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LCA of Off-Grid Energy Systems in the Nordics

Department of Mechanical and Materials Engineering
Bachelor's thesis

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22.5.2025
Turku

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Subject: Mechanical Engineering
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Title: LCA of Off-Grid Energy Systems in the Nordics
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Number of pages: 28 pages
Date: 22.5.2025

As the demand for sustainable energy grows, off-grid systems have become a promising alternative to traditional grid-based energy systems, especially in remote and rural areas. This study evaluates greenhouse gas emissions of off-grid energy generation through life cycle assessment (LCA) studies, comparing them to traditional grid electricity in the Nordics. Off-grid energy systems can significantly reduce emissions as compared to fossil-fuel-based electricity production but may struggle to provide meaningful benefit in the Nordics. The emissions of off-grid systems depend highly on system design, components, and energy storage choices. Especially battery manufacturing and replacements constitute one of the biggest shares in greenhouse gas emissions. The study discusses that while off-grid systems can provide clear energy independence and sustainability advantages, careful consideration and planning are essential for long-term benefits.

Key words: Life cycle assessment, off-grid, emissions, sustainability, Nordics, green energy

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1 Introduction

Sustainably produced and affordable energy is one of the most critical challenges of our time. As global energy consumption continues to rise, the environmental impact of fossil fuels-based energy has become more apparent. In efforts to reduce the environmental impact of energy conversion, sustainability assessment tools such as life cycle assessment (LCA) have become valuable tools in evaluating the environmental sustainability of different energy systems. LCA is commonly used as it enables a detailed look into an energy system's emissions during its life cycle. By examining energy systems using LCA, we can pinpoint different hotspots in energy generation, which helps us avoid or prefer different products in the system to reduce emissions.

The main goal of this thesis is to examine off-grid energy systems with the use of LCA and compare them to the grid electricity in the Nordics in the context of sustainability. The comparison between the two brings out interesting points, as while off-grid systems are considered sustainable, how will they compare to the grids of Nordic countries where the energy mixes are some of the most sustainable in the world? Common off-grid energy generation methods, energy storage, and optimization are also examined, as they create the basis for an off-grid system and play a key role in its sustainability.

The motivation for this thesis comes from the growing interest in off-grid systems and sustainable energy systems as a whole, as well as the importance of comparing off-grid and grid electricity. As grid electricity constantly becomes more sustainable, understanding the differences and trade-offs in different energy systems is becoming increasingly important.

2 Background and Theory

2.1 Life cycle assessment

Life cycle assessment is a sustainability assessment tool used to determine the sustainability of a product, business, or service. LCAs can be used to measure multiple different environmental and also social issues. The impacts include climate change, freshwater use, toxic impacts on human health, depletion of non-renewable resources and, eco-toxic effects.[1] There are many different LCA standards and, for example, ISO standards are used in LCAs as they function as a framework to provide regulations and guidelines for the LCA. Standards are vital as they allow a fair comparison of data between different systems. ISO standards related to LCA are ISO 14040 & ISO 14044. ISO 14040 focuses on the principles and the framework of LCA, and ISO 14044 focuses on the requirements and guidelines. Following these standards plays a key role in conducting a successful and credible LCA.

LCA results are related to functional units that present the relevant information. A functional unit is a quantified measure of the function of a product or system. For example, when examining greenhouse gas (GHG) emissions in energy generation, the functional unit can be defined as kWh. Choosing a correct functional unit is important to perform a meaningful LCA.

LCAs are conducted by first determining the goal and scope of the LCA. In the goal, the functional unit is defined, and the scope defined the boundaries of which activities and processes are to be included in the product’s life cycle. The goal also aims to answer questions such as: “Why is this study performed? Which question(s) is it intended to answer and for whom is it performed?”.[1] The scope in LCA plays a key role when examining a system or a product as the outcome of the LCA may vary significantly depending on the system boundaries. When defining the scope, it is important to note that some products may have major environmental concerns in their end-of-life disposal.[1]

Life cycle inventory or LCI is one of the main phases of LCA as it involves the collection of all inputs and outputs during a product or a system’s life cycle. Inputs are considered as, for example, used materials and energy, whereas outputs are, for example, emissions and waste. ISO standard 14067 provides materials-specific information about the carbon emissions caused by different materials and products, which is essential for a credible LCI.[1] Figure 1 shows the key stages in a product's life cycle from where these inputs and outputs are identified.

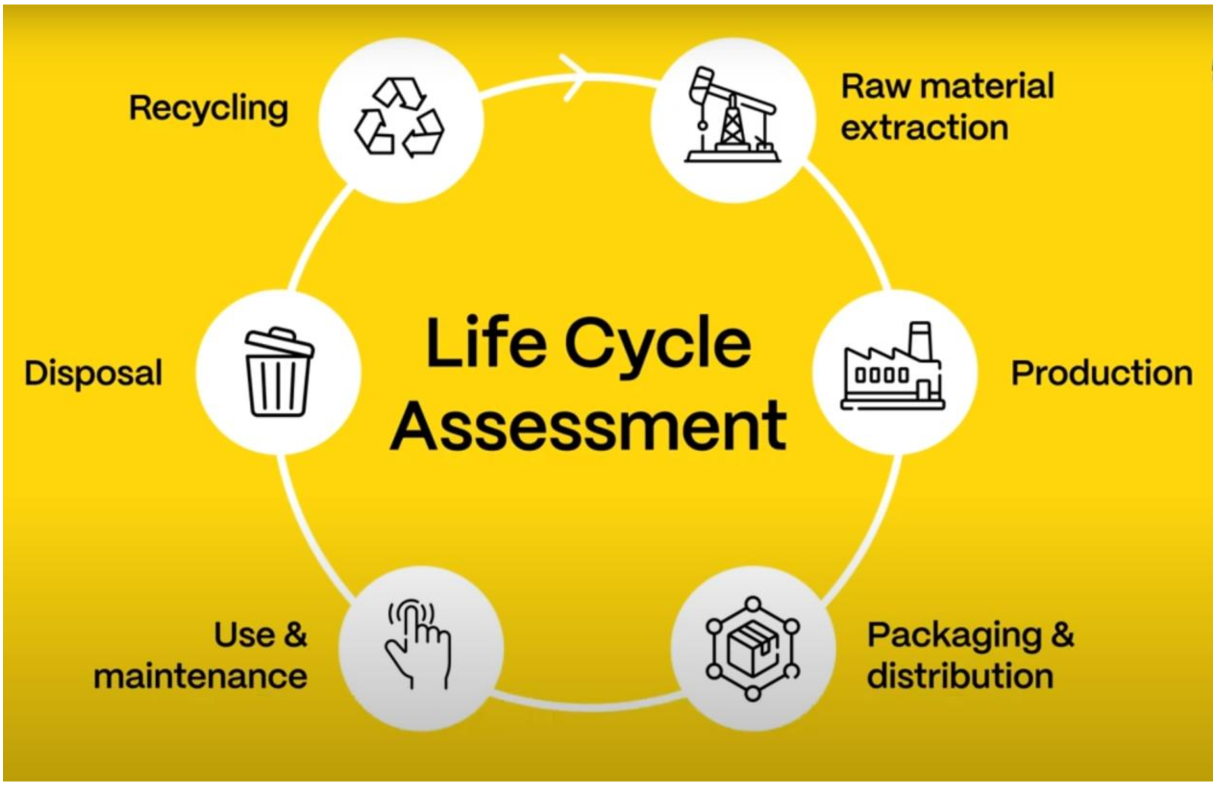

Figure 1: Stages of a product's lifecycle[2]

Life cycle impact assessment, or LCIA, is the final analytical phase of an LCA. In LCIA, the data gathered from the LCI is evaluated and translated into environmental impact categories such as climate change or human health. LCIA is the key stage in LCA, where the environmental significance is examined. The final stage of the LCA is interpretation, which involves examining results, drawing conclusions, and making decisions based on the results of the LCA. Interpretation is crucial as LCAs can produce complex results with a large amount of data. Without proper interpretation, the results may be misleading or incomplete.[1]

2.2 Challenges and limitations of LCA

Challenges of life cycle assessment arise from uncertainties in defining the scope and secondary data. While there are tools used to calculate for example emissions in LCA, the data can vary depending on the tool used as data may be outdated or calculated differently. There can also be major differences in LCAs covering similar products, if the system boundaries and related processes have been defined and selected in different ways. For example, different LCAs may include or exclude emissions from packaging and transport or may have differences in the life cycle stages. The outcome of the LCA may change drastically if the scope of the LCA includes end-of-life disposal. LCA databases such as Ecoinvent[3] provide estimates for emissions created by materials and processes globally, but due to regional differences in production methods, energy sources and regulations, the actual results will vary when realized in different countries. The use of functional units can also create challenges, as there are multiple ways to measure a product’s environmental impact, which can make comparisons between LCAs difficult. Even though LCAs are standardized, they can still produce different results. To get accurate and meaningful conclusions, it is important to know how to interpret data and to take a closer look at the LCA in question.[1]

2.3 Importance and application of LCA

There are many motivations for performing LCAs. One motivation behind LCAs is for businesses and institutions to make more sustainable decisions based on science. Comparison of different solutions or products with LCAs enables a closer examination of the environmental impact. Using sustainability assessment tools such as life cycle assessment, we can pinpoint the so-called hotspots that create the highest impact on the environment in various life cycle stages. Identifying these different hotspots is necessary as they lead to a closer examination and thus to solving the issue. LCA is a valuable tool that offers a way to draw conclusions from scientific data and present it to stakeholders such as investors and regulators.[1]

2.4 Basics of energy systems

Energy systems are the foundation of our society as they enable our modern world to function. Energy is a necessity outlined in the United Nations' sustainability goals, highlighting the need for clean and affordable electricity for everyone.[4] Different energy systems produce and sell electricity to users using the electricity network. Energy systems are, for example, coal & nuclear power plants, biomass plants, wind farms, and photovoltaic power stations.

2.5 Energy storage and distribution

Energy storage systems are necessary when surplus energy is generated, or one wants to store energy for future use. In the grid, energy is not typically stored, as the electricity generated is consumed almost immediately. Energy storage plays a key role in off-grid systems if they rely on variable renewable energy like wind and photovoltaic power. Common forms of energy storage are rechargeable batteries and hydroelectric dams. Other means of energy storage include, for example, hydrogen, methanol, compressed air, and thermal energy storage.

2.6 Global energy-based emissions

Energy sources are one of the primary sources of pollution in the world due to the increasing demand for new technologies and the growing population. In 2023, the total emissions produced by primary energy production were over 40 gigatonnes, which accounted for 87% of the world's greenhouse gas emissions. China is producing and consuming primary energy more than any other countries, as it produced 196 exajoules (EJ) while generating 21.1 gigatonnes, accounting for more than half of the world's energy emissions. In 2023, China's energy mix comprised 55.2% coal, 14.2% oil, 14.1% hydropower, 8.8% natural gas, 5.4% renewables and 2.3% nuclear. China's coal consumption added up to 56% of the global consumption. Thus, it accounted for 35% of global energy consumption, remaining the world's dominant power source. While renewable energy generation is growing fast, fossil fuels still dominate as the primary energy source. Even though goals and targets have been set and different countries have started to act upon the emissions caused by energy production, it will take a long time to phase out fossil fuels as the primary energy source.[5]

Table 1 shows the drastic difference in emissions generated between renewable and fossil fuel-based electricity and the high variability of emissions in the sources.

Table 1: CO2e emissions for different energy sources[6]

Energy type	CO2e [kg/MWh]
Wind energy	3–41
Solar energy	13–190
Hydropower	2–20
Nuclear power	3–35
Biomass	8.5–130
Natural gas	380–1000
Oil	530–900
Lignite	800–1300
Hard coal	660–1050

3 Off-grid energy systems

Off-grid energy generation is defined as generating electricity outside of the main electricity network or the grid. This includes, for example, a cabin in the woods that uses a solar panel to produce electricity. An off-grid energy system can be a solid alternative if the normal energy network is unavailable or too costly to build infrastructure for. Off-grid energy generation is versatile as there are many electricity generation methods. Depending on the need, goal, and geographical location, one might choose to produce electricity by utilizing wind energy, solar radiation, fossil fuels, or a combination of different energy sources called hybrid energy systems. The size of the off-grid energy system can be optimized by projected energy demand, which helps to determine the required initial investment. Off-grid energy systems are mostly found in remote and rural areas such as islands, developing countries, and isolated villages.[7]

The main reasons for choosing to produce electricity off-grid are cost and convenience, depending on geographical location and the country’s grid policies. The pros of off-grid energy generation include versatility as they are easily customizable to fit specific needs and have stable cost savings after a high initial investment. Depending on the energy system, the emissions created by the off-grid system producing electricity tend to be low, as using renewable energy sources is common. Independence from the grid is also valuable, as, for example, storms or geopolitical crises could lead to power outages. Cons of off-grid energy include high initial investment as the possible infrastructure built in remote locations is expensive, maintenance costs, and system reliability. While the initial investment in infrastructure and transport of the products is significant, most off-grid energy systems are projected to pay themselves back. Geography can be either a positive or a negative aspect, as when we move around the globe, some sources of energy become more relevant compared to others, such as solar power near the equator.[7]

3.1 Common renewable energy options

3.1.1 Wind power

Wind power is one of the oldest energy sources adopted by humans and for thousands of years. Its main use was sailing, pumping water, and milling grain. In today's world, wind power is used to generate electricity with the use of wind turbines. Wind turbines work by turning kinetic energy of the wind to electricity by capturing it in the turbine's blades. The amount of wind is highly dependent on geography, as wind speed and air density are the main driving factors of the energy potential. Locations that have an average wind speed of at least $4\,\frac{m}{s}$ are considered the most effective places to utilize wind power. These locations include for example Southern Patagonia in the tip of South America, where the average wind speed ranges from $9 - 11.2\,\frac{\mathrm{m}}{\mathrm{s}}$[8]. Efficiency of the turbines is dependent on the size of the blades and its altitude, which is why in general, most wind turbines tend to be large. The size of the wind turbines creates an issue where they take up massive amounts of space and thus are generally built in remote and rural areas that have minimal contact with the population. In some cases, for example Britain, where the average wind speeds are favourable for wind power, but the available landmass is limited, they utilize offshore windfarms. Offshore windfarms reduce noise and visual impact, while still providing the benefit of wind power.

One of the biggest issues of wind power is the one-off cost, as the wind turbine, its infrastructure, labour, and transportation are costly compared to its energy production in the short term. While the cost of the wind turbine itself is fluctuating, the average cost of a 2 MW wind turbine is approximately 2 million euros or around 1 million per MW[9]. Together with labour, transportation, infrastructure and land, the cost of a single 2 MW wind turbine is estimated to cost between 2.5 – 3 million euros. In a study published by nature (2024) [10] shows that single 2 MW Vestas wind turbine produced 3893 MWh (Megawatt hours) in a year. The price of electricity for the first year of the 2 MW turbine can be estimated to be $0.71\,\frac{€}{kWh}$, while neglecting operational costs. Variables such as labour, infrastructure and transport can have major differences when it comes to costs when considering different locations. In remote areas, the possibility of having to build roads leads to deforestation as well as increased costs. Terrain may be challenging and bring issues for the needed infrastructure. For example, piling is usually necessary for a stable structure, which in remote and rural areas can be expensive and labour-intensive due to logistics and equipment. For offshore wind turbines, the levelized cost of energy (LCOE) is more than doubled compared to land-based wind turbines, which accounts for infrastructure and maintenance among other expenses.[11] Manufacturing and transportation are the main emission driving factors during the wind turbines life cycle but are negligible compared to the amount of emissions savings it makes during its life cycle. Most of the emissions come from the use of materials such as concrete, limestone and steel. The disposal of the wind turbine blades may also be challenging as they are usually made from fiberglass and resin. Often, they end up as landfill, but this may be regulated based on different countries policies. Because they are not recyclable, they permanently damage our ecosystems. While it may not be a problem yet, the massive surge of wind power during recent years may potentially pose problems for the future.[12]

The best reason for choosing to produce electricity by using wind turbines is sustainability. Because most of the world’s energy is still generated by fossil fuels, the role of renewable energy such as wind power is crucial to lower emissions all over the world. While the initial investment for wind power is high, the wind turbine is projected to pay itself back in around 10 years depending on cost and electricity price. Also, the maintenance and other operational costs are often projected to be minimal during its projected 20–25-year lifecycle. While geography can be either a positive or a negative depending on location as wind speed varies, wind power can be a suitable option if it meets the desired requirements.

3.1.2 Photovoltaic power

Photovoltaic (PV) power, or solar power is one of the most widely used sources of renewable energy in the world. Solar power has been utilized since the 19th century, but major technological advancements and the demand for sustainable energy have turned it into a major competitor in the energy sector. PV panels are used to transform sunlight into electricity through photovoltaic cells that utilize the photoelectric effect to generate a flow of electrons. The performance of solar power generation is highly dependent on solar irradiance, orientation of the panel, and temperature. Best places to utilize solar power are found near the equator such as Sahara Desert and most of the Arabian Peninsula, due to the solar irradiance being highest in the world as seen in figure 2. The use of PV energy is flexible as scalability is easily manageable. For example, residential rooftops, commercial buildings, and large solar farms are a great example of its scalability. PV farms take up massive amounts of land as scalability is key in producing PV power efficiently. While the land usage is massive, solutions have been created such as floating solar farms that aim to utilize lakes and reservoirs for PV panels.

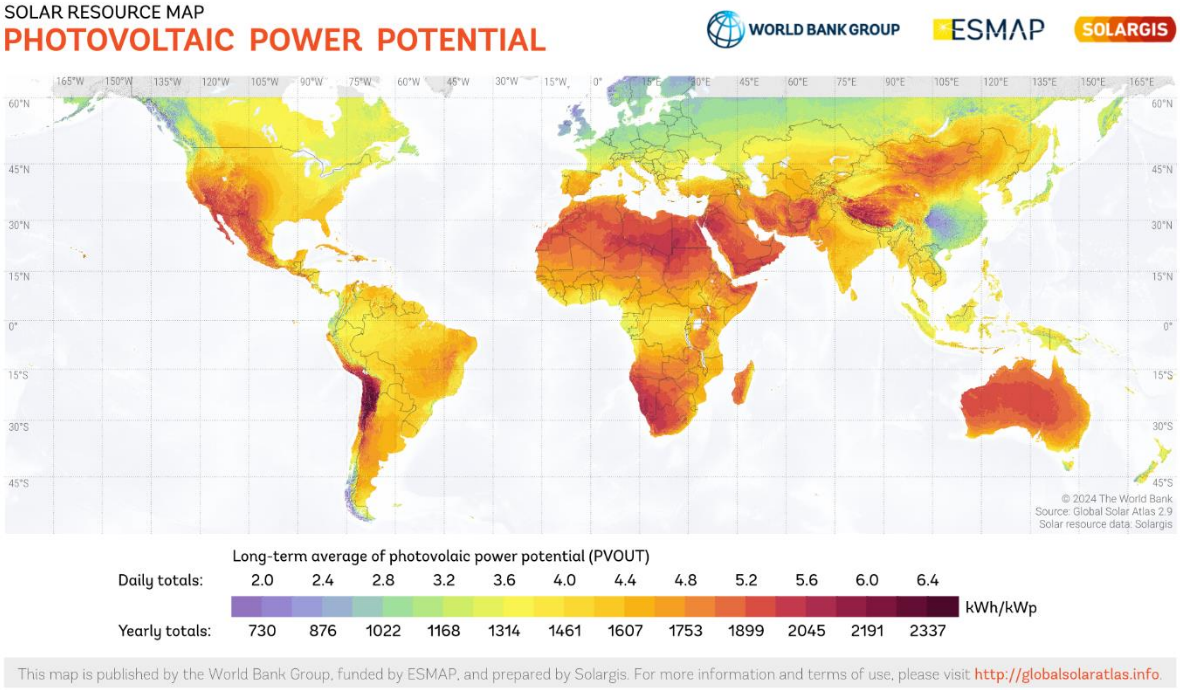

Figure 2: Photovoltaic power potential[13]

While the cost of PV systems has decreased, the initial investment in photovoltaic systems remains high due to high amounts of labour, equipment, land and the panels. The price of 1kW of installed PV panels averaged 758€ in 2023[14] with a declining trend. Investment needed for a 1 MW PV power station with the average installation price of the PV panel is thus projected to be around 758 000 € without including land use. A research concluded[15] that a PV power station in India with a capacity of 1 MW is projected to generate approximately 1 440 000 kWh yearly. With these estimations the cost of electricity produced by a 1 MW PV power station for its first operating year is $0.526\frac{\text{€}}{kWh}$. With the estimated lifespan of 25-30 years, they are projected to pay themselves back in the span of 10 years depending on the energy prices. With minimal maintenance costs mostly focused on cleaning the panels at least once a year makes the owning of a PV power station passive and easily manageable. The gradually lowering cost, flexibility and passivity makes it highly likely for homeowners to consider adding PV panels to their residences, as a way of saving money.

Like wind power, PV power's attractiveness also comes from its sustainability as the generation of electricity does not produce emissions. The main sources of pollution in PV power arise from its manufacturing, transportation, and installation. The materials used in PV panels such as silicon, glass, aluminium produce the largest part of emissions during the panel’s lifespan. However, the emissions avoided over the panel’s lifetime will compensate for the emissions generated during its manufacturing. One of the main problems with PV power is the end-of-life disposal of PV panels. Most PV panels also contain harmful elements such as lead, cadmium and other toxic substances making them harmful waste. While recycling programs are being implemented, their effectiveness can vary a lot from country to country due to regulations and policies.

3.1.3 Hybrid energy systems

Hybrid energy systems consist of multiple energy sources, such as wind and PV power. As both wind and solar power have weaknesses due to being variable energy sources, a hybrid system can come into question as it enables a more stable energy source. A hybrid system can generate electricity more efficiently by generating PV and wind power during their peak times. Due to wind and solar power often peaking at different times, the hybrid system can provide a more stable source of electricity, which is valuable or even necessary for different implementations. Hybrid systems are more complex than singular systems as they require more infrastructure, components, and labour, making them more expensive. Wind turbines in hybrid systems benefit the most as the lifetime of the components and maintenance time is increased by only running the wind turbine during peak times. While still having necessary maintenance costs, such as cleaning the PV panels, the operating costs are minimal after the big initial investment.[16]

Hybrid systems, such as systems consisting of wind and solar, are most beneficial in areas that have strong seasonal differences in weather conditions and solar irradiance. For example, in Finland where sunlight is almost constant in the summer and non-existent during the winter. For areas with consistent sunlight during the year, a hybrid system will not be as beneficial as a plain photovoltaic system, which would be less expensive and produce electricity more efficiently. Due to the benefits of hybrid systems, they are widely implemented in the form of hybrid renewable energy parks, such as the Gujarat hybrid renewable energy park. It is estimated to produce 30 GW of electricity when entirely constructed, making it the biggest in the world, powering around 18 million Indian households.[17]

3.2 Fossil fuel-powered generators in off-grid energy systems

Using generators in off-grid energy systems plays a crucial role in maintaining a stable and continuous energy source due to its ability to produce electricity on demand. Renewables such as wind and PV power are usually produced as the primary energy source to minimize emissions caused by the generator. In contrast, the generator acts as insurance to provide energy if needed. Generators are commonly used in remote communities, construction sites, and mines with variable sizes and fuels. While new generators have been produced for renewable fuels like methane, diesel and gas generators remain the most popular due to price and fuel availability. As the use of renewable energy has increased in the grid, the role of efficient generators has increased due to growing energy demand and the need for stability during times when renewable energy sources are insufficient. By producing a stable flow of energy, the generators help the grid's electricity prices to remain at a reasonable level due to supply and demand.[18]

While today’s diesel engines are very efficient, the need for more sustainable fuels such as methane, hydrogen, and ammonia remain. Major drawbacks of next-generation fuels are their availability and price, as the market is either small or non-existent. Next-generation fuels such as ammonia and hydrogen produce no carbon emissions when burnt. However, production often involves the use of energy from fossil fuels, which are harmful to the environment. The development of next-generation engines that run on, for example, ammonia remains a key milestone in sustainable on-demand energy production.

3.3 Energy storage

A major driver of emissions in energy systems is the requirement of storing energy, which is often done by using rechargeable batteries. Most common battery used in energy storage systems is Lithium-ion (Li-ion) batteries due to its high energy density, long lifespan and rechargeability. Compared to other batteries such as lead-acid and nickel-metal hybrid, Li-ion batteries are lighter and more efficient, making them usually the most viable option for storing energy. While being the most common battery, it has some significant issues due to its sustainability due to manufacturing and recycling. Some of the raw materials is needed to produce Li-ion batteries, such as lithium, cobalt, and nickel, which significantly impact the environment by causing deforestation and polluting water. Other issues include child labour linked to cobalt mines in the Democratic Republic of Congo[19], leading to major ethical issues in the whole supply chain of the Li-ion battery. For the efficiency of the battery, temperature plays a key role as cold temperature reduces the efficiency and power output of the battery and high temperature can create safety risks as well as accelerate the degradation of the battery. Because of this the batteries temperature needs to be regulated which also consumes energy. Due to the valuable materials in Li-ion batteries, recycling plays a key role in making it more sustainable in a world where these batteries are used. Different recycling methods include, for example pyrometallurgical recovery and hydrometallurgical metal reclamation, which have different strengths and weaknesses in the processes but often lead to material loss and energy loss.[20] While storing the energy in rechargeable batteries may not be the most sustainable option, they are essential due to the limited alternatives for more environmentally friendly options.[21]

Other common methods of storing energy include hydroelectric dams and flywheels. Hydroelectric dams work by using electricity to pump water to an elevation and running it through a turbine to harness the stored electricity when needed. A Flywheel is an energy storage system that converts electricity to kinetic energy by accelerating the flywheel rotor. The rotor maintains rotational speed due to inertia and low friction coefficient, making it an efficient way to store energy. Emerging energy storage methods include supercapacitors and solid-state batteries, which both suffer from high manufacturing costs. Compared to the most common Li-ion battery, supercapacitors and solid-state-batteries have a faster charging rate and solid-state batteries have a higher capacity. Adopting new energy storage methods is slow as the Li-ion battery is mass-produced and provides significant cost efficiency compared to new methods.

In off-grid energy systems, energy storage plays a critical role as a constant source of electricity may be needed. Without energy storage the users of the systems would have to rely on the system to constantly produce a stable amount of electricity, which is not always possible with renewable energy sources. This also emphasizes the possible need for a generator that can produce electricity on demand if the current energy storage is insufficient. The different energy storage systems sold on the market vary a lot depending on the size and the need of the system.

While many modular energy storage systems are quite basic and only involve batteries and their temperature control, there are also more complex solutions, such as Wärtsilä’s GridSolv Quantum, that involves machine learning to optimize the storing and distribution of electricity.[22]

3.3.1 Use of surplus power

Commonly excess power is stored in batteries or different energy storage systems, but other methods of storing involve using the energy to create substances such as hydrogen, ammonia, or methane, which creates emission free fuel if renewable energy is used. By using excess energy to create hydrogen, it acts as an energy storage, which can be either sold or used. The market for green hydrogen is expected to increase as hydrogen-powered engines for energy generation and transport are being developed and are showing promise.[23] The needed infrastructure and other requirements to be able to convert electricity to these energy forms are large, which makes them inefficient for smaller energy systems. The market for green hydrogen, ammonia, and methane is small due to costs, regulations and availability. While the use of, for example, hydrogen still poses issues due to its storage, transportation, and production costs, it may still be a viable solution in the future.[21] Other more traditional means of using surplus energy include heating, producing fresh water, and selling it to the grid if possible.

4 Energy mix of the grid in the Nordics

Nordic countries Finland, Norway, Sweden, Denmark, and Iceland are heavy consumers of electricity, which all have commitments to reduce energy-based emissions by the adoption of renewable energy sources. Due to drastic geographic, political, and economic differences in the countries, the electricity mix of the grid electricity varies a lot. The percentage of renewable energies in the Nordics have steadily increased and continues to grow steadily with major drivers being hydropower, nuclear, biomass, and wind power resulting in the Nordic countries have some of the lowest grid emissions in the world. Norway's mountainous terrain with lakes and rivers makes it one of the best countries in the world to utilize hydropower. Finland and Sweden both mainly utilize hydropower and nuclear energy as their main source of electricity. Denmark as a mostly flat and windy country, as well as the home of a wind turbine giant Vestas Wind Systems, gets most use out of wind power as well as solar power.[24]

As seen on table 2, there are drastic differences in the Nordic country's grids energy mixes, as hydropower is a dominating source of electricity in Norway and Sweden. Wind power has also quickly risen to one of the most common and most utilized sources of electricity in the Nordics compared to photovoltaic power as the seasonality of the Nordics is more inclined to being windy.

Table 2: Energy mix of Nordic countries[24]

Energy source	Country			
	Norway	Sweden	Finland	Denmark
Hydropower	94.8%	47.9%	22.2%	
Wind power	3.2%	10.5%	3.3%	54.4%
Solar power		2.5%	7.9%	26.8%
Nuclear power		35.5%	40.5%	
Biomass		3.6%	17.6%	5.4%
Waste	0.1%		1.0%	3.0%
Gas	1.1%		2.1%	2.8%
Coal			1.3%	5.4%
Oil				2.2%
Other	0.8%		4.1%	

The focus on renewable energy accelerated during 2020 when the European green deal was approved as part of fighting climate by reviewing existing laws and by introducing new legislation, framing, and innovation. The main goal of the deal was to focus on making Europe a net-zero emitter of greenhouse gas emissions by 2050. This has made European countries more inclined to invest in green energy, and by doing so, they have also created a massive market for renewable energy systems, which has accelerated their development and produced jobs. Due to the significant financial spike caused by the approval of the deal, many European companies have risen as key players in the renewable energy sector and expanded their operations, investing in innovative technologies. This led to rapid advancements in solar, wind, and battery storage solutions, promoting Europe as a global leader in green energy. European green deal also accelerated the growth of offshore wind energy in countries like Germany, Denmark, and the Netherlands and the utilization of photovoltaic systems in Spain and Italy. The EU has also invested billions of euros in green hydrogen development with the intention of researching and exporting it.[25]

Sustainable energy is a major priority for many European countries, with the goal of being a net-zero emitters by the year 2050. By producing more and more renewable energy each year, European countries are slowly detaching from fossil fuels such as gas and coal. The EU Emissions Trading System plays a key role in shifting to renewable energy by increasing the price of carbon emissions, which makes fossil fuel-based electricity increasingly unprofitable.

4.1 Grid emissions in Nordic countries

Table 3 shows the average emissions per MWh of different Nordic countries grids during 2024. Norway and Sweden produce notably cleaner energy than Finland and Denmark due to the high potential of hydropower as well as Sweden’s nuclear power concentration. The emissions produced in different Nordic countries make a key reference when comparing the sustainability of off-grid systems in the region.

Table 3: CO2e emissions from energy production in 2024[24]

Country	CO2e [kg/MWh]	Main source of energy
Norway	18	Hydropower
Finland	83	Nuclear power
Sweden	18	Hydropower
Denmark	173	Windpower

5 LCA in off-grid energy systems

LCA is an important tool when comparing emissions of different energy systems. One of the big differences between off-grid energy conversion and grid energy is the need for energy storage in off-grid systems. Energy storage is one of the biggest factors when considering emissions, especially when considering large storage requirements.

Table 4 shows results from an LCA study[26] between residential scale PV and wind systems. The study compares the GHG emissions per kWh of electricity delivered over the full lifecycle of each system. In residential scale, the study shows major differences in emissions between residential scale wind and PV power, which is mainly influenced by the high steel usage of wind turbines.

Table 4: LCA examples of residential off-grid systems[26]

System type	Size	Energy storage	GHG emissions (kg $\frac{CO2e}{MWh}$)
PV + battery	Residential 1.29 – 3.45 kWp	Li-ion battery (6-22 kWh)	105
PV + battery	Residential 1.29 – 3.45 kWp	Lead acid battery (10-37kWh)	131
Wind + battery	Residential 5 kW	Li-ion battery (6-22 kWh)	440
Wind + battery	Residential 5 kW	Lead acid battery (10-37kWh)	470

A recent LCA study[27] evaluates the emissions of an off-grid energy system in Chile. The study focuses on cradle-to-gate greenhouse gas emissions and brings up important hotspots during the systems life cycle. By looking at emissions produced from production, transportation, and operation, the LCA paints a clearer picture of emissions caused by the system when compared to using traditional grid electricity.

The study conducts an ex-ante life cycle assessment as it evaluates environmental impacts of an off-grid energy system before its implementation. Multi-objective optimization (MOO) was used to balance costs and emissions in the energy system based on life cycle emissions data. The goal of the LCA was to assess emissions of an off-grid energy system for an astronomical observatory in Chile that would be primarily powered by using photovoltaic panels and using batteries and/or hydrogen as energy storage. A photovoltaic system was selected due to the region's high solar irradiance, making it an ideal source of renewable energy. The scope of the LCA was defined as cradle-to-gate. LCI is also utilized in the study as data is presented on the emissions caused by material inputs, energy use and emissions associated with components like photovoltaic panels, lithium iron phosphate (LFP) batteries and hydrogen storage. Due to LCI datasets such as Ecoinvent are not regularly updated, the study uses updated life cycle inventories for data as the accuracy for emissions is higher.

The results of the LCA study show a clear correlation between cost and emissions in the system. As costs are reduced, the emissions increase. The systems lowest and highest emissions ranged from 67 kg $\frac{CO2e}{MWh}$ and highest being 376 kg $\frac{CO2e}{MWh}$, with levelized cost of energy (LCOE) being highest and lowest, respectively. The optimization of the system uncovers the "low-hanging fruit" as the study shows that at certain points even minor costs can have significant reductions in emissions. Especially in the high-end range of the emissions produced (253-376 kg $\frac{CO2e}{MWh}$), the required increase in costs to reduce emissions was 0.02 $\frac{\$}{kg\ CO2e}$. Compared to the low-end of emissions produced (67-98 kg $\frac{CO2e}{MWh}$), the cost to reduce emissions was 1.28 $\frac{\$}{kg\ CO2e}$. The massive cost difference to lower emissions per kilogram of GHG emphasizes the need for optimization and research, as small changes in investment can lead to notable differences. The study points out that battery-based systems have lower emissions compared to hydrogen storage systems due to hydrogen storage requiring a larger PV system. This directly increases the emissions thus diminishing the possible emission savings of the hydrogen storage. Battery lifetime assumption of 6.8 years can have a major impact on the results due to saving or generating a lot of emissions if the lifetime varies. The key takeaway being that optimization is important as the projected emissions can vary drastically based on the size of the investment.

6 Discussion

As the LCA study[27] concluded, the main driving factor of an efficient off-grid system is using a correct renewable energy source and optimization. When planning out an off-grid system, it is necessary to research the needs and what suits the best, which in the studies situation was determined to be an off-grid system powered by photovoltaic panels and diesel generators with an energy storage system consisting of batteries. Due to the high solar irradiance and average low wind speeds in the area, the obvious choice for the LCA was to use a photovoltaic system as the main source of energy. When considering emissions and costs, optimization is vital as it provides key information for determining the most suitable size and necessary components of the off-grid system. It is essential to focus on system's main goal as key is to determine what is required. Due to flexibility of off-grid systems, the invested amount highly determines the type and efficiency of the system, whether it is more focused on producing electricity cheaply or whether it is more inclined to being sustainable.

Energy storage is one of the main hotspots in the LCA, where most trade-offs between costs and emissions happen. As LFP batteries and hydrogen storage systems were compared, the results had a lot of variability in costs and emissions. The lifespan of the batteries was determined to be 6.8 years, compared to the hydrogen systems components having a longer lifespan of minimum 10 years. The main issue of using a hydrogen storage system was that the system would need to be larger to operate efficiently. Batteries were determined as the optimal storage solution even with their shorter lifespan. By assessing the need for reliability of the system, it can be determined whether fossil fuel generators would provide additional value to the end user. For example, a larger system connected to a hospital, or a military facility would be a good example of where backup power is valuable. In the LCA, diesel generators were used due to their convenience and need for reliability. While generators are not the most sustainable option, they enable the use of smaller and more cost-effective storage system while also reducing the need for additional backup energy sources.

With the use of LCA, wind, and PV power can be compared by their emissions. Studies show that typically wind energy produces less emissions compared to solar, when accounting for manufacturing, installation, operation, and end-of-life recycling. As Table 1 shows, wind and

PV energy can be expected to produce emissions in range of 3 – 41 kg $\frac{CO2e}{MWh}$ and 13 – 190 kg $\frac{CO2e}{MWh}$, respectively. Compared to the off-grid system in Chile, consisting of photovoltaic panels, generators, and energy storage that produced emissions in the range of 67 – 376 kg $\frac{CO2e}{MWh}$ the emissions from the off-grid system tend to be higher due to the systems necessities such as energy storage. While the emissions from the off-grid system tends to higher as well as have more variability than normal renewable energy generation, the produced emissions are still clearly smaller compared to fossil fuels such as oil that has a range of 530 – 900 kg $\frac{CO2e}{MWh}$ depending on the system. The variability of emissions emphasizes the differences in materials, energy usage during manufacturing, and end-of-life disposal, which in PV power can be drastic.

As the LCA study's scope was determined as cradle to gate, the emission values don't include some of the major emissions that take place at the end of the system's life cycle. For example, recycling and disposal of PV panels make up a large part of its emissions. It is important to note that comparing LCAs can be challenging due to system boundaries and the variability of geographical factors. This emphasizes the need for careful observation of different LCAs.

6.1 Comparison of grid and off-grid energy

Even though off-grid energy systems are mostly considered sustainable and provide flexibility and independence, their use from a sustainability perspective is highly dependent on the region. As many countries have different energy mixes, the benefits of a sustainable off-grid system may be diminished by the fact that electricity from the grid could be even more sustainable. In Norway, where the grid is almost fully comprised of hydroelectricity, the off-grid system fails to provide any meaningful benefit regarding sustainability. With Nordic countries having some of the cleanest grids, the use of off-grid systems can be questioned. However, the suitability of an off-grid system depends on context, as in location and specific needs. Remote locations that would require a massive investment for a grid access remain the most practical situation to utilize off-grid energy, even in countries that have a world class electricity infrastructure.

Generally, grid electricity remains the most cost-efficient energy source in the Nordics, as the usual grid prices vary from 0.08 - 0.30 $\frac{€}{kWh}$. Off-grid systems require large amounts of capital, depending on size and type, which in many cases is larger than the investment for a grid access. While the system is projected to pay itself back over time, the off-grid system from an investment standpoint may not be the best.

6.2 Future and long-term considerations

When considering the long-term sustainability of off-grid energy systems, it is important to consider not only sustainability but also the reliability of the system as well as economic viability. Off-grid energy systems can provide major benefits as well as challenges when compared to grid electricity.

As grid electricity depends on large-scale working infrastructure, disruptions can be common. Natural events such as storms, falling trees, and heavy snowfall can lead to damages that interrupt the flow of electricity in the grid, and may require a lot of work to fix especially in remote areas. Also, geopolitical risks that include conflicts and cyberattacks can have an impact on the grid leading to power outages especially during times of global geopolitical uncertainty. While off-grid systems are independent of most of these issues, they come with other setbacks such as regular maintenance. Off-grid systems can also be prone to system malfunctions that may lead to serious issues, especially when considering larger systems that power multiple households. This highlights the need for careful design and planning of the system. While costly, the repairing of the system can be faster as the ownership is usually private.

One of the most important areas of technological advancement in off-grid energy systems is battery technology or overall energy storage systems. Energy storage is commonly one of the largest sources of emissions in off-grid energy systems due to having a high environmental impact. Better batteries would lead to fewer replacements, lower emissions, and overall better performance. By reducing emissions from batteries, the off-grid system would be even more attractive from an environmental standpoint.

7 Conclusion

The comparison between off-grid systems and grid-based electricity in the Nordics highlights the complexity between sustainability, cost, and reliability. While in some cases, off-grid systems offer significant flexibility and potential emissions reduction, context is critical as electricity mix, carbon emissions, energy needs, and geography play a key role when comparing off-grid and the-grid electricity. Off-grid energy remains a solid alternative in areas where grid access is unavailable. However, in regions where grid emissions are low, such as Sweden and Norway, off-grid electricity may not be as feasible due to its projected emissions. This highlights the need to assess the system's goal and requirements when choosing between off-grid and grid electricity. Optimization of off-grid system is key to determining the most suitable system for a particular situation by balancing emissions and costs. It’s also important to keep in mind that the amount of renewable energy in the grid is gradually increasing, making the future comparison of emissions between the two choices complex and unpredictable. As new technologies evolve, energy storage systems become more and more environmentally friendly, allowing for cleaner off-grid systems and making them an even better choice in the context of sustainability. Overall, sustainable energy remains one of the key objectives in the world, as fossil fuel-based energy is slowly being phased out, which highlights the importance of evaluating different energy systems using sustainability assessment tools such as LCA.

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