Larsen, David

Analysis of benefits of hybridization of power supply for safety critical components, both economically and environmentally

Bacheloroppgave i ingeniørfag - maskin (nettbasert)

Veileder: La Rosa, Angela Daniela

Mai 2023

Bacheloroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for vareproduksjon og byggteknikk

NTNU
Kunnskap for en bedre verden

Larsen, David

Analysis of benefits of hybridization of power supply for safety critical components, both economically and environmentally

Bacheloroppgave i ingeniørfag - maskin (nettbasert)
Veileder: La Rosa, Angela Daniela
Mai 2023

Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for vareproduksjon og byggteknikk

NTNU
Kunnskap for en bedre verden

Acknowledgment

I would like to thank the professors at NTNU and the engineers in my workplace who have showed interest in my project and given me valuable insights and guidance along the way. A special thanks to dr. Angela Daniela La Rosa for tutoring in her classes on LCA. Finally, I would like to thank my wonderful wife for the patience with me, for all the late hours I have spent during my years at the university.

Kongsberg, May 2023

Abstract

This project is a life cycle assessment on a surveillance system used on airports, that is required to operate 24/7/365. It will be conducted an economic LCA analysis for the different setups, with two configurations being analyzed and there will be a non-economic LCA for the photovoltaic (PV) panel, to check if it should be included in the final recommended system configuration.

The sizing of the hybrid power pack must be calculated, both the size of the PV-panels (if present) and the battery.

Calculation/rationale for the choices should be made, for example what battery type to choose. What would be the most economic option will also be calculated. Also, operational reliability should be considered.

The structure of the document is meant to comply with ISO14040 and ISO14044, which is the governing standards for performing an LCA-analysis.

The work with performing this analysis have provided me with valuable insight into production processes and supply chains. It has also provided me with training and a general framework for calculation of a prospect for a project.

It has also provided some insight into different energy production methods, both full scale for the grid, and localized node-production. I have further honed my skills in performing environmental and cost-benefit analysis, and the dependency between these.

Software

LCA-simulations carried out in: SimaPro 9.3.0.2

Document produced in: Microsoft Office Word

Tables produced in: Microsoft Office Excel (embedded)

System schemes: diagrams.net

NPV calculations: Python 3 Jupyter Notebook (Anaconda Navigator)

List of abbreviations

Abbreviation	Term
BMS	Battery management system
CFC	Chlorofluorocarbons
CO2(eq)	Carbon dioxide equivalent
CR	Customer requirement
DALY	Disability adjusted life yearly
DOD	Depth of discharge
FLA	Flooded lead acid (battery)
GWP20	Global Warming Potential 20 years
HTP	Human toxicity potential
IPCC	The Intergovernmental Panel on Climate Change
ISO	The international standards organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
Li-ion	Lithium-ion
ODP	Ozone depletion potential
PTP	Pan Tilt Platform
PV	Photovoltaic
SR	System requirement
UN	United Nations
UPS	Uninterrupted power supply
UV	Ultraviolet

List of figures

List of tables

Contents

1 Introduction

The contents of this LCA fathoms the emissions and environmental impact of a surveillance system connected directly to the power grid versus a hybrid system, having both a power bank (battery) and a PV-panel. Other renewable energy sources, such as vertical wind turbines are another workable technology for this task, either as a replacement or to be used in tandem. This paper will not discuss this further, but the author recommends conducting such assessment to design the best suited system, tailored for the specific need of the client and/or location of use.

The long-term impacts for the PV-panels were calculated with the SimaPro software, while some of the assumptions were drawn from external sources or an engineering estimate is given. The system is designed to last for 30 years (both PV-panel and surveillance platform). Former studies already have shown the benefits/sustainability of PV-panels, but the report will focus on proving this. Earlier, published work (1) have been used for reference purposes and earlier coursework done by the author (2) have been elaborated upon. Uncited graphics is self-made.

This thesis will investigate the theoretical benefit of having a redundant energy source and will discuss some scenarios where this can be beneficial, regarding safety and operational capabilities. First, we will establish the system configurations, then decide if we want to implement PV-panels to the design and at last make a full evaluation of the system.

1.1 Background

We use the LCA for assessing the aspect of environmental impact from a product (or system). To do this we must compile an inventory of inputs and outputs. The inventory list must be subject to an analysis of the related environmental impacts.

This document is written to be in accordance with ISO-standard 14040 (2006) (3) and 14044 (2006) (4), witch concerns LCA principles and framework, and requirements and guidelines, respectively.

The background for this LCA is that much of our energy consumption as used by systems which stand-alone uses a limited amount of electricity, but figures add up, and a considerable amount of the power goes to waste by idling systems. The cost of power is steadily increasing, and power reduction actions may be more profitable than ever.

2 Determining the framework of the system

Customer requirements (CR):

CR1: Back-up power without pollution, both exhaust and noise

CR2: Must be able to power the system for a minimum of 10 hours without external power input, starting with a full battery.

CR3: Projected lifetime for system is 30 years.

CR4: The system is to be scaled to be able to power a PTP sensor system (5).

The following power consumption data is given*:

Table 1 Power consumption, system.

PTP	
Nominal	340W
Maximum	650W
Display and controls	
Nominal	60W
Maximum	150W
Combined system	
Nominal	400W
Maximum	800W

**These data are symbolic only and does not in any way have any connection to the actual product referred to.*

System requirements (SR):

SR1: Battery pack shall be 4kWh minimum.

SR2: Solar panels (if added) shall supply 2x the nominal power consumption when overcast. 30% production in low light situations is assumed (6).

SR3: The linear decrease of effect shall be <1% annually for the PV-panels.

SR4: The system shall be designed with a calculated lifetime of at least 30 years, ensuring long-term reliability and durability.

SR5: The system shall be serviceable to be able to last for 30 years.

After the customer requirements are converted into system requirements, we can move onwards to the next step which is to calculate if it is beneficial, both economically and environmentally to add the PV-panels, of is just the power-bank should be added.

2.1 Battery

This life cycle analysis does not compare a traditional flooded lead-acid (or AGM/gel) type battery, to one of lithium-ion cells for use in solar energy applications, as this have been done in several other papers (7,8,9,10,11). As a basis for these calculations is the supplied a use-case for the system, but hopefully it can provide a general recommendation. In order to fully utilize the potential of the PV-panel an energy storage solution is needed (12).

The functional unit for the economic analysis is the number of use-cycles delivered from the battery pack alongside a cost-benefit calculation.

2.2 PV-panel

For the purpose of providing an analysis of a photovoltaic (PV) panel is to verify that it is indeed not contributing negatively to the total climate accounting, and to be able to estimate the break-even so that we can use it an input for the economic analysis. The functional unit will be kgCO2-eq./1 m^2 (13).

I will incorporate work I have done previously in the subject “EcoDesign, autumn 2022” (2), where I already have explored parts of this topic. The study addresses three different system configurations:

Table 2 System configurations.

Scenario	Description
1	Baseline scenario, system connected directly to the power
2	Hybrid system with PV-panel and lead-acid battery bank
3	Hybrid system with PV-panel and lithium-ion battery bank

The presence of a fossil fuel powered generator is not taken into consideration, as it is assumed all configuration will have this as a (extra) back-up.

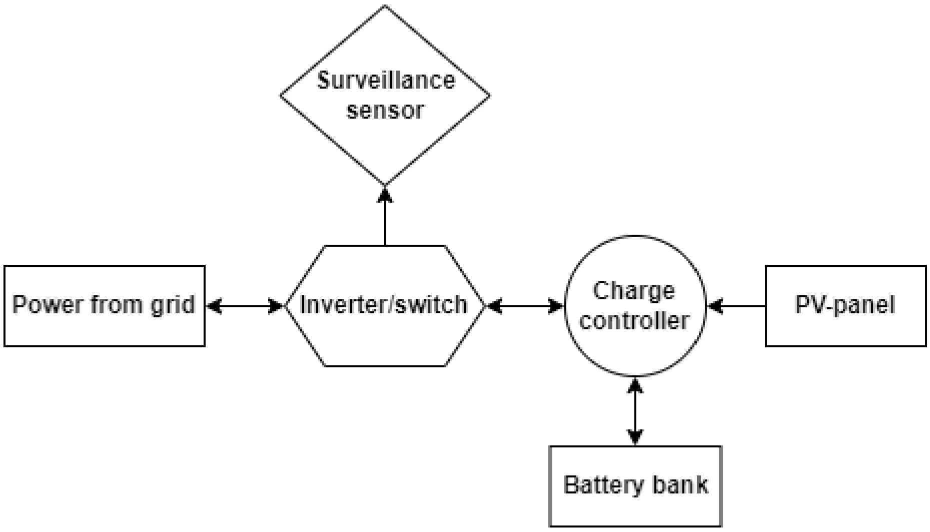

Figure 1 System overview.

3 Non-economic LCA analysis

LCA analysis provides an overview of the system's environmental footprint throughout its life cycle (14).

The LCA consolidates production, acquisition, ownership/operation, and disposal/recycling emissions/savings into a single report. It can be used for:

- Assessing alternative concepts of operations for different system configurations.
- Evaluating and comparing different design alternatives in terms of durability and practicality.
- Conducting long-term planning for the most optimal configuration, utilizing multiple scenario models for key parameters.

The analysis may be performed early in a systems life cycle but will consequently contain a certain degree of uncertainty. If the analysis is updated or performed later in the life cycle of the system, the uncertainty will be lower, but since the system already is fielded it will always be a possibility that a non-optimal solution was chosen. However, if said system was a pre-planned pilot, and a part of collecting metrics as part of a research plan, it could be advantageous.

In the early phases data from previous (similar) systems are used - later data from specific analyses will replace these and thus decrease the uncertainty.

As we become ever more dependent upon electric power we strain the established power grid, and alternate sources of power is called for. However, many solutions have historically been quite expensive, note aesthetically pleasing, noisy, complex, or simply have not been a "viable" option, as many projects is price-driven, and a contractor will not spend the extra time and effort into installing such equipment. If it in the future is to be part of the building code that power reducing/producing systems is to be implemented, we might see a quicker shift. For instance, some buildings are power positive, such as "Powerhouse Telemak", located in Porsgrunn (15).

Here the contractor has utilized, among other things, solar power in order to make a building that is self-sufficient. As the name suggests the building in question have a power surplus. This is one of the things I will discuss/explore; is it possible to design a hybrid power system that will make the surveillance system self-sufficient? We will then have several positive effects:

- Not reliant on power grid, makes this system well suited for remote installations, e.g., airports in rural territories.
- Redundant power source, the system will act as a UPS (uninterrupted power supply), with a very quick reaction time, so that the system will not need rebooting in case of a fallout of the power grid. Many installations on remote locations may already have emergency generator, but they may take several second to start up. If the site experiences frequent, but short in duration interruptions a power bank UPS is ideal.
- Will potentially reduce start-ups and potentially wear and service cost for the fuel-powered back-up systems.

After installation, the PV-panel produces zero emissions throughout its lifespan, but the production process involves significant environmental impact due to the use of rare earth metals, including silicon (16), and other minerals. The extraction, handling, and disposal of these materials contribute to this impact. Therefore, two separate break-even points must be considered: the environmental impact and the economic implications of the installation. Additionally, it is crucial to maintain or preferably enhance the safety of the system.

According to the Intergovernmental Panel on Climate Change (IPCC) for United Nations (UN) the need for wide implementation of such concepts is deemed urgent (17).

4 Goal and scope

4.1 Goal

The goal of the LCA was to find out which of the system configurations of the surveillance system that has the biggest environmental impact savings in CO2- equivalents during its lifespan.

However, this task proved quite substantial for one person, and the focus is therefore upon conducting an analysis of a PV-panel, to seek to prove that it itself does not contribute negatively to the overall environmental footprint of the system.

Another initial goal was to determine how much energy is required to power said systems consumes during a year with normal usage (both economic and environmental impact rely on this).

An LCA may be looking to answer the following bullet points:

- What is the global warming potential (GWP) of the surveillance system during operation?
- What proportion of emissions is attributed to production compared to operations?
- How does the energy consumption for producing the upgrade package compare to the energy savings achieved through its installation?

The goal of this thesis is to provide a study for different configurations of a commercially available surveillance system, with pan-tilt-panorama sensors for remotely operated airport control towers. The system used as inspiration is the KONGSBERG PTP (5), which is a part of a larger system KONGSBERG REMOTE TOWERS (18).

One goal of this thesis is to create abasis for different configurations of an already established surveillance solution to research if we can make it more eco-friendly, economical, dependable/reliable, aiming to find the most optimal configuration. For the calculation of the PV-panel and battery bank some data from former studies on this matter will be utilized, as this paper is combining separate studies (1,2).

For the battery data from previous papers have been compared, alongside an economic analysis, in order to map the differences between the technologies, and to lay out the pros and cons for each type.

4.2 Scope

To compare the power consumption between two configurations, kWh per year can serve as a suitable unit. Additionally, to assess the difference in production emissions, tons of CO2-equivalents can be considered as another viable unit. However, if we account for the power required to manufacture the different systems, we may opt for a single unit of measure. The primary focus of this study is the environmental aspect. To facilitate a comparative analysis of the systems' environmental impact, emissions are categorized into impact categories. Further details on this categorization are provided later in this document.

This study looks at different midpoint and endpoint categories. The following three midpoint categories are included, as they are deemed the most crucial:

- Global Warming Potential (GWP)
- Ozone Depletion Potential (ODP)
- Human Toxicity Potential (HTP)
    - Carcinogenic
    - Non-carcinogen

For the included endpoint categories, the corresponding entries is climate change and human health.

In every aspect of this life cycle analysis these scenarios will be fundamental. The impact category “Climate change” will have the impact indicator GWP20 (14).

4.3 System boundaries

Defining system boundaries is crucial to determine which components are included in the study and what is considered as the surroundings. The boundaries we establish will directly affect our results, so it is essential to be clear, concise, and accurate in this process. For this LCA the system consists of production, transportation, and recycling, see figure 2. The boundary has been set at the production level, excluding recycled components for this build.

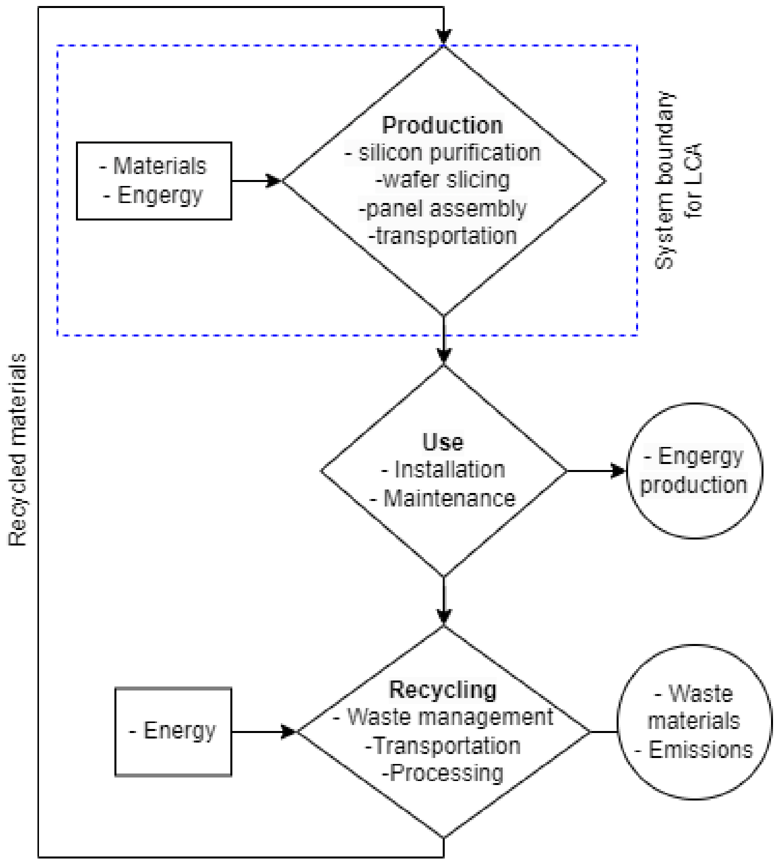

Figure 2 LCA System Boundary.

5 Life cycle inventory

LCI includes data gathering and calculation methods that compute the input and output factors of product systems. Here the construction of the system is explained, followed by the production process, assumptions, and the inventory list (3).

5.1 Assumptions

It is assumed that it is needed 4400MJx12 to create 12m^2 of PV-panel (13). The surveillance system is assuming to use 0,4kWh constantly (on average) for 262 000 hours. The transportation is assumed to be done by ship for 10 000 km.

The data collection is based on necessary assumptions related to factors such as electricity mix, transport, precise energy usage, panel weight, and recycling. The average sun radiation received on Norway's land surface ranges from 700-1000 kWh/m2 (19). Considering the efficiency of 21.13% for the 450W x 6 solar panels (20), it is reasonable to estimate a lifetime production of approximately 52 MWh/m^2 over 30 years.

5.2 Inventory list

Because of the increasing globalization of the industrial world, the shipping of goods is to increase evermore, and must be considered in all LCAs, at the transportation is a part of the total pollution. Many technologies require rare earth metals (21), and they are often found in poorer parts of the world (22). In such placed the labor is often cheap, but the wealth of the land seldom comes to benefit the general population in those regions. This poses a moral question we as technologist must ask ourselves: where do we source our materials and labor? This also applies to the production of batteries and its raw materials.

In this part there are tables with an overview of inputs, outputs, and values for calculations in SimaPro.

The inventory list (Table 3) compiles and quantifies the resource use and emissions for production of the PV-panel. This is a simplified process for the sake of an example and is an engineering estimate.

Table 3 Life cycle inventory, main components.

Materials/fuels	Quantity	Unit
Aluminum alloy, AlMg3 {RoW}| production | APOS, U	2,5	kg
Solar glass, low-iron {RoW}| production | APOS, U	1	kg
Ethylene vinyl acetate copolymer {RoW}| production | APOS, U	3	kg
Polyethylene terephthalate, granulate, amorphous {RoW}| production | APOS, U	0,5	kg
Polyvinylidenchloride, granulate {RoW}| production | APOS, U	0,5	kg

6 Life cycle impact assessment

During the life cycle impact assessment (LCIA) stage of the life cycle assessment (LCA), the focus is on assessing the potential environmental impacts. This evaluation comes from the basic flows found in the LCI.

The emphasis of this LCA is to assess the Global Warming Potential (GWP) (non-economical) and the system configuration with the most economical sustainability (economic analysis), for the operation of one system operating on the power grid, compared to a system where most of the power production comes from a hybrid PV-battery-system, both stationed in the same place in Norway.

The endpoint category is the impact on the natural environment. The goal of the LCA for the batteries is to assess how the difference in weight, longevity of the product when in use etc. is more eco-friendly. The midpoint category is therefore the global warming potential (kg CO2-Eq).

The life cycle impact assessment phase is the third phase of an LCA as described in ISO 14040. (3,4) The results and evaluation of the potential environmental impacts throughout the life cycle of the product are accounted for in this part of the LCA. The calculation methods for the in SimaPro are ReCiPe 2016 Midpoint (H) and CML-IA Baseline (14).

6.1 Methodology

Based on the goals of this LCA, the following methods in SimaPro have been selected and listed below.

IPCC 2021, developed by the Intergovernmental Panel on Climate Change, is the updated successor to the IPCC 2013 method. It incorporates Global Warming Potential (GWP) climate change factors over a 20-year timeframe, considering the carbon cycle response. This method focuses on evaluating CO2 emissions from diverse processes. It is based on the latest edition of the authoritative government distribution version of the IPCC climate report, "AR6 Climate Change 2021." (14).

The ReCipe 2021 mid- and endpoint (H) method is a collaborative effort between RIVM, Radboud University, Norwegian University of Science and Technology, and PRé Sustainability. This method offers the flexibility to choose midpoint and endpoint indicators. For the endpoint analysis, the ReSiPe Endpoint (H) analysis method is utilized, which encompasses Human Health, Ecosystems, and Resources as endpoints. The midpoint analysis employs the CMLIA baseline to extract indicators such as "Abiotic Depletion," "Global Warming Potential (GWP)," "Ozone Layer Depletion," "Human Toxicity," "Acidification," and "Eutrophication." The combined set of midpoint categories forms the foundation for the endpoints. To ensure the quality of the results, they are tested using both the Cut-off and APOS library (14).

6.2 Impact categories

Impact categories is groups of different emissions that affects the environment in different ways.

Each impact category in life cycle impact assessment (LCIA) is associated with a corresponding category indicator that describes the impact and its unit of measurement. Impact categories can be categorized at two levels in LCIA: midpoint and endpoint. Midpoint indicators address specific environmental issues like global warming, land use, and human toxicity. Endpoint indicators, on the other hand, consider the overall environmental impact on areas of *protection* (14).

GWP20 indicates that the impact calculation is measured over a 20-year period. Human Toxicity Potential (HTP) serves as an indicator for the release of known toxins that pose risks to human and mammal life. Chemicals like arsenic, ethanol, and manganese are closely monitored, and regulations or bans may restrict their release from products with specific uses. Ozone Depletion Potential (ODP) tracks the emissions of gases such as CFCs (chlorofluorocarbons) and halons, which contribute to the breakdown of ozone particles. These gas emissions lead to the formation of ozone holes, which weaken the Earth's natural protection against harmful UV radiation (23).

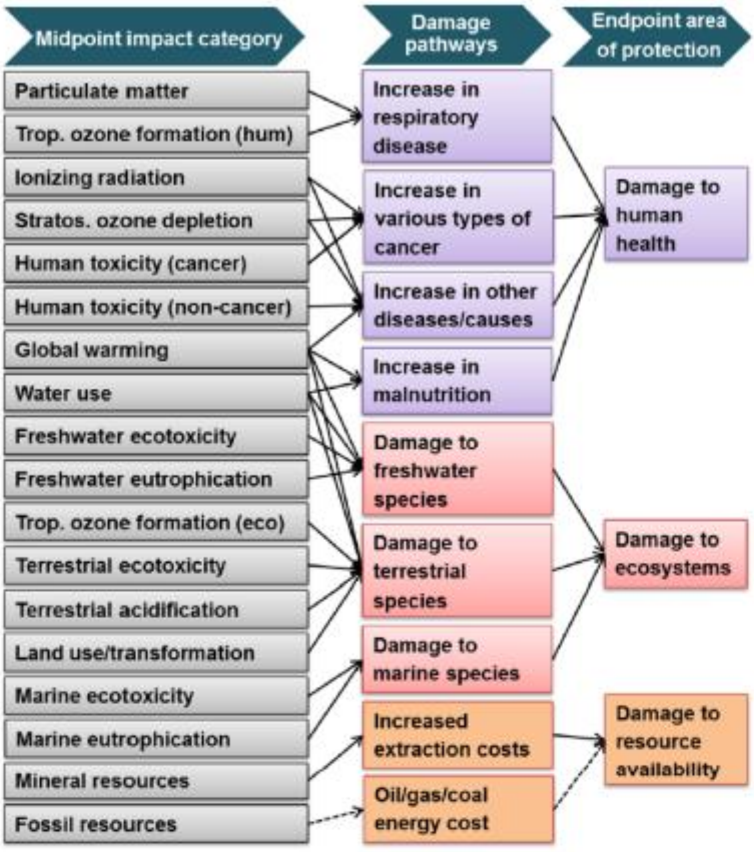

Figure 3 Impact category overview (24).

6.3 Results

This section describes the results obtained from the SimaPro software.

Comparison between operation, production, and transportation

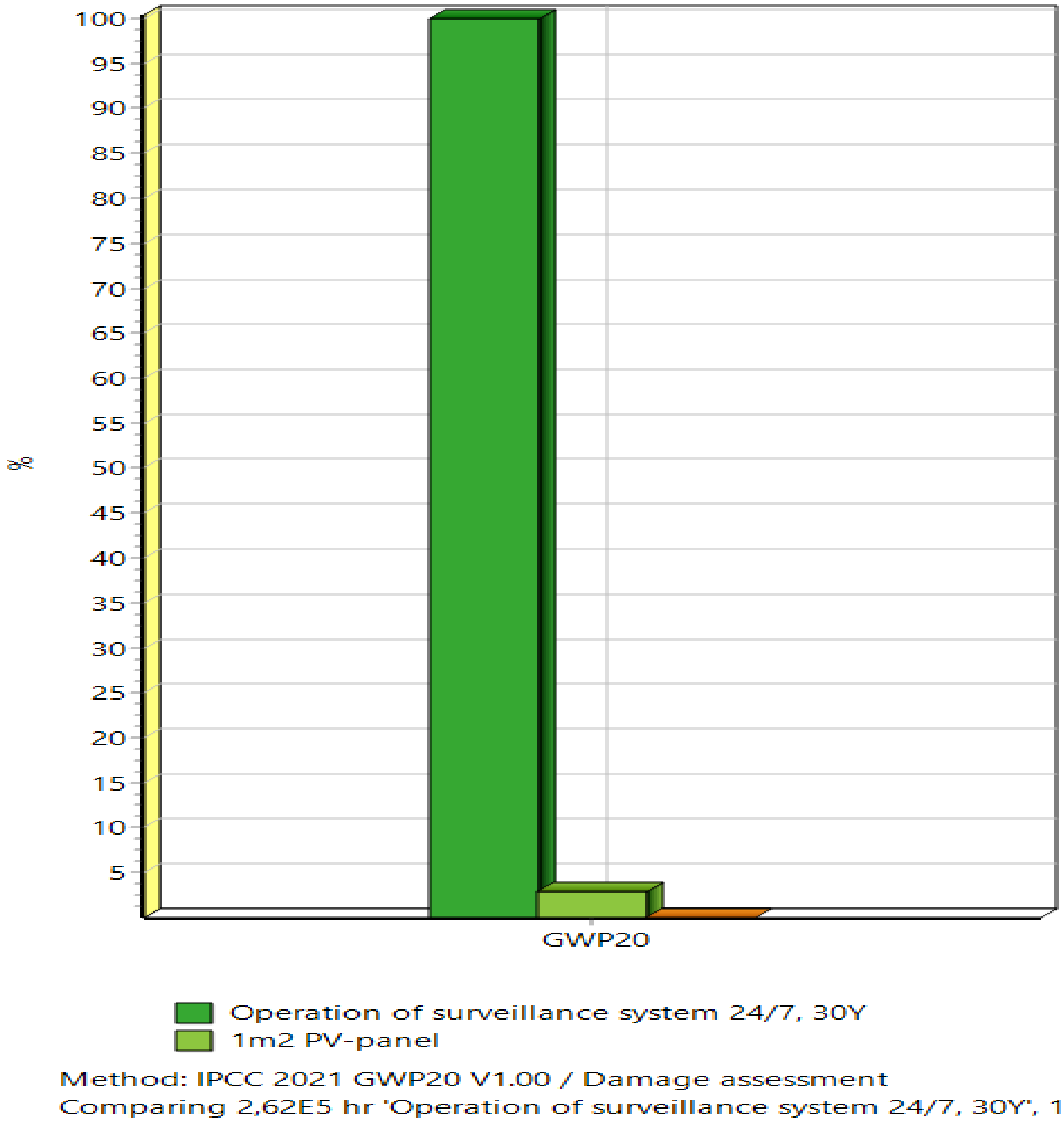

Figure 4 Emissions operation vs production.

Table 4 Overview, input LCA calculations.

CALCULATION:	**COMPARE**
RESULTS:	Impact assessment
PRODUCT 1:	262000 hr Operation of surveillance system 24/7, 30Y (from project Exam LCA (2))
PRODUCT 2:	1 m2 1m2 PV-panel (from project Exam LCA (2))
PRODUCT 3:	1 p Transport (from project Exam LCA (2)) (10tkm)
METHOD:	IPCC 2021 GWP20 V1.00
INDICATOR:	Damage assessment
CALCULATION:	Compare

Table 5 Damage overview.

Damage category	Unit	Operation of surveillance system 24/7, 30Y	1m2 PV-panel	Transport
GWP20	**kg CO2-eq**	2416,73994	71,4498716	0,09571227

Emissions of production of PV-panel, cut-off 4,5%

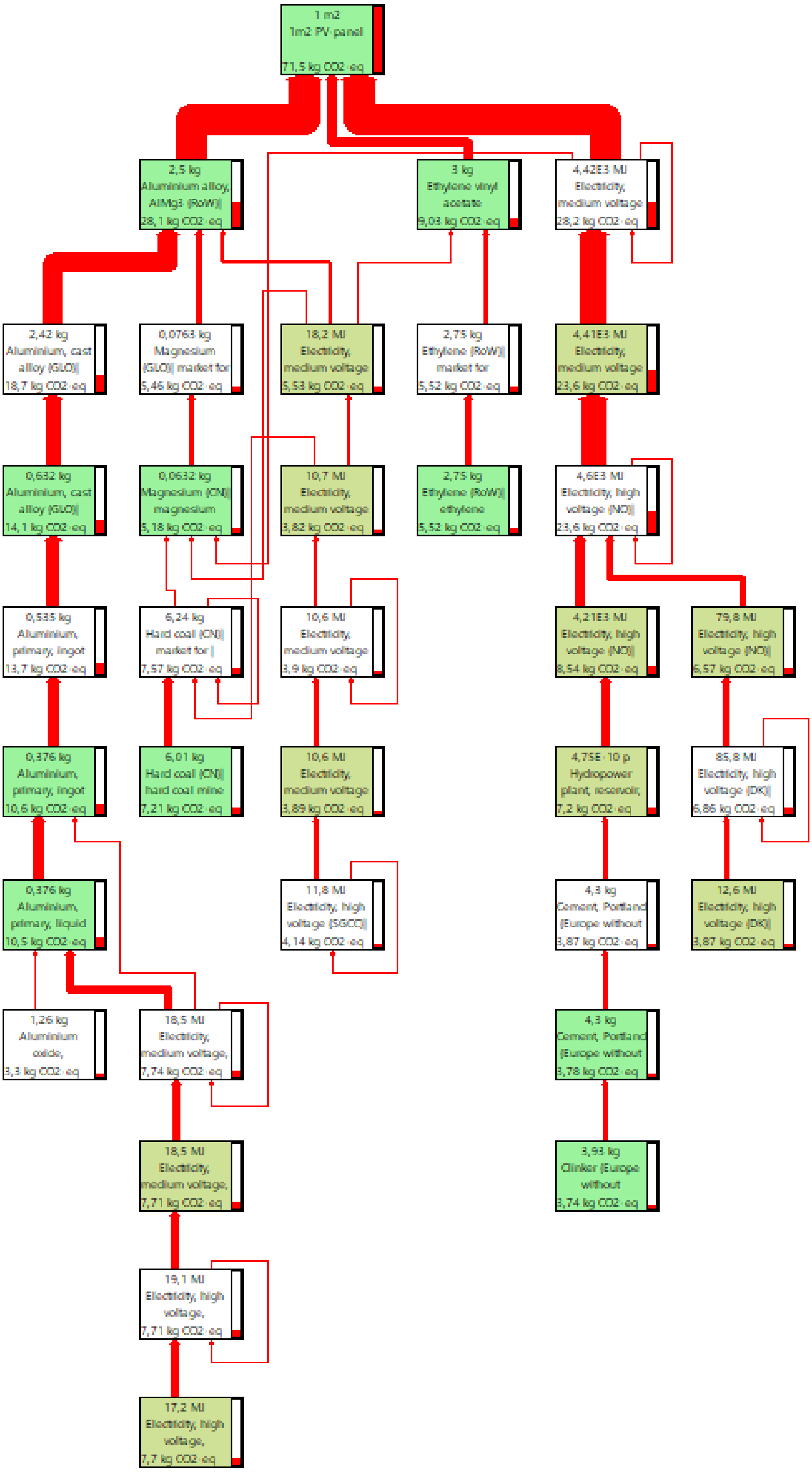

Figure 5 Emission allocation chart.

Health impact, midpoint

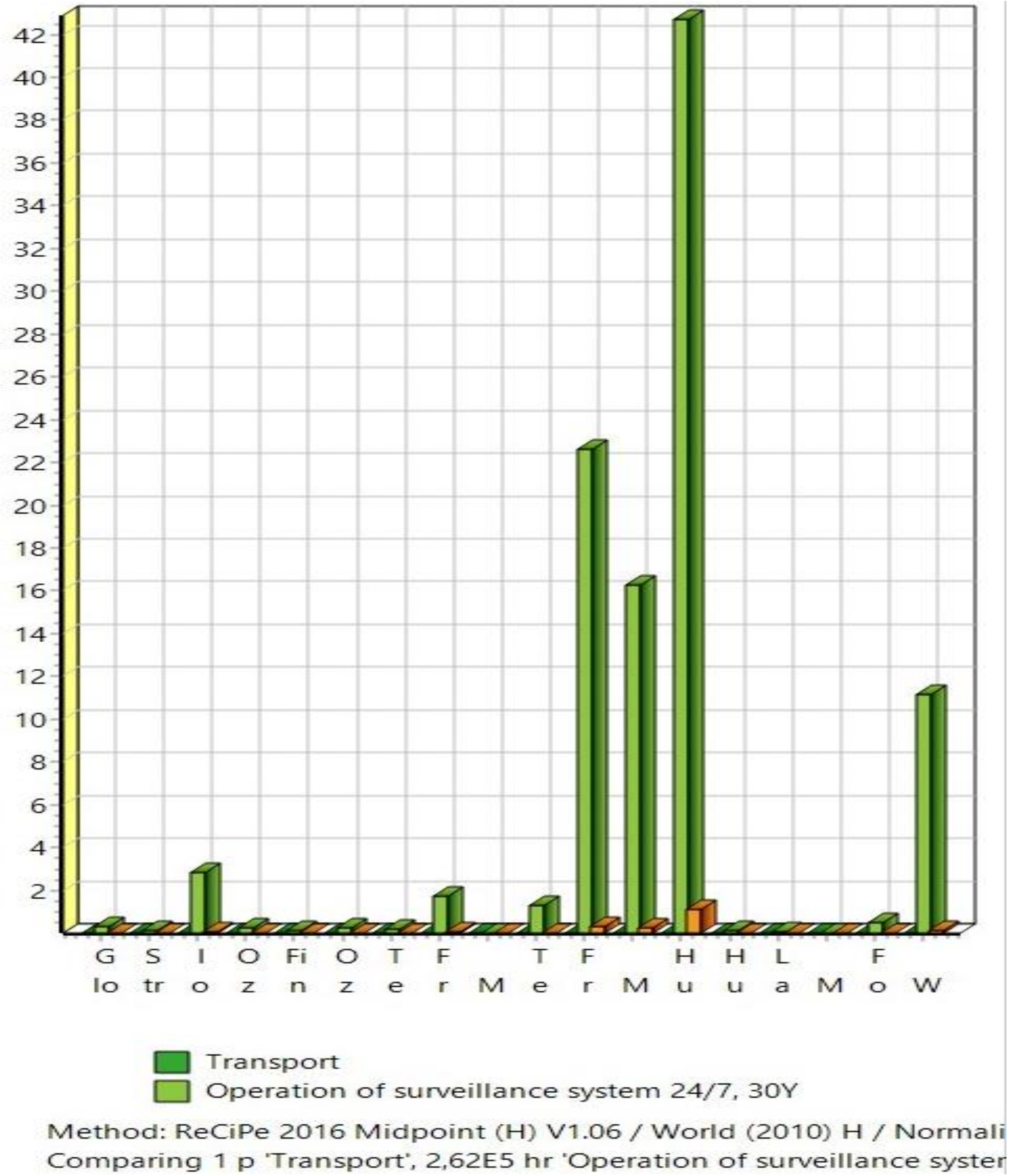

Figure 6 Health impact, midpoint. Transportations vs operation.

Table 6 Midpoint health impact results.

Impact category	Unit	Transport	Operation of surveillance system 24/7, 30Y	1m2 PV-panel
Global warming	kg CO2 eq	0,09372382	2322,52171	63,2595414
Stratospheric ozone depletion	kg CFC11 eq	6,5108E-08	0,00748364	0,00013657
Ionizing radiation	kBq Co-60 eq	0,00097183	1355,82899	17,8879262
Ozone formation, Human health	kg NOx eq	0,00194706	4,58145163	0,14776004
Fine particulate matter formation	kg PM2.5 eq	0,00062038	2,77813554	0,10561728
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,00196116	4,69097602	0,15400606
Terrestrial acidification	kg SO2 eq	0,00192997	6,56544242	0,22704691
Freshwater eutrophication	kg P eq	1,3413E-05	1,11260191	0,03028564
Marine eutrophication	kg N eq	3,1374E-07	0,09386599	0,00276149
Terrestrial ecotoxicity	kg 1,4-DCB	0,24626516	19943,8168	331,372261
Freshwater ecotoxicity	kg 1,4-DCB	0,00080145	570,421864	8,41986159
Marine ecotoxicity	kg 1,4-DCB	0,0012037	706,443717	10,6171657
Human carcinogenic toxicity	kg 1,4-DCB	0,00415245	439,898052	11,2079187
Human non-carcinogenic toxicity	kg 1,4-DCB	0,01334835	4338,84751	97,3466929
Land use	m2a crop eq	0,00129151	215,229782	3,71887603
Mineral resource scarcity	kg Cu eq	0,00018697	25,3452235	0,57514505
Fossil resource scarcity	kg oil eq	0,02756307	466,784528	18,8398626
Water consumption	m3	7,0671E-05	2975,60324	35,0928019

Health impact, endpoint

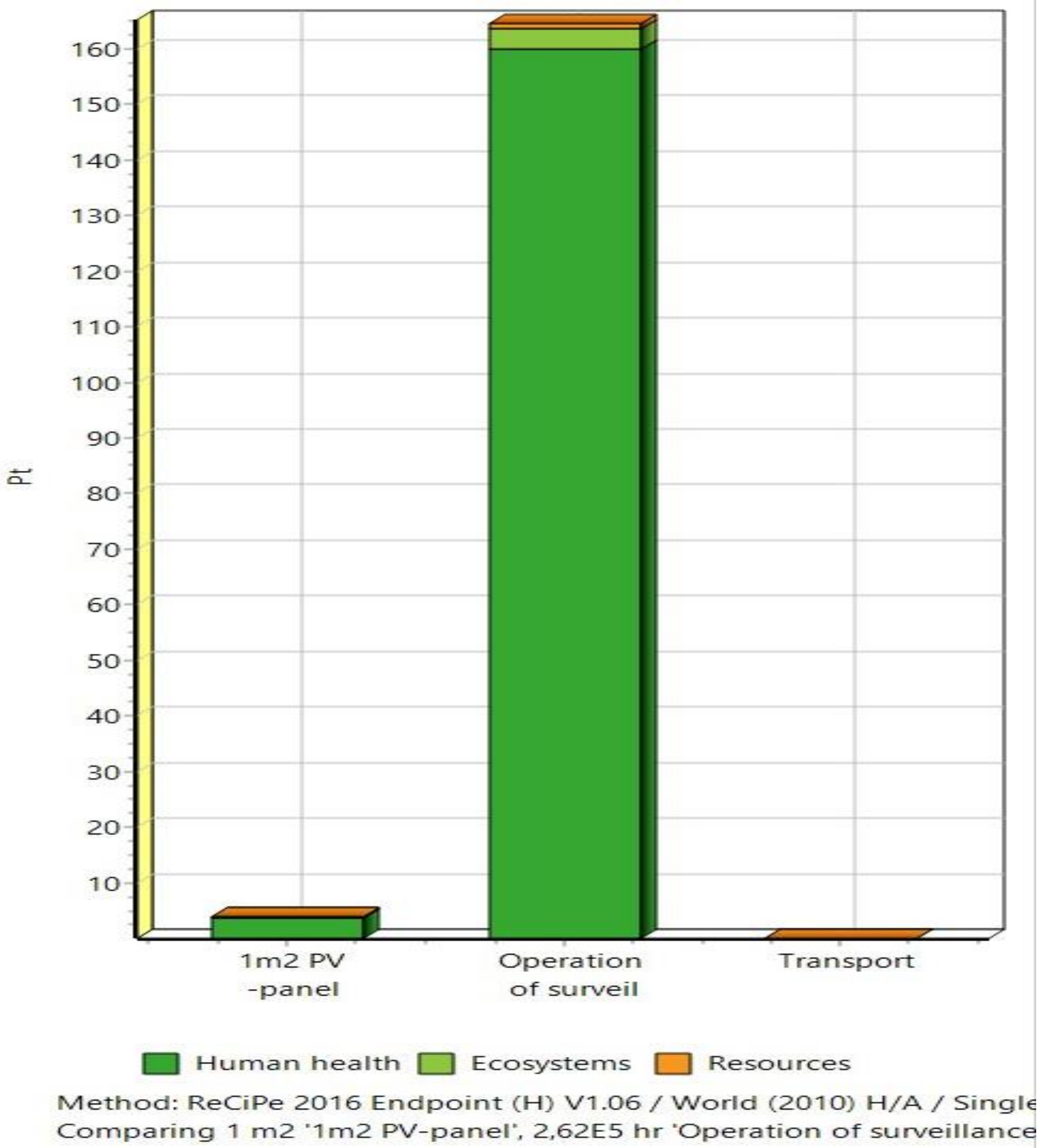

Figure 7 Health impact, endpoint. Productions vs operation vs transportation.

Table 7 Health impact, endpoint results.

Damage category	Unit	1m2 PV-panel	Operation of surveillance system 24/7, 30Y	Transport
Total	Pt	3,13837565	136,727795	0,00841635
Human health	Pt	3,01522123	132,340359	0,00807352
Ecosystems	Pt	0,0851759	3,49877165	0,00025583
Resources	Pt	0,03797852	0,88866437	8,7002E-05

7 Interpretation of LCA of PV-panel

In this chapter, the most crucial results associated to the various goals presented in the goal and scope is discussed. Possible sources of faults in the analysis are stated (1).

According to the findings in the global warming potential analysis, the aluminum smelting process contributes to a large amount of the GWP (figure 5) but is small compared to the emissions and health impact from the production of energy needed to operate system during its intended lifetime (figure 4,6,7 & table 4,5,6,7).

It is quite self-evident that the soundest solution to reduce overall emissions is to reduce the need for power to operate, either by reducing power draw, or to make sure the electricity comes from renewable sources. However, this can pose the threat of problem shifting, as even though we may get lower pollution locally, the mitigating technologies may be producing a net increase in emissions or, for instance, lower air quality at the production site.

The results concerning all the endpoint categories (figure 7, table 7) suggests that the production of the system is more destructive to the environment than the transport for assembly. Based on this, it’s interpreted that the aluminum production itself has the greatest process contribution. Seen under one, these processes make up a substantial part of the total, even if they are small-scale independently.

Transport represents a minor portion of GWP emission in this model and is almost negligible.

The yearly consumption of one system is 3504kWh and produces ~80 kg CO_2-eq in relation to GWP (based on Norwegian power-mix set @23g/kWh, adjusted with a linear ~0.5% decrease per year (25)). By making this assumption and adjusting, we secure that the calculation is more future proof by giving it some extra tolerance for progress. The processes of operation and production accounts for most of these emissions. The emissions related to transport for assembly of the system is negligible.

A basic calculation of 6 450W PV-panel producing 2700W for 30% of the time will cut the emissions related to production of power by 2128,7kWh/year (due to the ability to store overproduction in the power bank), reducing CO_2 eq. emissions by 48,96kg/year, meaning the emission related to production and transportation is making the PV-panels 1,7 times decreasing its initial impact during its lifetime. Since a Norwegian power-mix (with ~88% hydroelectric) (26), it is fair to assume that this figure will be even better in other regions.

During its 30-year lifetime the system it will potentially inhibit the emission of [1468,8 – (71,45*12)] = 611,4 kg CO_2-eq. The battery pack is excluded from this calculation as it is a system requirement to be installed regardless of its environmental impact. These calculations are quite conservative in nature, and even higher yields might be able in real world installations, but one should always make sub-optimal assumptions when scaling such installations.

It is also shown that a major contribution of emissions of the production of PV-panel comes from the sub-process of making aluminum, therefore this process should be performed with renewable energy if possible.

8 Economic analysis

Now that we have established that the PV-panels will not be environmentally disadvantageous for our system we need to perform an economic analysis for the different configurations of the system.

Table 8 Characteristics of configurations.

Characteristics	Lead-acid	Lithium-ion
Energy density (wh/L)	350Ah@12V/ (521x269x220mm) = **136**	100Ah@51,2V/(482x133x462) =**172**
Specific energy (Wh/kg)	4200Wh/70kg= **60**	5120Wh/44kg= **116**
Depth of discharge (nominal)*	**30-50%**	**80%**
Replacement timeframe (years, based on supplier guarantee)	1200cycles/ (365 cycles/year) = **~3,3years**	6000cycles/ (365 cycles/year) = **~16years**
Maintenance cost	YES**	NO
Battery cost (NOK/kWh)	6395kr/4,2kWh=**1522NOK**	26995kr/5,1kWh=**5293NOK**

** The way to define the number of cycles differ between the different battery technologies, as the lithium-ion based technology easily can handle several complete drains of the stored capacity, the lead-acid cannot do this repeatedly without taking mechanical damage over time (27).*

***Due to the more frequent change.*

This section considers the economic evaluation of a photovoltaic system. This evaluation consists of two cases, or configurations, of the system:

1) System with lead-acid battery (28)
2) System with lithium-ion battery (29)

The following assumptions was made for the inputs in the calculations:

a) The yield of the photovoltaic panel is 450W (six panels in system, as requirement is 800W@30% of system max yield)
b) The average interest rate of a solar loan is 4,925% *(15.may 2023)*, see *table 10* for collected data. Data is for collateral loans, specifically for PV-systems.
c) The performance of the PV-panel decreases linearly by <1% annually, so this depreciating phenomenon is neglected.
d) The cost of maintenance is total forecasted cost spread to equal annual payments.
e) The lifetime of the inverter (30) is assumed to be 16 years (31) (same as Li-Ion battery (30)), thus needing 1 replacement during the lifetime (30 years) of the system. No specific data was found from this vendor, but generally since we are installing less than the maximum capacity, we should expect there to be less strain on the equipment, thus making it last longer.
f) The lead acid batteries are not to surpass 30% DOD to maximize the cyclic lifetime (33). 4 Batteries is installed, both to accommodate this requirement, and to have the required charging voltage >48V.

g) The Lead-acid batteries will need replacement 9 times during the systems lifetime, as this is a safety critical installation.
h) The most reasonably priced options were chosen based on a rational judgement.
i) The system will operate 24/7, with assumed constant average power consumption.
j) It is assumed inflation and drop in price of the technology in question will cancel each other out.
k) The hourly rate for the installation and maintenance is 750kr for low price scenario, and 1000kr for high price scenario (34).
l) The system is to fully utilize the stored energy potential every night.

Table 9 Interest rates (35,36).

Bank	**Interest rate %**
Sparebank1	4,71
DNB	5,14
Average	4,925

8.1 Battery

To choose the most suitable battery we need to investigate several factors:

- The price (per kWh)
- The lifespan (number of use-cycles)
- Maintenance requirements
- The capacity

For this comparison two batteries offered from the same store, at the same time, have been chose to make the prices comparable.

8.1.1 Lithium

Table 10 Lifetime budget, system with lithium battery, (Not NPV adjusted).

Item/service	**Amount**	**Price per unit**	**Sum**
PV-panel	6	2995	17970
Hybrid inverter, int. install	1	22 950	22 950
Lithium Ion battery, initial price	1	26 995	26995
Labor hours, int. install of whole system	80	750	60000
Total initial system	-	-	**127 915**
Labor, maintenance	20	750	15 000
Lithium-Ion battery, replacement	1	26 995	26 995
Hybrid inverter, replacement	1	22 950	22 950
SUM	-	-	**192 860**
Component cost	-	-	117 860
Labor cost	-	-	75 000

Pros:

- Lightweight
- Can discharge up to 80% of stored capacity without taking damage.
- Virtually maintenance-free
- Long lasting, >10 years

Cons:

- Is flammable.
- Not permitted for most aeronautical applications
- More expensive but prices are dropping due increased demand in e.g., electric vehicles.

8.1.2 Lead-acid

Table 11 Lifetime budget, system with lead-acid battery, (Not NPV adjusted).

Item/service	**Amount**	**Price per unit**	**Sum**
PV-panel	6	2995	17970
Hybrid inverter, int. install	1	22 950	22 950
Lead-acid battery, int. install	4	6 395	25580
Labor hours, int. install of whole system	80	750	60000
Total initial system	-	-	**126 500**
Labor, maintenance	100	750	75 000
Lithium-Ion battery, replacement	36	6 395	230 220
Hybrid inverter, replacement	1	22 950	22 950
SUM	-	-	**454 670**
Component cost	-	-	319 670
Labor cost	-	-	135 000

8.4 Net present value (NPV)

The six panels combined have a theoretical yield 2700W@12m^2. The average solar radiation will be 300kWh per m^2 annually for this calculation (19). This setup will thus produce 3600kWh annually for this calculation. *Please note the discrepancy between this number and the number used for the LCIA of the PV panel.*

These assumptions are made:

- The investment cost in year 0 is:
  - C0_lithium = 127915kr
  - C0_lead = 126500kr
- The asset will have a linear annual value depreciation of 10% for the first 10 years.
- The technical lifetime is 30 years.
- The maintenance will be calculated as a yearly average since we cannot predict with full certainty when the components will fail. The annual fixed maintenance cost will be:
  - Maint_fixed_lithium= 2165kr
  - maint_fixed_lead=10939kr

- The interest rate is fixed at 4,925%
- For this scenario we assume the average electricity price to be 1,50kr/kWh for the next 30 years. There is one annual term for the billing of electricity.

Net present value is calculated form the following equation (37):

$$NPV = \frac{M}{(1+r)^t}$$

8.5 NPV of total electricity

Total cost if bought from grid:

```
t=30 #years
kWh=0.4 #power_consuption
hours=(24*365.25) #annual_operat
cost=1.5 #electricity
M=(kWh*hours*cost) #annual_grid_
r=0.04925 #interest_rate
summation=0
for i in range(1, t+1):
    summation+=M/(1+r)**i
NPV_grid_cost=summation
print(NPV_grid_cost)
```

```
81548.80572210703
```

Value of produced electricity from PV-panels:

```
t=30 #years
kWh=3600 #annual_power_production
cost=1.5 #electricity
M=(kWh*cost) #annual_cost_if_bought_from
r=0.04925 #interest_rate
summation=0
for i in range(1, t+1):
    summation+=M/(1+r)**i
NPV_production=summation
print(NPV_production)
```

```
83725.6732259826
```

8.6 NPV of total maintenance cost

Lithium, high hour rate:

```
t=30 #years
M=2332 #Maint_fixed_lithium
r=0.04925
summation=0
for i in range(1, t+1):
    summation+=M/(1+r)**i
maint_cost=summation
print(maint_cost)
```

```
36157.08703018359
```

Lead, high hour rate:

```
t=30 #years
M=11772 #Maint_fixed_lead
r=0.04925
summation=0
for i in range(1, t+1):
    summation+=M/(1+r)**i
maint_cost=summation
print(maint_cost)
```

```
182521.96763264207
```

Lithium, low hour rate:

```
t=30 #years
M=2165 #Maint_fixed_lithium
r=0.04925
summation=0
for i in range(1, t+1):
    summation+=M/(1+r)**i
maint_cost=summation
print(maint_cost)
```

```
33567.793061898585
```

Lead, low hour rate:

```
t=30 #years
M=10939 #Maint_fixed_lead
r=0.04925
summation=0
for i in range(1, t+1):
    summation+=M/(1+r)**i
maint_cost=summation
print(maint_cost)
```

```
169606.50729981918
```

8.7 NPV total expenses

Lithium, high hour rate:

```
maint_cost_lithium=36157
C0_lithium=147915 #investment_year_0
NPV_cost_lithium=(maint_cost_lithium+C0_lithium)
print(NPV_cost_lithium)
```

```
184072
```

Lithium, low hour rate:

```
maint_cost_lithium=33568
C0_lithium=127915 #investment_year_0
NPV_cost_lithium=(maint_cost_lithium+C0_lithium)
print(NPV_cost_lithium)
```

```
161483
```

Lead, high hour rate:

```
maint_cost_lead=182522
C0_lead=146500 #investment_year_0
NPV_cost_lead=(maint_cost_lead+C0_lead)
print(NPV_cost_lead)
```

```
329022
```

Lead, low hour rate:

```
maint_cost_lead=169607
C0_lead=126500 #investment_year_0
NPV_cost_lead=(maint_cost_lead+C0_lead)
print(NPV_cost_lead)
```

```
296107
```

8.8 NPV of cost of electricity from PV-panels

Lithium, high hour rate:

```
NPV_PV_cost_lithium=NPV_cost_lithium/(30*3600) #years*annual_production
print(NPV_PV_cost_lithium)
```

```
1.7043703703703703
```

Lithium, low hour rate:

```
NPV_PV_cost_lithium=NPV_cost_lithium/(30*3600) #years*annual_production
print(NPV_PV_cost_lithium)
```

```
1.495212962962963
```

Lead, high hour rate:

```
NPV_PV_cost_lead=NPV_cost_lead/(30*3600) #years*annual_production
print(NPV_PV_cost_lead)
```

```
3.0465
```

Lead, low hour rate:

```
NPV_PV_cost_lead=NPV_cost_lead/(30*3600) #years*annual_production
print(NPV_PV_cost_lead)
```

```
2.7417314814814815
```

8.9 Benefit cost

Lithium, high hour rate:

```
cost_benefit_lithium=NPV_cost_lithium-NPV_grid_cost
print(cost_benefit_lithium)
```

```
102523.19427789297
```

Lithium, low hour rate:

```
cost_benefit_lithium=NPV_cost_lithium-NPV_grid_cost
print(cost_benefit_lithium)
```

```
79934.19427789297
```

Lead, high hour rate:

```
cost_benefit_lead=NPV_cost_lead-NPV_grid_cost
print(cost_benefit_lead)
```

```
247473.19427789297
```

Lead, low hour rate:

```
cost_benefit_lead=NPV_cost_lead-NPV_grid_cost
print(cost_benefit_lead)
```

```
214558.19427789297
```

8.10 Combined results

Table 12 Combined results economic calculations.

Parameter	**Li-Ion**		**Lead-acid**	
Hourly rate	**1000**	**750**	**1000**	**750**
Initial investment cost	147 915	127 915	146 500	126 500
Total investment cost/ Life cycle cost	217 860	192 860	499 670	454 670
Life cycle benefit	184072	161483	329022	296107
Benefit cost	102523	79934	247473	214558
Net present value of electricity	1,70	1,495	3,04	2,74
Benefit cost ratio electricity	+13,3%	-0,33%	+102,7%	+82,7%

9 Conclusion

First the system parameters and configurations were defined, and the customer requirements were translated to system requirements. Based on these three system configurations were chosen for further inquiry.

It has been shown via the LCA analysis that the PV-panel is a sustainable alternate power source, even here in Norway, where the electricity-mix is more emission free than many other places in the world. Since the implementation a battery-based power storage system was a requirement a separate LCA have not been performed in this paper, but several studies have found batteries to be able to be sustainable or neutral (7,8,9). The more important questions were whether the implementation of a PV-panel was an economic sound investment (ignoring the redundancy-factor for this question) and which battery technology to choose.

Despite having av slight advantage in the initial investment cost, the lead-acid batteries are outclassed by the lithium battery in both labor-cost scenarios, even for the newer generations of. Since the lead acid batteries requires more frequent maintenance it can be a fair assumption to claim that the lithium batteries are more cost effective, reliable, and dependable. The lead-acid batteries are close to twice as expensive during the lifetime of the system when factoring in the component cost and service labor. The hour rate of labor is somewhat difficult to predict so far into the future, so one should elaborate on this and make a more advanced scenario model, as this is a substantial part of the lifetime cost. It must also be pointed out, yet again, that this is a quite narrow extract of data, and for example the pricing is from one vendor only.

For this scenario the system configuration with PV-panels and lithium batteries it has been shown that the system is both economically and environmentally beneficial to install for the system in question, based on a labor cost of 750kr/h and the interest rate 4,925%. Even though the economic and environmental impact may be marginal, the increase in self-sustainment and reliability may be bore important for the end user. This setup also enables such systems to be implemented in places without reliable grid power connection, this expanding the potential business case. An opportunity to sell aftermarket services is also presenting itself and should also be investigated.

Bibliography

1. Soares, W.M.; Athayde, D.D.; Nunes, E.H.M. (2018) LCA study of photovoltaic systems based on different technologies [Internet]. International Journal of Green Energy, 15:10, 577-583 [Cited May 21, 2023]. Available from: DOI: 10.1080/15435075.2018.1510408
2. Larsen, D. Life Cycle Assessment Report Project. [Course Exam] NTNU, TEK2002 EcoDesign; 25.11.2022. Available from: Inspera Asessment.
3. International Organization for Standardization (ISO) / Standard Norge (NS). NS-EN ISO 14040:2006. [Internet] Oslo: Standard Norge; 2006-09-01 [Cited May 21, 2023]. Available from: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=236802
4. International Organization for Standardization (ISO) / Standard Norge (NS). NS-EN ISO 14044:2006. [Internet] Oslo, Standard Norge, 2006-09-01 [Cited May 21, 2023]. Available from: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=236803
5. Kleven, H. KONGSBERG PTP [Internet]. Kongsberg, Kongsberg Defence and Aerospace; 2023. [Cited May 21, 2023]. Available from: https://www.kongsberg.com/kda/what-we-do/defence-and-security/aviation-security/remote-and-digital-towers/pan-tilt-platform/
6. Shinefar Solar. SF-M16/144 PV-panel specification [Internet]. [Cited May 21, 2023]. Available from: https://www.sparelys.no/pub/media/content/pdf/M16144%28430W-460W%29en-web.pdf
7. Sadhukhan, J.; Christensen, M. An In-Depth Life Cycle Assessment (LCA) of Lithium-Ion Battery for Climate Impact Mitigation Strategies [Internet]. Energies 2021, 14, 5555. [Cited May 21, 2023]. Available from: https://doi.org/ 10.3390/en14175555
8. Porzio, J.; Scown, C. D. Life-Cycle Assessment Considerations for Batteries and Battery Materials [Internet]. Advance Energy Materials Volume 11, Issue 33; First published July 14. 2021 [Cited May 21, 2023]. Available from: https://doi.org/10.1002/aenm.202100771
9. Yudhistira, R; Khatiwada, D; Sanchez, F. A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage [Internet]. Journal of Cleaner Production Volume 358, 15 July 2022, 131999 [Cited May 21, 2023]. Available from: https://doi.org/10.1016/j.jclepro.2022.131999
10. Kebede, A. A.; Coosemans, T.; Messagie, M.; Jemal, T.; Behabtu, H. A.; Mierlo, J. V.; Berecibar, M. Techno-economic analysis of lithium-ion and lead-acid batteries in stationary energy storage application [Internet]. Journal of Energy Storage Volume 40, August 2021, 102748 [Cited May 21, 2023]. Available from: https://doi.org/10.1016/j.est.2021.102748
11. Anuphappharadorn, S.; Sukchai, S.; Sirisamphanwong, C; Ketjoy, N. Comparison the economic analysis of the battery between lithium-ion and lead-acid in PV stand-alone application [Internet]. Energy Procedia Volume 56, 2014, Pages 352-358 [Cited May 21, 2023]. Available from: https://doi.org/10.1016/j.egypro.2014.07.167
12. Lausselet, C.; Lund, K.M.; Brattebø, H. LCA and scenario analysis of a Norwegian net-zero GHG emission neighbourhood: The importance of mobility and surplus energy from PV technologies [Internet]. Building and Environment Volume 171 15 March 2020 [Cited May 21, 2023]. Available from: DOI: 10.1016/j.buildenv.2020.107528
13. Ellen Bracquene, Jef R. Peeters, Wim Dewulf, Joost R. Duflou, Taking Evolution into Account in a Parametric LCA Model for PV Panels [Internet]. Procedia CIRP Volume

69, 2018, Pages 389-394 [Cited May 21, 2023]. Available from: https://doi.org/10.1016/j.procir.2017.11.103
14. Various authors, PRé Sustainability. SimaPro database manual Methods library [Internet]. The Netherlands, SimaPro; 2020 [Cited May 21, 2023]. Available from: https://simapro.com/wp-content/uploads/2020/10/DatabaseManualMethods.pdf
15. Powerhouse. Powerhouse Telemark [Internet]. Norway. [Cited May 21, 2023]. Available from: https://www.powerhouse.no/prosjekter/powerhouse-telemark/
16. Sawe, B.E. Which Country Produces The Most Silicon? [Internet]. Environment; August 1. 2017. [Cited May 21, 2023]. Available from: https://www.worldatlas.com/articles/which-country-produces-the-most-silicon.html
17. IPCC adaptation report. A damning indictment of failed global leadership on climate [Internet]. United Nations; 28 February 2022 [Cited May 21, 2023]. Available from: https://news.un.org/en/story/2022/02/1112852
18. Kleven, H. KONGSBERG REMOTE TOWERS [Internet]. Kongsberg, Kongsberg Defence and Aerospace; 2023. [Cited May 21, 2023] Available from: https://www.kongsberg.com/kda/what-we-do/defence-and-security/aviation-security/remote-and-digital-towers/
19. Norsk solenergiforening. Norske solforhold [Internet]. Odal, Norway [Cited May 21, 2023]. Available from: https://www.solenergi.no/hvorfor-solenergi
20. TrioWeb AS. SF-M16/144 PV-panel product page [Internet]. Åsheim, Norway [Cited May 21, 2023] Available from: https://www.sparelys.no/solcellepanel-450watt-all-black-mono
21. International Energy Agency. Mineral requirements for clean energy transitions [Internet]. IEA, Paris; 2021 [Cited May 21, 2023]. Available from: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions
22. LePan, N. Rare Earth Elements: Where in the World Are They? [Internet]. Elements; November 22, 2021 [Cited May 21, 2023]. Available from: https://elements.visualcapitalist.com/rare-earth-elements-where-in-the-world-are-they/
23. American Chemical Society National Historic Chemical Landmarks. Chlorofluorocarbons and Ozone Depletion [Internet]. University of California, Irvine; April 18. 2017 [Cited May 21, 2023]. Available from: http://www.acs.org/content/acs/en/education/whatischemistry/landmarks/cfcs-ozone.html
24. Goedkoop, M.J.; Heijungs, R.; Huijbregts, M.A.J.; De Schryver, A.M.; Struijs, J.; Van Zelm, R. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation [Internet]. National Institute for Public Health and the Environment, The Neterlands; 11/02/2018 [Cited May 21, 2023]. Available from: http://www.lcia-recipe.net.
25. Nowtricity. CO2 emissions per kWh in Norway [Internet]. [Cited May 20, 2023] Available from: https://www.nowtricity.com/country/norway/
26. Energy Facts. Electricity Production. [Internet] Norwegian Ministry of Petroleum and Energy; May 11. 2021 [Cited May 21, 2023]. Available from: https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/
27. Power Sonic corporation. The complete guide to Lithium vs Lead acid batteries [Internet]. Nevada, USA; 2023 [Cited May 21, 2023]. Available from: https://www.power-sonic.com/blog/lithium-vs-lead-acid-batteries/
28. TrioWeb AS. AGM SOLAR 250 product page [Internet]. Åsheim, Norway [Cited May 21, 2023]. Available from: https://www.sparelys.no/agm-batteri-350-agm-solar-12v#tab-1

29. TrioWeb AS. Telecom LiFePO4B battery product page [Internet]. Åsheim, Norway [Cited May 21, 2023]. Available from: https://www.sparelys.no/lithium-batteri-lifepo4-48v-5-1kwh-rack
30. TrioWeb AS. Solis S5-EH1P-L Hybrid Inverter product page [Internet]. Åsheim, Norway [Cited May 21, 2023]. Available from: https://www.sparelys.no/solis-1-fase-hybrid-3600-for-batterilagring-s5-eh13p-6k-l-1f-maler
31. Ginlong Technologies Co., Ltd. Solis S5-EH1P-L Hybrid Inverter manual [Internet]. Zhejiang, 315712, P.R.China [Cited May 21, 2023]. Available from: https://www.sparelys.no/pub/media/content/pdf/Solis/Solis_Manual_S5_EH1P3-6K-L_ENX_V1.pdf
32. Haicen company. Telecom LiFePO4B battery specification [Internet]. [Cited May 21, 2023]. Available from: https://www.sparelys.no/media/content/pdf/Haichen/HC-48100-Usersmanual-datasheet.pdf
33. TWb. AGM SOLAR 250 specification [Internet]. [Cited May 21, 2023]. Available from: https://www.sparelys.no/media/content/pdf/Agmsolar350.pdf
34. Vestvik, H. Hva koster en håndtverker? [Internet]. Stavanger, Norway: Kallesten Revisjon og Regnskap AS. [Cited May 21, 2023] Available from: https://www.kallesten.no/aktuelt/hva-koster-en-h%C3%A5ndverker-
35. SpareBank 1 Sørøst-Norge. Grønt lån til energitiltak [Internet]. Sandefjord, Norway. [Cited May 21, 2023]. Available from: https://www.sparebank1.no/nb/sorost/privat/lan/boliglan/gront-lan-til-energitiltak.html
36. DNB Bank ASA/Fjordkraft. Grønt lån fra DNB [Internet]. Bergen, Norway. [Cited May 21, 2023]. Available from: https://www.fjordkraft.no/solcellepanel/gront-lan/
37. Fernanado, J. Net Present Value (NPV): What It Means and Steps to Calculate It [Internet]. New York, USA; April 05, 2023 [Cited May 21, 2023]. Available from: https://www.investopedia.com/terms/n/npv.asp

NTNU
Kunnskap for en bedre verden