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Research Article

Wind, PV, and Hybrid Power Plant Operation in Competitive Nordic Electricity Market With High Profit Cannibalization

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This study presents a technoeconomic analysis of a hybrid wind-PV (photovoltaic) power plant (HPP) compared to onshore wind power plants (WPPs) and photovoltaic power plants (PVPPs) in the Nordic electricity market, focusing on locations in Finland and Sweden. Wind power capacity has recently increased significantly in the Nordics, increasing the profit cannibalization of wind power. Renewable energy subsidies have been phased out in Finland and Sweden, thus new wind and PV power value creation is formed from the power market. The PV power capacity has also encountered significant growth in the Nordics. However, the capacity is still relatively low, allowing more revenue for produced PV power compared to wind power. The lower PV power profit cannibalization has increased interest in HPPs instead of WPPs. This contribution studies the economic feasibility of wind and PV power in changing market conditions in the Nordic electricity market. The market operation is modeled with three different configurations including selling all the power into the day ahead spot market and baseload or pay-as-produced power purchase agreement (PPA). In addition, a battery energy storage system (BESS) investment is analyzed using the operating strategy of shifting production to more profitable spot price hours. This study shows that due to the profit cannibalization and high cost of capital, the power plants are currently not profitable in the Nordic electricity market except when the bidding area has high average spot prices. The worst profitability was with WPPs when exposed to the market shape risk and with PVPPs when pay-as-produced PPA was agreed upon due to the higher levelized cost of electricity. However, the PV power profit cannibalization is expected to increase in the future as more PVPPs operate in the Nordic power market. Thus, the PVPP shape risk may increase in the future as well.

1. Introduction

Variable renewable energy (VRE), particularly wind and photovoltaic (PV) power is expected to increase in Nordic electricity markets in the coming years. European Union (EU) climate law [1], domestic binding targets in Finland [2], and goals in Sweden [3] aim to reduce greenhouse gas (GHG) emissions significantly in the following years. Nordic Energy Research, an organization for energy research and policy development for a Nordic Council of Ministers, has developed five scenarios for further decarbonization in the Nordic countries. From the scenarios, direct electrification and power to X (P2X) have been identified as solutions to reduce GHG emissions [4]. The report [4] estimates that electricity demand in the Nordics would increase by 40%–100% by 2050 from 2020 due to the scenarios. Therefore, an increased demand for clean electricity production in the Nordics is expected in the future to achieve the GHG emission reduction goals. Similarly, the EU Agency for the Cooperation of Energy Regulations (ACERs) concludes that significant growth in investments toward low-carbon generation is required to achieve the decarbonization plans of the EU [5].

Wind power production in the Nordic countries has grown steadily in recent years. Statistics from Finland [6] and Sweden [7] show that the share of wind electricity production in total electricity production between 2018 and 2022 has increased from 7% to 14% in Finland and from 10% to 17% in Sweden. In addition, by 2026, a third of total electricity is expected to be produced with wind in Finland [8] and 28% in Sweden [9]. However, PV power production is still relatively low in the Finnish and Swedish power grids, as in 2022 PV generation reached 0.5% in Finland [6] and

1.1% in Sweden [7]. Nevertheless, the Finnish and Swedish transmission system operators (TSOs) outlook for future generation of PV power forecast the share to increase to 7% in Finland [8] and to 5% in Sweden in the most renewable energy-focused scenarios [10].

The Nordic electricity wholesale market price definition is based on the intersections of the merit-order curve of supply and demand bids based on the technological marginal prices and demand bids. This mechanism allows allocating the cheapest generators to win the bidding contest, enabling a competitive wholesale electricity market. Typically, the European electricity prices are connected to the prices of natural gas [11] and CO_2 emission trading system (ETS) price [12]. This is because the natural gas power generator's marginal price depends on the fuel and ETS price, and natural gas generation is typically the price-maker technology in the market [11]. However, an increasing share of VRE power generators is found to increase hours where more expensive dispatchable generators are not defining the prices, as the VRE generators are lower in the merit-order curve [13, 14]. Due to this effect, studies have found that a larger VRE power generation capacity in the market reduces the VRE power plant revenues as the electricity prices are closer to zero when the plants have high capacity utilization [15–17]. This effect is denoted as "profit cannibalization" as VRE power generators are "cannibalizing" the profits of all VRE power generators.

Many European countries have had subsidy schemes such as feed-in tariffs to support the expansion of VRE power generation capacity. The VRE power generators have received a premium for producing electricity. However, these subsidies are being phased out in the Nordics. For example, wind power plants (WPPs) commissioned after 2021 in Sweden [18] and after 2017 in Finland [19] cannot receive subsidies. Therefore, the revenue creation in the electricity spot market of new VRE power plants in the Nordics must rely on the market prices which have a larger profit cannibalization when more VRE power capacity is available in the market. Thus, commercial power purchase agreements (PPAs), that is, financial contracts between utility-scale power buyers and sellers, are proposed to secure revenue streams of VRE power producers which allow hedging against price developments in the electricity markets [5, 20]. Moreover, the PPAs are typically agreed for a long period, for example, 10 years [20, 21] which may increase the confidence of the revenue forecasts for many future years of operation and help to secure funding for the renewable power investment.

In the Nordics, the profit cannibalization is affecting the profitability of WPPs as the share of wind power is already relatively high. Thus, hybrid wind-PV power plants (HPPs), that is, integrated WPP and PV power plants (PVPPs) with common infrastructure, are proposed to increase profitability. The benefits include the synergy of wind and solar resources which is found to be especially beneficial in seasonal temporal resolution in [22–24]. However, the temporal synergy in hourly resolution is found to be less significant [22, 24] and the hourly production variation is expected to increase when PV power capacity increases in the production mix [22]. Nevertheless, Klyve et al. [25] found that the relatively low correlation between the production of wind and PV power is found to increase the HPP economic feasibility.

Thus, the literature indicates that the benefits of mixing wind and solar production profiles have some influence on alleviating the variation of production at hourly resolution and enabling a more stable seasonal production. However, increasing PV capacity in power system increases the profit cannibalization for PVPPs [16]. This development would also affect the profitability of HPPs negatively as the production profile depends on the PVPP production profile. Moreover, an important aspect for evaluating the profitability is the technology cost of wind and PV power. For example, the profitability in [25] was found to be highly sensitive to the PVPP investment cost. In addition, the economic benefits of shared infrastructure are relevant. For example, Ludwig et al. [26] found that additional savings are possible from undersizing the grid connection without significant curtailment, thus saving in costs without much revenue losses.

The scope of this study is to analyze the economic prospects of WPP, PVPP, and HPP in the Nordic electricity market associated with an absence of wind and solar power subsidies and high profit cannibalization of wind power. In addition, the cost of debt is currently rather high for renewable energy projects compared to recent history in the Nordics (Section 2.7.3). Thus, this study will give a comprehensive overview on the investment prospects for WPP, PVPP, and HPP projects in Swedish and Finnish locations of the Nordic electricity market. Furthermore, this study will analyze the benefits of shifting VRE generation to more profitable hours utilizing a battery energy storage system (BESS). The study questions this study answers are as follows:

1. What is the profitability of WPP, PV, and HPP in the Finnish and Swedish locations of the Nordic electricity market based on the 2023 market situation?
2. What are the benefits of PPAs from the perspective of a power producer? How do the PPA benefits change in different power plant configurations?
3. What are the economic benefits of integrated BESS operating in the electricity wholesale market, shifting the VRE production to more profitable hours and how do the benefits differ depending on different power plant configurations?

2. Materials and Methods

This section explores the methodology of this study. The methods are documented in more detail in the master's thesis [27].

2.1. Nordic Electricity Market. The Nordic electricity market consists of a few different market mechanisms to ensure a stable and economically optimal balance of electricity supply and demand. Below, the most relevant mechanisms are covered briefly.

The day ahead (DA) spot market is an electricity marketplace where electricity spot prices for the next day's hours are determined [28]. For each period, electricity producers

2023 Spot price (€/MWh)			
FI	56.5	NO2	79.4
SE1	40.0	NO3	38.6
SE2	40.0	NO4	29.9
SE3	51.7	NO5	67.0
SE4	64.9	DK1	86.8
NO1	67.0	DK2	81.3

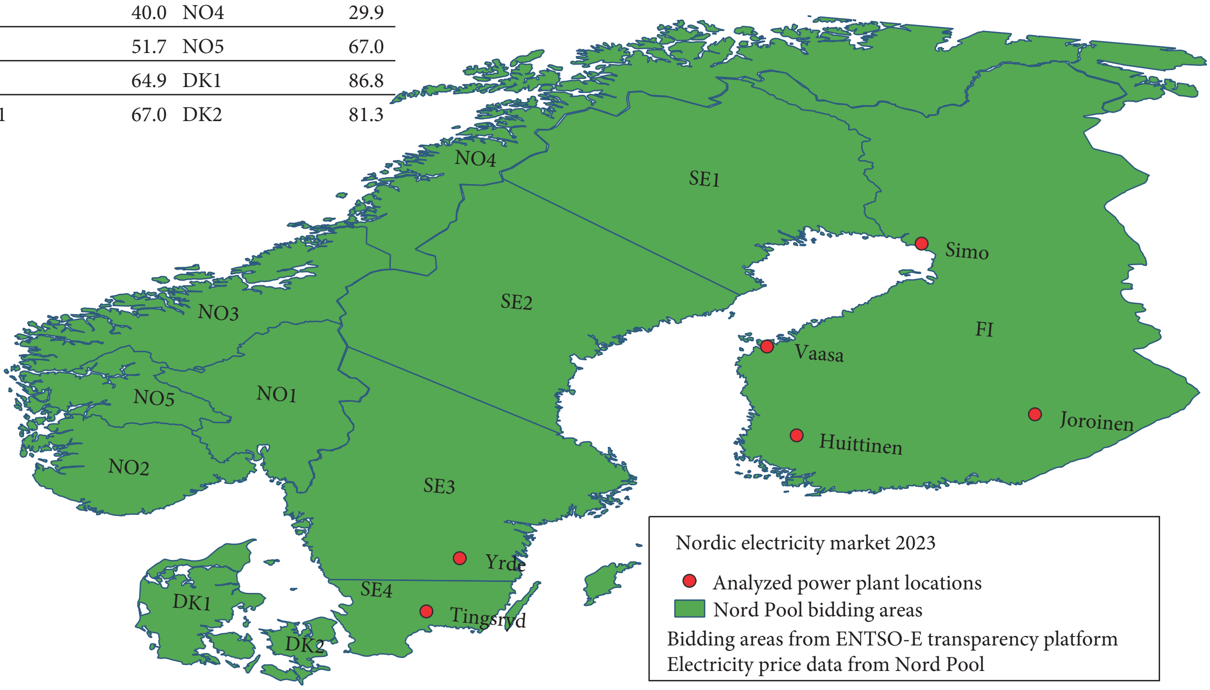

Figure 1: Nordic electricity market overview and sites analyzed in this study. Table at the upper left-hand corner presents the 2023 average electricity DA market prices for each bidding area visualized in the map. DA, day ahead.

bid on the market with the available electricity at their corresponding marginal price. The electricity spot price is defined from supply and demand curve intersections where the supply curve is defined with the merit order of the bids. VRE power technologies are typically first in the merit order because the technology has a near-zero marginal cost or even negative marginal cost with feed-in-tariffs [13]. The market participants submit the bids for production or consumption by the DA market closure time at 12:00 p.m. CET the day before the delivery hour.

Finally, the Nord Pool calculates and publishes the DA spot prices for each bidding area shown in Figure 1 at 12:42 p.m. which are derived from the supply and demand curve accompanied with consideration of grid congestion between the bidding areas [28]. Figure 1 shows the 2023 average DA spot market prices for each bidding area. The values show that the Nordic electricity prices are relatively low except in Danish bidding areas, which is likely explained by the higher electricity price dependency on fossil-fuel generation and electricity import costs from Germany [11]. In Finland, Sweden, and Norway, the electricity prices are mainly defined with renewable energy generators [11].

After the announcement of DA market spot prices, an intraday market is opened at 14:00 CET, always closing 1 h before the delivery hour [28]. In the Nordics, the intraday market is operated by Nord Pool [29] where market participants may buy balancing production on a pay-as-bid basis. The intraday market is typically used to balance VRE forecasting errors and replace unavailable supply due to unexpected outages [29]. Furthermore, the local TSO is responsible for keeping the electricity grid supply and demand stable at the delivery moment [28]. Because of this, the Nordic TSOs have established different reserve market mechanisms for maintaining the grid frequency at every point in time [28].

This study models the power plant operation solely in the DA spot market which is a simplified representation of reality. Due to the stochasticity of the wind and PV power production, trading in the intraday market and participating in the imbalance settlement due to forecast error or other unexpected outages is a part of the real operation. In addition, the BESS could be operated in reserve markets for a higher revenue potential [30].

2.2. Power Plants. Table 1 shows the assumed specifications for the WPP, PVPP, and BESS. The parameters specified are used in the renewables.ninja API [32] to model the capacity factors (CFs) of the WPP and PVPP at hourly resolution. Staffell and Pfenninger's [33] study explains in detail the methodology for calculating the wind power production. In summary, the calculation is based on utilizing wind speed data in 2, 10, and 50 m distances from MERRA-2 dataset which are used to interpolate the wind speed in the specific coordinate location. The interpolated wind speeds are then extrapolated to the height of the turbine given as parameter which returns the wind turbine output when the power curve of the given turbine model is used.

The PV power CF calculation method is explained in [34]. The solar irradiance and ground temperature data are

Table 1: WPP, PVPP, and BESS specification.

Component	Description
PVPP	Fixed installation at 45° tilt and 180° azimuth angle. Total 10% conversion losses of all system components
WPP	8 MW Vestas V164-8.0 MW turbines [31] with a hub height of 140 m. Turbine wind cut-in and cutout speeds are 4 m/s and 25 m/s, respectively
BESS	4-h charging/discharging in max power. Total capacity 20 MWh. The self-discharge rate is 1%/h and the charge, and discharge efficiency is 95%

Note: Power plant capacities are specified for each case separately.
Abbreviations: BESS, battery energy storage system; PVPP, PV power plant; WPP, wind power plant.

Table 2: Coordinates of analyzed locations which are acquired from the references in the table.

Location	Latitude WGS84	Longitude WGS84	References
Vaasa	63.0898	21.7452	[35]
Huittinen	61.1511	22.5866	[36]
Simo	65.7072	25.0189	[37]
Joroinen	62.0932	27.9030	[38]
Tingsryd	56.4669	14.6070	[39]
Yrde	57.7276	15.2518	[40]

acquired from MERRA-2 dataset which are interpolated to the specific coordinate location. The estimated values are then used in a diffuse fraction model for an estimate of solar irradiance in an inclined plane defined with the parameters for panel tilt and azimuth angle. Finally, the estimated PV power output is calculated with the parameter for panel efficiency. A more detailed explanation of the methods from [33, 34] is presented in [27].

The model does not consider the cut-in and cut-off speeds. Thus, additional data processing is done for the wind CFs to change values to zero when the wind speeds are outside of the bounds of the wind speed cut-in and cut-off speeds. In addition, the BESS parameters are utilized in the modeling of the BESS in the hourly operating model presented in Section 2.5.

2.3. Locations. Table 2 shows the locations analyzed in this study, four being in Finland and two in Sweden, visualized in Figure 1. The coordinates shown in the table are utilized to acquire the WPP and PVPP data for each geographical location from renewables.ninja [32]. The Finnish locations are the same as the locations analyzed in earlier work [27, 41]. However, the coordinates are slightly changed to represent actual WPP or PVPP locations. The municipalities of Tingsryd and Yrde in Sweden were selected because plans in these locations include the construction of PVPPs to convert WPPs into HPPs [42, 43]. In addition, the power plants in Sweden are in two different Swedish bidding areas, Tingsryd in SE4 and Yrde in SE3, which allows a more comprehensive analysis of the Nordic electricity market.

Figure 2 presents the annual CFs of PVPP and WPP in different locations, based on the weather data for years from 2014 to 2023 [32]. This study utilizes the 2023 data year for the hourly operating model. The figure shows that the 2023 meteorological year is a quite typical year for VRE power generation as the CFs are close to the median annual values. However, the wind CFs are slightly lower in 2023 compared to the median value in Finland and close to the median value in Sweden. Thus, slightly worse than median revenues from WPP are expected in Finland. Moreover, the PV CFs show

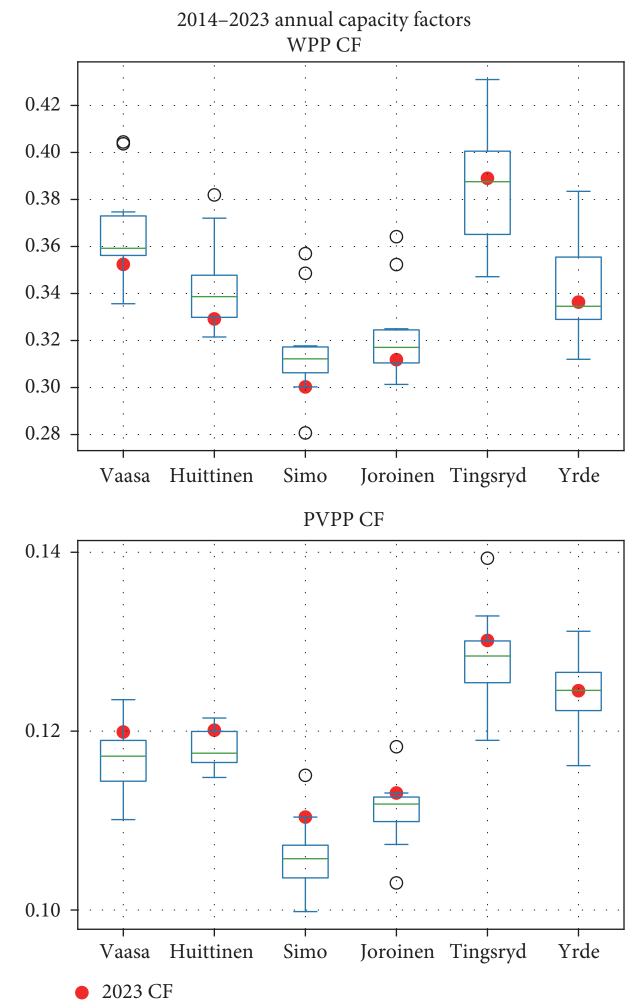

Figure 2: Estimated annual capacity factors of WPPs and PVPPs during 2014–2023 in analyzed locations. Additionally, 2023 results are illustrated to show how representative the 2023 data year is when estimating the power plant operation over a long period. The annual capacity factors are calculated from mean hourly capacity factors calculated with Renewables.ninja [32] utilizing the specifications from Table 1 and coordinates from Table 2. PVPPs, PV power plants; WPPs, wind power plants.

Table 3: Parameters for the PPA cases.

Case	PPA type	c_{PPA} €/MWh	P_t^{PPA} MWh
SPOT	No PPA	—	—
BL	Baseload	56 (50[a])	Annual (monthly[a]) median
PV	Pay-as-produced	50	Hourly volume

Note: The cases are created by combining the PPA case with the power plant configuration case from Table 4, for example, SPOT HYBRID.
Abbreviation: PPA, power purchase agreement.
[a]BL PV case has monthly median PPA power delivery with a lower PPA price.

that solar generation in 2023 was typical in Sweden and slightly higher than the median value in Finland. Thus, slightly better revenues, compared to the median, can be expected in Finland from the PVPP.

Nevertheless, selecting the 2023 data for the modeling was also decided due to the high profit cannibalization compared to older data years found in previous studies [27, 41]. In Finland, wind power production was 8.2 TWh in 2021 and 14.5 TWh in 2023 [6]. Therefore, the estimated profitability was found to be significantly higher with the 2021 data year compared to 2023 [27, 41]. Furthermore, the 2022 data include exceptionally high electricity prices due to the energy crisis in Europe, making the year unrealistically profitable for electricity producers [27, 41]. Thus, the data year 2023 is selected as it shows the most realistic representation of profit cannibalization from historical data while still being a non-anomalous meteorological year in the Nordics.

2.4. Market Operation. This analysis includes an assessment of PPAs to the investment profitability. The main parameters considered for the PPA include the volume of PPA and the PPA price. The volume, that is, the power delivered from the PPA, has some different methods that contain a shape risk on either the producer or consumer side. The shape risk is formed by the mismatch of the power generation profile and the demand profile [21]. The shape risk arises from the exposure to the electricity spot market variable electricity prices. The exposure might not cause a significant risk if the electricity market volatility is low. However, in the Nordic electricity market, the price volatility is high due to the high wind power capacity in the power market [44, 45]. Thus, the risks from the market exposure can be significant for the party exposed to the shape risk.

Two types of PPAs, the baseload PPAs and pay-as-produced PPAs, are identified for this study, with the opposite sides carrying the shape risk of the PPA. First is the baseload PPA where the delivered volume is fixed on a specific time, for example, yearly or monthly resolution [46–48]. In the baseload PPA, the residual volume, that is, the deficit or excess production after subtracting the delivered PPA volume, should be balanced by the producer with some balancing agent such as the electricity wholesale market [46–48]. Therefore, the shape risk is carried by the producer when a baseload PPA is agreed. Second is the pay-as-produced PPAs where the volume delivered to the PPA consumer is defined as the total or fraction of the actual power plant production [46–48]. Therefore, the pay-as-produced, PPAs transfer the shape risk to the buyer.

For the PPA pricing, the latest estimates for pay-as-produced PPA prices are utilized for this study which are acquired from LevelTen Energy PPA price indexes. In Sweden, the PPA price was 48 €/MWh for PV power in 2024 Q2 and 68 €/MWh for wind power in 2023 Q1 [49]. In Finland, the PPA price for PV was 53 €/MWh in 2024 Q1 and 50 €/MWh for wind in 2024 Q1 [49]. All the recent PPA prices appear to be around 50 €/MWh with the only exception of the wind PPA price in Sweden. LevelTen does not present recent data for the wind PPA price in Sweden, the latest being the 2023 Q1. However, the PPA prices for wind power before the energy crisis were at the same level in Finland and Sweden. Thus, it can be expected that the PPA price in Sweden has decreased similarly to the Finnish PPA prices. Therefore, this study assumes that the pay-as-produced PPA prices are 50 €/MWh for all power plant configurations and locations.

The baseload PPA prices are based on the current electricity market prices because the profitability depends on the revenues and expenses from buying and selling residual load in the wholesale market. In addition, Brunnberg and Johnsen [47] states that the pay-as-produced PPAs could expect ~10% lower PPA price compared to the baseload PPA. Thus, the baseload PPA price is assumed to be 56 €/MWh or 10% higher than the pay-as-produced PPA. This value is close to the average spot price in Finland which was 56.5 €/MWh in 2023 (Figure 1). However, the 2023 average spot price was 51.7 €/MWh in the SE3 bidding area where the assumed power plant in Yrde is located and 64.9 €/MWh in the SE4 bidding area where Tingsryd is located (Figure 1). Therefore, the baseload PPA price in Yrde is higher, and in Tingsryd, the price is lower than the spot prices, which is expected to affect the profitability of the PPA contract compared to operation only in the DA spot market.

Table 3 shows the market operation cases analyzed. They are used with the power plant configurations, as shown in Table 3. For example, the HPP case with baseload PPA is defined as the *BL HYBRID* case. Furthermore, the *BL PV* case has a slightly different PPA configuration where the volume is defined as monthly median instead of annual median production. This selection was made because the annual median value for PV production is 0 MW. Moreover, the PPA price for the BL PV is 10% lower because the monthly profile forces the consumer to act either by balancing production

TABLE 4: Parameters for power plant configuration cases.

Case	$P^{\text{wind}}_{\text{nominal}}$ MW	$P^{\text{PV}}_{\text{nominal}}$ MW
HYBRID	64	178
WIND	128	0
PV	0	356

Note: The completed cases are created by combining the PPA cases shown in Table 3 with the power plant configuration case, for example, SPOT HYBRID.

with other electricity sources or adjusting the consumption to match the PPA profile.

The WPP and PVPP capacities for each case are adjusted to produce approximately the same total annual production in *HYBRID*, *WIND*, and *PV* cases, respectively (Table 4). In the hybrid power plant case, a wind power capacity of 64 MW consisting of eight turbines is installed and in the WIND case, 16 turbines are installed to match the PVPP generation which is not accounted for. However, due to the variation of CFs depending on the location, the annual electricity production has some differences between the power plant cases.

2.5. Operating Model. This study estimates the annual revenues with the annual average CFs of WPP and PVPP and the capture rate. The capture rate is defined with Equation (1) where annual revenues from electricity sales and costs from electricity procurements (R_{annual}) are divided into annual wind and PV power generation ($E^{\text{wind}}_{\text{annual}}$ and $E^{\text{PV}}_{\text{annual}}$) the annual electricity productions are calculated with the CFs, power plant capacity, and total hours of the year (8760 h):

$$c_{\text{capture}} = \frac{R_{\text{annual}}}{E^{\text{wind}}_{\text{annual}} + E^{\text{PV}}_{\text{annual}}}. \tag{1}$$

The R_{annual} is estimated utilizing a solution from a linear optimization problem first introduced in [27]. Equation (2) shows the calculation method of R_{annual} which includes the revenues and expenses from the DA spot market and revenues from PPA. The parameter c^{spot}_t represents the spot price in an hour t and linear optimization problem decision variables P^{tomarket}_t and $P^{\text{from market}}_t$ represent the power delivered and procured in the DA spot market for an hour t:

$$R_{\text{annual}} = \sum_{t\in T} c^{\text{spot}}_t P^{\text{to market}}_t - c^{\text{spot}}_t P^{\text{from market}}_t + c^{\text{PPA}} P^{\text{PPA}}_t. \tag{2}$$

Other decision variables include curtailed power ($P^{\text{curt.}}_t$), BESS discharge power ($P^{\text{discharge}}_t$), BESS charge power (P^{charge}_t), and stored energy in BESS (E^{storage}_i). In addition, two binary variables are defined. $B^{\text{is charging}}_{\text{t}}$ controlling the BESS flow direction and $B^{\text{from site}}_{\text{t}}$ controlling the power flow from or to the power plant site. The optimization problem is designed to maximize the profits from the DA spot market (Equation 3). The model energy balance constraint (Equation 4) ensures that power delivery and procurement are optimized by the BESS charging and discharging to shift the VRE production to more profitable hours. In addition, the energy balance constraint allows power curtailment to avoid expenses from negative DA spot market prices as the bid price to the DA spot market is assumed to be 0 €/MWh:

$$\text{Max}.\sum_{t\in T} c^{\text{spot}}_t \left(P^{\text{to market}}_t - P^{\text{from market}}_t\right), \tag{3}$$

$$P^{\text{to market}}_t - P^{\text{from market}}_t + P^{\text{charge}}_t - P^{\text{discharge.}}_t + P^{\text{curt.}}_t = P^{\text{wind}}_t + P^{\text{PV}}_t - P^{\text{to PPA}}_t \forall t \in T. \tag{4}$$

The BESS energy balance is controlled with constraints shown in the equations below. Equation (5) represents the BESS energy balance constraint where the previous hour ($t-1$) stored energy and power inflow and outflow considering losses define the stored energy in a current hour (t). The first and last hours of the model are modeled with additional constraints. Equation (6) forces the first hour of stored energy to be the initial guess value ($\text{E}^{\text{initial}}$) which is assumed 0 MWh in this study. Equations (7) and (8) ensures that the last hour of the model can only charge or discharge with the available energy stored in the BESS. Lastly, Equations (9) and (10) ensure that BESS cannot charge and discharge at the same hour:

$$E^{\text{storage}}_t = E^{\text{storage}}_{t-1}\eta_{\text{loss}} + P^{\text{charge}}_{t-1}\eta_{\text{charge}} - \frac{P^{\text{discharge}}_{t-1}}{\eta_{\text{discharge}}} \forall t \in T, \tag{5}$$

$$E^{\text{storage}}_0 = E^{\text{initial}}, \tag{6}$$

$$\frac{P^{\text{discharge}}_{t_{\text{last}}}}{\eta_{\text{discharge}}} \le E^{\text{storage}}_{t_{\text{last}}}\eta_{\text{loss}}, \tag{7}$$

$$P^{\text{charge}}_{t_{\text{last}}}\eta_{\text{charge}} \le E^{\text{storage}}_{\text{max}} - E^{\text{storage}}_{t_{\text{last}}}\eta_{\text{loss}}, \tag{8}$$

$$P^{\text{charge}}_t \le B^{\text{is charging}}_t P^{\text{charge}}_{\text{max}},\ \forall t \in T, \tag{9}$$

$$P^{\text{discharge}}_t \le \left(1 - B^{\text{is charging}}_t\right) P^{\text{discharge}}_{\text{max}}.\ \forall t \in T. \tag{10}$$

Moreover, the model ensures power flow from site or to site to be at maximum the grid connection capacity with Equations (11) and (12). In addition, the constraints ensure that electricity can only flow in one direction with the binary variable. Furthermore, Equation (13) ensures that the model does not procure negatively priced power to be allocated into curtailed power which is unrealistic:

$$P^{\text{to market}}_t \le B^{\text{flow from plant}}_t \left(P^{\text{grid}}_{\text{max}} - P^{\text{to PPA}}_t\right),\ \forall t \in T, \tag{11}$$

$$P^{\text{from market}}_t \le \left(1 - B^{\text{flow from plant}}_t\right)\left(P^{\text{grid}}_{\text{max}} + P^{\text{to PPA}}_t\right),\ \forall t \in T, \tag{12}$$

$$P_t^{\text{curt.}} \leq B_t^{\text{flow from plant}} P_t^{\text{hybrid}}. \quad (13)$$

For the *HYBRID* cases, the grid connection is assumed to be 75% of nominal power capacity which was found in [27] to be in the range of economically optimal size. The net benefit from the reduced grid connection stems from the reduced capital expenditure (CAPEX), on the one hand, and on reduced revenues from electricity sales, on the other hand. Profit cannibalization leads to reduced electricity prices on average when both WPP and PVPP are producing close to the nominal power capacity. Thus, a partial grid connection of the nominal capacity is economically beneficial option [27]. In addition, the hybrid power plant produces less frequently close to nominal power capacity compared to power plants with only WPP or PVPP power [27]. This further reduces the influence of a smaller grid connection on the lost revenue. For the *WIND* and *PV* cases, the grid connection is assumed at 100% of nominal capacity as there is significantly more hours when the production is close to nominal power capacity.

2.6. Financial Model

2.6.1. Net Present Value (NPV). The assessment of the power plant economic feasibility is conducted with a discounted cash flow method which returns the investment NPV. This study assumes an economic lifetime of 25 years ($I = 25$). First, the earnings before interest and after taxes (EBIAT_i) for each investment year i is calculated (Equation 14). The gross revenues from the electricity spot market and PPA contracts utilizing the modeled capture price and annual electricity production are subtracted from annual operation and maintenance (O&M) costs and annual depreciations. This term is also called earnings before interests and taxes (EBITs), which is converted into EBIAT by multiplying it with $1 - \tau$, where τ is the corporate tax rate:

$$\text{EBIAT}_i = \left(c_{\text{capture}} E_i^{\text{annual}} - C_i^{\text{O\&M}} - D_i\right)(1 - \tau). \quad (14)$$

Equation (15) shows that the O&M costs consist of the fixed and variable O&M costs of WPP, PVPP, and BESS. The variable O&M costs are calculated from the total annual cost for each power plant component with the annual power generation (Equation 16). In addition, the fixed O&M costs are calculated with the nominal capacities of the power plant components where the BESS nominal capacity is the energy storage capacity (Equation 17):

$$C_i^{\text{O\&M}} = C_i^{\text{VO\&M}} + C^{\text{FO\&M}}, \quad (15)$$

$$C_i^{\text{VO\&M}} = c_i^{\text{VO\&M},w} E^{\text{annual},w} + c_i^{\text{VO\&M,PV}} E^{\text{annual,PV}} + c_i^{\text{VO\&M},s} E^{\text{annual},s}, \quad (16)$$

$$C^{\text{FO\&M}} = c_i^{\text{FO\&M},w} P_{\text{nominal}}^{w} + c_i^{\text{FO\&M,PV}} P_{\text{nominal}}^{\text{PV}} + c_i^{\text{FO\&M},s} E_{\text{nominal}}^{s}. \quad (17)$$

In this study, the depreciations are calculated with a straight-line depreciation which calculates the annual depreciation value as the asset CAPEX divided by the estimated useful life of the asset. In this study, the initial power plant investment is assumed to achieve the end of useful life at the end of the investment estimation period $I = 25$ years. Moreover, additional reinvestments are also depreciated to have the asset value zero at the end of the economic lifetime. The maximum annual depreciation is, however, set to 20% of the asset value to be within acceptable limits of Finnish and Swedish depreciation legislation [50].

With the estimation of the EBIAT_i for each year, a free cash flow (FCF_i) also, FCF to the firm is calculated (Equation 18). This value presents the cash flows after investments before paying debt and equity expenses associated with the weighted average cost of capital (WACC) [51]. The FCF is calculated by adding the tax-shielded income from the depreciations, and by subtracting the CAPEX (C_i^{CAPEX}). Moreover, the change in working capital should be considered [51]. However, this study assumes that change in working capital remains zero for each investment year. CAPEX consists primarily of the initial CAPEX from the power plant and additional reinvestments which are explained in future sections:

$$\text{FCF}_i = \text{EBIAT} + D_i - C_i^{\text{CAPEX}}. \quad (18)$$

Finally, the estimated FCFs for each economic year allow calculating the NPV of the power plant investment with Equation (19) from [51]. The WACC is selected as an appropriate discount rate as it contains the required capital to satisfy the cost of debt and equity:

$$\text{NPV} = \sum_{i \in I} \frac{\text{FCF}_i}{(1 + \text{WACC})^i}. \quad (19)$$

2.6.2. Internal Rate of Return (IRR). The NPVs are highly dependent on the assumed WACC. Therefore, the power plant investment economic feasibility is also evaluated with IRR calculated by iteratively finding a suitable IRR to satisfy the left-hand side in Equation (20). The IRR indicates which is the discount rate or WACC to have NPV of zero. Therefore, the IRR results show the conditions for the cost of capital required for the different cases and locations to have positive NPV:

$$0 = \sum_{i \in I} \frac{\text{FCF}_i}{(1 + \text{IRR})^i}. \quad (20)$$

2.6.3. Cost and Revenue Escalation. This study assumes that inflation will be 2% annually in the future years during the project lifetime which is based on the European target inflation [52]. In addition, an estimate for project revenue and cost escalation for the future years is made.

The power plant revenues depend on the electricity wholesale situation, in particular, the overall prices in the market and the profit cannibalization level. The electricity prices in the future are influenced by the supply and demand situation and how frequently the renewable energy producers are the price-makers and price-takers due to the merit-order effect [16]. The current ambitions and forecasts presented in the introduction indicate that the Nordic wholesale power market expects a large increase in power supply and demand. In addition, multiple grid expansion projects in the Nordics are under development in the Nordics, which is expected to alleviate the balance of VRE power supply and electricity demand [53].

However, profit cannibalization is expected to increase in future in the Nordic power market because the cannibalization is associated with the share of VRE power in the electricity market [16, 54]. Therefore, there is a possibility that the power plant revenues will decrease in the future due to profit cannibalization. However, the PPA producers could have the PPA price adjusted with inflation and the electricity market situation [55] which could allow for increasing future nominal revenues for the power plant. Furthermore, fossil-fuel prices contribute to the wholesale electricity prices when those generators are the price-makers [11]. Therefore, an increase in ETS and fuel prices could have an increasing effect on future electricity wholesale prices. This study assumes that the power plant revenues increase at the rate of inflation, offsetting the inflation effect in real value terms. However, due to the uncertainty, the parameter is assessed in the sensitivity analysis.

Furthermore, the costs of the power plant are also assumed to increase at the rate of inflation to offset the effect of inflation. This assumes that the increased costs of labor and materials reduced by technological innovation during the project lifetime increase the costs at the same rate as the assumed inflation.

2.7. Costs

2.7.1. Wind and PV Power Plant. The WPP and PVPP capital investment and O&M costs are assumed from data provided by the Danish Energy Agency [31]. This presents the values as euros with the 2020 inflation level. Thus, all financial data from [31] are adjusted to euros in June 2024 utilizing the Finnish consumer price index (CPI) from [56]. The CPI has increased by 18% from the 2020 average to June 2024 which is applied to the prices.

For the WPP, the 2025 values from [31] are assumed and for the PVPP, the average values of 2020 and 2030 are assumed because the data lacks 2025 data for the PVPP. Table 5 shows the assumed values of CAPEXs and fixed and variable O&M costs for the studied WPP and PVPP. In addition, the table shows assumed annual degradations for both power plants which are utilized to discount electricity production in future years in the discounted cash flow calculation.

Table 5 also shows the assumed technical lifetimes of WPP and PVPP. The technical lifetimes are higher compared to the assumed economic lifetime of 25 years in this study. The differences between the technical and economic lifetimes include an uncertainty regarding the possible residual value generation after the inspected economic lifetime. For example, [58] estimated that including a residual value in ROI calculation after a 20-year PVPP investment lifetime could decrease the levelized cost of electricity (LCOE) of

Table 5: CAPEX, O&M costs, technical lifetimes, and annual degradation assumed for the WPP and PVPP.

Parameter	Unit	Wind	PV	References
CAPEX	k€/MW	1276	465	[31]
Fixed O&M	k€/MW	19.1	11.7	[31]
Variable O&M	€/MWh	2.1	0.0	[31]
Technical lifetime	Years	27	38	[31]
Annual degradation	%	0.65	0.35	[31, 57]

Note: Costs adjusted to June 2024 euro with the Finnish CPI.
Abbreviation: PV, photovoltaic.

the power plant by 12%. Nevertheless, this study assumes that the project residual value is 0 € which indicates that the positive residual values of the power plant are equal to the possible dismantling costs of the power plant.

Moreover, the inverter, a major component of PVPP, has a significantly shorter technical lifetime compared to the PVPP. Therefore, this study includes an additional investment for a new inverter. Danish Energy Agency [31] estimated the lifetime of the PVPP inverter at 14 years calculated from the average of 2020 and 2030 values and the cost of the inverter to 30 k€/MW. Thus, the inverter reinvestment is assumed to occur in year 15, which is after 14 years of operation in the discounted cash flow model.

2.7.2. BESS. The capital investment and O&M costs of BESS are based on the latest cost projections for utility-scale BESS presented by the National Renewable Energy Laboratory (NREL) [59]. The BESS costs are converted from 2022 dollars to June 2024 euros with the average 2022 dollar to euro conversion rate of 0.951 and CPI increase of 7.8% from 2022 average to June of 2024 [56].

However, recent surveys indicate that stationary BESS costs have decreased significantly in recent years due to decreased raw-material costs [60]. The prices in Europe can be estimated with the data in [60] to be ~180 k$/MWh which is significantly lower than the values presented by NREL [59]. The difference can be explained because the values in [59] does not consider market developments, which is a likely explanation for the differences in the values. Therefore, this study assumes the low value for BESS CAPEX from NREL [59] presented in Table 6.

The NREL has estimated the fixed O&M to be a high-end value from different literature sources. NREL selected this value as it assumes that the BESS maintains the maximum capacity during the entire lifetime of its operation [59] with additional investments covered in the O&M costs. However, the technical lifetime of the BESS is assumed to be 15 years [59]. Therefore, an additional BESS investment is included in year 16 of the economic model to allow assuming that the BESS is operated during the entire economic lifetime of the hybrid power plant. The BESS reinvestment includes only the battery cell costs which is 78% of the total BESS cost according to [61]. The reinvestment BESS cost is assumed to be the 2040 CAPEX estimate from NREL [59] multiplied by 78%. Table 6 shows both the assumed values for O&M costs and the reinvestment CAPEX.

Table 6: Assumed BESS costs in this study based of values from [59].

Parameter	Initial CAPEX	Reinvestment CAPEX	Fixed O&M	Variable O&M
Unit	k€/MWh[a]	k€/MWh[a]	k€/MWh[a]	€/MWh[b]
Value	296	206	11.93	0.0

Note: The values are adjusted with Finnish CPI to represent June 2024 euro.
Abbreviation: BESS, battery energy storage system.
[a]Euros per storage capacity in MWh.
[b]Euros per MWh discharged.

2.7.3. WACC. In [27] and [41], a WACC of 7% was used in valuation of the HPP investment. In this study, a further analysis of the WACC is made utilizing the appropriate WACC parameters based on the methodology in [62]. Equation (21) shows the calculation method used to calculate an estimate for the WACC. E and D are the equity and debt rates of the analyzed company and τ is the corporate tax rate. This study assumes that $D = 70\%$ and $E = 1 - D = 30\%$ which is according to the European association for wind industry WindEurope, in range of typical companies investing to WPPs [63]:

$$\text{WACC} = \frac{E}{E+D} r_E + \frac{D}{E+D} r_D (1-\tau). \quad (21)$$

r_E represents a cost of equity which is calculated utilizing Equation (22). The RfR in the equation is the risk-free rate which is typically defined as 10-year government bond yield rate which is seen according to [64] suitable in typical mature market situations. Thus, this study uses the October 2024 average 10-year government bond yields of Finland and Sweden to define the RfR:

$$r_E = RfR + \beta \times \text{MRP}. \quad (22)$$

The MRP represents the market risk premium which indicates additional return exceeding the risk-free rate in the specified market portfolio [62]. The values for Finland and Sweden are the results surveyed in [65]. The variable β indicates how the specific investment risk compares to the entire market portfolio. When $\beta > 1$, the specific investment opportunity is more volatile than the entire market [62]. The beta is estimated with unlevered beta $\beta_U = 0.53$, which is estimated in [66] for publicly listed European green and renewable energy companies. A levered beta is then calculated utilizing an Equation (23) which adjusts the β_U to the specified debt-to-equity ratio:

$$\beta = \beta_U \left(1 + (1-\tau)\frac{D}{E}\right). \quad (23)$$

Finally, r_D represents the cost of debt which is calculated with Equation (24). RfR_{EU} represents an European risk-free rate which is defined with 10-year German government bond yield rates in [62] as a representative economy of Europe. This study utilizes the October 2024 value of 2.39% [67]. Moreover, the CDS represents credit default swap spread [62], which values are selected from [66], and the calculation

Table 7: Financial parameters used in the calculation on the cost of debt, cost of equity, and calculated WACC for Finland and Sweden.

Parameter	Unit	Finland	Sweden	References
τ	%	20.0	20.6	[50]
RfR	%	2.82	2.02	[69, 70]
MRP	%	6.20	5.70	[65]
CDS	%	0.34	0.28	[66, 68]
β	—	1.66	1.65	[66]
Results		**Finland**	**Sweden**	
r_E	%	13.1	11.6	—
r_D	%	5.7	5.7	—
WACC	%	7.1	6.6	—
$\text{WACC}_{\text{real}}$	%	5.0	4.5	—

Abbreviation: WACC, weighted average cost of capital.

method is presented in [68]. Finally, the PS represents a project spread specific for the HPP [62]. This study assumes a value of 3.0%, which was assumed in [62] for onshore WPPs:

$$r_D = RfR_{\text{EU}} + \text{CDS} + \text{PS}. \quad (24)$$

The selected parameters and calculated cost of equity, cost of debt, and WACC are shown in Table 7 for Finland and Sweden. The WACC for Finland is calculated at 7.2%, which is close to the previously assumed 7%. The WACC in Sweden is slightly lower at 6.7%, which is explained mainly by the lower risk-free-rate. In addition, a real WACC where the future inflation assumption is deducted with the Fisher equation (Equation 25) is shown in Table 7. The real WACC is utilized to calculate the LCOE (Section 2.7.4):

$$\text{WACC}_{\text{real}} = (1 + \text{WACC})/(1 + r_{\text{inflation}}) - 1. \quad (25)$$

2.7.4. LCOE. To compare the resulting capture prices to NPVs in the results section, a LCOE is calculated for each power plant configuration in all locations. The LCOE is calculated by dividing the discounted costs of power plant operation with the discounted power generation (Equation 26):

$$\text{LCOE} = \frac{\sum_{i \in I} (C_i^{\text{CAPEX}} + C_i^{\text{O\&M}})(1 + \text{WACC})^{-1}}{\sum_{i \in I} (E_i^{\text{WPP}} + E_i^{\text{PV}})(1 + \text{WACC}_{\text{real}})^{-i}}. \quad (26)$$

Figure 3 shows the LCOEs for each power plant configuration in all locations. The figure shows that the LCOE is lowest for the *WIND* cases and highest for the *PV* cases. The

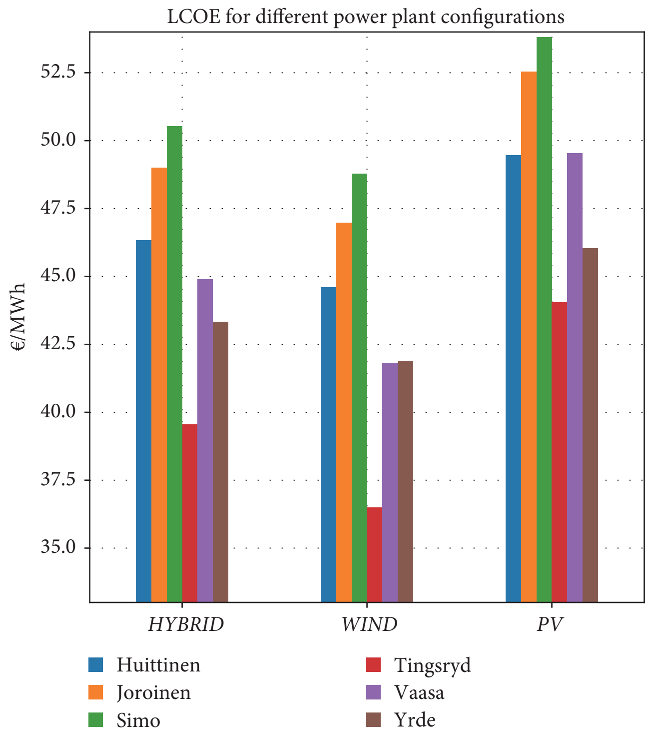

Figure 3: Levelized cost of electricity (LCOE) in different locations for HYBRID, WIND, and PV cases. The LCOEs do not include the costs of BESS and taxes. BESS, battery energy storage system.

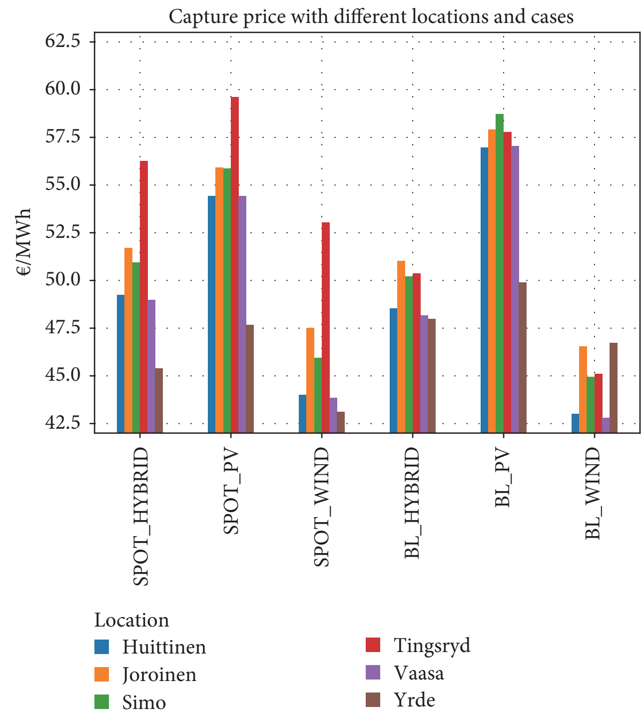

Figure 4: Capture prices of the modeled cases in different locations. PP cases are not shown because the capture price is the same as the pay-as-produced PPA price PP cases. PPA, power purchase agreement.

HYBRID cases are between of other two cases as can be expected. The LCOEs show that the *PV* cases must have a higher capture price compared to *HYBRID* and *WIND* cases to achieve the same profitability. It is important to note that the LCOE calculation does not include the costs from corporate taxes which disallows direct comparison of capture prices and LCOEs because the tax expenses depend on which case is inspected. Thus, the capture prices must be slightly higher than the LCOE to have a positive NPV.

3. Results and Discussion

3.1. Capture Price. Figure 4 shows the capture prices yielded by the hourly operating model for all cases and locations. While interpreting the results, it is important to note the differences of average DA spot market prices. The SE4 bidding area where the Tingsryd is located had the highest price of 64.8 €/MWh and SE3 bidding area where Yrde is located had the lowest price of 51.7 €/MWh in 2023. The locations in Finnish bidding area encountered the price of 56.5 €/MWh in 2023, which is between the average prices in SE4 and SE3.

Figure 4 also shows that the Tingsryd site would clearly achieve the highest capture price when a PPA is not made. However, with a baseload PPA, the capture price would be at the same level as in the Finnish locations. This can be explained by the low baseload PPA price (55 €/MWh) compared to the average spot prices in SE4 bidding area. The opposite occurs in Yrde where the *BL* cases yield higher capture prices than *SPOT* cases, which is explained by the higher PPA price than the average spot price.

In the Finnish locations, the variation is relatively low. However, the Vaasa and Huittinen locations are achieving slightly lower capture prices than locations in Joroinen and Simo. This is likely explained by the geographical proximity to existing wind power capacity and the profit cannibalization due to higher probability of producing electricity simultaneously with other wind generation [71, 72]. As Western Finland has the highest concentration of wind power in Finland [73], Vaasa and Huittinen can be expected to yield the lowest capture prices in Finland.

When comparing the results from *WIND*, *PV*, and *HYBRID* cases, the *WIND* cases yield clearly the lowest and *PV* cases the highest capture prices and *HYBRID* case is in between the other cases. This indicates that the PV power production hours achieve significantly higher electricity prices compared to the WPP. The main contribution for the difference is probably the profit cannibalization level of wind power which is expected to be more dire compared to PV in the Nordic countries due to more developed wind power capacity in contrast to PV power capacity discussed in Section 1. Thus, the results indicate that the *HYBRID* cases capture prices improve compared to *WIND* cases due to the better performance of PVPP in DA spot market.

For illustrating the revenue creation of analyzed VRE power plants compared to overall spot market situation, Figure 5 shows the capture rates, that is, the capture price divided by the annual average spot price. In *SPOT* cases, the capture rate in *WIND* cases is close to 0.9 and the *PV* cases close to 1.0. These results indicate that the profit cannibalization effect is more significant for wind power than for PV power.

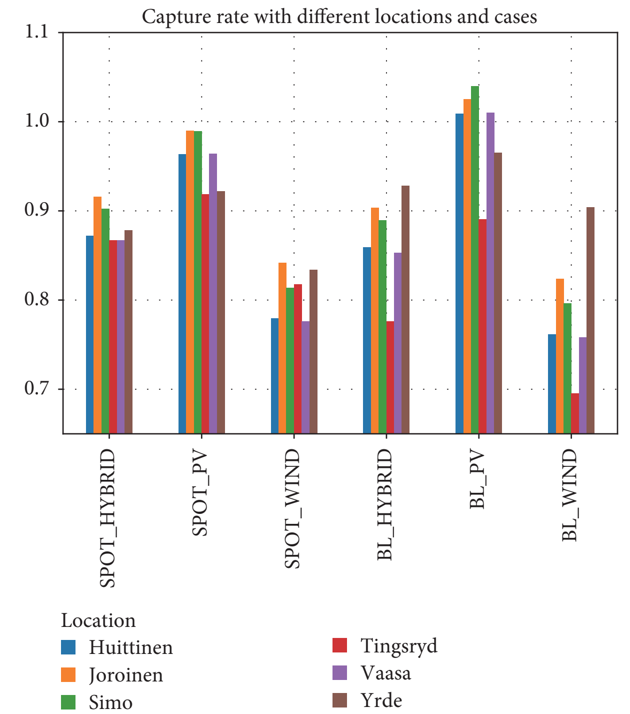

FIGURE 5: Capture rates of modeled cases in different locations.

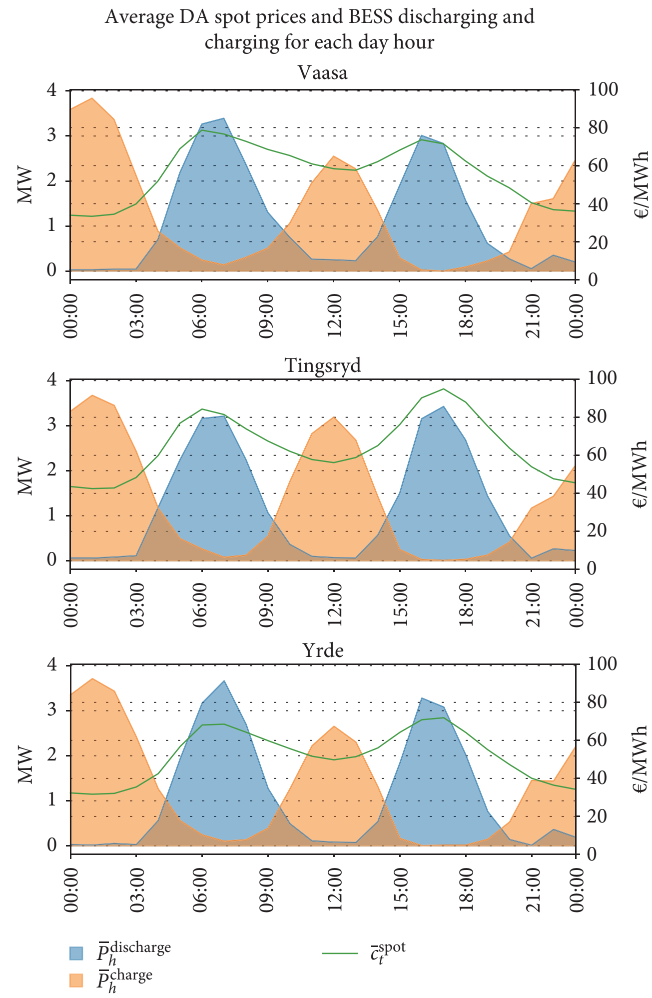

FIGURE 6: Average DA spot market price and BESS discharge and charge power for each hour of the year 2023. DA, day ahead; PPA, power purchase agreement.

Moreover, the *BL PV* case achieves the highest capture rate of all cases although the PPA price is lower (50 €/MWh) due to the monthly resolution for defining the PPA volume. This is likely explained by avoiding balancing power procurement during wintertime when the PPA volume is 0 MWh. In addition, during other seasons, the *BL PV* case requires more balancing power procurement during night hours which have lower spot prices (Figure 6), thus, getting additional revenue from procuring cheap power and selling it with the higher PPA price. However, this result questions if the consumer should procure the electricity with this kind of PPA because the consumer could alternatively buy the same power from the DA spot market with a lower price.

Furthermore, Figure 5 shows that in Finland, the *BL* cases have a little impact on the capture rates compared to *SPOT* cases except for the *PV* case. This indicates that the DA spot market exposure due to balancing requirements in *BL* cases has a similar impact as the potential revenues solely from the spot market for the VRE power plants analyzed. However, the baseload PPA may protect the producer from lower electricity market prices as seen in the site in Yrde assuming no price indexing to electricity market prices in the PPA.

3.2. BESS. Figure 7 shows the revenue creation of the BESS in relation to the overall revenue of the power plants. The BESS revenue is estimated with Equation (27), which calculates the total revenues and expenses in the DA spot market with BESS discharging and charging:

$$R^{\text{BESS}} = \sum_{t \in T} c_t^{\text{spot}} \left(P_t^{\text{discharge}} - P_t^{\text{charge}} \right). \qquad (27)$$

The results show that the BESS increases the annual revenues of the power plant by 1.6%–2.6%. In addition, the highest benefit of BESS is with only the WPP and the lowest benefit with the PVPP. However, the additional revenues from the BESS are less than the investment and operating costs over the lifetime for the HPP, which suggests that the BESS investment is not economically justified [27, 41]. The economically optimal size was calculated for the *PV* and *WIND* cases in this study with the same outcome.

When inspecting the absolute revenues of BESS in different cases in the same price area, the values vary only by a small fraction. The larger percentages for the WPP as the WPP annual revenues are the lowest. This is explained by the behavior due to the optimization problem where the BESS is operated to maximize revenues by shifting production to higher DA spot prices in addition to a minor possibility to avoid curtailment. Thus, Figure 6 shows the differences of the BESS discharging and charging with average day hour values with three different DA market price data, which shows the highest variation between the cases.

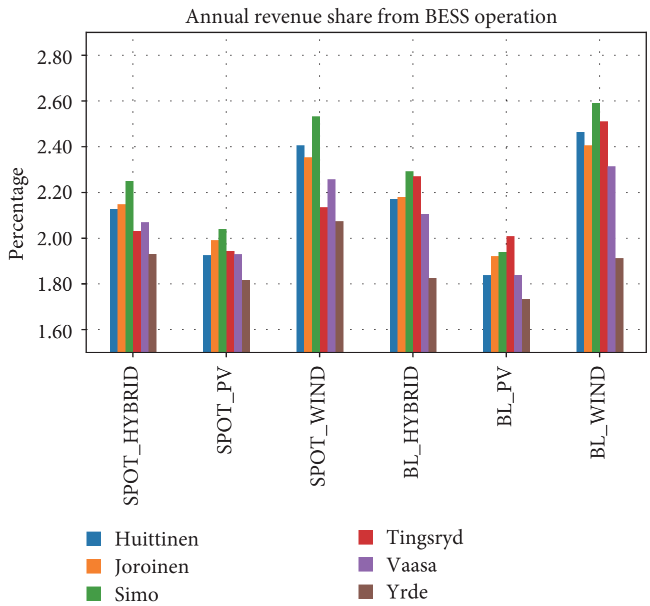

FIGURE 7: Annual revenue share created by BESS discharging and charging cycles for different cases and locations. BESS, battery energy storage system.

The figure shows that the BESS operates generally in the same manner. The night and noon hours are reserved for the charging and peak price hours of morning and evening are reserved for discharging. The main difference is the charging depth during noon, which depends on how much the electricity prices decrease compared to the peak hours in each market area. In Tingsryd (SE4), the difference is most significant which leads to more charging during noon compared to Vaasa (FI) and Yrde (SE3).

In conclusion, the operation of BESS with the operating strategy analyzed allows increased revenues for the power plant. However, the recent literature has shown that the BESS does not increase the power plant profitability after accounting for the operating costs and CAPEX [27, 74]. The simplicity of the model may understate the actual potential of the BESS due to the potential flexibility of the BESS. According to [30], the BESS economic benefits could be maximized by participating in intraday and auxiliary markets in addition to the DA spot market as the BESS could be flexible enough to allocate the production to find the most valuable electricity prices. For example, the BESS profitability could be increased by participating in a frequency containment reserve (FCR) market where the capacity volume and power generation could be allocated to the FCR market [75].

3.3. NPV. Figure 8 shows the NPVs for each case and location. The figure shows that the current investment environment for wind and PV power in Finland and Sweden is dire. Most of the locations in Finland yield negative NPVs. In Sweden, the Tingsryd is the only location that has clearly a positive NPV which can be contributed to the high capture price from high average DA spot prices and good CFs of wind and PV power.

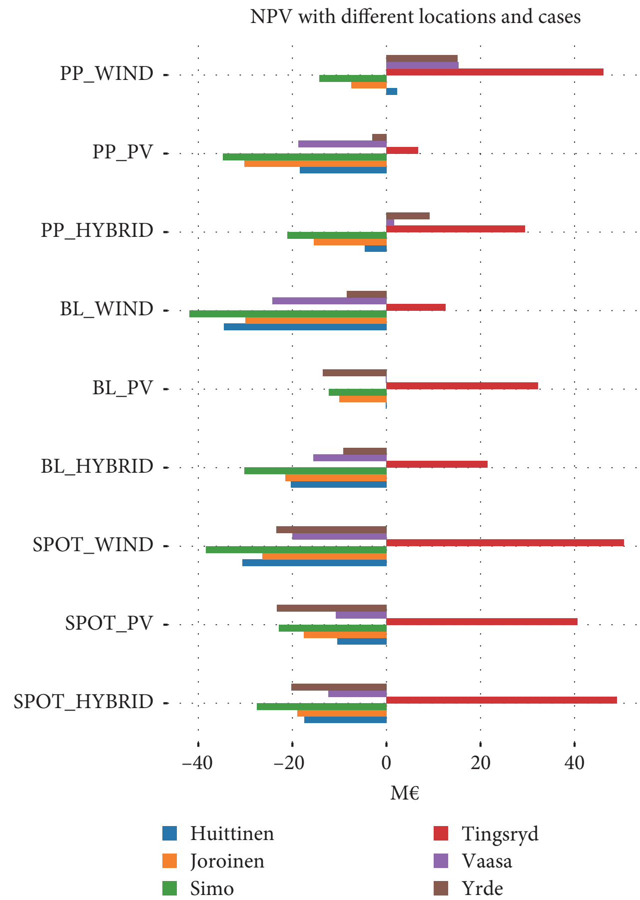

FIGURE 8: Net present values of modeled cases in different locations.

The results for *PP* cases are the most straightforward to interpret as the capture prices of *PP* cases are always the PPA price of 50 €/MWh. The *PP PV* case profitability is modest, which can be explained with higher PV LCOE (Figure 3), in many cases, higher than the 50 €/MWh PPA price. Similar but less dire results are found with the *PP HYBRID* case, where LCOEs are too high in some locations. The *PP WIND* case achieves positive NPVs in most locations, which again can be explained with the lower wind LCOE compared to the PPA price. However, the willingness of power consumers to agree on pay-as-produced PPAs is questionable especially as the *SPOT WIND* case achieves generally lower capture prices compared to the PPA price (Figure 4). Thus, the consumer would have to pay more from PPA while carrying the profile risk instead of procuring power from the spot market at a lower price.

The *BL* cases show that the *PV* case would yield the highest NPVs, which is primarily explained by the exceptionally high capture price due to the monthly PPA volume. The lowest NPVs are found in *BL WIND* case explained by the lowest capture prices. Moreover, similar results are found with the *SPOT* cases with the exception that the *SPOT PV* case NPVs are closer to the results of the *SPOT HYBRID*. This is explained by the small difference in capture rates between these cases. The NPVs overall are slightly higher

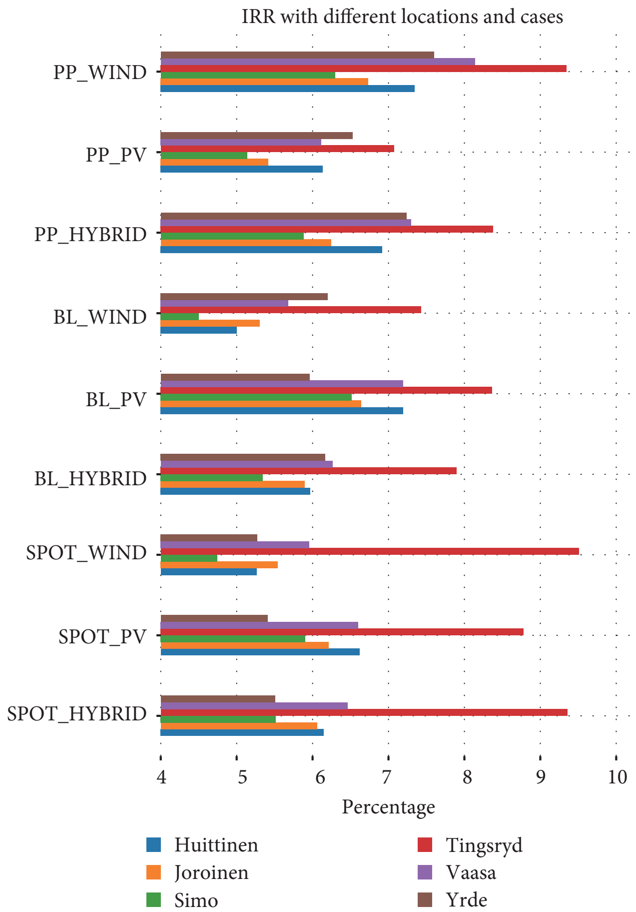

Figure 9: Internal rates of return of modeled cases in different locations.

in the *SPOT* cases compared to the *BL* cases, which is due to the slightly higher capture rates.

Based on this analysis, the hybrid power plant brings benefits as a lower LCOE when increasing the share of wind power capacity, and as a higher capture price when increasing the PV power capacity. The results indicate that the wind-only power plant is still the most beneficial with pay-as-produced PPAs due to the lowest LCOE. The PV-only power plant is the most beneficial when the production is exposed to the DA spot market prices or to profit cannibalization effect. However, the PV power capacity is expected to increase considerably in the Nordics in the future (Section 1). Thus, the profit cannibalization effect will increase for the PV power as well if the new projects are realized. Thus, in future, the PV power profitability might encounter the same problems as wind power currently.

3.4. IRR. Figure 9 shows the IRRs for each location and case. The differences in the locations and cases are explained by the findings discussed with the NPV results (Section 3.3). However, the figure illustrates which WACC would enable profitable power plant investment. For example, with 5% WACC, many of the cases and locations could still have a profitable investment for all power plant configurations. The lower WACC values could have been a realistic assumption before the recent increases in cost of debt. According to [76], in 2019, the onshore WPP WACC ranged between 2.4% and 5.0% in Finland and 3.2% and 8.0% in Sweden. Thus, lower WACCs could be expected if the cost of debt decreases in the future.

3.5. Investment Prospects. Based on the results of this study, the investment environment toward VRE power in the Nordics is difficult. With the current WACC and the cannibalization in DA spot market, the investments are not feasible in most situations analyzed in this study. Thus, it is reasonable to expect that the currently planned investments in wind and PV power may not realize without a lower cost of capital or some other revenue streams not analyzed in this study. The PPA prices could be increased to make these investments more profitable. However, other studies analyzing PPAs from the consumer point-of-view expect much lower PPA prices. For example, a study analyzing green hydrogen costs including a power procurement from PPAs has estimated a 33 €/MWh baseload PPA and 30 €/MWh pay-as-produced PPA price [74] and a study located in Spain has assumed the PV pay-as-produced PPA price at 35 €/MWh [77].

Furthermore, the PPA contracts can be expected to have more shape risks for the side carrying it because the increasing amount of VRE production increases the profit cannibalization in the DA spot market. From the producer side of view, the pay-as-produced PPAs are the most desirable option as they avoid the shape risk. For example, Tigerstedt [78] pointed that wind power producers in Sweden have agreed long-term baseload PPAs with prices that are significantly lower than the electricity market prices currently. Currently, a WPP in Sweden is seeking bankruptcy protection due to the exposure to unsustainable electricity market prices with a long-term baseload PPA [78]. It is difficult to expect that the consumers would accept the profile risk from pay-as-produced PPAs without cheap power price which is not sustainable for the VRE power producer in the current market situation based on the results of this study. Thus, the VRE power PPAs have currently significant limitations if configured similarly as in this study.

3.6. Sensitivity Analysis. As the results discussed previously are based on the discounted cash flow calculations, this study inspects the sensitivity of the results for relevant assumed parameters. The sensitivity analysis is conducted by recalculating the NPVs after adjusting the inspected parameter 25% higher or lower. The NPV calculated with base value for the parameter is then deducted by the NPV calculated with the adjusted NPV to acquire a change of NPV if the parameter is changed.

Figure 10 shows a tornado chart visualizing the results of the sensitivity analysis. The figure shows that the 25% reduction of WACC (5.4% in Finland and 5.0% in Sweden) would have the largest positive impact on the project NPV. When comparing to the NPVs in Figure 8, the potential NPV increase could make many of the projects feasible. In addition, the CAPEX reduction of PVPP and WPP and longer investment lifetime could have a significant positive impact on the NPV as well.

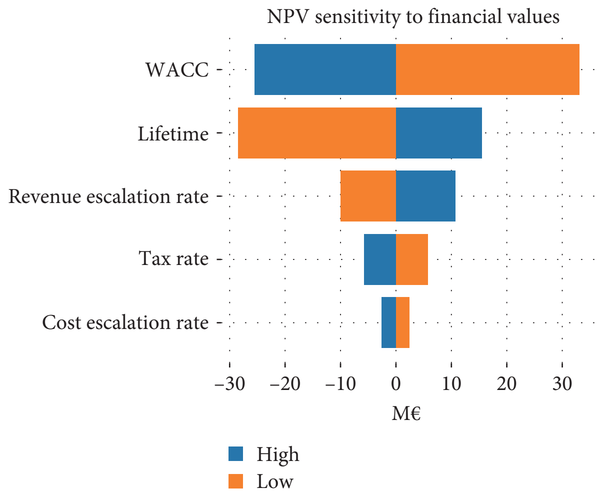

FIGURE 10: NPV sensitivity to the relevant financial parameter. The chart presents how much the NPV changes when the financial parameter is increased or decreased by 25%. The values are the average values of all cases where the parameter is influencing the results, that is, the PV CAPEX is not considered for the WIND cases.

Similarly, the same values, which have a large positive impact, have a significant negative impact on the NPV if the parameter changed to the other direction. The smaller investment lifetime (19 years) would have the largest negative impact which is explained by the effect of discounting the cash flows, increasing the impact of earlier years. Moreover, the revenue escalation rate has a significant negative impact on the NPV if the rate would be worse than assumed. In particular, the figure shows 10 M€ reduction of NPV from the decrease to 1.5% from the 2.0% escalation rate. However, the revenue escalation could also be 0% or even negative if the capture prices decrease in the future. Thus, the investment prospects could be significantly worse if the market situation deteriorates in the future.

4. Conclusions

This study analyzed the operation of WPPs, PVPPs, and HPPs in the Nordic electricity market with different market operations. The influence of pay-as-produced and baseload PPAs on the investment profitability was analyzed. Due to the reduced capture rates in the Nordic electricity market caused by the profit cannibalization of wind power, cases exposed to the shape risk were found generally not profitable due to the low capture rates and high WACC. The investment in Southern Sweden was the only profitable location in all cases due to high average DA spot prices in this bidding area. In addition, the PVPP operation with a monthly baseload PPA was found to be slightly more feasible economically as it benefits from the low cost of procuring balancing power to the PPA consumer.

Moreover, the pay-as-produced PPAs are profitable with the current WACC when the site has high CFs of WPP and PVPP and low LCOE. However, the willingness of consumers to agree to a relatively high price for pay-as-produced PPA while exposed to a significant shape risk in the electricity market is uncertain. In particular, the capture prices of the same profile from DA spot market are in many cases lower than the pay-as-produced PPA price which could allow a lower procurement price for the consumer with the same shape risk. Thus, this study indicates that with the current WACC and VRE power profit cannibalization, the prospects of profitable WPP, PVPP, and HPP investment in the Nordics are challenging with PPAs or power trading in the DA spot market.

This study also included an analysis on the operation of an integrated BESS in the power plant to shift the VRE production to more profitable spot price hours. The results showed that a 1.7%–2.6% increase in operating profits is possible when the 20 MWh/5 MW BESS is installed in the power plant. However, the literature points that the BESS could utilize the high flexibility in intraday and reserve markets to achieve higher profitability. This should be analyzed further in the Nordic power markets where prices are influenced by a high profit cannibalization.

Therefore, to improve the situation in the Nordic electricity markets to allow new investment decision toward VRE power generation, two important factors could improve the situation. First, a decline of WACC would improve the project economics, and this is expected with the cost of debt likely decreasing in near future. Second, new flexible electricity consumption could utilize the low electricity prices when the VRE power generation is high, thus alleviating the price fluctuations. The solutions could be, for example, energy storage systems, flexible hydrogen production, and larger interconnection capacities between the bidding areas, allowing a larger geographical area to benefit from large VRE generation in parts of the Nordics.

Furthermore, the results of this study found that the HPP is never the most optimal power plant configuration in the analyzed cases compared to WPP and PVPP. The WPP was the most optimal with pay-as-produced PPAs by having the lowest LCOE. PVPP, in turn, has the highest capture price allowing the most optimal operation with the baseload PPA and spot market cases containing the shape risk. However, other studies have analyzed the option of upgrading existing WPP to HPP, thus saving in capital costs associated with infrastructure and improving the economic feasibility of HPP. Furthermore, if the cannibalization develops for PV power to the same level as for wind power, the HPP should be analyzed again to identify if it could become the most beneficial option for cases including the shape risk.

Data Availability Statement

Calculation methods and data are available upon request from the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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