energies

MDPI

Article

Optimal Sizing of Hybrid Renewable Energy Sources Under Cable Pooling Conditions

Michał Szypowski, Andrzej Wędzik * and Tomasz Siewierski

Institute of Electrical Power Engineering, Lodz University of Technology, Stefanowskiego Str. 20, PL 90-537 Lodz, Poland; szmich@p.lodz.pl (M.S.); t.siewierski@p.lodz.pl (T.S.)
* Correspondence: andrzej.wedzik@p.lodz.pl; Tel.: +48- (42)-631-26-08; Fax: +48-(42)-631-26-06

Abstract

As renewable energy sources (RESs) become increasingly prevalent, limitations on connecting new sources arise due to insufficient suitable locations and grid constraints. Existing RES installations introduce challenges such as generation variability, the necessity for costly reserves, and overproduction, which can lead to forced outages. In response, grid operators have adopted more flexible connection policies, notably "cable pooling", which only restricts the power injected at a given node rather than the total capacity of the connected sources. This article proposes a method for optimal sizing of diverse RES combinations connected to high-voltage networks under cable pooling conditions from an investor's perspective. The most prominent findings show the existence of a strong relationship between optimal RES sizing and composition on financial objectives, revenue sources, and market prices. Subsequent achievements involve demonstrating that the profitability of energy storage without subsidies is essentially limited to participation in the capacity market and that the reduction of RES generation depends on the investor's financial objective, not on the market type.

Keywords: optimal sizing; hybrid renewable energy sources; cable pooling; energy storage systems

1. Introduction

As renewable energy sources (RESs) become increasingly prevalent, limitations on connecting new sources have emerged due to the scarcity of suitable locations and grid constraints [1]. Existing RES installations introduce challenges such as generation variability, the necessity for costly reserves, and overproduction, which can result in forced outages. Consequently, grid operators who previously calculated the sum of the power from various sources and storage devices at a single connection point are now adopting a more flexible approach known as "cable pooling". This method restricts only the power injected into the network at a specific node, rather than the total power of all connected sources. Cable pooling facilitates a more economical and adaptable solution by enabling the connection of multiple RES technologies and energy storage systems (ESSs) to a single network node, thereby forming a hybrid renewable energy source (HRES). This approach allows for the installation of higher-capacity RESs at a given location and contributes to a more stable power supply, as demonstrated in [2]. Regulatory frameworks have begun to reflect these developments. In Poland, current regulations [3] permit connecting two or more RES installations, potentially owned by different producers, to a common connection point, and a proposed amendment [4] seeks to include ESSs in the cable pooling framework.

Check for updates

Academic Editor: King Jet Tseng

Received: 21 November 2025
Revised: 5 February 2026
Accepted: 9 February 2026
Published: 12 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Hungary has mandated ESS co-location for solar photovoltaic (PV) assets exceeding a certain capacity, while in France, co-located ESSs and PV systems are eligible to participate in the Contract for Differences, which features auctions with high strike prices [5].

The integration of various RESs, constrained by connection capacity or costs, has been addressed in several studies. For example, [6] examines the connection of a hydroelectric power plant to a floating PV (FPV) system located in the adjacent reservoir, and [7] explores the integration of FPV with offshore wind farms and wave energy converters. S. Golroodbari et al. [8] assess the feasibility of adding an offshore FPV farm to an existing Dutch offshore wind farm in the North Sea, considering a fixed cable capacity constraint. The cable linking the offshore park to the onshore grid is currently underutilized due to the wind farm's low-capacity factor. The integration of FPV systems with other renewable technologies is further examined in [9], which demonstrates the feasibility and advantages of such combinations through specific examples. Article [10] illustrates the potential to expand PV capacity by installing new sources at the connection points of existing hydroelectric plants. The benefits of combining PV and wind turbine (WT) sources, including increased installed power and energy output, are documented in [11,12]. K. Obradović et al. [13] investigate the distinct physical design requirements of PV/WT hybrid renewable energy systems compared to single-technology facilities, emphasizing spatial layout optimization, electrical design, and macro-siting. Challenges associated with co-locating WT and PV farms, particularly the shading of PV panels by turbine structures and rotor blades, are discussed in [14]. Additionally, [15] presents a spatiotemporal decision-making model for evaluating the development of utility-scale PV, onshore WT, and hybrid PV/WT power plants, incorporating technology-specific parameters and infrastructure costs into the techno-economic assessment.

Numerous studies have addressed the optimization of HRES composition, with a primary focus on isolated systems implemented in real-world locations lacking grid connectivity. For example, publication [16], developed a Mixed Integer Linear Programming (MILP) optimization algorithm to design an optimal hybrid system comprising solar, wind, and diesel generators, along with battery storage (BESS), for a mountain hut in South Tyrol, Italy. In [17], particle swarm optimization was employed to determine the optimal sizing of a solar/wind/battery HRES for a rural community in Rivers State, Nigeria, aiming to minimize total economic cost, total annual system cost, and levelized cost of energy using a two-step approach. The Hybrid Optimization Model for Multiple Energy Resources (HOMER) Pro Software (v. 3.11) was utilized in [18] to minimize net present cost, cost of energy, and CO_2 emissions for a hybrid energy system (solar, wind, and diesel-powered generator) with battery storage in northern Bangladesh. Medina-Santana et al. [19] introduced a sizing methodology incorporating long short-term memory cells for long-term weather prediction, multivariate clustering for scenario generation, and a nonlinear mathematical formulation to determine optimal HRES sizing for a rural community on Mexico's Pacific Coast. K. Kusakana et al. [20] applied linear programming to optimize the initial cost of system components in islanded PV/WT hybrid renewable energy systems. In [21], the Jaya-Grey Wolf Optimizer, a novel hybrid optimization tool, was used to optimize HRES component sizing for smooth operation and cost-effectiveness, achieving the dual objectives of minimizing net annual cost and the probability of power supply loss in a standalone microgrid. Genetic Algorithm and Particle Swarm Optimization techniques were implemented in [22] to select the optimal size of photovoltaic/wind/battery HRES. In [23], an optimal sizing method for a PV and ESS system was proposed to maximize annual net profit from electricity sales to the Dutch day-ahead market, with the results analyzed as a function of energy and technology prices.

The selection of an optimal HRES structure to ensure adequate customer demand coverage or minimize network exchange has been extensively investigated. M. A. Mohamed et al. [24] optimized on-grid renewable energy systems using multiple renewable sources, emphasizing large-scale applications tailored to specific energy loads. The study employed the Walrus Optimization Algorithm, Coati Optimization Algorithm, and Osprey Optimization Algorithm to identify optimal system sizing and energy management strategies that reduce grid electricity costs. Ref. [25] proposed an optimal sizing strategy for a grid-connected PV/WT hybrid system with demand-side scheduling, modeling energy consumption for various load types to facilitate scheduling. Paper [26] reported on linear programming optimization models for PV/WT hybrid system, demonstrating their effectiveness in reducing grid energy use in wine production. Paper [16] presented an optimal sizing method for hybrid energy systems integrating PV, WT, and BESS, ensuring that total monthly solar and wind energy generation meets monthly energy demand. In publication [27], the primary objective was to supply the base load in the Helsinki area using HRES size optimization. The results indicate that an HRES is at least 10.5 times more cost-effective than a single-source RES.

The recent literature has examined several challenges associated with HRES under cable pooling conditions. Paper [11] analyzes energy curtailment, time duration, the capacity factor, and enhancements in the stability coefficient of the grid system in PV/WT hybrid renewable energy system operating under cable pooling conditions. Ref. [28] addresses the selection of suitable deep learning models for multistep, multivariate forecasting of 24 h PV/WT generation in cable pooling scenarios.

From the literature presented, various objectives for HRES structure optimization emerge: grid electricity cost [24] or grid exchange [26], demand-side scheduling [25], monthly [16] or base [27] Energy demand, improvement capacity factor and stability coefficient [11,29], sustainable balance among energy production, economic viability, and environmental responsibility [30], system stability [31], cost minimization while ensuring energy demand coverage in isolated systems [17–23]. Authors employ a wide range of optimization methods. In computational practice, both linear methods (e.g., Linear (LP) and Mixed Integer Linear Programming (MILP) optimization algorithms) and nonlinear ones (NLP, Genetic Algorithm, and Particle Swarm Optimization) are utilized. In recent years, researchers have also turned to modern hybrid methods, such as the Jaya-Grey Wolf Optimizer, Walrus Optimization Algorithm, Coati Optimization Algorithm, and Osprey Optimization Algorithm. The choice of these methods depends on how the problem is formulated and the complexity of the mathematical model used.

The authors of the article in publication [32] introduced a method for selecting the energy-supply structure for residential premises based on hourly energy consumption and generation. The present study adopts this method to determine, from the investor's perspective, the optimal sizing of an HRES source connected to a high-voltage network under cable pooling conditions. The grid-scale installation, as illustrated in Figure 1, comprises the most used RES technologies–PV and WT–supplemented by a lithium-ion BESS, reflecting current market practices. The objective of this study is to analyze the relationship between the optimally selected device composition and variables such as the investor's financial goal, the type of market from which revenues are derived, and prevailing market prices. A notable research gap exists regarding the influence of HRES income sources and an investor's financial objectives on HRES composition, particularly under cable pooling conditions. This paper addresses this gap by investigating the following topics:

1. How does the choice of income source influence the optimal HRES structure?
2. How does an investor's financial goal influence the optimal HRES structure?
3. When is it profitable to include the BESS in the HRES structure?
4. How significant is the advantage of HRES over single-source RES?
5. How large is RES generation reduction under cable pooling conditions?

The first and second of the above points have not yet been addressed in any sources known to the authors.

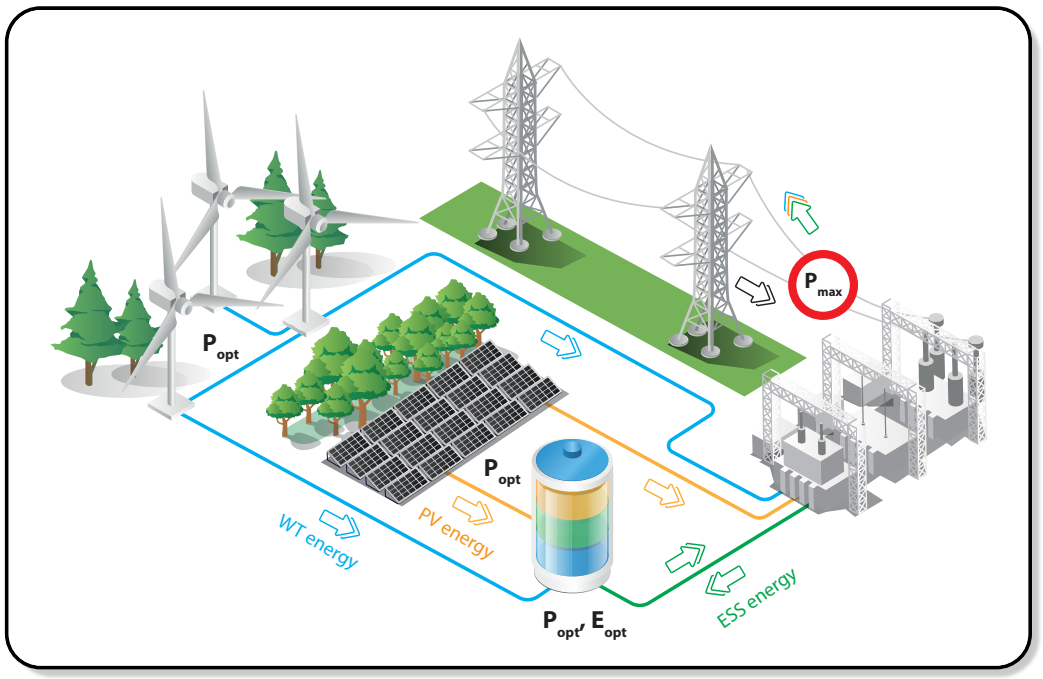


Figure 1. The structure of the analyzed hybrid renewable energy system.

The remainder of the paper is organized as follows: Section 2 defines the problem, Section 3 presents its mathematical formulation, Section 4 details the calculations and results, Section 5 discusses general observations, and Section 6 provides the conclusion.

2. Definition of the Optimization Problem

The optimization problem involves determining the power and capacity of PV, WT, and lithium-ion battery ESS installations composing the HRES. The objective is to maximize the financial return on investment while restricting the exchange of active power with the grid to a specified constant value, set at 100 MW for this study. For grid-scale RES most often, the limit is based on the technical and operational parameters of the HV network to which the RES is connected and is determined by the transmission or distribution system operator. Investment efficiency is evaluated using the Net Present Value (NPV) method. Three variants of the financial objective are analyzed:

1. Maximizing the ratio of NPV to capital costs, NPV/CAPEX.
2. Maximizing NPV while maintaining a minimum NPV/CAPEX ratio. In this study, NPV is required to be at least 0.9 times CAPEX, corresponding to an average annual capital income of at least 3%.
3. Maximizing NPV with a constraint on CAPEX. For this analysis, CAPEX is limited to \$300 M (equivalent to \$3000 per kW of connection capacity).

The three financial objectives listed above were selected due to limitations of the applied optimization methods. These objectives are expected to be achieved using a simplified formula. First, maximize the financial leverage of initial outlays (NPV/CAPEX). Second,

maximize NPV while achieving a minimum expected rate of return on invested capital. The 3% average rate of return applied in the second optimization objective corresponds to the cash flow discount rate used in the NPV calculation. The weighted average cost of capital (WACC) for bankable power generation projects in the European Union ranges from 14% to 1.1%, depending on the technology, risk tolerance, and geographic location, with the lowest values observed for PV projects in Germany. Third financial objective, maximize NPV while accounting for investment constraints (CAPEX) resulting from limited available capital. The assumed amount, \$300 M, allows for an investment comprising of approximately 100 MW WT combined with 100 MW PV and 100 MW ESS with a capacity of 100 MWh.

For each financial objective, three types of installation revenue sources are evaluated:

1. Power Purchase Agreement (PPA), with a price range of \$50–\$250 per MWh considered. Investments were deemed unprofitable for PPA prices below \$50 per MWh.
2. Day Ahead Market (DAM), with DAM price variations ranging from one-quarter to four times the base prices.
3. Capacity Market (CM) in combination with DAM, with a CM price range of \$40–\$300 per MW considered.

The selected price ranges ensure that further increases or decreases do not significantly influence the optimal HRES composition or result in an unprofitable investment (NPV < 0).

For comparison, the optimization was also performed for individual technologies. A 30-year operational lifetime is assumed for all installations (based on [33–35]), except for batteries, which are assigned a 15-year lifetime. Repeatable annual generation cycles are modeled using weather data for PV installations [36] and actual WT generation data (own data from a real installation). Similarly, a repeatable annual cycle is used for DAM, based on data from [37]. This approach introduces uncertainty, particularly regarding DAM price fluctuations, which are simulated through various DAM price levels. Previous research has examined the impact of wind and PV generation fluctuations [14], revealing that, provided that total annual generation remains constant, these fluctuations have a minimal effect on the selection of installation parameters. Over longer periods, generations may change due to climate change, although the extent of such changes is uncertain. Additional parameters include the potential reduction of ESS investment costs through subsidies.

The degradation of storage capacity over time is not explicitly modeled for the sake of simplicity and because the level of degradation depends on the exact battery chemistry. It can be partially addressed by increasing capital capacity costs and decreasing capacity limits. For example, a 20% degradation over 15 years corresponds to approximately a 10% increase in capital capacity costs and narrowing the capacity range from 1 to 10 h to between 0.9 and 9 h. Sample calculations for the capacity market and 20% degradation over 15 years using this simplified method confirmed that although the exact results depend on the inclusion of ESS capacity degradation, the general conclusions remain unchanged.

The calculations limit the annual number of battery cycles to the number corresponding to 320 full discharges, which, given an assumed lifespan of 15 years, results in a total of 4800 cycles, which is consistent with the value given in the literature.

An hourly generation interval is adopted as a simplification; a shorter interval may be used to reduce calculation uncertainty if data are available. Due to the specificity of the optimization problem described and the various financial objective variants adopted by the authors; two types of optimization methods (computational engines) will be used for the calculations. These include an LP algorithm for solving financial objectives 2 and 3, and an NLP algorithm for solving financial objective 1. A more detailed description of the selected algorithm's structure is provided in Section 3.

All data was taken from the available current sources for actual installations and is included in Appendix B.

3. Mathematical Model

Cases under consideration:

Case 11 – PPA, financial objective 1;
Case 12 – PPA, financial objective 2;
Case 13 – PPA, financial objective 3;
Case 21 – DAM, financial objective 1;
Case 22 – DAM, financial objective 2;
Case 23 – DAM, financial objective 3;
Case 31 – CM, financial objective 1;
Case 32 – CM, financial objective 2;
Case 33 – CM, financial objective 3.

Objective functions:

F.1. **Objective function 1.**–maximizes the ratio of total NPV to capital costs:

$$f = -\frac{Total_NPV}{Total_CAPEX}, \qquad \text{for cases 11, 21 and 31.} \tag{1}$$

F.2. **Objective function 2.**–maximizes the total NPV value over the installation lifetime:

$$f = -Total_NPV, \qquad \text{for cases 12, 13, 22, 23, 32 and 33.} \tag{2}$$

Common constraints:

Total CAPEX calculation [$] as a sum of five components: costs common for the whole site, costs related to power of PV, WT and ESS, and costs related to ESS capacity taking into account the level of ESS funding (β):

$$\begin{aligned} Total_CAPEX = \\ 1000 \cdot \Big[& Common_CAPEX \cdot Max_Connection_Power + (WT_CAPEX - \\ & Common_CAPEX) \cdot WT_Installed_Power + \\ & (PV_CAPEX - Common_CAPEX) \cdot PV_Installed_Power + \\ & (ESS_Power_CAPEX - Common_CAPEX) \cdot (1-\beta) \cdot ESS_Installed_Power + \\ & ESS_Capacity_CAPEX \cdot (1-\beta) \cdot ESS_Installed_Capacity \Big]. \end{aligned} \tag{3}$$

Total NPV calculation [$] as a sum of yearly income from all three considered markets multiplied by constant reflecting their 30-year discounted sum, taking into account the level of DAM prices (α) and active participation in DAM (ACT), and less-so the 30-year discounted sum of installation O&M costs and less CAPEX:

$$\begin{aligned} Total_NPV = \\ & NPVC \cdot \Big[ACT \cdot \Big(\sum_{i=1}^{NH} (Grid_Sold_Energy(i) \cdot \alpha \cdot (DAM_Energy_Price(i) - Imbalance_Cost)) - \\ & \sum_{i=1}^{NH} (Grid_Bought_Energy(i) \cdot (\alpha \cdot (DAM_Energy_Price(i) + Imbalance_Cost) + \\ & Transmission_Fee)) + 1000 \cdot CM_Power_Price \cdot ESS_Power_In_CM \Big) + \\ & (1 - ACT) \cdot PPA_Energy_Price \cdot \sum_{i=1}^{NH} Grid_Sold_Energy(i) \Big] - \\ & 1000 \cdot NPVC \cdot [Common_O\&M_Cost \cdot Max_Connection_Power + \\ & (WT_O\&M_Cost - Common_O\&M_Cost) \cdot WT_Installed_Power + \\ & (PV_O\&M_Cost - Common_O\&M_Cost) \cdot PV_Installed_Power + \\ & (ESS_Power_O\&M_Cost - Common_O\&M_Cost) \cdot ESS_Installed_Power + \\ & ESS_Capacity_O\&M_Cost \cdot ESS_Installed_Capacity] - Total_CAPEX. \end{aligned} \tag{4}$$

For assurance of the full use of grid connection capacity, the sum of the installed RES power has to be at least equal to connection capacity:

$$WT_Installed_Power + PV_Installed_Power + ESS_Installed_Power \geq Max_Connection_Power. \quad (5)$$

ESS capacity assumed to be between 1 and 10 h:

$$ESS_Installed_Power \leq ESS_Installed_Capacity \leq 10 \cdot ESS_Installed_Power. \quad (6)$$

Empty storage at the year's start:

$$ESS_Stored_Energy(0) = 0. \quad (7)$$

Empty storage at the year's end:

$$ESS_Stored_Energy(NH) = 0. \quad (8)$$

Energy balance at the i-th hour:

$$\begin{aligned} &WT_Used_Energy(i) + PV_Used_Energy(i) + ESS_Discharging_Energy(i) - \\ &ESS_Charging_Energy(i) = \\ &(1 + Auxiliary_Energy_Losses) \cdot Grid_Sold_Energy(i) - Grid_Bought_Energy(i). \end{aligned} \quad (9)$$

Energy sent to grid not greater than the grid connection capacity:

$$0 \leq Grid_Sold_Energy(i) \leq Max_Connection_Power. \quad (10)$$

Energy acquired from grid not greater than the grid connection capacity and equal 0 at PPA market:

$$0 \leq Grid_Bought_Energy(i) \leq Max_Connection_Power \cdot ACT. \quad (11)$$

Used WT energy at the i-th hour not greater than available generation:

$$0 \leq WT_Used_Energy(i) \leq WT_Output(i) \cdot WT_Installed_Power. \quad (12)$$

Used PV energy at the i-th hour not greater than available generation:

$$0 \leq PV_Used_Energy(i) \leq PV_Output(i) \cdot PV_Installed_Power. \quad (13)$$

Energy stored in ESS at the i-th hour:

$$\begin{aligned} ESS_Stored_Energy(i) = \; & ESS_Stored_Energy(i-1) + \\ & ESS_Charging_Energy(i) \cdot ESS_Efficiency - \\ & \frac{ESS_Discharging_Energy(i)}{ESS_Efficiency}. \end{aligned} \quad (14)$$

ESS discharging power at the i-th hour not greater than installed ESS power:

$$0 \leq ESS_Discharging_Energy(i) \leq ESS_Installed_Power. \quad (15)$$

ESS charging power at the i-th hour not greater than installed ESS power:

$$0 \leq ESS_Charging_Energy(i) \leq ESS_Installed_Power. \quad (16)$$

ESS stored energy at the i-th hour not greater than installed ESS capacity:

$$0 \leq ESS_Stored_Energy(i) \leq ESS_Installed_Capacity. \quad (17)$$

Constraint limiting the annual number of ESS cycles:

$$ESS_Efficiency \cdot \sum_{i=1}^{NH} ESS_Charging_Energy(i) \leq \frac{Battery_Cycle_Life}{Battery_Year_Life} \cdot ESS_Installed_Capacity. \quad (18)$$

Case-dependent market specific constraints:

For cases 11, 12 and 13, energy cannot be bought from the grid:

$$ACT = 0. \quad (19)$$

For cases 21, 22, 23, 31, 32 and 33, energy can be bought from the grid:

$$ACT = 1. \quad (20)$$

For cases 11, 12, 13, 21, 22 and 23, there is no CM in these cases:

$$ESS_Power_In_CM = 0. \quad (21)$$

For cases 31, 32 and 33, ESS power assigned to CM not greater than connection capacity:

$$0 \leq ESS_Power_In_CM \leq Max_Connection_Power. \quad (22)$$

For cases 31, 32 and 33, ESS power assigned to CM not greater than ESS power:

$$ESS_Power_In_CM \leq ESS_Installed_Power. \quad (23)$$

For cases 12, 22 and 32, average yearly income $\geq$ 3%:

$$Total_NPV \geq 3\% \cdot NH \cdot Total_CAPEX. \quad (24)$$

For cases 13, 23 and 33, CAPEX is limited to \$3 M per 1 MW of connection capacity:

$$Total_CAPEX \leq 3{,}000{,}000 \cdot Max_Connection_Power. \quad (25)$$

The search variables are as follows:

$ESS_Installed_Capacity$ – Installed ESS useful capacity [MWh];
$ESS_Installed_Power$ – Installed ESS power [MW];
$PV_Installed_Power$ – Installed PV panels power [MWp];
$WT_Installed_Power$ – Installed WT power [MW].

Other variables used in the model:

ACT – ESS active market participation indicator [Boolean];
$ESS_Charging_Energy(i)$ – ESS charging energy at the i-th hour [MWh];
$ESS_Discharging_Energy(i)$ – ESS discharging energy at the i-th hour [MWh];
$ESS_Stored_Energy(i)$ – Energy stored in ESS at the end of the i-th hour [MWh];
$ESS_Power_In_CM$ – ESS power assigned to CM [MW];
$Grid_Bought_Energy(i)$ – Electricity bought from grid at the i-th hour [MWh];
$Grid_Sold_Energy(i)$ – Electricity sale to grid at the i-th hour [MWh];
$PV_Used_Energy(i)$ – Used solar energy at the i-th hour [MWh];
$Total_CAPEX$ – total capital investment [$];
$Total_NPV$ – NPV value over installation lifetime [$];
$WT_Used_Energy(i)$ – Used wind energy at the i-th hour [MWh].

Multiplier calculating NPV for $Installation_Lifetime$ years of equal yearly cash flow YCF at discount rate R:

$$NPVC = \frac{1-(1/(1+R))^{Installation_Lifetime}}{1-1/(1+R)}, \qquad NPV = YCF{\cdot}NPVC. \tag{26}$$

The following parameters are used in calculations:

To investigate the dependence on energy prices on DAM:

$$\alpha - \text{coefficient changing } DAM_Energy_Price(i) \text{ values [–]}, \qquad \alpha = 0.25\text{–}4.0;$$

To investigate the dependence on ESS subsidy:

$$\beta - \text{reduction of ESS CAPEX due to subsidy [–]}, \qquad \beta = 0.0\text{–}0.9.$$

Symbols not previously defined are provided in Appendix B. The optimization problem for financial objective 1 is formulated as a nonlinear program (NLP) with linear constraints (3)–(23) and the objective function F.1 (1), which is expressed as the quotient of first-degree polynomials. For financial objectives 2 and 3, the problem is a linear program (LP) with both the objective function F.2 (2) and the constraints (3)–(24) for financial objective 2 and (3)–(23), (25) for financial objective 3—being linear relationships. Based on real installations, ESS capacity is limited to between 1 and 10 h. ESS operation, accounting for efficiency, power, capacity, and annual cycle number limits, is represented by Equations (6)–(8) and (14)–(18). The optimization process determines the charging and discharging volume for each hour. Maximum PV and WT generation are based on the installed capacities and deterministic weather data (Equations (12) and (13)), while the actual used generation is also determined through optimization. Grid exchange, constrained by connection capacity, is described in Equations (10) and (11). The components of NPV are specified in Equations (3) and (26), market conditions are detailed in constraints (19)–(25), and the formulas for total capital investment and NPV calculation are provided in Equations (3) and (4).

The objective functions and constraints used for the optimization of each case are summarized in Table 1.

Table 1. Variants of the objective function and constraints depending on the financial objective and the market.

Financial Objective		1	2	3
		MAX(NPV/CAPEX)	MAX(NPV) while maintaining a minimum NPV/CAPEX ratio	MAX(NPV) with a constraint on CAPEX value
Objective Function		F1	F2	F2
Constraints for all Markets		(1)–(18)	(1)–(18) + (24)	(1)–(18) + (25)
Additional constraints depending on Market	PPA	(19) + (21)		
	DAM	(20) + (21)		
	CM	(20) + (22) + (23)		

4. Calculation Methods and Results

The problem was modeled in the Mosel® language, and the calculations were performed using the Xpress® IVE (v. 1.26.00) [38] software under default settings. In addition to the search variables, annual energy consumption and grid supply, losses within the internal installation and the ESS, and reductions in PV and WT generation were also calculated. The data corresponding to the maximum NPV served as the starting point for the NLP calculations. The global extremum for NLP-feasible problems has always been reached within several minutes, while the LP problems were solved within seconds. A flowchart illustrating the optimization process is presented in Figure 2.

The results were transferred to and analyzed in an MS Excel 365 platform spreadsheet. The selected result tables are provided in Appendix A, and a summary of case-by-case results is presented below.

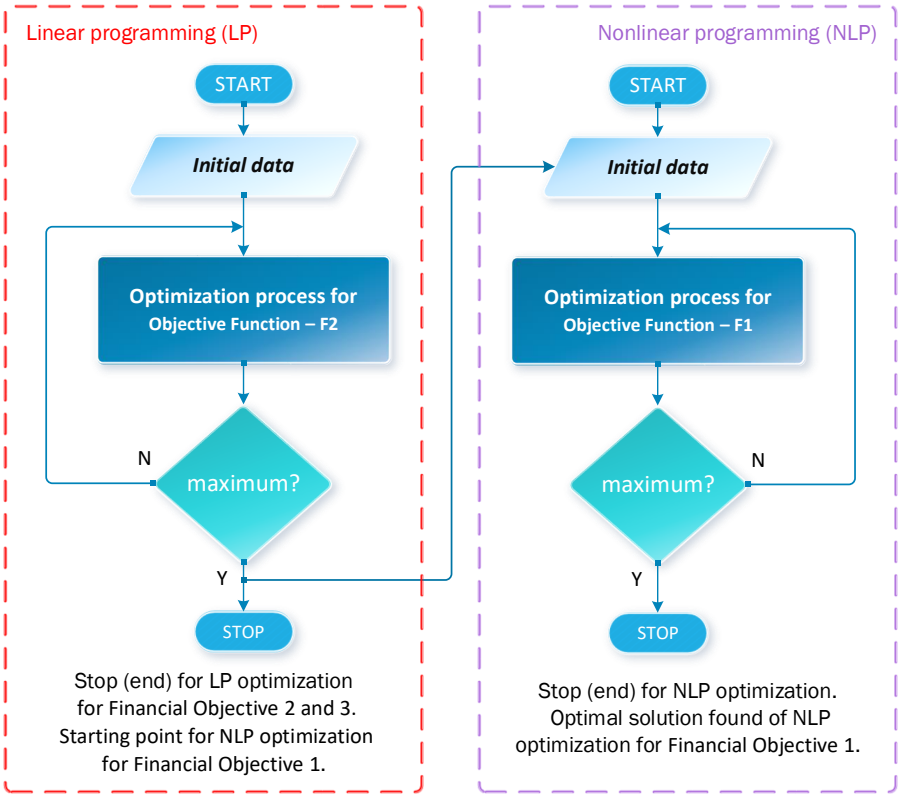


Figure 2. Flowchart illustrating the optimization process used for the calculation of specific variants.

Case 11–PPA, financial objective 1.

Sample results are shown in Table A1 and Figure 3. The main observations are as follows:

- ESS profitability: ESS is not profitable for any of the PPA prices analyzed. The results not presented here show that this is also the case for a subsidy covering up to 90% of the ESS CAPEX.
- The RES output reduction is negligible, independently of the PPA price.
- The increase in the NPV/CAPEX value compared to the use of single PV technology is relatively small. This is also the case for single WT technology for PPA prices > 60 $/MWh. Grid output is larger for single WT technology than for the energy mix for PPA prices < 90 $/MWh, while in other cases HRES gives greater output.
- Due to the higher CAPEX and also the higher efficiency of WT, their share increases as the PPA price increases.

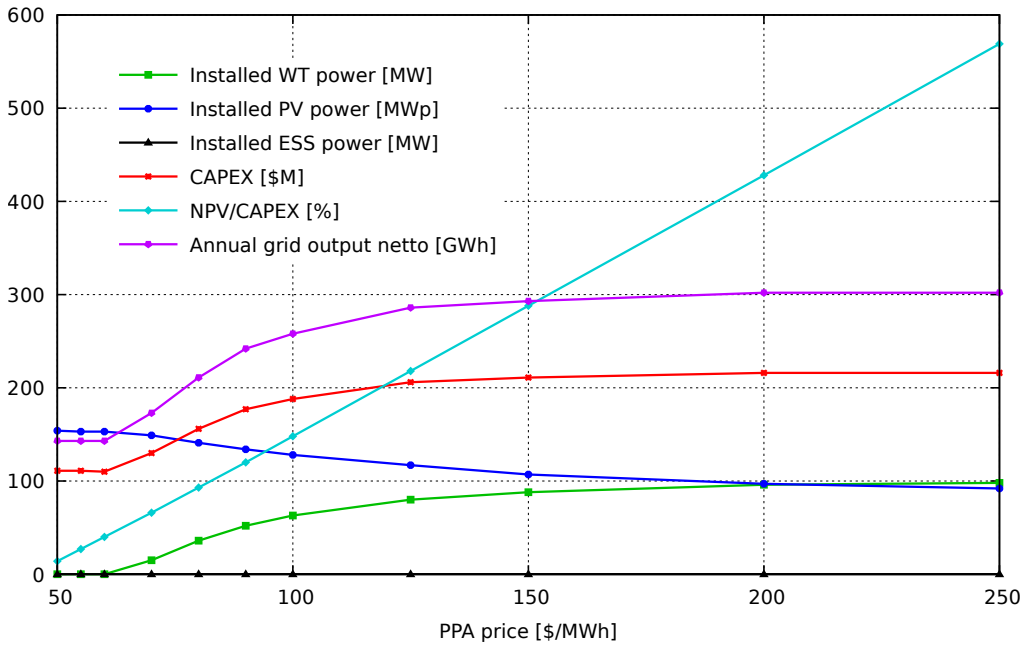


Figure 3. Case 11 without ESS CAPEX subsidy: calculation results depending on the PPA price.

Case 12–PPA, financial objective 2.

Sample results are shown in Table A2. The main observations are as follows:

- Lack of solutions for the assumed average profit level of 3% and PPA price < 80 $/MWh.
- Without subsidies, the participation of ESS is profitable only at a PPA price > 150 $/MWh. The results not presented here show that, with an increasing ESS subsidy, both its capacity and energy expressed in [h] increase. Single ESS technology results in a lack of solutions across all PPA prices.
- The RES output reduction increases with the PPA price increase.
- The increase in the NPV value and grid output compared to the use of single PV (especially) or WT technology is significant.

Case 13–PPA, financial objective 3.

Sample results are shown in Table A3. The main observations are as follows:

- ESS is not profitable for any of the PPA prices analyzed. Further calculations show that only for PPA prices > 150 $/MWh and ESS CAPEX subsidy > 85%, small ESS were selected.

- The RES output reduction is very low, independently of the PPA price.
- The increase in the NPV value and grid output compared to the use of single PV (especially) or WT technology is significant.
- Due to the higher CAPEX and also the higher efficiency of WT, their power increases as the PPA price increases while PV size remains stable.

Case 21–DAM, financial objective 1.

Sample results are shown in Table A4. The main observations are as follows:

- Installation is profitable only for DAM multiplier > 0.33.
- ESS without subsidy is not profitable for any of the DAM multipliers analyzed. Further calculations show that only for DAM price multiplier > 2.0 and ESS CAPEX subsidy > 80% were ESS selected.
- The RES output reduction is very low, independently of the DAM multiplier.
- The NPV/CAPEX value increase compared to the use of single PV and WT technologies is significant for single PV technology and, for larger DAM multipliers, also for single WT technology. The grid output is largest for single WT technology.
- Depending on the DAM multiplier share of PV and WT power differs significantly.

Case 22–DAM, financial objective 2.

Sample results are shown in Table A5 and Figure 4. The main observations are as follows:

- No solution exists for the assumed average profit level of 3% and the DAM price multiplier < 0.75.
- The participation of ESS is profitable for the DAM price multiplier > 1.0. The higher the ESS CAPEX subsidy, the lower the DAM price multiplier for ESS selection and the larger power and capacity of selected ESS's. The results not presented here show that a single ESS leads to no solutions for all DAM price multipliers.
- The RES output reduction is very significant for nearly all DAM price multipliers.
- The NPV value and grid output are significantly larger compared to the use of single PV (especially) or WT technology.

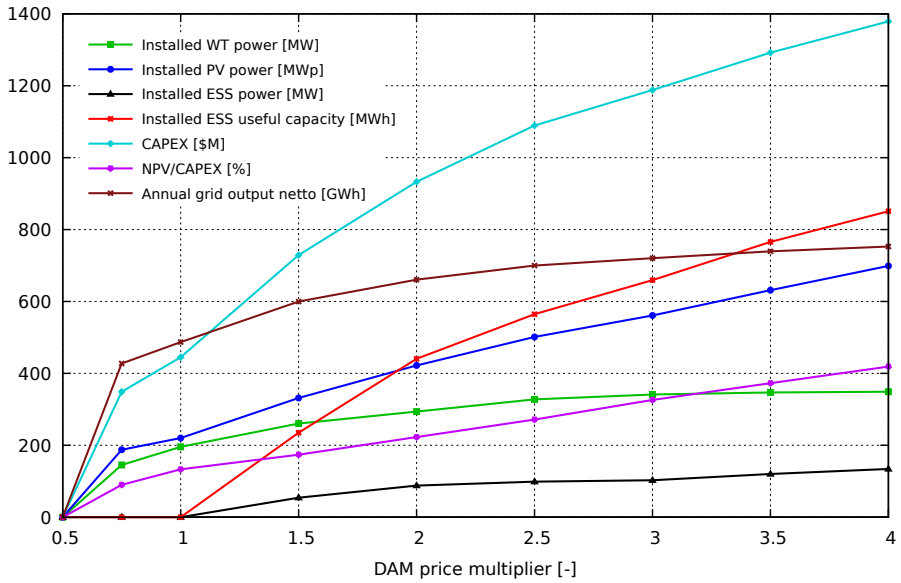


Figure 4. Case 22 without ESS CAPEX subsidy: calculation results depending on the DAM price multiplier.

Case 23–DAM, financial objective 3.

Sample results are shown in Table A6. The main observations are as follows:

- ESS is not profitable for any of the DAM price multipliers analyzed. Further calculations show that ESS was selected, starting with a DAM price multiplier of 0.75 and an ESS CAPEX subsidy of 90%. The higher the DAM multiplier, the lower the subsidy required for ESS selection. For the DAM price multiplier < 0.5 only PV and WT were selected regardless of the size of the EXX CAPEX subsidies.
- The RES output reduction is <10%, independently of the DAM multiplier.
- The increase in the NPV value and grid output is significant for the DAM price multiplier > 0.33, compared to the use of single PV, WT, or ESS technology.

Case 31–CM+DAM, financial objective 1.

Sample results are shown in Table A7. The main observations are as follows:

- ESS is profitable for any of the CM prices > 120 $/kW, for the CM price > 160 $/kW, only ESS is selected. The results not shown here show that the lower the DAM price multiplier, the lower the CM price, at which ESS is profitable (always with power 100 MW and capacity 1 h).
- The RES output reduction is negligible, independently of the CM price.
- The increase in the NPV/CAPEX value and grid output compared to the use of single technologies depends on the CM price and technology.
- For the DAM price multiplier > 2.0, only WT are selected; for the DAM price multiplier < 0.5, only PV and ESS are selected.

Case 32–CM+DAM, financial objective 2.

Sample results are shown in Table A8. The main observations are as follows:

- For the DAM price multiplier < 0.75, no solution exists for CM prices < 120 $/kW.
- The same energy mix is selected for any of the CM prices analyzed: 196.5 MW PV, 239.6 MW WT, and 100 MW/1 h ESS (1 h is the minimum allowed capacity). Further calculations show that for the DAM price multiplier > 1.0, higher DAM prices select, higher PV & WT power values, along with higher ESS capacities [h]; for the DAM price multiplier < 0.5 only PV and ESS are selected.
- The RES output reduction strongly depends on the DAM multiplier.
- The increase in the NPV value and grid output for HRES is significant compared to the use of single PV, WT, or ESS technology.

Case 33–CM+DAM, financial objective 3.

Sample results are shown in Table A9 and Figure 5. The main observations are as follows:

- ESS is always selected above some CM price level. While WT and PV installed power decreases with the CM price increase, the ESS power increases up to 100 MW (always with 1 h capacity). The results not presented here show that the lower the DAM values, the lower the CM price values for which ESS are selected, with power up to 100 MW and a capacity of 1 h.
- For the DAM price multiplier < 0.5, only PV and ESS are selected.
- The RES output reduction strongly depends on the DAM multiplier.
- While the increase in the NPV value is significant compared to the use of single PV (especially), WT, or ESS technology for all CM prices, grid output for CM > 100 $/kW is greatest for single WT sources.

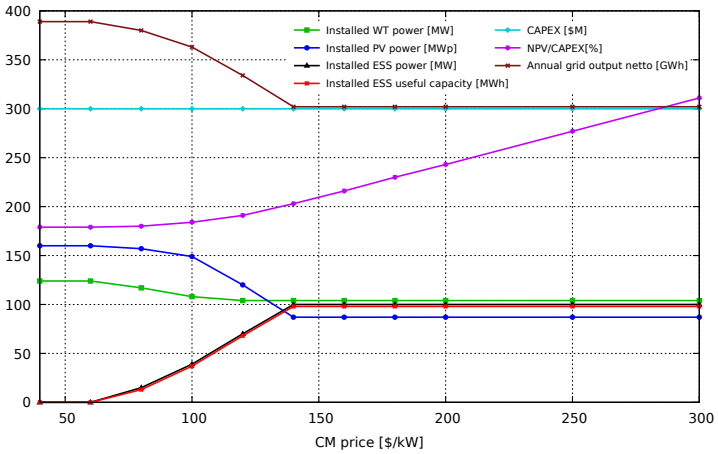


Figure 5. Case 33 without ESS CAPEX subsidy and with the DAM price multiplier = 1.0: calculation results depending on the CM price.

5. Key Observations

It should be noted that the results are site-specific and depend on the proportion and distributions of PV and WT generation, as well as on price volatility in the DAM.

The analysis revealed the following patterns:

- The optimal composition of energy sources across all markets is strongly influenced by the financial objective of the investment, as illustrated for the DAM in Figure 6.

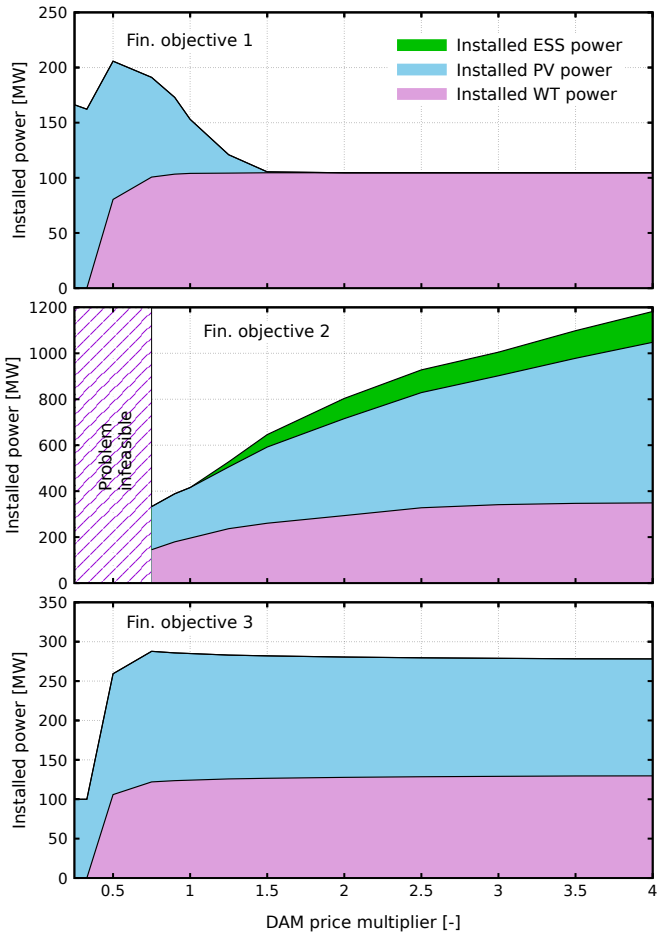


Figure 6. Optimal composition of sources depending on the financial objective of the investment for DAM.

- For all financial objectives considered, the optimal composition of sources depends on the investment income source, as demonstrated for financial objective 1 in Figure 7.

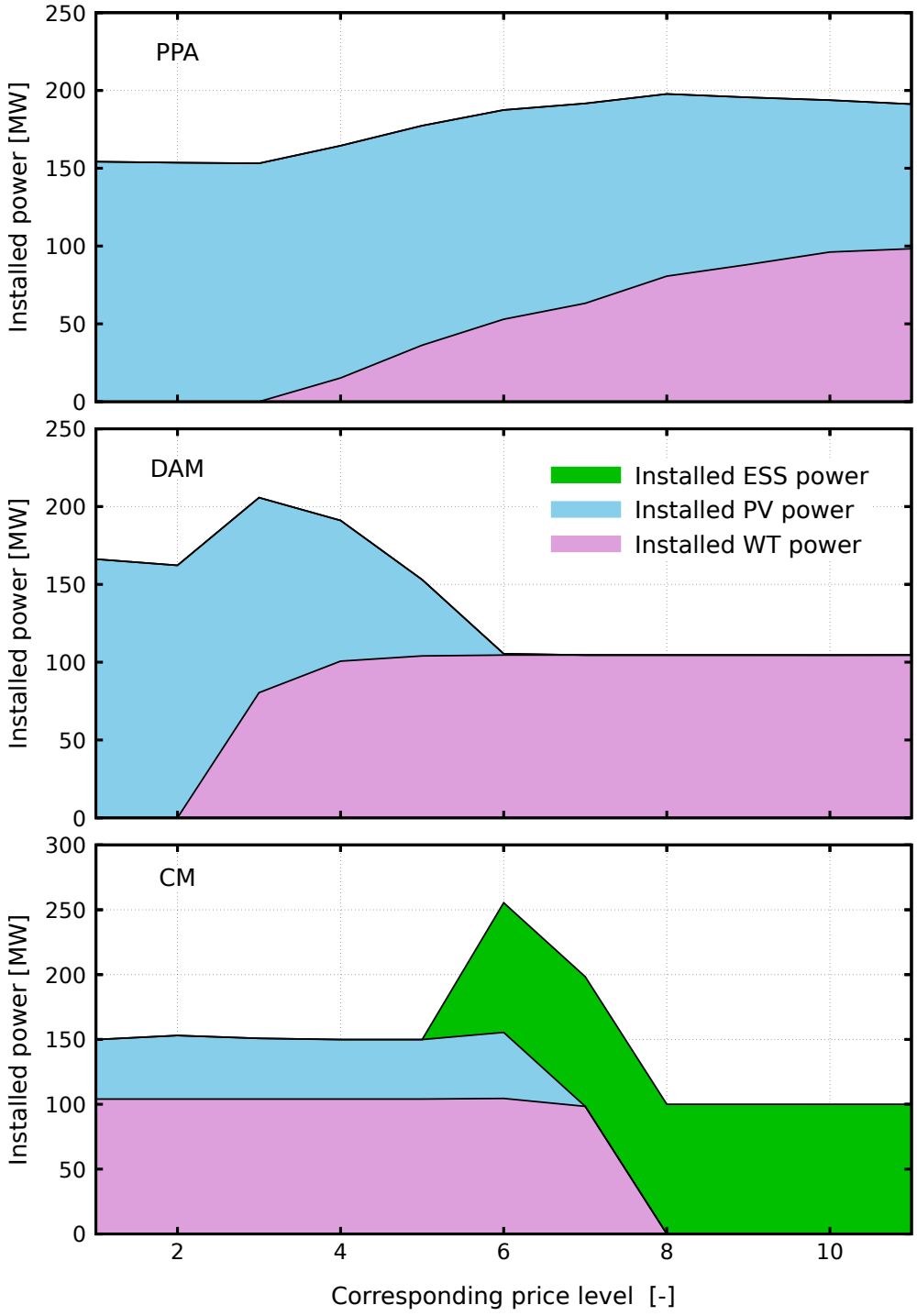


Figure 7. Optimal composition of sources depending on the source of income and corresponding price level for financial objective 1.

- The influence of price levels on the optimal composition of sources varies depending on financing options and financial objectives. In cases 11, 12, 21, 22, and 31, the impact is greater, while in cases 13, 23, 32, and 33, it is less pronounced (see Figures 3–5);
- Participation in the CM results in source selection being strongly influenced by DAM prices, as shown in Figure 8.

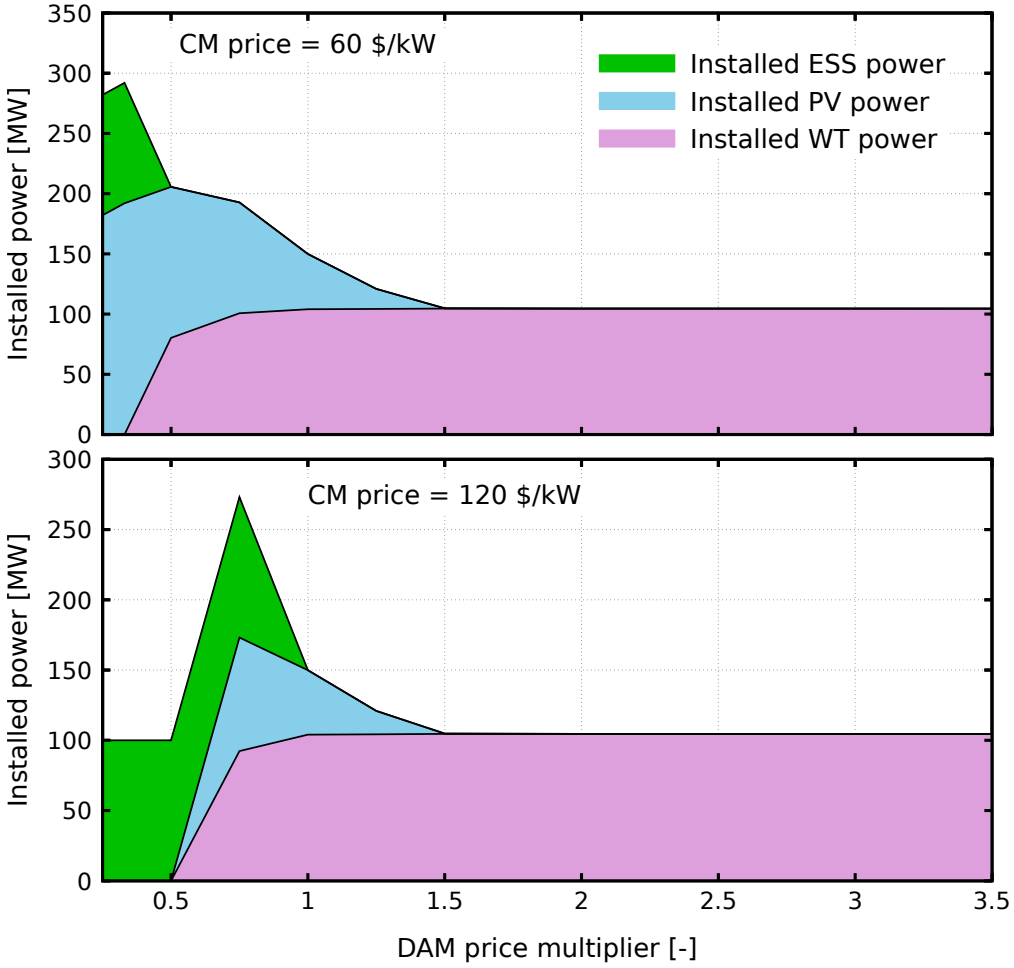


Figure 8. Optimal composition of sources depending on the DAM price for financial objective 1 and CM.

- For PPA and all financial objectives, as well as for the DAM with financial objective 1, ESS are generally not profitable, regardless of subsidies. For DAM with financial objectives 2 and 3, subsidies for ESS capital expenditures enable profitability at lower DAM prices (see Figure 9). In the absence of subsidies, ESSs are primarily selected for participation in the CM, and, in some cases, they are the only sources selected.
- In most scenarios, both the financial objective and grid output were significantly higher for HRES compared to single technologies, as shown in Figures 10 and 11.
- The production variability of HRES was substantially lower than that of single technologies. For example, in May in Case 23, the coefficient of variation was 1.12 for PV only, 0.99 for WT only, and 0.69 for HRES.

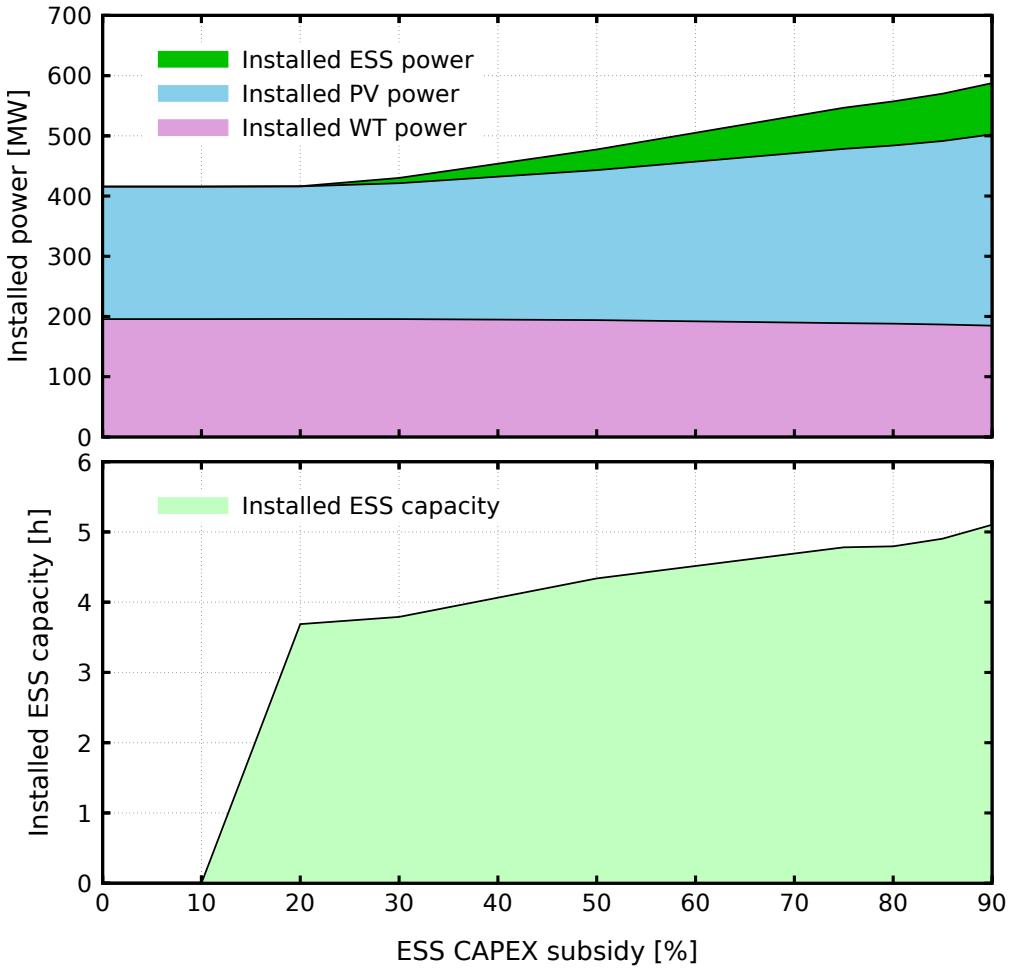


Figure 9. Optimal composition of sources depending on the ESS CAPEX subsidy for financial objective 2 and the DAM price multiplier = 1.0.

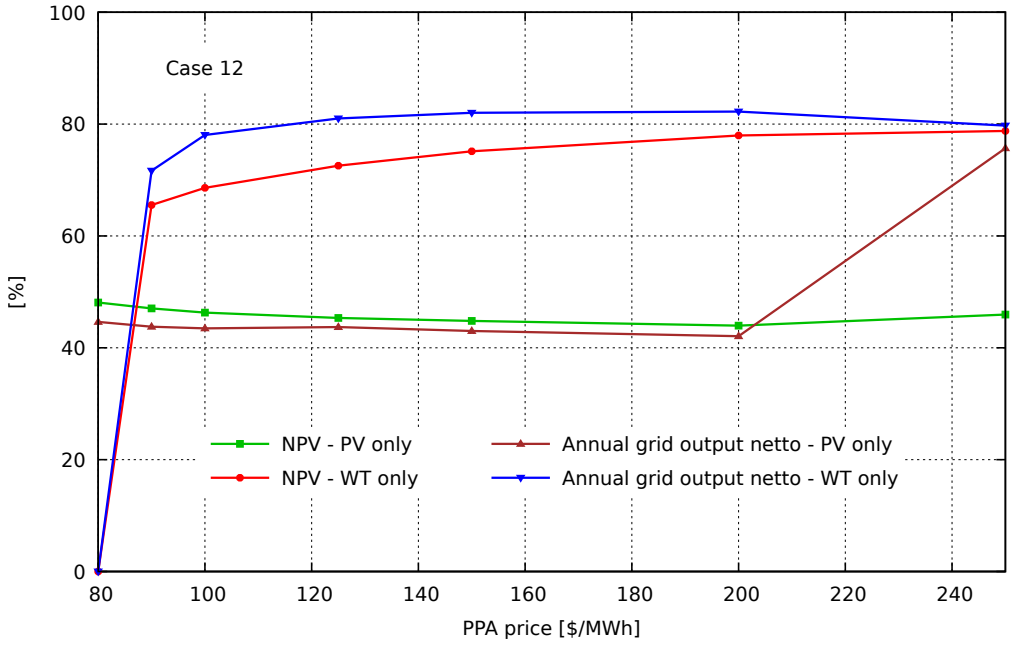


Figure 10. Single technology NPV and grid output in relation to HRES in Case 12.

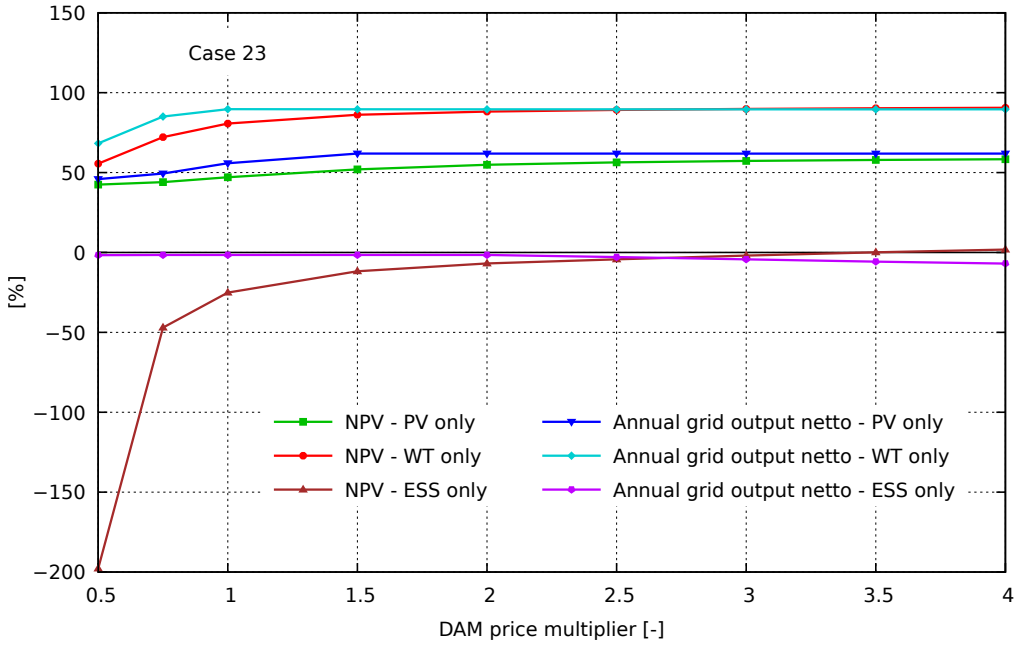


Figure 11. Single technology NPV and grid output in relation to HRES in Case 23.

6. Summary, Conclusions, and Future Research Directions

The presented method allows for selecting an optimal mix of RESs while simultaneously limiting active power transfer with the grid. The results indicate a strong dependence of the optimal HRES structure and total combined power on the financial target, revenue sources, and prevailing market prices. Due to higher investment costs, the share of WT relative to PV is greater at higher market prices. The profitability of ESSs without subsidies is largely restricted to participation in the capacity market. At CM prices > 120 $/kW the technology mix may consist solely of ESSs. A profitable share of ESSs in a PPA requires a price exceeding 150 $/MWh, which is only possible with preferential rather than market prices. The profitability of including ESSs in the energy mix for DAM is possible only under high price volatility. For the latter two markets, the conclusions are practically independent of ESS investment cost subsidies.

Consistently, both the profitability and total generation of HRES generally exceed those of individual technologies. The reduction in RES generation is influenced by the financial target, ranging from a few percent for financial objectives 1 and 3 to over 40% for financial objective 2, and is practically independent of market type.

Based on the above statements, it follows that an investment decision in HRES must account for planned revenue sources and the investor's financial objective, in addition to weather conditions. It can be expected that the optimal composition of sources will differ significantly depending on the expected rate of return or the amount of available capital. The accuracy of the method can be enhanced by using weather and market data from several consecutive years. On the other hand, considering the large, difficult-to-predict changes in market prices alongside the rapid growth of RES generation, the greatest weight should be given to long-term fixed-value contracts, such as PPA and CM contracts, especially for investments involving ESSs.

Due to the strong dependence of the optimal source mix on DAM prices shown in the article, further investor analysis should include calculating financial results for selected variants under various DAM price scenarios when these prices serve as a revenue source. This issue is particularly critical when the DAM is the sole revenue stream. Such analyses can be conducted by calculating the NPV using a methodology analogous to the one applied in this study.

The advantage of the method presented in the article is its relative simplicity and short calculation time, enabling the simulation of many both weather and market variants.

Future research will extend the presented analyses by incorporating uncertainties in renewable generation and market prices, sensitivity analyses, and calculations with various data sets for different climatic and market conditions.

Author Contributions: M.S., Conceptualization, Methodology, Supervision, Formal analysis, Writing—original draft preparation. A.W., Formal analysis, Investigation, Data curation; Validation, Writing—review & editing; T.S., Investigation, Validation, Data curation; Writing—editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Dataset available on request from the authors. The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Results Tables

Table A1. Case 11 without ESS CAPEX subsidy: calculation results depending on the PPA price.

PPA Price	**[$/MWh]**	**50**	**55**	**60**	**70**	**80**	**90**	**100**	**125**	**150**	**200**	**250**
Installed WT power	[MW]	0	0	0	15.2	36.3	53.0	63.2	80.7	88.1	96.1	98.3
Installed PV power	[MWp]	154	154	153	149	141	135	128	117	107	97.6	92.9
Installed ESS power	[MW]	0	0	0	0	0	0	0	0	0	0	0
CAPEX	[$M]	112	111	111	131	157	177	188	207	211	217	217
NPV/CAPEX	[%]	14.1	27.1	40.1	66.3	93.3	121	148	218	288	429	569
Annual net grid output	[GWh]	144	143	143	173	212	242	259	286	294	302	302
RES output reduction	[%]	1.10	1.00	1.00	0.80	0.60	0.70	0.70	0.80	0.70	0.80	0.80
NPV/CAPEX–PV only	[%]	14.1	27.1	40.1	66.2	92.3	118	144	210	275	405	536
NPV/CAPEX–WT only	[%]	−3.30	10.8	24.9	53.1	81.4	110	138	208	279	420	561
Annual net grid output –PV only	[GWh]	144	143	143	142	142	141	141	141	140	140	139
Annual net grid output –WT only	[GWh]	232	232	232	232	231	231	231	231	231	231	231

Table A2. Case 12 without ESS CAPEX subsidy: calculation results depending on the PPA price.

PPA Price	**[$/MWh]**	**50**	**55**	**60**	**70**	**80**	**90**	**100**	**125**	**150**	**200**	**250**
Installed WT power	[MW]	Problem infeasible [a]				104	145	160	196	231	285	334
Installed PV power	[MWp]					140	186	196	216	234	288	353
Installed ESS power	[MW]					0	0	0	0	0	15.8	46.5
Installed ESS capacity	[MWh]					0	0	0	0	0	51.3	218
CAPEX	[$M]					257	347	376	443	506	649	843
NPV	[$M]					231	332	421	660	917	1472	2093
Annual net grid output	[GWh]					352	433	453	493	523	580	645
RES output reduction	[%]					2.90	12.6	15.8	22.6	28.3	35.4	38.9
NPV–PV only	[$M]					111	156	195	299	411	647	961
NPV–WT only	[$M]						217	289	479	689	1147	1648
Annual net grid output –PV only	[GWh]					157	189	197	215	225	244	488
Annual net grid output –WT only	[GWh]						310	354	399	429	477	515

[a] The gray area indicates the range of variables and parameters for which the problem is infeasible.

Table A3. Case 13 without ESS CAPEX subsidy: calculation results depending on the PPA price.

PPA Price	**[$/MWh]**	**50**	**55**	**60**	**70**	**80**	**90**	**100**	**125**	**150**	**200**	**250**
Installed WT power	[MW]	71.9	104	106	116	121	122	123	124	125	126	127
Installed PV power	[MWp]	147	148	155	167	168	166	165	161	159	156	155
Installed ESS power	[MW]	0	0	0	0	0	0	0	0	0	0	0
CAPEX	[$M]	213	262	269	293	300	300	300	300	300	300	300
NPV	[$M]	19.7	53.8	90.1	166	245	325	405	604	804	1203	1603
Annual net grid output	[GWh]	292	357	364	388	395	395	395	395	396	396	396
RES output reduction	[%]	2.00	3.40	4.10	6.50	7.30	7.20	7.20	7.20	7.10	7.10	7.10
NPV–PV only	[$M]	16.2	31.9	48.2	82.4	119	156	195	299	411	647	892
NPV–WT only	[$M]	−28.4	−5.50	18.1	42.6	95.8	155	219	289	468	647	1006
Annual net grid output –PV only	[GWh]	153	158	165	174	183	189	197	215	225	243	243
Annual net grid output –WT only	[GWh]	221	231	237	250	278	307	333	354	355	355	355

Table A4. Case 21 without ESS CAPEX subsidy: calculation results on the DAM price multiplier.

DAM Price Multiplier	**[−]**	**0.25**	**0.33**	**0.5**	**0.75**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Installed WT power	[MW]	0	0	80.4	101	104	105	105	105	105	105	105
Installed PV power	[MWp]	166	162	125	90.4	49.0	0.80	0	0	0	0	0
Installed ESS power	[MW]	0	0	0	0	0	0	0	0	0	0	0
CAPEX	[$M]	119	117	212	219	197	166	165	165	165	165	165
NPV/CAPEX	[%]	−44.6	−21.8	30.8	113	196	364	534	703	873	1042	1212
Annual net grid output	[GWh]	152	149	288	300	270	227	226	226	226	226	226
RES output reduction	[%]	3.10	2.50	2.60	2.50	2.20	2.10	2.10	2.10	2.10	2.10	2.10

Table A4. *Cont.*

DAM Price Multiplier	**[−]**	**0.25**	**0.33**	**0.5**	**0.75**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
NPV/CAPEX–PV only	[%]	−44.6	−21.8	26.7	98.0	169	312	455	598	741	884	916
NPV/CAPEX–WT only	[%]	−59.7	−32.6	25.1	110	195	364	534	703	873	1042	1212
Annual net grid output –PV only	[GWh]	152	149	146	145	144	143	142	142	142	142	142
Annual net grid output –WT only	[GWh]	228	227	227	226	226	226	226	226	226	226	226

Table A5. Case 22 without ESS CAPEX subsidy: calculation results depending on the DAM price multiplier.

DAM Price Multiplier	**[−]**	**0.25**	**0.33**	**0.5**	**0.75**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Installed WT power	[MW]	Problem infeasible [a]			145	196	260	294	328	341	347	349
Installed PV power	[MWp]				188	220	332	422	501	561	631	699
Installed ESS power	[MW]				0	0	54.2	87.9	98.8	103	120	134
Installed ESS useful capacity	[MWh]				0	0	235	441	565	659	766	851
CAPEX	[$M]				349	445	729	933	1089	1188	1292	1379
NPV	[$M]				314	592	1267	2079	2958	3874	4816	5776
Annual net grid output	[GWh]				428	487	600	661	700	720	739	753
RES output reduction	[%]				14.1	23.9	31.1	34.9	39.6	41.9	43.7	45.4
NPV–PV only	[$M]				130	254	523	826	1,154	1500	1856	2223
NPV–WT only	[$M]				218	444	973	1573	2219	2900	3608	4337
Annual net grid output –PV only	[GWh]				175	217	243	266	280	289	296	303
Annual net grid output –WT only	[GWh]				305	390	460	504	534	559	577	591

[a] The gray area indicates the range of variables and parameters for which the problem is infeasible.

Table A6. Case 23 without ESS CAPEX subsidy: calculation results depending on the DAM price multiplier.

DAM Price Multiplier	**[−]**	**0.25**	**0.33**	**0.5**	**0.75**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Installed WT power	[MW]	0	0	106	122	124	127	128	129	129	130	130
Installed PV power	[MWp]	100	100	153	166	161	155	1 53	151	150	149	149
Installed ESS power	[MW]	0	0	0	0	0	0	0	0	0	0	0
CAPEX	[$M]	75.8	75.8	268	300	300	300	300	300	300	300	300
NPV	[$M]	−39.0	−22.4	77.0	306	539	1005	1472	1939	2406	2873	3340
Annual net grid output	[GWh]	93.8	93.8	358	389	389	390	390	390	390	390	390
RES output reduction	[%]	0.60	0.60	5.40	8.60	8.60	8.50	8.50	8.50	8.50	8.60	8.60
NPV–PV only	[$M]	−39.0	−22.4	32.7	135	254	523	808	1093	1378	1664	1949
NPV–WT only	[$M]	−95.1	−52.3	42.8	221	435	866	1298	1730	2161	2593	3025
NPV–ESS only	[$M]	−161	−158	−152	−144	−135	−118	−101	−83.5	−47.1	2.70	60.5
Annual net grid output –PV only	[GWh]	93.8	93.8	164	192	217	241	241	241	241	241	241
Annual net grid output –WT only	[GWh]	216	216	244	331	349	349	349	349	349	349	349
Annual net grid output –ESS only	[GWh]	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−11.2	−16.8	−22.4	−27.1

Table A7. Case 31 without ESS CAPEX subsidy and with the DAM price multiplier = 1.0: calculation results depending on the CM price.

CM Price	**[$/kW]**	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**250**	**300**
Installed WT power	[MW]	104	104	104	104	104	105	98	0	0	0	0
Installed PV power	[MWp]	45.9	49.0	46.8	45.9	45.9	50.9	0	0	0	0	0
Installed ESS power	[MW]	0	0	0	0	0	100	100	100	100	100	100
Installed WT power	[MWh]	0	0	0	0	0	100	100	100	100	100	100
CAPEX	[$M]	195	197	195	195	195	276	234	87.7	87.7	87.7	87.7
NPV/CAPEX	[%]	196	196	196	1965	196	204	220	249	306	421	536
Annual net grid output	[GWh]	267	270	268	267	267	269	208	−6.10	−6.10	−6.10	−6.10
RES output reduction	[%]	2.20	2.20	2.20	2.20	2.20	1.70	2.00	0	0	0	0
NPV/CAPEX—PV only	[%]	169	169	169	1694	169	169	169	169	169	169	169
NPV/CAPEX–WT only	[%]	195	195	195	195	195	195	195	195	195	195	195
NPV/CAPEX–ESS only	[%]	−54.5	−14.2	26.2	66.6	107	147	188	228	269	369	470
Annual net grid output –PV only	[GWh]	144	144	144	144	144	144	144	144	144	144	144
Annual net grid output –WT only	[GWh]	226	226	226	226	226	226	226	226	226	226	226
Annual net grid output –ESS only	[GWh]	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10

Table A8. Case 32 without ESS CAPEX subsidy and with the DAM price multiplier = 1.0: calculation results depending on the CM price.

CM Price	**[$/kW]**	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**1 80**	**200**	**250**	**300**
Installed WT power	[MW]	197	197	197	197	197	197	197	197	197	197	197
Installed PV power	[MWp]	240	240	240	240	240	240	240	240	240	240	240
Installed ESS power	[MW]	100	100	100	100	100	100	100	100	100	100	100
Installed WT power	[MWh]	100	100	100	100	100	100	100	100	100	100	100
CAPEX	[$M]	537	537	537	537	537	537	537	537	537	537	537
NPV	[$M]	608	649	689	729	770	810	850	891	931	1032	1133
Annual net grid output	[GWh]	515	515	515	515	515	515	515	515	515	515	515
RES output reduction	[%]	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3
NPV–PV only	[$M]	608	649	689	729	770	810	850	891	931	1032	1133
NPV–WT only	[$M]	444	444	444	444	444	444	444	444	444	444	444
NPV–ESS only	[$M]	Problem infeasible [a]				107	147	188	228	269	369	470
Annual net grid output –PV only	[GWh]	217	217	217	217	217	217	217	217	217	217	217
Annual net grid output –WT only	[GWh]	390	390	390	390	390	390	390	390	390	390	390
Annual net grid output –ESS only	[GWh]	Problem infeasible [a]				−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10

[a] The gray area indicates the range of variables and parameters for which the problem is infeasible.

Table A9. Case 33 without ESS CAPEX subsidy and with the DAM price multiplier = 1.0: calculation results depending on the CM price.

CM Price	**[$/kW]**	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**250**	**300**
Installed WT power	[MW]	124	124	117	109	105	104	104	104	104	104	104
Installed PV power	[MWp]	161	161	157	149	121	87.7	87.7	87.7	87.7	87.7	87.7
Installed ESS power	[MW]	0	0	15.9	39.0	70.8	100	100	100	100	100	100
Installed WT power	[MWh]	0	0	15.9	39.0	70.8	100	100	100	100	100	100
CAPEX	[$M]	300	300	300	300	300	300	300	300	300	300	300
NPV	[$M]	539	539	539	542	552	574	610	651	691	732	832
Annual net grid output	[GWh]	389	389	381	364	334	302	302	302	302	302	302
RES output reduction	[%]	8.60	8.60	6.40	4.10	2.20	1.70	1.70	1.70	1.70	1.70	1.70
NPV–PV only	[$M]	254	254	254	254	254	254	254	254	254	254	254
NPV–WT only	[$M]	435	435	435	435	435	435	435	435	435	435	435
NPV–ESS only	[$M]	−54.5	−14.2	26.2	66.6	107	1 47	188	228	269	369	470
Annual net grid output –PV only	[GWh]	217	217	217	217	217	217	217	217	217	217	217
Annual net grid output –WT only	[GWh]	349	349	349	349	349	349	349	349	349	349	349
Annual net grid output –ESS only	[GWh]	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10	−6.10

Appendix B. Data, Symbols and Variables

Summary of data used in the article and their symbols:

Technical data:

$Battery_Cycle_Life$ — expected battery life [cycles], $Battery_Cycle_Life = 4800$ [39]

$Battery_Year_Life$ — expected ESS battery lifetime [year], $Battery_Year_Life = 15$ [33]

$ESS_Efficiency$ — one-way energy storage efficiency [–], $ESS_Efficiency = 0.922$ (corresponding to A/C–A/C round trip efficency at invertor = 0.85 [39])

$Auxiliary_Energy_Losses$ — installation auxiliary energy losses, $Auxiliary_Energy_Losses = 0.03$ (3% of transmitted energy) [40]

$Installation_Lifetime$ — expected installation lifetime [year], $Installation_Lifetime = 30$ (based on [33–35])

$Max_Connection_Power$ — maximum active power exchange with the grid [MW], assumed $Max_Connection_Power = 100$

NH — number of hours [h], $i = 1...NH$, $NH = 8760$

$PV_Output(i)$ — PV energy output at the i-th hour [MWh/MWp], [36]

$WT_Output(i)$ — WT energy output at the i-th hour [MWh/MW], (own data from real installation)

Economic data:

$Battery_CAPEX$	ESS battery replacement CAPEX [$/kW], $Battery_CAPEX = 200$ [33]
$Common_CAPEX$	CAPEX common for the whole site: transformer, interconnection, land acquisition, control, common electrical works [$/kW], $Common_CAPEX = 100$ (estimated on the base of [33])
$Common_O\&M_Cost$	fixed O&M annual cost common for the entire site: transformer, interconnection, control, security [$/kW], $Common_O\&M_Cost = 5$ (estimated on the base of [41])
CM_Power_Price	contracted capacity market (CM) price [$/kW], $CM_Power_Price = 40$–300 [42]
$DAM_Energy_Price(i)$	day-ahead market (DAM) prices at the i-th hour [$/MWh] [37]
PPA_Energy_Price	contracted electricity price at the PPA market [$/MWh], $PPA_Energy_Price = 50$–250 [43]
$ESS_Capacity_CAPEX$	ESS capacity CAPEX [$/kWh], $ESS_Capacity_CAPEX$ = 401 $/kWh [33]
$ESS_Capacity_O\&M_Cost$	ESS capacity fixed O&M annual cost [$/kWh], $ESS_Capacity_O\&M_Cost = 10.613$ [33]
ESS_Power_CAPEX	ESS power CAPEX [$/kW], $ESS_Power_CAPEX = 376$ [33]
$ESS_Power_O\&M_Cost$	ESS power fixed O&M annual cost [$/kW], $ESS_Power_O\&M_Cost = 22.43$ [33]
$Imbalance_Cost$	average cost of imbalance [$/MWh], $Imbalance_Cost = 3$ [44]
PV_CAPEX	PV CAPEX [$/kW], $PV_CAPEX = 658$ [41]
$PV_O\&M_Cost$	PV fixed O&M annual cost [$/kW], $PV_O\&M_Cost = 7.56$ [41]
R	discount rate [–], $R = 0.03$ [45]
$Transmission_Fee$	transmission fee [$/MWh], $Transmission_Fee = 3$ [46]
WT_CAPEX	WT CAPEX [$/kW], $WT_CAPEX = 1483$ [41]
$WT_O\&M_Cost$	WT fixed O&M annual cost [$/kW], $WT_O\&M_Cost = 35$ [41]

Other symbols:

BESS	battery energy storage system
CAPEX	capital costs
CM	Capacity Market
DAM	Day Ahead Market
ESS	energy storage system
FPV	floating PV
HRES	hybrid renewable energy source

LP	linear problem
MILP	Mixed Integer Linear Programming
NLP	nonlinear problem
NPV	Net Present Value method
PPA	Power Purchase Agreement
PV	solar photovoltaic
RES	renewable energy source
WT	wind turbine

References

1. Wędzik, A.; Siewierski, T.; Szypowski, M. The Use of Black-Box Optimization Method for Determination of the Bus Connection Capacity in Electric Power Grid. *Energies* **2020**, *13*, 41. [CrossRef]
2. Błaszczyk, A.; Matuszak-Flejszman, A.; Nawrocki, K. Determinants of the development of photovoltaics in Poland. *Renew. Energy* **2024**, *233*, 121161. [CrossRef]
3. Ustawa z Dnia 17 Sierpnia 2023 r. o Zmianie Ustawy o Odnawialnych Źródłach Energii Oraz Niektórych Innych Ustaw. Dz.U. 2023, Poz. 1762. 2023. Available online: https://dziennikustaw.gov.pl/DU/rok/2023/pozycja/1762 (accessed on 10 June 2025).
4. Sejm RP. Rządowy Projekt Ustawy o Zmianie Niektórych Ustaw w Celu Dokonania Deregulacji w Zakresie Energetyki. Druk nr 1310. 2025. Available online: https://www.sejm.gov.pl/Sejm10.nsf/druk.xsp?nr=1310 (accessed on 10 June 2025).
5. Review Energy. Top Markets for Renewable and Co-Location: Germany, GB, Ireland, and Poland. 2024. Available online: https://www.review-energy.com/otras-fuentes/top-markets-for-renewable-and-co-location-germany-gb-ireland-and-poland (accessed on 15 May 2025).
6. Alhassan, M.O.; Opoku, R.; Uba, F.; Obeng, G.Y.; Sekyere, C.K.; Nyanor, P. Techno-economic and environmental estimation assessment of floating solar PV power generation on Akosombo dam reservoir in Ghana. *Energy Rep.* **2023**, *10*, 2740–2755. [CrossRef]
7. Kazemi-Robati, E.; Silva, B.; Bessa, R.J. Stochastic optimization framework for hybridization of existing offshore wind farms with wave energy and floating photovoltaic systems. *J. Clean. Prod.* **2024**, *454*, 142215. [CrossRef]
8. Golroodbari, S.; Vaartjes, D.; Meit, J.; van Hoeken, A.; Eberveld, M.; Jonker, H.; van Sark, W. Pooling the cable: A techno-economic feasibility study of integrating offshore floating photovoltaic solar technology within an offshore wind park. *Sol. Energy* **2021**, *219*, 65–74. [CrossRef]
9. Garrod, A.; Neda Hussain, S.; Ghosh, A.; Nahata, S.; Wynne, C.; Paver, S. An assessment of floating photovoltaic systems and energy storage methods: A comprehensive review. *Results Eng.* **2024**, *21*, 101940. [CrossRef]
10. Jurasz, J.; Tomczyk, P.; Bochenek, B.; Kuriqi, A.; Kasiulis, E.; Chen, D.; Ming, B. Solar-hydro cable pooling – Utilizing the untapped potential of existing grid infrastructure. *Energy Convers. Manag.* **2024**, *306*, 118307. [CrossRef]
11. Li, Y.; Janik, P.; Schwarz, H. Cable Pooling for Extending the Share of Renewable PV and Wind Generation—A Regional Perspective. In Proceedings of the 2023 International Conference on Clean Electrical Power (ICCEP), Terrasini, Italy, 27–29 June 2023; pp. 487–491. [CrossRef]
12. Mertens, S. Design of wind and solar energy supply, to match energy demand. *Clean. Eng. Technol.* **2022**, *6*, 100402. [CrossRef]
13. Obradović, K.; Dkhili, N.; Sied, M.E.; Réthoré, P.E.M.; Das, K. From the idea to construction: Aspects of relevance of the optimized physical design of renewable hybrid power plants. *Sustain. Energy Technol. Assess.* **2025**, *78*, 104325. [CrossRef]
14. Dekker, N.J.; Slooff, L.H.; Jansen, M.J.; de Graaff, G.; Hovius, J.; Jonkman, R.; Zuurbier, J.; Pronk, J. Wind turbine dynamic shading: The effects on combined solar and wind farms. *J. Renew. Sustain. Energy* **2023**, *15*, 063703. [CrossRef]
15. Elkadeem, M.R.; Younes, A.; Jurasz, J.; AlZahrani, A.S.; Abido, M.A. A spatio-temporal decision-making model for solar, wind, and hybrid systems—A case study of Saudi Arabia. *Appl. Energy* **2025**, *383*, 125277. [CrossRef]
16. Gursoy, G.; Baysal, M. Improved optimal sizing of hybrid PV/wind/battery energy systems. In Proceedings of the 2014 International Conference on Renewable Energy Research and Application (ICRERA), 19–22 October 2014; pp. 713–716. [CrossRef]
17. Ukoima, K.N.; Okoro, O.I.; Obi, P.I.; Akuru, U.B.; Davidson, I.E. Optimal Sizing, Energy Balance, Load Management and Performance Analysis of a Hybrid Renewable Energy System. *Energies* **2024**, *17*, 5275. [CrossRef]
18. Ahmed, M.R.; Hasan, M.R.; Al Hasan, S.; Aziz, M.; Hoque, M.E. Feasibility Study of the Grid-Connected Hybrid Energy System for Supplying Electricity to Support the Health and Education Sector in the Metropolitan Area. *Energies* **2023**, *16*, 1571. [CrossRef]

19. Medina-Santana, A.A.; Cárdenas-Barrón, L.E. Optimal Design of Hybrid Renewable Energy Systems Considering Weather Forecasting Using Recurrent Neural Networks. *Energies* **2022**, *15*, 9045. [CrossRef]
20. Kusakana, K.; Vermaak, H.; Numbi, B. Optimal sizing of a hybrid renewable energy plant using linear programming. In Proceedings of the IEEE Power and Energy Society Conference and Exposition in Africa: Intelligent Grid Integration of Renewable Energy Resources (PowerAfrica), Johannesburg, South Africa, 9–13 July 2012; pp. 1–5. [CrossRef]
21. Arfa, M.; Bilal, M.; Muhammad, F. An Optimization Approach Towards Optimal Sizing of Stand-Alone Microgrid with Renewable Energy Sources and Battery Management System. In Proceedings of the 2024 International Conference on Frontiers of Information Technology (FIT), Islamabad, Pakistan, 9–10 December 2024; pp. 1–5. [CrossRef]
22. Ashagire, A.A.; Adjallah, K.H.; Bekele, G. Optimal sizing of Hybrid energy Sources by Using Genetic Algorithm and Particle Swarm Optimization algorithms considering Life Cycle Cost. In Proceedings of the 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), Mauritius, Mauritius, 7–8 October 2021; pp. 1–6. [CrossRef]
23. van Druten, E.; van Wieringen, S. Cable pooling to add renewables amid grid congestion: Exploring optimal integration of solar and batteries with existing onshore wind under cost uncertainty. *Sustain. Energy Grids Netw.* **2025**, *44*, 101971. [CrossRef]
24. Mohamed, M.A.; Shadoul, M.; Yousef, H.; Al-Abri, R.; Sultan, H.M. Multi-agent based optimal sizing of hybrid renewable energy systems and their significance in sustainable energy development. *Energy Rep.* **2024**, *12*, 4830–4853. [CrossRef]
25. Saidi, M.; Li, Z.; Elghali, S.B.; Outbib, R. Optimal Sizing of hybrid grid-connected energy system with demand side scheduling. In Proceedings of the IECON 2019—45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 14–17 October 2019; pp. 2209–2214. [CrossRef]
26. Teixeira, R.; Cerveira, A.; Silva, A.; Baptista, J. Hybrid renewable energy system optimisation for application in the winemaking sector. In Proceedings of the 2024 IEEE 22nd Mediterranean Electrotechnical Conference (MELECON), Porto, Portugal, 25–27 June 2024; pp. 272–277. [CrossRef]
27. Fam, A.M.; Lehtonen, M.; Pourakbari-Kasmaei, M.; Fotuhi-Firuzabad, M. Optimal Sizing of a Wind-PV Grid-Connected Hybrid System for Base Load—Helsinki Case. In Proceedings of the 2023 19th International Conference on the European Energy Market (EEM), Lappeenranta, Finland, 6–8 June 2023; pp. 1–6. [CrossRef]
28. Aksan, F.; Janik, P.; Suresh, V. Multivariate Multi-step Forecasting for Cable Pooling Applications. In Proceedings of the 2023 International Conference on Clean Electrical Power (ICCEP), Terrasini, Italy, 27–29 June 2023; pp. 237–244. [CrossRef]
29. Canales, F.A.; Jurasz, J. Assessing micro-scale solar-wind-hydro complementarity in a mountainous catchment through the stability coefficient. *Sustain. Energy Technol. Assess.* **2025**, *82*, 104537. [CrossRef]
30. Roman, J.; Klojzy-Karczmarczyk, B.; Wróblewski, R.; Ceran, B. Analysis of the use of waste gasification in a hybrid generation system to supply an industrial demand and power grid through cable pooling. *Renew. Energy* **2025**, *244*, 122721. [CrossRef]
31. Rens, G.; Nair, R.; Save, N. Sensor Technology in a Changing Electrical Grid. *IET Conf. Proc.* **2021**, *2021*, 2276–2279. [CrossRef]
32. Szypowski, M.; Siewierski, T.; Wędzik, A. Optimization of Energy-Supply Structure in Residential Premises Using Mixed-Integer Linear Programming. *IEEE Trans. Ind. Electron.* **2019**, *66*, 1368–1378. [CrossRef]
33. National Wind Technology Center (NREL). NREL Annual Technology Baseline (ATB)—Utility-Scale Battery Storage. 2024. Available online: https://atb.nrel.gov/electricity/2024/utility-scale_battery_storage (accessed on 15 May 2025).
34. Wiser, R.; Bolinger, M. Benchmarking Anticipated Wind Project Lifetimes: Results from a Survey of U.S. Wind Industry Professionals. Report, Lawrence Berkeley National Laboratory, Electricity Markets & Policy Group. 2019. Available online: https://eta-publications.lbl.gov/sites/default/files/wind_useful_life_report.pdf (accessed on 10 April 2025).
35. U.S. Department of Energy (DOE)-Energy Technologies Office. End-of-Life Management for Solar Photovoltaics. 2025. Available online: https://www.energy.gov/eere/solar/end-life-management-solar-photovoltaics (accessed on 15 May 2025).
36. Photovoltaic Geographical Information System (PVGIS). API Non-Interactive Service. 2025. Available online: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis/getting-started-pvgis/api-non-interactive-service_en (accessed on 15 May 2025).
37. Polskie Sieci Elektroenergetyczne S.A. (PSE S.A.). Rynkowa Cena Energii Elektrycznej (RCE)-Dane Archiwalne. 2025. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-rb/raporty-dobowe-z-funkcjonowania-rb/podstawowe-wskazniki-cenowe-i-kosztowe/rynkowa-cena-energii-elektrycznej-rce (accessed on 10 June 2025).
38. FICO® Xpress Optimization. FICO® Xpress: Optimizer Reference Manual & Mosel User Guide. 2025. Available online: https://www.fico.com/en/products/fico-xpress-optimization (accessed on 10 February 2025).
39. Viswanathan, V.; Mongird, K.; Franks, R.; Li, X.; Sprenkle, V.; Baxter, R. 2022 Grid Energy Storage Technology Cost and Performance Assessment. Technical Report, Pacific Northwest National Laboratory (PNNL), 2022. Available online: https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf (accessed on 10 April 2025).
40. Sanchez, C. Auxiliary Power and Losses for PV and BESS Projects—Part 2. 2024. Available online: https://www.linkedin.com/pulse/auxiliary-power-losses-pv-bess-projects-part-2-sanchez-p-e--ypgic/ (accessed on 10 April 2025).

41. International Renewable Energy Agency (IRENA). Renewable Power Generation Costs in 2023. Report, International Renewable Energy Agency (IRENA), Abu Dhabi, 2024. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf (accessed on 15 May 2025).
42. Elżbieciak, T. Rynek Mocy 2024: Fala MagazynóW Energii i MałA Namiastka Gazu. 2024. Available online: https://wysokienapiecie.pl/106689-morska-energetyka-wiatrowa-czas-na-dzialanie/ (accessed on 10 June 2025).
43. Urząd Regulacji Energetyki (URE). Aukcje OZE 2024—Dane Archiwalne. 2025. Available online: https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/12358,Aukcje-OZE-2024-16-TWh-energii-elektrycznej-o-wartosci-51-mld-zl-Prezes-URE-pods.html (accessed on 10 June 2025).
44. de Jong, C. The Future Is Green—The Financials of Renewable Power and PPA Contracts. 2020. Available online: https://www.kyos.com/wp-content/uploads/2020/04/The-future-is-green-the-financials-of-renewable-power-and-PPA-contracts-1.pdf (accessed on 10 April 2025).
45. European Commission, Directorate-General for Regional and Urban Policy. Guide to Cost-Benefit Analysis of Investment Projects—Economic Appraisal Tool for Cohesion Policy 2014–2020. Guide, European Commission, 2014. Available online: https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf (accessed on 15 May 2025).
46. Polskie Sieci Elektroenergetyczne S.A. (PSE S.A.). Taryfy Dla Energii Elektrycznej. 2025. Available online: https://www.pse.pl/dokumenty (accessed on 10 June 2025).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.