Overcoming Wind Intermittency: A Supply-Side Solution

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1 Abstract

This study addresses the critical challenge of wind power intermittency on the supply side by proposing a biomass-wind hybrid energy system. It investigates the potential of integrating wind and biomass energy generation to enhance system reliability and optimize social welfare. The research applies an optimization framework analysis based on hourly output generation data from Denmark's electricity zones. The results reveal that the biomass-wind hybrid system reduces intermittency costs by 316,808.11 DKK, improving system reliability and stabilizing the energy supply, with total social welfare reaching 2,802,793,352.36 DKK. This project involves an initial literature review and presents the hybrid system model, followed by an economic analysis of the results. The paper examines broader implications of the energy system, highlighting the specific advantages and trade-offs associated with biomass use. The study emphasizes that hybrid systems represent a practical, cost-effective solution to wind intermittency, however, further research is needed to ensure its long term feasibility in the context of the global green energy transition.

2 Introduction

Wind power has emerged as a cornerstone of the green transition as the global push for renewable energy accelerates amid the climate crisis. Wind turbines offer a zero-carbon alternative to conventional power plants and, as the sector matures, are an increasingly cost-effective way to generate electricity (Schrøder Kristensen et al., 2023). It is estimated that global cumulative wind power capacity exceeded one terawatt in 2023 (Lee and Zhao, 2024). In particular, Denmark has played a leading role in wind energy development. According to the Danish Energy Agency (2024), large-scale onshore and offshore wind farms powered 53.8 percent of Danish electricity consumption in 2023, up from 1.9 percent in 1990. This is the highest share of wind power in electricity generation globally (World Wind Energy Association, 2024). It is forecast that by 2030, wind energy will cover almost 70 percent of energy consumption in Denmark (Schrøder Kristensen et al., 2023). The case of Denmark demonstrates that integrating wind power into the energy mix is essential to achieve real emissions reductions. Yet, the challenge of wind intermittency presents a significant obstacle. Although wind is an inexhaustible resource, it occurs randomly and irregularly, causing power output to fluctuate over time (Ren et al., 2017). This renders wind power a non-dispatchable energy source, since turbines can only produce electricity if the wind is blowing, irrespective of demand (Hughes, 2012).

This study aims to investigate how supply-side solutions can mitigate the impacts of wind intermittency by performing an optimization framework analysis on Denmark's domestic electricity zones (DK1 and DK2). There are several technological solutions available to manage wind intermittency. According to Ren et al. (2017), intermittency can be compensated using high-accuracy forecasting or various storage solutions, such as pumped hydroelectric storage which absorbs excess wind energy, later using it to pump water to generate electricity during periods of high demand (Rahimi et al. (2013). Hybrid energy systems (specifically biomass-wind) can also alleviate intermittency by combining multiple renewable energy sources to improve supply balance and enhance overall system efficiency (Amjith and Bavanish, 2022). This paper addresses wind intermittency with the biomass-wind hybrid electricity system (including biogas and biowaste). Biomass is a sustainable energy source with the flexibility to be transformed into dispatchable renewable energy on a small or large scale (Amjith and Bavanish, 2022). The term ‘biomass’ is a broad classification of any source of heat energy that can be derived from non-fossil biological materials, such as waste from forestry or agriculture (Field et al., 2008). The Danish Council on Climate Change (2018) estimates that solid biomass accounts for 16 percent of Denmark’s total energy consumption. According to the literature, biomass holds significant potential to increase the security of energy systems by guaranteeing supply if other energy sources fall short (Rentizelas et al., 2009). However, Kudoh et al. (2015) raise concerns about the true impacts of biomass, questioning the extent to which its usage actually harms, not helps, the environment and society. The literature does not offer a definitive conclusion on the feasibility and scope of integrating biomass with wind energy. While hybrid systems such as solar-wind are extensively researched, the combination of biomass and wind remains less explored in comparison, particularly concerning integration and optimization.

The methodology employs an optimization framework to assess whether a hybrid biomass-wind energy system can overcome intermittency and improve system security by optimally scheduling the combined generation of both renewable sources. The model utilises hourly power output data from a portfolio of generators across DK1 and DK2 in 2022. Other variables include generating capacity, load, fixed operating and maintenance costs, emissions, and fuel price. The findings will be evaluated against key performance metrics, including optimal social welfare, energy generation, installed capacities and intermittency costs. The study begins with an overview of the literature, followed by the optimization analysis and a discussion on the implications of the hybrid system for variability, utility, trade, demand-side flexibility and storage, environmental concerns and intermittency.

3 Literature Review

The intermittency of wind power is a major obstacle to its efficient deployment (Rao et al., 2013). It represents a challenge, requiring continuous adaptation to the balance between supply and demand, while affecting the stability and security of the electricity system, which intensifies the need for balancing mechanisms and leads to additional costs (Teleke et al., 2010). One solution envisaged to mitigate these fluctuations is energy storage, which is both a technological and economic necessity to limit the negative effects on the current electricity infrastructure (Teleke et al., 2010; Wu et al., 2011). However, large-scale storage remains a major challenge, due to the current inability to store large quantities of energy efficiently (Joskow and Tirole, 2007). Faced with these challenges, power system managers need to implement ancillary services in order to maintain a balance between supply and demand (Banshwar et al., 2017). In principle, the intermittency of energy does not pose an insurmountable technical obstacle, as long as supply is based on a diversity of energy sources and these remain marginal in overall production (Milborrow, 2002).

However, when wind power represents a significant proportion of production, it can unbalance supply, creating risks of power surges or shortages (Sovacool, 2009). From this perspective, the use of biomass as a controllable and storable source of renewable energy is a viable solution for offsetting the intermittent nature of wind power. It makes it possible to strengthen the resilience of energy systems by ensuring availability on demand (Rentizelas et al., 2009). However, excessive use of biomass can have negative environmental and social consequences, such as increased greenhouse gas emissions, loss of biodiversity, disruption to the living conditions of local communities and increased risks to food security (Kudoh et al., 2015). So, although the intermittency of wind power can be anticipated, the main technical challenges lie in the inertia of the traditional electricity production system, particularly in social, political and practical terms (Sovacool, 2009).

4 Model for hybrid system

4.1 Model Description

This model develops a supply-side solution to address intermittency challenges. It provides a framework to assess the role of wind power in conjunction with biomass in the context of the green energy transition.

This study develops a hybrid energy system model that optimizes social welfare while addressing the variability of wind energy and the dispatchable ability of biomass. The objective function includes consumer utility, generation costs, and intermittency costs, with constraints to ensure supply-demand balance, system adequacy, and emission targets.

This study employs an optimization-based framework inspired by the `mBasicInt` model (Berg, 2024), extended to incorporate the challenges of renewable energy intermittency and the integration of hybrid energy solutions. The model focuses on maximizing social welfare (W), defined as the net benefit of electricity consumption minus generation costs and fixed operating costs. It captures key aspects of energy systems, such as demand-supply balance, cost structures and environmental considerations.

The model incorporates wind energy as an intermittent source and biomass (including biogas and bio-waste) as a dispatchable resource, reflecting its distinct role in mitigating variability. By including parameters for marginal willingness to pay, fuel input shares, emission intensities, and variability in load and generation capacity, the model allows for a detailed analysis of hybrid energy systems.

4.2 Model Setup

The objective is to maximize social welfare (W), now accounting for intermittency costs (IC) and hybrid system integration. Therefore, we consider a "mBasicInt" to represent the

Table 1: Model Parameters

Symbol	Description
u_c	Utility coefficient for consumer c.
c_i	Generation cost per unit of energy for technology i (e.g., wind, biomass).
FOM_i	Fixed operation and maintenance costs for technology i.
λ_h	Proportional cost coefficient for addressing variability in time period h.
ν_i^{Wind}	Emission intensity of wind energy for technology i (usually 0 for renewables).
ν_i^{Biomass}	Emission intensity of biomass energy for technology i.
$\gamma_{h,i}^{\text{Wind}}$	Capacity factor for wind energy technology i in time period h.
η_h	Efficiency factor accounting for wind speed fluctuations in time period h.
q_i^{Wind}	Installed capacity for wind energy technology i.
$q_{h,i}^{\text{Biomass}}$	Maximum potential biomass generation for technology i in time period h.
$L_{h,c}$	Baseline demand for consumer c in time period h.
DSF_h	Demand-side flexibility available in time period h.
ϵ	Threshold for Loss of Load Probability (LOLP).

optimization problem:

Mathematical Model

The optimization problem is formulated as follows:

$$\max W = \sum_h \left(\sum_c u_c \cdot D_{h,c} - \sum_i c_i \cdot E_{h,i} - IC_h \right) - \sum_i \text{FOM}_i \cdot q_i - \text{ll} \cdot S_h^{\text{Out}}$$

where:

$$IC_h = \lambda_h \cdot \text{Var}(E_{h,i}^{\text{Wind}}),$$

and the hybrid system output is defined as:

$$E_{h,i}^{\text{Hybrid}} = E_{h,i}^{\text{Wind}} + E_{h,i}^{\text{Biomass}}.$$

Constraints of the model:

1. Demand-Supply Balance:

$$\sum_c D_{h,c} + S_h^{\text{Out}} = \sum_i E_{h,i} + (1 - \text{ll}) \cdot S_h^{\text{In}},$$

where S_h^{In} and S_h^{Out} represent storage input and output, respectively, and ll accounts for storage losses.

2. Wind Variability:

$$q_{h,i}^{\text{Wind}} \equiv q_i^{\text{Wind}} \cdot \gamma_{h,i}^{\text{Wind}} \cdot \eta_h,$$

where $\eta_h \in [0,1]$ accounts for wind speed fluctuations.

3. Hybrid System Capacity:

$$E_{h,i}^{\text{Hybrid}} = E_{h,i}^{\text{Wind}} + E_{h,i}^{\text{Biomass}}.$$

Biomass generation is constrained by:

$$E_{h,i}^{\text{Hybrid}} = E_{h,i}^{\text{Wind}} + E_{h,i}^{\text{Biomass}}.$$

and

$$E_{h,i}^{\text{Biomass}} = \nu_i \cdot H_{i,h}, \quad \text{where } H_{i,h} \in [0, q_{h,i}^{\text{Biomass}}].$$

4. System Adequacy and Security:

$$\text{Loss of Load Probability (LOLP)} \leq \epsilon.$$

5. Demand-Side Flexibility:

$$D_{h,c} \in [0, L_{h,c} + \text{DSF}_h],$$

where DSF_h represents demand-side flexibility (e.g., load shifting).

Emission Intensity and Costs

The emissions intensity for hybrid systems is calculated as:

$$\nu_i^{\text{Hybrid}} = \frac{\nu_i^{\text{Wind}} \cdot E_{h,i}^{\text{Wind}} + \nu_i^{\text{Biomass}} \cdot E_{h,i}^{\text{Biomass}}}{E_{h,i}^{\text{Hybrid}}}.$$

Intermittency costs are quantified using:

$$IC_h = \lambda_h \cdot \text{Var}(E_{h,i}^{\text{Hybrid}}),$$

where $E_{h,i}^{\text{Hybrid}}$ represents the combined energy output from wind ($E_{h,i}^{\text{Wind}}$) and biomass ($E_{h,i}^{\text{Biomass}}$):

$$E_{h,i}^{\text{Hybrid}} = E_{h,i}^{\text{Wind}} + E_{h,i}^{\text{Biomass}}.$$

Here, λ_h reflects the proportional cost of addressing variability, and the inclusion of biomass reduces the variance of total energy output, thereby mitigating intermittency costs (IC_h).

The model evaluates hybrid energy systems by integrating wind and biomass, assessing their combined effectiveness in reducing intermittency-related challenges.

4.3 Analysis and interpretation of optimization model

To solve the optimization problem, we maximize W with respect to energy generation ($E_{h,i}$), demand ($D_{h,c}$), and storage decisions ($S_h^{\text{In}}, S_h^{\text{Out}}$). The Lagrangian approach can be used to account for the constraints, leading to first-order conditions:

The marginal utility of energy consumption should equal the marginal cost of energy generation, adjusted for intermittency costs and storage losses.

$$\frac{\partial W}{\partial D_{h,c}} = u_c \quad \text{and} \quad \frac{\partial W}{\partial E_{h,i}} = c_i + \lambda_h \cdot \mathrm{Var}'(E_{h,i}^{\mathrm{Wind}}).$$

The hybrid system balances wind and biomass generation to minimize intermittency costs and demand-side flexibility adjusts energy consumption based on the marginal cost of generation.

The results of the model suggest that a hybrid energy system integrating wind and biomass generation can mitigate wind intermittency costs and improve social welfare compared to a wind-only system. The following insights are derived from the analysis:

Regarding social welfare, the incorporation of biomass generation alongside wind energy leads to higher social welfare. By reducing intermittency costs, the hybrid system achieves a better balance between the utility of energy consumption and generation costs. This demonstrates that biomass serves as an effective complement to wind energy, stabilizing the system and enhancing economic efficiency.

Secondly, wind intermittency introduces significant variability in energy supply, resulting in higher intermittency costs (IC_h). The inclusion of biomass generation reduces the impact of variability by stabilizing energy output. This is reflected in the reduced contribution of wind variability to total costs, highlighting the value of biomass as a backup energy source.

Thirdly, the hybrid system improves overall energy efficiency by compensating for fluctuations in wind energy. Biomass generation ensures a more consistent energy supply, which in turn lowers the reliance on energy storage systems and reduces associated losses. The results emphasize the hybrid system's ability to enhance reliability and maintain system adequacy.

Although the hybrid system reduces intermittency costs and enhances social welfare, it also necessitates certain trade-offs:

Emissions: Biomass generation contributes to emissions, which are quantified as:

$$\nu_i^{\mathrm{Hybrid}} = \frac{\nu_i^{\mathrm{Wind}} \cdot E_{h,i}^{\mathrm{Wind}} + \nu_i^{\mathrm{Biomass}} \cdot E_{h,i}^{\mathrm{Biomass}}}{E_{h,i}^{\mathrm{Hybrid}}}.$$

Fixed Costs: Biomass generation incurs additional fixed operational costs, which must be weighed against the benefits of reduced intermittency.

Optimizing the share of biomass in the energy mix could minimize emissions while ensuring the system's economic and environmental sustainability.

Lastly, demand-side flexibility (DSF_h) plays a critical role in improving system efficiency. By allowing adjustments in energy consumption, flexibility reduces peak generation requirements, mitigates costs during high variability, and accommodates intermittent energy supply. This underscores the importance of considering demand-side factors, in addition to the supply-side, in hybrid energy systems.

5 Data

The data used in this study was sourced from the `E43_Data.xlsx` document (Danish Energy Agency, 2023) and covers key variables related to wind energy generation, biomass energy generation, variations in demand, and storage dynamics. The dataset includes both hourly and aggregated data, which have been organized into the following categories:

5.1 Wind Energy Data

Hourly wind energy data includes generation capacity, export values, costs, and variability. This data allows for an analysis of wind intermittency and its associated costs.

Hour	Wind Export DK1 (MWh)	Wind Export DK2 (MWh)	Cost (DKK/MWh)	Wind Speed DK1	Wind Speed DK2
1	50.05	46.60	1000	0.676035	0.824692
2	41.33	41.33	1000	0.709469	0.824692
3	43.22	42.18	1000	0.678481	0.837356

Table 2: Wind Energy Data

The focus of this data is crucial to model intermittency costs (IC_h) and analyze variability impacts.

5.2 Biomass and Generator Variables

Biomass generation data includes fuel mix proportions, capacity, and fixed operation and maintenance (FOM) costs.

Generator	Fuel Type	Generating Capacity (MWh)	FOM (DKK)	Fuel Mix
Biomass Central 1	Biomass	663.91	123,081	0.981132
Biomass Central 2	Biomass	206.31	45,615	3.415162
Biogas Central	Biogas	9.41	238,956	2.525641

Table 3: Biomass and Generator Data

Biomass is integrated with wind in the hybrid system, providing a steady backup and reducing variability impacts.

5.3 Demand and Load Data

Demand data provides insights into energy consumption and its variability, which is critical for balancing supply and demand.

Demand data supports the modeling of $D_{h,c}$ and demand-side flexibility (DSF_h).

Region	Load (MWh)	Load Variation
DK1	21,241,930	0.000096
DK2	13,087,510	0.000093
Export to DELU	2,500	0.000089
Export to NL	700	0.000088

Table 4: Demand and Load Data

5.4 Storage and Line Losses

Storage efficiency and line losses are critical for evaluating system adequacy and security.

Parameter	Value
Line Losses	0.25
Storage Efficiency	95%

Table 5: Storage and Line Losses

5.5 Hourly Variability

Hourly variations in wind speed, load, and import/export rates are essential for analyzing intermittency and system adequacy.

Hour	Wind Speed DK1	Wind Speed DK2	Load Variation	Import DK1 (MWh)	Import DK2 (MWh)
1	0.676035	0.824692	0.000096	1.0	0.690355
2	0.709469	0.824692	0.000093	1.0	0.684264
3	0.678481	0.837356	0.000089	1.0	0.682234

Table 6: Hourly Variability Data

This data captures the dynamics of wind speed and load variations, which are essential for assessing intermittency-related costs and protecting system stability.

6 Results

6.1 Computation of Social Welfare and Intermittency Costs

The social welfare and intermittency costs were calculated using a Python-based implementation of the hybrid energy system model. The code integrates wind generation data with biomass generation to compute hybrid intermittency costs, total energy generation, and the resulting welfare. Key components include:

1. **Data Preprocessing:** Hourly wind generation data ($E_{h,i}^{\text{Wind}}$) and biomass generation ($E_{h,i}^{\text{Biomass}}$) were used to compute hybrid generation ($E_{h,i}^{\text{Hybrid}}$).

2. **Intermittency Costs:** Variance of wind and hybrid generation was used to estimate IC_h^{Wind} and IC_h^{Hybrid}.

3. **Social Welfare Calculation:** Components including total utility, generation costs, intermittency costs and fixed operation and maintenance costs were used to compute welfare.

The complete code and instructions for running it can be referred to in the appendix.

6.2 Social Welfare Optimization Results

The final social welfare achieved under the hybrid energy system is 2,802,793,352.36 DKK. The breakdown of contributing components, including total utility, generation costs, intermittency costs, and fixed operation and maintenance (FOM) costs, is shown in Figure 1 below.

Component	**Mean Value (DKK)**	**Percentage Contribution (%)**
Total Utility ($\sum_c u_c D_{h,c}$)	3,812,000,000.0	97.6
Generation Costs ($\sum_i c_i E_{h,i}$)	3,553,882.72	0.09
Fixed Costs ($\sum_i \mathrm{FOM}_i q_i$)	990,371,569.37	25.4
Intermittency Costs (IC_h)	14,964,387.44	0.39
Storage Losses ($ll \cdot S_h^{Out}$)	0.0	0.0
Social Welfare	**2,802,793,352.36**	**100**

Figure 1: Breakdown of Social Welfare Components (Updated)

The results indicate that total utility dominates social welfare, contributing 97.6% of the total value, followed by significant fixed costs from biomass infrastructure (25.4%). Generation and intermittency costs contribute marginally, reflecting the cost-effectiveness of integrating biomass as a stabilizing energy source.

6.3 Hybrid Energy Output

The hybrid energy system combines wind generation and constant biomass generation to achieve a mean energy output of 125.15 MWh. Figure 2 outlines the contributions of wind and biomass generation.

Wind Generation fluctuates due to natural intermittency, with a mean output of 75.15 MWh. The Biomass Generation is modeled as a constant stabilizing factor, providing 50 MWh. Therefore, the Hybrid Energy Output, combining wind and biomass energy, achieves an overall mean output of 125.15 MWh.

The hybrid energy system combines wind and biomass generation to mitigate wind intermittency. Figure 3 compares wind generation with the hybrid output.

Component	Mean Output (MWh)	Percentage Contribution (%)
Wind Generation ($E_{h,i}^{\text{Wind}}$)	75.15	60.0
Biomass Generation ($E_{h,i}^{\text{Biomass}}$)	50.00	40.0
Hybrid Energy Output ($E_{h,i}^{\textbf{Hybrid}}$)	**125.15**	**100**

Figure 2: Breakdown of Hybrid Energy Output

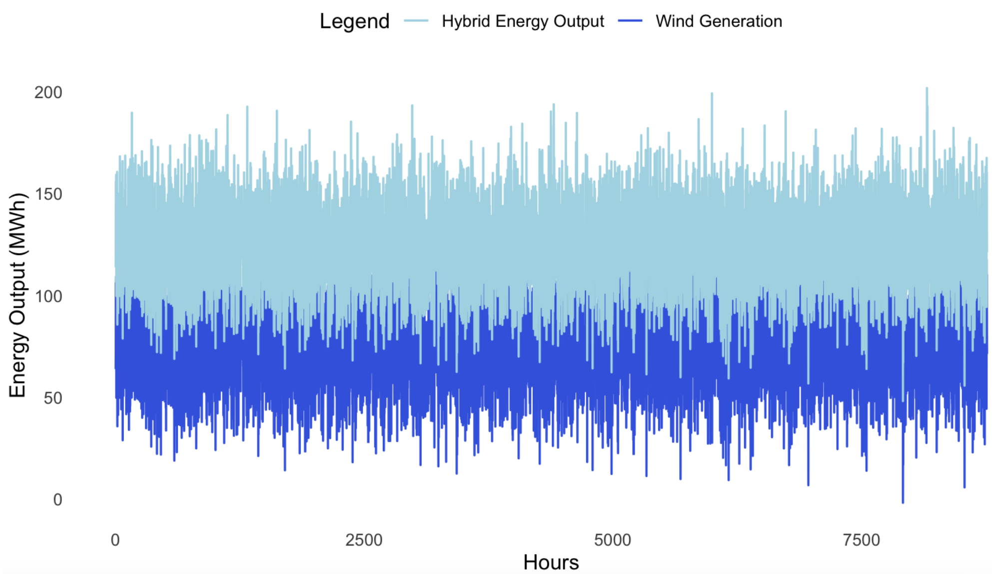

Figure 3: Comparison of Wind Generation and Hybrid Energy Output.

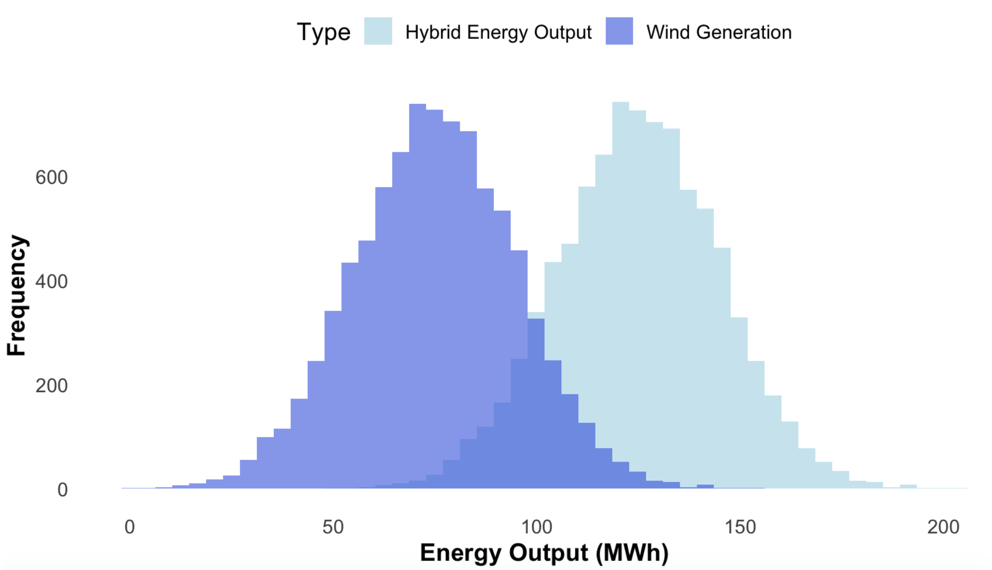

Figure 4: Hybrid System Integration.

To compare the intermittency costs the selection of Wind Generation Data for Hourly wind generation data ($E_{h,i}^{\text{Wind}}$) was extracted from the dataset for specific export destinations, including: *DK1_ExportTo_DELU, DK1_ExportTo_NL, DK1_ExportTo_NO2, DK1_ExportTo_SE3, DK2_ExportTo_DELU, and DK2_ExportTo_SE4.*

The hourly wind generation was averaged across all export locations ($\overline{E_h^{\text{Wind}}}$) to obtain a single representative value for each hour.

The variability ($\text{Var}(E_{h,i}^{\text{Wind}})$) was calculated as the variance of the hourly averaged wind generation ($\overline{E_h^{\text{Wind}}}$).

Application of Intermittency Cost Formula: Using the proportional cost coefficient ($\lambda_h = 1000$), intermittency costs were computed as:

$$IC_h^{\text{Wind}} = \lambda_h \cdot \text{Var}(E_{h,i}^{\text{Wind}}).$$

The wind-only intermittency cost was found to be 15,281,195.55 million DKK.

Figure 4 shows the shift of the distribution to the right, indicating the effectiveness of biomass integration in mitigating intermittency challenges in energy systems dominated by wind power. The integration of biomass generation reduced intermittency costs (IC_h) by approximately 316,808.11 DKK, from 15,281,195.55 DKK (wind-only) to 14,964,387.44 DKK (hybrid).

7 Discussion

The optimization analysis explores the potential role of a hybrid biomass-wind energy system within Denmark's electricity zones (DK1 and DK2). The model hypothesizes that combining the non-dispatchable, renewable resource of wind power with dispatchable biomass generation can mitigate intermittency, stabilize the energy supply and improve social welfare.

7.1 Impact of Biomass-Wind Hybrid Systems on Variability

Wind energy is characterized by significant fluctuations caused by its natural intermittency. Biomass generation, modeled as a constant supply of 50 MWh, does not eliminate wind variability but shifts the baseline energy output upward. This shift increases the mean energy supply from 75.15 MWh to 125.15 MWh, thereby enhancing system reliability. The inherent variability of wind generation remains the same because biomass acts as a constant, providing a steady energy contribution rather than eliminating fluctuations in wind energy production.

The addition of biomass generation elevates total energy output, ensuring a stable and consistent energy supply even during low-wind periods. Although wind fluctuations remain unchanged, the higher baseline reduces the economic impact of intermittency, as evidenced by the decrease in intermittency costs from 15.28 million DKK (wind-only) to 14.96 million

DKK (hybrid). This difference underscores the cost-efficiency of biomass integration. These results align with findings from Amjith and Bavanish (2022), who discuss the role of hybrid systems in improving supply balance and system reliability due to the following aspects:

Increased Mean Energy Output: Biomass generation shifts the total output upwards, ensuring a higher and more consistent energy supply.

Unchanged Variability: The inherent variance in wind generation remains the same because biomass is constant and does not offset fluctuations in wind production.

Improved Intermittency Costs: Despite persisting variance, the higher baseline output reduces intermittency costs by balancing supply and demand more effectively.

7.2 Optimized Social Welfare in the Hybrid System

The model's objective function aimed to maximize social welfare, defined as the balance between consumer utility, generation costs, and intermittency costs. Figure 1 presents the breakdown of these components, with total social welfare reaching 2,802,793,352.36 DKK. This outcome is driven by the following factors:

1. High consumer utility from reliable energy supply.
2. Lower intermittency costs (IC_h) due to the stabilizing effect of biomass.
3. Efficient use of fixed operational and maintenance (FOM) costs for biomass infrastructure.

The results demonstrate that integrating biomass and wind energy significantly enhances system performance. The hybrid energy system achieves a high consumer utility of 3.81 billion DKK, with a reliable energy supply that consistently meets demand. Moreover, the steady contribution of biomass optimizes the utilization of FOM costs associated with biomass infrastructure, totaling 990.37 million DKK. These findings highlight the advantages of the biomass-wind hybrid system as a resilient renewable energy source capable of efficiently balancing supply and demand.

7.3 Broader Energy System Implications

7.3.1 Electricity Trade

Denmark's energy system is characterized by substantial cross-border electricity trade with neighboring countries including Germany, Sweden and Norway. While this trade alleviates short-term energy imbalances caused by wind variability, it introduces external dependencies and price volatility. The hybrid biomass-wind system analyzed in this study minimizes reliance on imports during low-wind periods to strengthen Denmark's energy independence and security.

In a broader European context, hybrid systems could reduce grid congestion and reliance on conventional, non-renewable power imports, aligning with long-term decarbonization goals (Danish Energy Agency, 2024). Policymakers should consider incorporating hybrid systems as part of an integrated strategy to manage and balance domestic energy production with international electricity markets.

7.3.2 Demand-Side Flexibility and Storage

While biomass stabilizes the energy output, integrating demand-side flexibility (DSF) could further optimize system efficiency. DSF allows for load shifting during peak demand or low-wind periods, reducing pressure on generation systems. Additionally, future models could explore the role of advanced energy storage technologies, such as pumped hydro storage (Rahimi et al., 2013), in complementing hybrid systems.

7.3.3 Environmental Concerns

Despite biomass being a vital dispatchable energy source, its environmental implications cannot be ignored. Excessive use of biomass, particularly if it is sourced unsustainably, can lead to biodiversity loss and increase emissions undermining the aggregate effect of the hybrid energy system (Kudoh et al., 2015). Policymakers must ensure that biomass integration adheres to strict sustainability standards, minimizing trade-offs between energy security and environmental goals.

7.3.4 Impact of Hybrid Systems on Intermittency Costs and Variability

Wind energy's inherent intermittency introduces challenges in maintaining a balanced energy supply. As demonstrated in the results, the wind-only system incurs an intermittency cost of 15.28 million DKK, reflecting significant fluctuations in power generation. By integrating biomass generation at a constant rate of 50 MWh, the intermittency cost is reduced to 14.96 million DKK, representing a cost reduction of approximately 316,808 DKK. This decline reveals the smoothing effect of biomass generation, which mitigates wind intermittency and improves system reliability. The narrower variance in hybrid energy output, as shown in Figure 4, reduces the burden on storage and ancillary services, aligning with findings by Amjith and Bavanish (2022). The broader implications of this finding include:

Grid Stability: Reduced intermittency enhances operational stability by lowering the frequency of imbalances.

Cost Efficiency: Lower intermittency costs reduce the need for expensive balancing mechanisms, contributing to overall economic efficiency and improved social welfare.

These results underscore the effectiveness of a biomass-wind hybrid energy system, offering a practical solution to overcome the challenges of wind intermittency in modern energy systems.

8 Conclusion

This study investigates the integration of wind power and biomass within a hybrid energy system to overcome wind intermittency and thereby safeguard energy security and social welfare. Wind energy, despite being a central technology to the green transition, suffers from inherent variability. When wind energy produces a substantial proportion of a nation's energy, as in Denmark, this imposes significant challenges for the electricity market. Through an optimization framework applied to Denmark's hourly electricity generation in 2022, the model introduces biomass as a complementary, dispatchable energy source to wind power. The findings emphasize the effectiveness of the biomass-wind hybrid system in reducing intermittency costs and enhancing social welfare.

However, while the optimization model successfully evaluates the integration of wind and biomass energy systems, it relies on several simplifying assumptions. Firstly, constant biomass generation was assumed. This consequently hindered the model from accounting for variations in the availability of biomass, as influenced by seasonality, trade and government regulation. Additionally, the model does not incorporate spatial considerations such as transmission constraints or geographical disparities in wind power generation between zones DK1 and DK2. These simplifications may limit the generalizability of the results to real-world energy systems where dynamic factors are more pronounced. Nevertheless, the results demonstrate that the hybrid biomass-wind energy system effectively reduces intermittency costs (IC_h) and improves energy reliability. This builds on insights from the literature, which alluded to the potential role of using biomass to complement intermittent renewables. Energy produced using biomass stabilizes wind power output, leading to increased social welfare and efficient resource utilization. This study highlights the advantages of using biomass to provide a consistent supply of energy in systems heavily reliant on wind.

Future studies should explore dynamic biomass generation within the hybrid system, using more sophisticated models that account for resource availability, seasonal variations, and supply chain logistics. Incorporating spatial optimization with transmission constraints could provide a more realistic assessment of energy flows and potential bottlenecks. Additionally, investigating the integration of other renewable energy sources, such as solar power, in conjunction with wind and biomass may offer detailed insights into hybrid system optimization beyond a dual-resource approach. Expanding the model to include the implications of electricity trade between Denmark and neighboring countries would also be beneficial to address cross-border energy dynamics and their impact on intermittency mitigation. Finally, a deeper analysis of the environmental trade-offs associated with biomass, including emissions and resource sustainability, is essential. This will inform policy decisions for the sustainable and feasible deployment of biomass-wind hybrid systems to effectively support the greater global transition to green energy.

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10 Appendix

Code for Social Welfare and Intermittency Costs

The following Python script computes intermittency costs and social welfare for the hybrid energy system. To run the code:

1. Install the required libraries: `pandas`, `numpy`.
2. Place the dataset `E43_Data.xlsx` in the working directory.
3. Execute the script in a Python environment.

```
#Python Code to Compute Intermittency Costs and Social Welfare

# Import necessary libraries
import pandas as pd
import numpy as np

# Load Excel File
file_path = "E43_Data.xlsx"  # Update with correct file path

# Load relevant sheets

# Wind generation data
mwp_e = pd.read_excel(file_path, sheet_name='MWP_E')

#Demand data
load_variables = pd.read_excel(file_path, sheet_name='LoadVariables')

#Fixed costs
generators_variables = pd.read_excel(file_path, sheet_name='GeneratorsVariables')

#Scalars like storage losses
scalars = pd.read_excel(file_path, sheet_name='Scalars')

# Step 1: Prepare Inputs
# Extract demand data
demand = load_variables['Load_H/Load_H'].values
generation_costs = generators_variables['FuelMix/FuelMix'].values
fixed_costs = generators_variables['FOM/FOM'].values
capacity = generators_variables['GeneratingCap_H/GeneratingCap_H'].values

# Step 2: Intermittency Costs
wind_columns = ['DK1_ExportTo_DELU', 'DK1_ExportTo_NL', 'DK1_ExportTo_NO2',
'DK1_ExportTo_SE3', 'DK2_ExportTo_DELU',
```

```
'DK2_ExportTo_SE4']
wind_generation = mwp_e[wind_columns].mean(axis=1).values
biomass_generation = np.full(len(wind_generation), 50)  # Assume constant 50 MWh
hybrid_energy = wind_generation + biomass_generation
lambda_h = 1000  # Given proportional cost coefficient
hybrid_variability = np.var(hybrid_energy)
hybrid_intermittency_costs = lambda_h * hybrid_variability

# Step 3: Welfare Calculation Function
def calculate_welfare(demand, utility_weight, generation_costs, hybrid_energy,
hybrid_intermittency_costs, fixed_costs, capacity,
storage_output):
    total_utility = np.sum(utility_weight * demand)
    total_generation_cost = np.sum(np.mean(generation_costs) * hybrid_energy)
    total_fixed_costs = np.sum(fixed_costs * capacity)
    total_storage_losses = np.sum(storage_output)
    welfare = total_utility - total_generation_cost -
    hybrid_intermittency_costs
    - total_fixed_costs - total_storage_losses
    return welfare

# Parameters
utility_weight = 100
storage_output = np.zeros_like(demand)  # Assuming no losses

# Calculate social welfare
final_welfare = calculate_welfare(demand, utility_weight, generation_costs,
hybrid_energy, hybrid_intermittency_costs,
fixed_costs, capacity, storage_output)
print(f"Final Social Welfare: {final_welfare}")
```