable, cycling the EV battery in mid-SoC range (20 % to 80 %) can further increase the lifetime of the battery, approximately 100 GWh of used batteries from EV are expected by 2030 thus a price of the second life batteries is expected to be reduced due to the high availability. According to Zhu et al. [4], to evaluate the economic viability of 2nd life for second life EV batteries, an understanding is required on the effect of several key parameters such as ability to compete with the new Li-ion batteries, compete with other types of battery, the availability of second life EV batteries, the factors that drive the cost of refurbishing the batteries and the performance of the second life batteries. In this thesis the ability to compete with the new Li-ion battery and ability to compete with lead-acid battery technology was analysed. The other possible influential factors such as the availability and amount of second life EV batteries are not analysed.

In EVs, usually some type of battery conditioning unit is installed that takes care of heating and cooling of the batteries to improve the efficiency and reduce the battery degradation. But in this thesis, battery is assumed to be placed inside the house being air cooled and no external battery conditioning is considered.

In EVs, there is a central BMS that takes care of all the battery modules, but when few modules are applied and used in second life application, they still require a BMS, thus result in needing an additional hardware (i.e., external BMS). This can be avoided if inverter manufactures can include BMS to support the EV battery modules.

Based on the literature review, 7 years is assumed as a lifetime for the second life EV batteries, but in reality, the battery's remaining lifetime will be affected by the battery operating condition in the battery's first life. So, there is an uncertainty in determining the remaining lifetime of the battery in second life application.

According to the literature review, the EV batteries life can be prolonged if the user avoid the high SoC and a low DoD, the second life EV batteries are intended to operate between 20 % SoC and 80 % SoC (i.e., avoid charging up to 100 % and discharge only up to 20 % DoD) but it was not possible to set those limits in HOMER simulation as the software assumes to-charge the battery up to 100 %.

In this simulation, multiyear mode is not used, hence the battery life is decided based on the lifetime energy through put and the float lifetime, but the temperature effects (temperature vs capacity, temperature vs lifetime) are not considered. So, the expected life of the battery may be slightly higher or lower than the values listed in section 3.

In HOMER, generator's lifetime of 15000 hours is used in the simulation, the output of the simulation indicated that the diesel generator can be used for the entire project's lifetime since the number of hours of operation is not exceeding the lifetime of the generator, but in reality, 25 years of life for a diesel generator may or may not be possible, a replacement might be needed during the project's lifetime.

4.1 Error estimation and uncertainties in the simulation results

For the PV electricity generation, optimization module in HOMER was used to create a synthetic hourly solar data from the monthly average data received from the NASA database (satellite date) for the reference locations. According to HOMER, the generated synthetic hourly data is virtually the same as real data and the differences in KPIs such as PV array production, fuel consumption, generator run time and storage throughout have an uncertainty of less than 5 % [19]. As a result of this, the economic KPIs such as NPC and LCOE have an uncertainty of less than 2 % [19]. Also, the optimization ran with 1 % precision for system design [38] (i.e., for example, 1 % of distance between upper and lower limit set for PV array size) and 1 % precision for NPC [38] (i.e., for example if the best optimised system has an NPC of 25.3 k€ then 1 % uncertainty is approximately ±0.25 k€). Uncertainty of the uncontrolled parameters such as the components price and components life are studies as a part of the sensitivity analysis.

According to Castrup [39], uncertainties from two sources can be combined as

$$U_x = \sqrt{U_{x1}^2 + U_{x2}^2}$$

where, U_x is combined uncertainty, U_{x1} and U_{x2} are uncertainties from two different sources.

Using the above equation: combined uncertainty for the KPIs (such as PV array production, fuel consumption, generator run time, storage life and storage throughout) is calculated as ≈5 %(combined value of 5 % and 1 %), combined uncertainty for economic KPIs (such as NPC, LCOE) is calculated as ≈2 %(combined value of 2 % and 1%). These combined uncertainties are applied on the simulation results (for all the references cases) and the values are presented in Table 4.1.

Table 4.1 HOMER simulation results with uncertainty applied for the reference cases

	Reference case's outcome with uncertainty value			**Combined uncertainty [%]**		
	NPC [k€]	**LCOE [€/kWh]**	**Solar fraction [%]**	**For NPC [%]**	**For LCOE [%]**	**For solar fraction [%]**
Lead acid battery - Athens	25.3 ± 0.6	0.9 ± 0.02	90 ± 5	2	2	5
New Li-ion battery - Athens	26.2 ± 0.6	0.9 ± 0.02	84 ± 4	2	2	5
Second-life EV battery - Athens	26.7 ± 0.6	0.9 ± 0.02	90 ± 5	2	2	5
Lead acid battery - Gotland	29.2 ± 0.6	1.00 ± 0.02	73 ± 4	2	2	5
New Li-ion battery - Gotland	29.3 ± 0.7	1.00 ± 0.02	71 ± 4	2	2	5
Second-life EV battery - Gotland	30.7 ± 0.7	1.1 ± 0.02	74 ± 4	2	2	5

For the simulations, one hour time step was used in HOMER and one hour resolution constant load profile was used which is not an actual representation of a typical house as the load in the house can be varying very often in a matter of seconds, such sudden change in load might affect the battery operation and performance i.e., the battery or the diesel generator might produce more electricity or less electricity than the required electricity. Thus, the PV production may not be accurate, in the results section all electricity production data (PV electricity production, excess electricity production, diesel generator electricity production) are rounded to the nearest ten. Solar fraction, excess electricity fraction and autonomy hours are rounded to the nearest integer value. The cost for the selected components is another uncertainty in the analysis, the cost is increasing regularly due to various market reasons, and it is not clear whether the price will continue to increase or will decrease in future. Also, the diesel price is assumed to be the same throughout the lifetime for simplification. Thus, the NPC was rounded to the nearest hundred. However, LCOE was rounded to one decimal value.

4.2 Solar fraction and excess electricity fraction

HOMER defines excess electricity as the surplus electrical production that should be curtailed since it cannot be used to serve the load directly or be stored [18]. From the simulations, it can be seen that: The solar fraction is higher in Athens compared to Gotland in all cases as expected. i.e., 90 % vs 73 % with lead-acid battery, 84 % vs 71 % with new Li-ion battery, 90 % vs 74 % with second life EV battery. A special case for the location Gotland with lead-acid battery was realised to derive the required PV array size to reach the same solar fraction as the primary location Athens, the results showed that to reach a solar fraction of 90 % in Gotland, the required PV size would be approximately 11 kW compared to 2.9 kW in Athens i.e., nearly 380 % increase in PV array size, at the same time the excess electricity fraction also reaches to 81 %.

Overall, the excess electricity fraction is higher in Athens compared to Gotland. i.e., 43 % vs 37 % with lead-acid battery, 48 % vs 41 % with new Li-ion battery, 46 % vs 40 % with second life EV battery. An optional on demand load such as an electric boiler or a small heat pump or an EV can be used in the system to make use of the excess electricity produced. However, such optional/additional devices are not considered in the simulation.

4.3 LCOE and NPC

From the simulation results show that the off-grid system is economically attractive in Athens than in Gotland. i.e., LCOE of 0.9 vs 1.0 €/kWh with lead-acid battery, 0.9 vs 1.0 €/kWh with new Li-ion battery, 0.9 vs 1.1 €/kWh when second life EV battery was used. Similarly, NPC was lower in Athens compared to Gotland. i.e., NPC of 25.3 vs 29.2 k€ with lead-acid battery, 26.2 vs 29.3 k€ with new Li-ion battery, 26.7 vs 30.7 k€ when second life EV battery was used.

4.4 Sensitivity analysis

Sensitivity analysis was performed on some of the key parameters: Increase in inverter life and battery life slightly decrease the NPC, LCOE in all cases. Changes in battery replacement price affects the NPC and LCOE as expected (i.e., increase in battery price increases the NPC and LCOE and vice versa). According to the initial boundary condition the allowed DoD of 50 % for lead-acid battery, 80 % for new Li-ion battery, 40 % for second life EV batteries were used. Sensitivity analysis was performed on different DoDs and the results show that increase in allowed DoD has a considerable impact on the solar fraction and excess electricity fraction. i.e., by allowing the battery to discharge to a lower level than initially assumed value then the solar fraction increases and excess electricity fraction decreases. However, discharging the battery lower than the recommended level age the battery faster.

5 Conclusions

For the simulation study, a single-family house with an annual demand of 2245 kWh/year located in Athens was chosen as primary location, the off-grid PV system was pre-sized for Athens and based on the pre-sizing results and what is state of art in the market the system components were chosen for system design. The system consists of 4 kW bi-directional inverter, 2.9 kW PV array, 7.2 kW genset and three battery bank options i.e., 16.5 kWh of lead-acid, 8 kWh new Li-ion and 12.6 kWh of second life EV battery. System performance with different storage options were simulated using HOMER for both locations and the KPIs are compared.

The simulation results show that the designed off-grid PV system can archive a solar fraction of 90 % in Athens and 73 % in Gotland when 16.5 kWh of lead-acid batteries are used with an allowed depth of discharge of 50 %. When a new Li-ion battery of 8 kWh with an allowed depth of discharge of 80 % is used then the achievable solar fraction is 84 % in Athens and 71 % in Gotland, When the second life EV battery of 12.6 kWh with an allowed depth of discharge of 60 % is used then the achievable solar fraction is 90 % in Athens and 74 % in Gotland. Sensitivity analysis is performed on the allowed depth of discharge and results showed that by the solar fraction can be increased by allowing the battery to discharge more than allowed depth of discharge, but it also decreases the battery lifetime.

The simulation results also show that the net present cost was lower in Athens for all the reference cases compared to Gotland. Net present cost and levelized cost of electricity for the off-grid system are 25.3 k€, 0.9 €/kWh in Athens and 29.2 k€, 1.0 €/kWh in Gotland when a lead-acid battery is used. When a new Li-ion battery is used then 26.2 k€, 0.9 €/kWh in Athens and 29.3 k€, 1.0 €/kWh in Gotland, when the second life EV battery is used then 26.7 k€, 0.9 €/kWh in Athens and 30.7 k€, 1.1 €/kWh in Gotland.

For the reference case in Athens, lead acid battery system has shown slightly lower NPC than new Li-ion battery and second life EV battery. For the reference house in Gotland, both lead acid battery and new Li-ion battery system have shown similar NPC and it is slightly lower than second life EV battery. So, the major deciding factor between lead acid batter or new Li-ion battery is the initial investment cost which is lower for lead acid battery compared to Li-ion battery. However, considering the fact that the price for the Li-ion battery is expected to continue to fall in future, Li-ion battery can be economically an attractive storage option.

Also, the second life EV battery LCOE is fairly comparable to the new Li-ion and lead acid battery system. In future, the massive inflow of used batteries from EV are expected to be available on the market for the second life application at a lower price than today. Thus, in future, second life EV batteries can become a good choice. Second life EV batteries can be used in off-grid PV systems as a storage option with the help of an external BMS, in future, if inverter manufactures can include such central BMS into the inverter design to support second life batteries so that the additional /external BMS can be avoided.

5.1 Future work:

Thermal effects and the kinetic effect due to charging/discharging can be included in the simulations to study the battery degradation when all the necessary inputs are available.

Second life batteries lifetime and battery degradation can be studied better when the battery is cycled between 20 % to 80 % SoC and when SoH is known to the user.

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Appendix A
Check-list before submitting your first draft

Please go through this check-list before you submit your first draft to your supervisor. To show that you have done it; mark the done parts by clicking on the check box☒. If the instructions in this document are not followed, your supervisor can refuse to read your thesis. You will remove the checklist from the appendix after you have received grade and the comments from the examiner.

☒ Use the given thesis template and do not change the style. Note the page breaks after each section were taken away to make the document shorter. Please add them where it is necessary. Each section should always start on a new page.

☒ Always use the spell check in the text editor before you hand in a report to avoid misspellings. Set the language before you start writing in the document. You can use US or UK English but you must be consistent with the one style all the way through the thesis

☒ Use the check-list in [7] for the SI rules and style conventions.

☒ The Abstract should include the important parts of introduction, method, results and conclusion with focus on method and conclusions.

☒ The Abstract should stand alone from the report, thus no references or cross-reference to figures or tables should be made.

☒ All abbreviations have to be listed in alphabetical order in the Abbreviation section and have to be introduced the first time they are used in the text; same for the nomenclature list.

☒ Do not include a list of figures to the thesis.

☒ Does the Introduction give a good background to the research question and is it put into perspective and do you describe why it is relevant to make this investigation?

☒ Does the Method section clearly describe the procedure of the study and performed experiments and are the main simplifications and limitations of the method discussed.

☒ Preferably the used method should be motivated in relation to the aim of the study and other possible methods.

☒ Are the results clearly presented and easy to understand for the reader?

☒ Have you really looked at the results with critical eyes and tried to find contradictory data and unexplainable results or trends?

☒ Have you critically evaluated the results and critically discussed simplifications and uncertainties in the method and possible implications for the results due to these imperfections?

- ☒ Have you critically evaluated the results and critically discussed simplifications and uncertainties in the method and possible implications for the results due to these imperfections?

- ☒ Are your results put in relation to the results from other similar studies?

- ☒ Excluding or avoiding the presentation of data which does not fit what you expect is strictly forbidden. Just if you know that there was a specific mistake in the measurement or the methodology for that particular data point, then the data could be excluded and the criteria to exclude data should be given in the Method section.

- ☒ Recommendation for further work should be included in the thesis.

- ☒ Are all figures, tables, equations, references and appendices referred to in the text? Use the Word cross-reference function.

- ☒ A report is usually a formal text where personal words such as "I", "we", "us", "our" etc. are seldom or never used. Therefore formulate without using these words, i.e. the passive form, e.g.:
  Do not write:
  I will investigate the effect of climate on xxxx.

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  The effect of climate on xxxx will be investigated.

- ☒ Original figures (copy/paste) used from other sources should be referred in the figure text and permission needs to be requested from the author. In that case the figure text will include "[ref] with permission from (the publisher/copyright owner)" This should be only done if it is really necessary to understand the context. Otherwise avoid it.

- ☒ Redrawn figures used from other sources should be referred in the figure text. In that case the figure text is "Reprinted from [ref]".

- ☒ All statements and conclusions presented must be backed up with either a reference, a logical discussion, which explains the point of view or it should be concluded from your own results.

- ☒ If you use labels in equations or figures they must be explained the first time they appear and then shown in a nomenclature list (with units) placed before the reference section.

- ☒ Use consistent terminology if you talk about the same thing: e.g. do not use once "solar radiation" and somewhere else "sunlight".

Appendix B
Summary of your thesis for the examiner