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Implementation Possibilities of Off-grid Hybrid Renewable Energy Systems

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As energy demands rise and the urgency for climate neutrality grows, off-grid Hybrid Renewable Energy Systems (HRES) offer a promising solution for decentralized and sustainable energy generation. This thesis explores the technological and economic aspects of implementing HRES, with a focus on Southwestern Finland—a region with favorable conditions for solar and wind energy. The thesis analyzes different system configurations, infrastructure requirements, operational strategies, maintenance concerns, and lifecycle sustainability. A detailed case study of a large-scale horticultural business' energy system in Turku is presented, demonstrating real-world application through solar installations, biomass boilers, electric boilers, and energy storage solutions. The findings reveal that while initial infrastructure investments are significant, HRES can enhance energy resilience and self-sufficiency, especially when tailored to specific geographic and operational contexts. The thesis concludes that practical implementation of HRES is not only viable but increasingly essential for future energy independence and environmental sustainability.

Keywords: HRES, renewable energy, wind energy, solar energy, off-grid, Finland

Table of Contents

1 Introduction

The use of various renewable energy sources is rapidly growing in popularity and necessity, as Finland, along with other Nordic countries, has an ambitious goal to be climate neutral by as soon as 2035. [1] With the constantly growing need for more electricity, for example with the steadily growing number of electric vehicles, data centers and other high-power applications, more resilient and flexible energy systems and sources will likely be increasingly relevant in the future. The increasing electricity consumption combined with unsteady weather conditions due to climate change and subsequently harder-to-predict weather total to uncertainty in the energy market. The uncertainty in turn leads to larger price fluctuations followed by hesitation among consumers. Finland has one of the world's highest energy consumptions per capita due to extreme climate conditions, but notably exceeded 40% of total energy consumption coming from renewable sources in 2021, including transport consumption [2,3].

To further accelerate renewable energy adoption, several different strategies could be used. One alternative could be to incentivize the implementation of hybrid renewable energy systems (HRES). These systems could benefit from relatively sunny and windy weather conditions present in (Southwestern) Finland [4,5], but only a little information in academic literature is available on the topic of techno-economic assessment of such systems.

In HRES, several renewable energy sources such as solar, wind and renewable fuels can be combined in almost infinite ways and proportions. An ideal system also includes the possibility to store energy for situations when supply and demand do not match, as often is the case when considering for example wind and solar energy. Energy can be stored in multiple ways, for instance as chemical energy in batteries or as heat energy in some storage mass. The right option for a certain system depends on the application and other components of the system. Several versions of HRES's have gained popularity in Finland in the last few years, but only a little information is available on the relation between economic factors and renewable energy adoption rate [6]. In Finland, most of the renewable energy consumed is produced on the national level for the main grid, but HRES implementation and local microgrids could make the transition easier.

This thesis aims to introduce different HRES's and explore their applications, implementation and suitability mainly in Southwestern Finland. Also, an existing hybrid system from a local company is introduced and assessed in the form of a case study. Implementation possibilities based on said system are explored.

2 Theory

2.1 Description of different energy systems

Traditionally, an energy system refers to a national power grid to which the government-funded and managed power plants produce energy. In Finland, production technology shifted from mainly hydropower and industrial surplus in the 1960’s to nuclear power and increased import by 2000’s [7]. In the last 20 years, the production has further transitioned to even more nuclear energy accompanied by wind energy as a close second [2]. With energy and electricity production increasingly driven and determined by the market, smaller and more local grids and systems have gained traction.

New systems are encouraged by an increasing number of pollution-related restrictions and guidelines to utilize renewable and sustainable sources of energy. Despite the obligations, smaller systems are in most cases more reasonable to be implemented with renewable solutions. For example, solar and wind power are more easily scaled to smaller sizes than nuclear or hydroelectric power plants.

In the following section, different configurations and system features are introduced.

2.1.1 Different configurations

One internal study from University of Turku explores an optimized HRES and its performance in many Northern European cities. That system is designed for 100 people in the harsh Nordic climate, and it consists of solar and wind power with the help of a biodiesel generator as a backup energy source. In the system, energy is also stored in batteries to be used when wind and solar energy is unavailable.

This system could be relatively easy to implement because all its components are readily available and are widely used in existing off-grid systems, for example in seasonal residence and other rural applications, as projected in another study on renewable energy consumption [6]. The system could also be supplemented with hydro power and other energy storage solutions, for instance thermal batteries. These solutions are not explored in the internal research project but could be viable for certain locations. Also, the optimized system produces alternating current (AC) straight from the generator and the wind turbine, and converts the direct current (DC) from the solar panels and the battery to AC. With certain component changes and appropriate use, lower voltage systems with only DC could be beneficial. These low voltage direct current (LVDC) microgrids [8] eliminate the need for converters and many other components making the system itself less complex, cheaper and potentially safer.

The introduced energy sources and storage solutions can be combined in different ways to fit a certain need or purpose, and different combinations vary greatly in economical and infrastructural convenience.

2.1.2 Infrastructure

New energy systems require a lot of new infrastructure if they are intended to be off-grid. With smaller systems, similar to the internal study's one, the price of planning, modification and implementation can quickly get disproportionally high compared to the price of actual generation and storage related components of the system. However, the large variability in energy prices can counterbalance that equation and make HRES's more appealing. Here the following are included in the CAPEX costs: purchase and installation of supporting components, such as inverters and electrical centers, and construction of necessary buildings and structures.

The required additional components and modifications are defined by the architecture and planned usage of the system. If the system is entirely off-grid, then there is more freedom to choose components, voltages and other specifications when designing the system. For example, LVDC systems have many advantages in efficiency and cost but also face some challenges in implementation and adaptation. However, most systems today are connected to the grid, even if they are declared as being off-grid systems. That makes it possible to route possible surplus electricity back to the grid, have the system architecture more standardized and have a sufficient and reliable backup energy source.

Another factor to consider in infrastructure design, and HRES implementation in general, is the feasibility to use different systems in certain environments. For example, wind turbines cannot be built near airports, and many countries have a regulatory minimum distance for turbines near settlements. Wind turbines are usually not feasible within cities due to limited space and regulations. Construction permits may also prohibit solar panels in some areas. Similar challenges are faced if a backup generator big enough for a small community would be installed in an existing neighborhood. Areas yet to be built could allow more freedom to place different components and systems, but realistically, an HRES would only be feasible for communities in at least semi-rural areas. Similar HRES benefits could be achieved in cities if the size of the microgrid was significantly larger, but then implementation would most likely face difficulties in decision-making at the city level as the total costs would be much higher.

2.1.3 Operation of different energy systems

The operation of an HRES covers the logical functioning of the system, i.e. dispatch strategies [9], other logical operation and also the required programming to enable the system to function as desired. Many of these properties are defined by the architecture of the system considered. Different dispatch strategies define the guidelines for generator and storage operation when the renewable sources are not generating enough energy at a certain time. The logic behind the energy distribution and production is executed on a software level and it defines the way the electricity is distributed and managed in the system and, further, which factors have the highest value or importance. Different algorithms target certain functions of the system, for instance the probability of losing different parts of the system or load expectations and averages.

HRES’s and other independent energy systems are typically divided into three categories based on their connection type to the main grid: grid-connected, partially connected and off-grid. [8] Each type has its benefits and drawbacks, and the right choice is dependent on the environment and requirements of the user. Usually when the grid is available, the system is connected to the grid to minimize customer outages. The other end of the spectrum is the off-grid option, for example in remote and rural areas. Although not as reliable as grid-connected systems, off-grid systems can be more efficient due to the architectural freedom. Additionally, the systems may offer a cheaper option instead of expanding the main grid’s coverage. Partially connected systems harness the benefits of both former types while drawbacks come from increased complexity and additional need for infrastructure.

In a microgrid joined to the main grid, there is the procedure of implementing and managing the grid connection to maximize reliability and cost-effectiveness. For example, if the cost of used electricity is prioritized, drawing from the grid could substitute for backup generator usage. Decisions like this form the logical function of the system, which is also present on off-grid systems but includes decisions between different sources and/or storages. A few different logic rulesets have been demonstrated where variables for managing the system include, but are not limited to current power difference between demand and production, state of charge of a battery along with its charge history, weather data and current power levels of different sources [10]. These variables can be used to calculate the optimal, or desired, plan of action and times of switching between different drains and sources.

As a result, good programming is essential in any efficient HRES with complexity beyond systems with only one energy source and one storage solution with no grid connection. Operating an HRES requires a lot of additional expertise throughout the lifetime of the system from initial building through service and maintenance to end-of-life decommissioning and recycling. These necessities are considered in the next section.

Additional factors affecting the use and operation of an HRES are for example the suitability of a certain component to a specific environment or the threats the system imposes on natural ecosystems. Preventing compatibility factors with wind turbines are for instance nearby airports and residential buildings whereas shading trees and structures affect the placement of solar panels. Building regulations could affect both options. There have also been reports on wind turbines disturbing birds, bats and even terrestrial animals [11] with similar effects necessary to be assessed with every other component of the system.

2.1.4 Service and circular economy of different systems

Most renewable energy systems face operational and maintenance challenges similar to those of photovoltaics [12]. Examples of these are risks in cleaning and repairs and obstacles in recycling. Similar problems can be expected with wind turbines [13] and biodiesel generators [14]. Most parts of an HRES need maintenance, such as the main components, but even batteries and transformers. With photovoltaic being one of the most accessible and socially best-accepted renewable energy sources, the need for maintenance of solar panels is frequently misunderstood. The main factors in service and maintenance are related to uniform and reliable cooling required to reach optimal performance, defects and degradation in the panels and dirt accumulation on the panels [12]. These all contribute to the need for continuous maintenance and service of the system, which introduces additional costs along with risks in various forms for workers performing the recommended monthly maintenance.

Other renewable energy sources also have their specific risks, such as high places with wind turbines, high voltages with batteries and mechanical dangers with generators. These are important factors to consider for a microgrid as most of the service is expected to be done by the user to mitigate costs, which are already high from the initial investment to the system. In the internal study of the University of Turku, it is calculated that for most applications in the Nordic countries, the optimum HRES does not include solar energy, but rather only wind turbines and batteries. This calculation is subject to change as solar panels are becoming cheaper with price data [15] showing 310$/kW in 2023 compared to 950$/kW used to originally calculate the optimum system. Nonetheless, regular service and end-of-life considerations are relevant for all types of systems and definitely affect the calculations on viability if rightly taken into account.

The proportion of initial cost to service and maintenance cost vary for each technology. As a large share of renewable energy technology is relatively new, the availability of comprehensive research on lifetime maintenance costs is limited. For example, with commercial large-scale wind turbines the initial investment is large due to the scale which brings down the maintenance cost in proportion. Newer turbines require less maintenance than older ones, but they are still estimated to be 1.5 % to 2 % annually of the initial investment [16]. These costs translate to at least tens of thousands of euros per turbine as modern multi-megawatt turbines tend to cost over 1 million euros per megawatt [17], or somewhere around 1.5 cents/kWh approximately [18] . Maintenance costs naturally scale down with the system, but at the size of a typical HRES the proportion of the costs to the investment tend to increase. The same principle applies to solar panels, which usually have lower maintenance needs, but still are calculated to cost about 0.75 cents/kWh in maintenance throughout their lifetime [19].

For generators, maintenance and service are often considered almost marginal, especially in backup use. However, typically at least an oil change is recommended annually by manufacturers. This means that even with minimal maintenance the costs can easily total to multiple percent of the initial investment over the full lifetime of the generator. The nature of the generator’s use mitigates some of the cost consideration as one is paying a premium for the security of the backup energy source.

Lastly, batteries are usually considered maintenance free for their planned lifetime with supporting actions limited to maintaining the right temperature and humidity for optimal function. Additionally, since most energy systems use lithium-based batteries, they offer a leading advantage in recyclability due to their simple construction and high recyclability of lithium [20]. On the other hand, solar panels and wind turbines both face serious problems with recyclability and recycling rates as they are complex in structure and combine many different materials in a way that is not as cost-effective to dismantle as manufacturing new ones.

2.2 Literature review of energy systems

HRES’s combine multiple renewable energy sources to reach a more reliable, cost effective and versatile alternative to full grid-dependency in times when uncertainty and large fluctuations are present in the global energy market. HRES’s may increase resilience and reduces dependence on centralized infrastructure which can bring desired flexibility with constantly rising energy consumption and its nature to be in spikes [9]. These large and quick fluctuations have led to energy companies introducing power charges [21] and those in combination with social and psychological factors [22] may lead towards wider HRES implementation in the future.

2.2.1 Economic assessment of different technologies

For solar panels, local offers for systems for one household including installation range around 1-2 € per watt of maximum capacity with an average system for example being 6kW at around 6500€ [23,24]. Examples of larger MW-range solar parks [25,26] show that the price per watt remains at around 1 €/W (maximum capacity) even with the larger systems comparable to the needed scale for a microgrid for 100 people. Comparing this to the price of just the solar panels [15], it can be estimated that roughly two thirds, or at the very least over half, of the cost of the system comes from installation and infrastructure. Solar panels are advertised and expected to last somewhere around 20-30 years, but data monitoring [27] shows the real lifetime of panels can actually frequently be half of the expected.

Wind turbines seem to follow the same principle, that the price per watt stays fairly constant across the size scale. The most affordable ones start from a few hundred watts with prices mostly in line with 1 €/W [28] and larger turbines (on land) come with slightly higher costs at about 1,5 €/W [17]. The increase in €/W is due to the significant change in the scale and robustness of the construction, whereas for example larger solar energy systems require simply more of the same panels. This makes the initial investment of wind turbines somewhat more expensive than solar panels in certain cases, but in turn they require less land and space. The expected lifetime for large wind turbines is usually around 20-30 years [29] with small wind turbine manufacturers promising similar expectancies [30]. Interestingly, already in 2020, 28 % of Europe’s wind turbines were over 15 years old. That makes it a longer-lasting investment than solar panels and the maintenance comparison favors wind turbines even more. Simulations [31] show average site visits for off-shore wind turbines being less than twice a year for a lifetime of 40 years, when solar panels are recommended to be at least cleaned monthly, as stated before in this thesis.

Diesel backup generators do not scale similarly to wind turbines and solar panels compared in cost per unit of power. In the internal study the capacity of the backup biodiesel generator was 150 kW, which typically cost 30 000 – 40 000 € in Finland [32,33]. This equals roughly 0.2 or 0.3 cents per watt, but that excludes the cost of fuel. This means that the generator is not directly comparable with solar or wind energy but still plays a major role in the system as a backup. When maintained and serviced properly, the diesel engine in the generator will last the lifetime of the system, so the investment to use renewable energy even as a backup could be better justified. In the scale of a system for 100 people, the price of the generator is only a few percent of the total cost, as it usually comes as a ready unit and only needs a simple connection to the microgrid to supply backup power when needed. In the optimized hybrid system, the generator is only needed during a couple of months in Finnish circumstances, thus the irregular and minimal usage does not significantly influence the total CAPEX and OPEX of the system.

A substantial portion of the total costs of many HRES’s is related to batteries. Although the prices have dramatically decreased in the last 20 years, batteries are still relatively expensive, with household-size options available locally [34,35] varying between 300 and 800 €/kWh and larger commercial options [36], more relevant to the system considered, typically cost somewhere around 500 €/kWh. The smaller options exclude installation and infrastructure costs, so the price per kilowatt hour for an installed system once again stays roughly the same regardless of the size of the batteries. With provided warranties usually ranging from 10 to 20 years with multiple thousand charge cycles and lifetime expectancies significantly longer, the batteries can be expected to last as long as other components of the system.

Calculations and estimations of total costs for different systems become increasingly more complex when different combinations and configurations are evaluated. A financially reasonable system can be very different for each case and location. In most cases for small communities or even companies the optimal system is out of reach due to a constrained budget. This means that compromises and crucial decisions must be made on which components and functions to prioritize in the system. For example, a system with sufficiently large battery storage to completely cover all usage for a day will be significantly more expensive than a system with a smaller capacity compensated with ways to produce electricity more evenly. In addition, the system with more batteries generally requires less space making it more widely suitable for different demands.

2.2.2 Economic assessment of infrastructure

Taking solar energy as an example, the panels themselves should only equal to approximately a third [15] of the cost of the complete system [23–26]. With the estimated infrastructure and construction costs on solar farms being at least as much as the panels themselves, or even double, it is clear that infrastructure costs would also be a major part of an HRES investment. While the type of household that would benefit, or could even make use of, from an HRES is a detached house outside of city centers, the energy consumption is higher than the average per capita. Finland has long winters and variable electricity consumption, so a shared HRES for a 100 people would need to be in the MW-scale.

As previously estimated, the cost per unit of power or capacity stays relatively constant regardless of the size of the system. Although every HRES requires the same basic components [37] for management and distribution of electricity, such as converters and cables, the reduced power of a smaller system in turn requires less expensive versions of those components. As listed in [10], the investment cost further include cables and accessories for every main component (solar panels, wind turbines, batteries, inverters), parts and construction for distribution, metering instruments and accessories, development and installation, and fuel. Many of the listed costs include work and services and are thus tied to the location of the system. This is why such a big part of the complete system cost is everything other than the main components themselves, especially in Finland, where the price level index [38] is above average and is expressly high compared to developing countries where HRES's are more important and topical.

Again, the vast variety of different systems make it difficult to estimate any general costs for infrastructure as almost every system has different requirements. When designing an HRES, one should consider precisely the needed function of the system along with location-tied costs and their proportion. Additionally, different renewable energy sources and storage solutions can range significantly in price with varying scales and certain specifications. Required modifications to existing infrastructure should also be considered as some systems may not require it. Local restrictions, permissions and enactments affect the process as well.

Electricity transport and grid fees in Finland are among the average across Europe [39]. The fees consist of infrastructure and operation costs for the grid and are collected by the grid company in each country. There are significant differences between countries in the level of the collected fees, which puts implementation of HRES in varying economical environments depending on the location. The differences in fees are explained by dissimilar scales and extents of infrastructure along with each country having their own energy production structure [40]. As previously stated in this thesis, economic factors are one of the most important deciding elements when considering an HRES. The lower fees in Finland, when compared to for example Germany or Spain, make it less feasible to adopt off-grid options for the price of electricity related reasons.

3 Case study

In this section, a local garden company’s energy system in Turku, Finland is studied. All the information was gathered directly from the company which is a grower, wholesaler and importer of flowers and decorative plants. They have 4.5 hectares of greenhouses which require heating and electricity throughout the year, and their energy system is constantly under development. The latest changes are made in effort to reduce dependency on fossil fuels and also to lower the cost of used electricity. These changes include new heating boilers and the implementation of solar panels, with plans to introduce other strategies to become even more self-sufficient.

3.1 Preview of the system

The greenhouses are heated to a large extent with lights required to grow the plants. The lights used to combine for approximately 3 MW, but greenhouse decommissions have reduced that number slightly. When additional heating is needed the boilers provide that via central heating. Previously the boilers burned coal, but starting from December 2023, two 3MW boilers burn woodchips for the same system. In reality, with varying quality and moisture levels of the woodchip loads the actual power output from the boilers is usually around 2x2MW. The full 6 MW combined is still achievable with high quality woodchips. This is sufficient for all the heating needed during the winter, in addition to the lights’ heating effect. Over a six-month period, the boilers burned a total of 16 000 m^3 of chips, with moisture levels varying between 20 and 50 percent. This totals approximately 3 900 tons used with the combined energy content being ~13 500 MWh. Especially the moisture in the chips is told to have been a constant problem, which can be deducted from the reported moisture levels sometimes being well above average, and industry standards [41]. The high moisture and poor quality are the result of a recycled variety of chips is used. This has been combatted with the addition of higher quality raw wood chips mixed in.

In addition to the woodchip boilers, the company has also acquired three 1MW electric boilers, which started operation and were connected to the grid in February 2025. The boilers are expected to have their own electricity connection soon so that they can utilize the cheaper hourly spot price [42], when available. Currently the main purpose of these boilers is to sell balancing capacity and ability to the grid accompanied by the same ability of the aforementioned lighting. Said availability to balance and buffer the electricity consumption and frequency in the grid is then compensated monthly by the electricity network/grid company.

An essential part of the heating system working with the boilers is the 2500 m^3 hot water reservoir acting as heat storage. This allows the chip boilers to be mostly run on stable power; charging the storage during the days when the heating demand is lower and drawing from the storage during colder nights. The utilized temperature range in the tank is between 60 and 85 degrees Celsius, which results in an energy capacity of roughly 75 MWh, enough for a day’s worth of heating during the winter in case of a system failure. The heat storage is generally used to diminish the need to adjust the power output of the boilers to keep sufficient heating to the greenhouses. Even during the heating season, the sunshine is enough to keep the greenhouses warm, so the woodchip boilers charge the heat storage. Extremely low temperatures and lack of sun are of course an exception. Overnight, the heat storage is then used to compensate for heating not covered by the boilers.

The company added solar power to their energy system a little less than a year ago to cover basic electricity usage over the summer when heating is not needed. This includes cold rooms, circulation pumps and office buildings. The solar panels are 175 kW combined with actual production peaks around 140 kW. This is enough to eliminate the need to buy electricity during the days in the summer, of course producing additional electricity in the heating season as well. Some of the panels began production in May 2024 and the rest in July 2024. The panels combined have produced approximately 80 MWh of electricity by April 2025, which compared to for example the heat storage capacity of 75 MWh seems somewhat low. Still, the company is happy with their investment in solar energy as their self-sufficiency has improved and an important part of the obligatory consumption is covered by them. The solar panels could benefit from batteries tied to the system, but after all the combined power usage of the whole garden is so large that the batteries and solar panels would need to be separated into their own subsystem to unlock full potential.

Supporting the high power consumption and enabling flexible electricity usage is a separate 110 kV transformer just for the garden, provided by the local energy company. The transformer enables the company to have a prioritized sub-grid and significantly lower transfer fees for the electricity that they buy. This special arrangement is subject to change as the energy company is planning to build a proper separate small grid for the garden company. An administrative microgrid would allow the garden company to have multiple electricity connections with different terms and prices for different operations. For example, the electric boilers could be driven with cheap hourly spot-price electricity when available and in turn the constant smaller consumption could utilize a different connection with relatively low fixed price electricity.

Other support technology includes two backup generators. One is only for shutting and running down the woodchip boilers safely in case of a power outage and the other one is for obligatory property and

facility electricity. The generators are not used to maintain normal operation of the garden or greenhouses as those would require a power plant, not a backup generator.
Another speculative aspect of the system is the possible introduction of batteries to store electricity. Again, the company is faced with the difficulty of their consumption being so high, that only the largest battery storage system [36,43] in the country at 36 MWh would be sufficient for their needs. There has been some speculation and discussion with the grid and energy companies about a 10 MWh battery, but no decisions have been made. The battery would not be large enough for the garden's own use but instead would make sense financially to charge the battery with cheap electricity and sell it later back to the grid with a higher price along with the ability to equalize and offset the grid. Like the electric boilers but in the other direction, i.e. production instead of consumption.

The company has not considered adding hydropower or wind turbines to their system as there is no major body of running water nearby whereas the Turku airport is close enough to obstruct the implementation of high wind turbines.

3.2 Costs and viability

The 2x3 MW woodchip biomass boilers installed in existing facilities combined with a new building for chip storage were circa 4 million € in total. That equates to roughly 67 €c/W (eurocents per watt) which undercuts previously stated solar and wind energy investments. The comparison can be justified, because the same amount of energy would be used for heating regardless of the source and the addition of electric boilers provide flexibility in the heating methods. The woodchips bought are also competitively priced when compared to current fixed electricity pricing. The viability equation could potentially change if spot-priced electricity could be extensively utilized.

The initial investment for the three 1 MW electric boilers was 600 000 €, with the installation being in an existing facility formerly occupied by a coal-burning boiler. The price per watt for this subsystem is then only 20 €c/W, further increasing the gap to direct renewable sources. Of course, renewable electricity could be used to run the boilers, but that would require buying it from the grid as, for example, a solar farm large enough would not be viable. The boilers are currently used in their grid-balancing property for a few hours every now and then. More extensive use of the boilers for the company's own heating requirements would need the cheaper spot-price electricity connection to be realized. If possible, this heating option should be entertained, as a significant part of the national grid's electricity is already produced by renewable sources.

The solar panel subsystem for the nominal 175 kW was 140 000 € in total. This corresponds to a price of 80 €c/W, which falls closer to the cost for solar energy systems. Reducing the cost was the minimal need for stands, other hardware and system infrastructure, as the panels were installed flat on an existing roof and plugged into a system already combining different energy sources in multiple locations across the garden. The panels have already produced approximately 80 MWh meeting their expected production with the full year average of just over 10kW and a daylight average over the summer being roughly 25 kW. The actual highest power level from the solar panels has been around 140 kW.

3.3 Application possibilities

There are multiple good examples and models to gather from the garden company case at hand, which can be applied to HRES's elsewhere:

- Many larger companies could benefit from a sub-grid allowing multiple electricity connections and contracts to optimize costs.
- Solar energy is especially beneficial for applications where the electricity consumption over summer is lower or otherwise fitting for solar coverage.
- Batteries can be financially feasible even for only buying and selling the capacity on the side.
- Direct electric heating should be considered as an additional option if cheap electricity is available.
- Dividing energy dependency to multiple sources is rational, even if not following the optimal HRES formula.
- Energy could be stored cheaper as heat, if the application and environment is suitable.
- Designing an HRES should start from basic considerations of fitting and unfitting renewable energy sources for the current application.

4 Discussion and conclusions

This thesis has assessed the techno-economic feasibility and practical implementation of Hybrid Renewable Energy Systems (HRES), with a focus on their application in Finland. A review of local data and research shows that not a lot of academic information is available on the topic. Through theoretical analysis, a literature review and a real-world case study, several key insights and conclusions can be drawn.

4.1 Key findings

While HRES require considerable upfront investment and carful planning, they offer promising benefits in terms of energy independence, operational flexibility and environmental sustainability. The strengths of HRES come from flexibility in their configurations, allowing tailored combinations of solar, wind and other renewable sources with backup generation and energy storage.

Challenges in HRES adoption include economic, operational, maintenance and infrastructural variables. While initial capital costs are high, component prices continue to decline through product development and increased supply. Knowledge and expertise in optimal system operation and maintenance are built up with ongoing research and monitoring of existing systems. Programming and relying on forecasts are an essential part of any energy system, and they continue to improve through developments in technology. Finally, new infrastructure can introduce regulatory and standardization challenges on top of bearing a high economic load. The transition may be facilitated with careful system architecture choices and suitable do-it-yourself solutions where it is possible and safe to reduce installation costs.

4.2 Case study insights

The energy system of the horticultural company in Turku provides a concrete example of a hybrid approach that blends multiple energy sources such as biomass heating, electric boilers, and solar generation. Key takeaways include:

- **Heat storage as a viable option**: Thermal energy storage proved to be a simple yet effective buffer, reducing reliance on real-time boiler adjustments and increasing system efficiency. Batteries may still be viable to use in the same system, but they should not be considered the right option for all systems.

- **Electric boilers and grid participation**: The ability to use cheap electricity efficiently when it is available could change economic considerations significantly. In turn, the option to sell balancing capacity to the grid introduces an additional income stream and demonstrates how HRES can complement national energy systems.

- **Geographical constraints**: The site's proximity to Turku Airport ruled out wind energy, highlighting the importance of location-specific assessments in system design.

- **System diversity:** Having multiple options, even if not all of them are renewable, is a good practice for resilience and self-sufficiency.

4.3 Future outlooks

Looking forward, several trends support the broader adoption of HRES. For example, technological advancements continue to drive down costs and improve the efficiency of renewable components, while energy markets evolve to reward flexibility. Additionally, societal attitudes are continuously more aligned with nearing sustainability goals, further increasing demand for renewable energy independence.

However, further research would be needed to analyze in detail the costs and benefits of different storage solutions along with HRES implementation in general locally in Finland. In addition, real-world degradation and lifecycles should continue to be monitored in the long term, even exceeding the planned lifetime of for example, solar panels and batteries. An important aspect is to also focus on the challenging recycling of soon to be abundant components, such as wind turbines and solar panels.

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