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Introduction and motivation

The Danish government has set a target to reach climate neutrality by 2050. This goal of carbon neutrality includes total independence from fossil fuels by 2050 with the government currently discussing changing the target to 2045. In 2022, roughly 57% of energy in Denmark comes from fossil fuels (Roser, 2022). To reach the 2045 target there are several important issues which must be addressed, but the two most important are the electrification of 80% of all energy usage in the country including within the transport and housing sectors (Energifonden, 2020). The second is to ensure that there is enough electricity produced locally coming from renewable sources. This essay will look to address the second issue by showing the costs associated with producing enough electricity to satisfy the current electricity demand. The Danish government has already made large steps towards solving this problem as only about 16% of the electricity produced locally within Denmark comes from fossil fuel sources (Roser, 2022). The breakdown in electricity production is 55% wind power, 23% bioenergy, 6% solar, 0,06% hydro and the rest from fossil fuels. Denmark was a first mover within the wind industry beginning to invest in the technology in the 70s, with the first commercial turbine in 1979. Denmark has also historically had a large agricultural sector and therefore the transition to using wood chips and other waste from farming has been rapid. Bioenergy in this case is only considering modern regenerative forms of bioenergy, not traditional methods (Roser, 2022). Biofuels represent an even larger part of the overall energy production for district heating. The first target on the road to 2050 is the 2030 target of having 100% of Danish electricity consumption be from renewables.

Our project will look to calculate and estimate the costs associated with producing enough electricity to meet the Danish demand for electricity, quarter by quarter. The model will minimize costs by finding the ideal blend of electricity production which also minimizes carbon emissions and stays below the current maximum capacity for specific technologies in Denmark. Our result will give an indication of the additional investment required to hit the 2030 target.

Literature Review

Articles and reports such as (BCG, 2022), (EU Commission, 2019), suggest that in order for Denmark to hit net zero the country must be able to electrify and produce more renewable electricity. The EU commission report highlights that the Danish energy consumption which is the most non-renewable is transport and heating (EU Commission, 2019). They should both look to be electrified as the only renewable options currently are electric vehicles and district heating through biomass which both represent the minority of the energy consumption. The BCG report highlights a further EUR 200 Bn is needed to reach the 2050 target. Our study will look to see how we can reduce this investment by optimizing current use.

There have been several articles written looking to analyze the potential for 100% renewable energy in Denmark and in other European countries. The chosen targets are differing between articles, (H. Lund, 2009) calculated how to integrate new ideas from experts to secure energy supply, reach the 50% target in 2030 and to a lesser extent raise energy exports. The target of energy security and 50% target are aligned with our proposed motivation. Their analysis includes a list of potential initiatives which were combined through the EnergyPlan model. Their conclusion suggests a number of emissions reducing initiatives and in terms of energy supply suggests a majority biomass and wind-based system with lower amount of solar PV. This model from 2009 was quite accurate in predicting current energy generation but required too many elements for us to repeat the method.

A 2017 paper from Gerbaulet uses a similar dispatch and investment model to our model but looks at the European energy market. It also includes potential investment in conventional power technologies but strives to hit the intended EU Energy regulation targets. The model includes three separate components: the dispatch of energy in Europe, the necessary grid upgrades and the overall power generation. Here we just wanted to use the dispatch model but instead only focus on electricity generation instead of three elements.

The model we are working with has been adapted based on several papers describing various elements of our model. We use an objective function in our model which was inspired by (Mahor, 2009). The concept of an economic dispatch model is to minimize the costs of meeting the electricity demand. In our analysis we therefore started by creating an objective function similar to the "*Simplified economic cost function*", which combines the costs of several potential energy sources to calculate the total generating cost.

Our model closely resembles models presented in (Chavan, 2011), they also use a linear economic dispatch model which looks to maximize efficiency or minimize costs while still living up to a specified set of constraints. In our problem formulation we have applied many of the techniques outlined in this article. The article describes the concept of load periods, which differentiates different potential energy consumption in periods. This was a valid consideration for our model as the demand for electricity varies across seasons. Along with this the article outlines how to set constraints on an economic dispatch model, which we also did since we wanted to consider potential maximum local capacity.

Problem description

We are implementing an economic dispatch model to minimize the cost of producing 100% of Denmark's electricity from renewable sources. In addition to this we will be looking to consider the potential maximum capacity of each energy source and the total emissions produced. We have several assumptions which are important to acknowledge in doing our analysis.

Assumptions:

1. Denmark has a closed energy system and therefore cannot export or import electricity.
2. There is no potential storage of electricity on our system.
3. The total supply and demand for electricity is consistent throughout the quarter. Therefore, the supply of electricity does not have to equal the peak demand.
4. While the energy system is closed and we do not take account of any storage, production is equal is to the demand.
5. The future energy demand will remain equal to the current demand despite the electrification of the energy system.
6. The current renewable technologies most prevalent in Denmark will remain the same.
7. Other factors such as weather data and wind speed data or sun time we assume they work optimally according to our needs.

Model description

Transforming the whole electricity production for 2022 of Denmark to a 100% renewable electricity (net zero) by utilizing the current capabilities of our renewable infrastructure. We aim to minimize the Operation and Maintenance cost of the existing infrastructures. We use time steps to make our model more flexible. Below is demonstrated a table with the variables and the parameters we used while and our Objective function and Constraints.

Table 1: Variable table

Variables Abbreviation	Variables Meaning
W_t	Electricity generated from wind energy for timestep t
H_t	Electricity generated from hydropower energy for timestep t
B_t	Electricity generated from biomass for timestep t
PV_t	Electricity generated from solar PV for timestep t

Table 2: Parameters

Parameters Abbreviation	**Parameters Meaning**
T	Represents a timestep/quarter (T=1,2,3,4)
C	Cw = Cost to produce 1 MWh from wind energy in DKK Ch = Cost to produce 1 MWh from hydro energy in DKK Cb = Cost to produce 1 MWh from Biomass/Biofuels in DKK Cpv = Cost to produce 1MWh from Solar PV in DKK
Capacity	Capacityw = Maximum capacity of electricity produced from wind energy Capacityh = Maximum capacity of electricity produced from hydro energy Capacityb = Maximum capacity of electricity produced from Biomass/Biofuels Capacitypv = Maximum capacity of electricity produced from Solar PV
MaxEmissions	Maximum limit of carbon emissions to produce the total amount of electricity
Emissions	Emissionsw = CO_2/MWh from wind Emissionsh = CO_2/MWh from hydro Emissionsb = CO_2/MWh from biomass/biofuels Emissionspv = CO_2/MWh from Solar PV
TP	Total production of electricity
P_t	Electricity production at timestep t (T=1,2,3,4)
Min_Variable_Prod	This number differs for each variable and represents a minimum percentage of production for each timestep

Aim of the model:

Achieve net zero in electricity production based on 2022 electricity production of Denmark. Transform the whole electricity production to renewable electricity and minimize the cost.

Objective Function:

$$Min = \sum_{t=1}^{4} C_w \times W_t + C_h \times H_t + C_b \times B_t + C_{pv} \times PV_t$$

Constraints:

$W_t \geq 0,\ \forall W \in R,\ t \in T$ (1)

$H_t \geq 0,\ \forall H \in R,\ t \in T$ (2)

$B_t \geq 0,\ \forall B \in R,\ t \in T$ (3)

$PV_t \geq 0,\ \forall PV \in R,\ t \in T$ (4)

Constraints (1) - (4) illustrate that all the variables must be either positive or zero while we cannot have negative electricity production.

$\sum_{t=1}^{4} W_t \leq Capacity_w\ \forall W \in R\ , t \in T$ (5)

$\sum_{t=1}^{4} H_t \leq Capacity_h\ \forall H \in R\ , t \in T$ (6)

$\sum_{t=1}^{4} B_t \leq Capacity_b\ \forall B \in R\ , t \in T$ (7)

$\sum_{t=1}^{4} PV_t \leq Capacity_{pv}\ \forall PV \in R\ , t \in T$ (8)

Constraints (5) - (8) ensure that the production of electricity from any source does not exceed the electricity capacity of that source for all timesteps.

$$\sum_{t=1}^{4} W_t \times Emissions_w + H_t \times Emissions_h + B_t \times Emissions_b + PV_t \times Emissions_{pv} \leq MaxEmissions\ \ \forall\, W, H, B, PV \in R, t \in T \ (9)$$

Constraint (9) ensures that the carbon emissions produced from the electricity production from all the electricity sources for all the timesteps do not exceed the Maximum CO2 emissions we have established as a target.

$$W_t + H_t + B_t + PV_t \leq P_t\ \forall\, W, H, B, PV \in R, t \in T\ (10)$$

Constraint (10) is being done for each timestep separately and ensures that for each timestep we do not exceed the production needed for that timestep.

$$\sum_{t=1}^{4} W_t + H_t + B_t + PV_t \leq TP\ \ \forall\, W, H, B, PV \in R, t \in T\ (11)$$

Constraint (11) ensures the production from all sources at all timesteps does not exceed the production we want to produce.

$Min\_W\_Prod_t \leq W_t\ \ \forall W \in R, t \in T$ (12)

$Min\_H\_Prod_t \leq H_t\ \ \forall H \in R, t \in T$ (13)

$Min\_B\_Prod_t \leq B_t\ \ \forall B \in R, t \in T$ (14)

$Min\_PV\_Prod_t \leq PV_t\ \ \forall PV \in R, t \in T$ (15)

Constraints (12) - (15) are being used as a safeguard to ensure that there will be generation from all renewable sources in every timestep.

$PV_1 \leq PV_2$ - tolerance $\forall PV \in R$ (16)

$PV_2 \leq PV_3$ - tolerance $\forall PV \in R$ (17)

$PV_4 \leq PV_2$ - tolerance $\forall PV \in R$ (18)

$W_2 \leq W_1$ - tolerance $\forall W \in R$ (19)

$W_3 \leq W_2$ - tolerance $\forall W \in R$ (20)

$W_2 \leq W_4$ - tolerance $\forall W \in R$ (21)

Constraints (16) - (21) are seasonal constraints. We are trying to simulate the peak season of each renewable and the offseason with lower capabilities with these constraints. The *"tolerance"* price is explained further in the discussion chapter.

Data for Modelling

To implement and extract results from the model presented in the previous chapters, we needed data that reflect reality as much as possible. In this effort we used a variety of sources. At first, we extracted data regarding O&M cost from each renewable energy source (IRENA, 2021). Furthermore, we used the IRENA electricity generation database to find the electricity generation capacity from each renewable source in Denmark for 2022. Additionally, we took into consideration the conversion efficiency percentage of each renewable for electricity generation and we adjusted the capacity of each renewable accordingly.

We also used data on total electricity production and production per quarter for 2022 from the Denmark's Global Climate Impact (Danish Energy Agency, 2023)

Lastly, we had to find carbon emissions data. We retrieved data concerning CO2/kwh from "*What Is the Carbon Footprint of Renewable Energy? A Life-Cycle Assessment"* and "*What Is the Carbon Footprint of Fossil Fuels? A Life-Cycle Assessment"* (Smoot, 2023) for each renewable and non-renewable. In addition, we decided to set a cap on carbon emissions, the carbon emissions generated in 2022, as both renewable and non-renewable energy sources were used to generate electricity. To find this number of emissions we multiplied the emissions from each energy source with the production generated from each source. The emissions data and the cap number for carbon emissions (MaxEmissions) have a significant role in our analysis. The constraint and the upper limit ensure that we will not release more emissions even when reducing the production costs. The data tables 3,4,5 and 6 represent the data we extracted from various public sources to implement our model.

Table 3: O&M and capacity data per source

Renewable electricity source	O&M cost (DKK/MWh)	Capacity (MWh)
Wind	41	27.940.896
Hydro	22	33.040
Biomass	35	9.425.760
Solar PV	11	4.060.161

Table 4: Electricity production per time period

	Electricity Production (MWh)
Timestep 1	10.849.000
Timestep 2	7.239.000
Timestep 3	6.819.000
Timestep 4	9.192.000
Total Production	**34.099.000**

Table 5: CO2 emissions per MWh generated

Electricity Source	CO2/MWh
Wind	11.500
Hydro	24.000
Biomass	230.000
Solar PV	41.000

Table 6: Maximum emissions constraint

Emissions	CO2/MWh
MaxEmissions	6.486.695.983.900

Findings

As part of our research, we are demonstrating our findings into a clear and concise table including the result of our objective function and the result of our variables summarized for all timesteps. Furthermore, below you can observe charts that offer specialized insights from our model. For this project to extract the results mentioned, we used Python programming language due to its powerful data processing capabilities and the best-fit architecture connectivity with our devices. The optimization modeling was handled by PuLP, a Python library that formulates and solves linear programming problems. It offers a convenient way to define the objective function and constraints and interfaces seamlessly with various solvers. We used the CBC solver through PuLP for its efficiency in solving big-scale linear programming problems. CBC, which stands for Coin-or branch and cut, is well-known for its performance and is a common choice in both academic research and industry applications. Visualization of the data was achieved using Matplotlib, a Python library known for its extensive suite of plotting tools, allowing for detailed and customizable representations of data. This enabled us to produce insightful stacked bar charts and pie charts that clearly illustrate the outcomes of our optimization, such as the mix of energy production and associated CO2 emissions. The integration of PuLP for optimization modeling, combined with the graphical effectiveness of Matplotlib, provided a comprehensive analysis of the energy production scenario, highlighting the potential of using open-source tools to draw meaningful conclusions in complex decision-making landscapes like the one we examine.

Table 7: Output per variable

Variable	**Output**
W_t	20.580.039 MWh
H_t	33.040 MWh
B_t	9.425.760 MWh
PV_t	4.060.161 MWh
MinCost (Objective Function)	1.219.071.850 DKK

Figure1: Production per Timestep and per renewable source (Mwh)

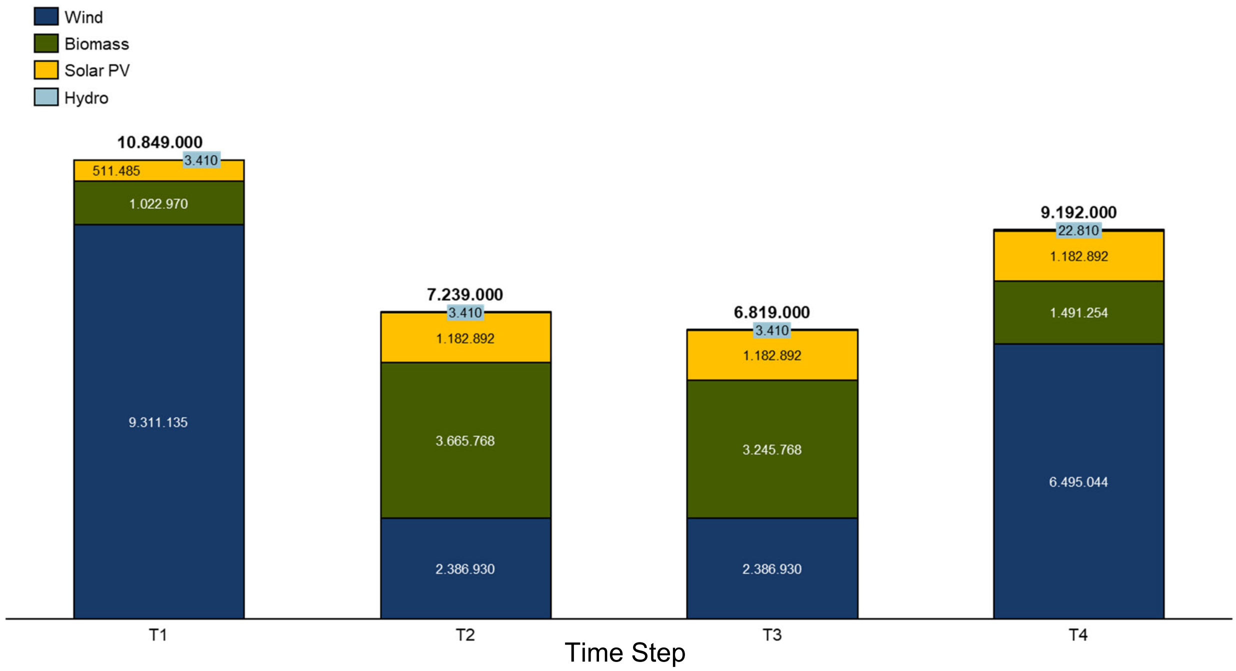


Figure 2: Total cost by electricity source

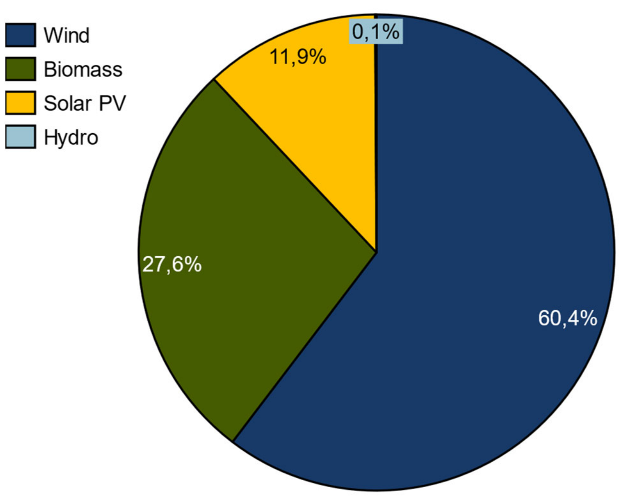
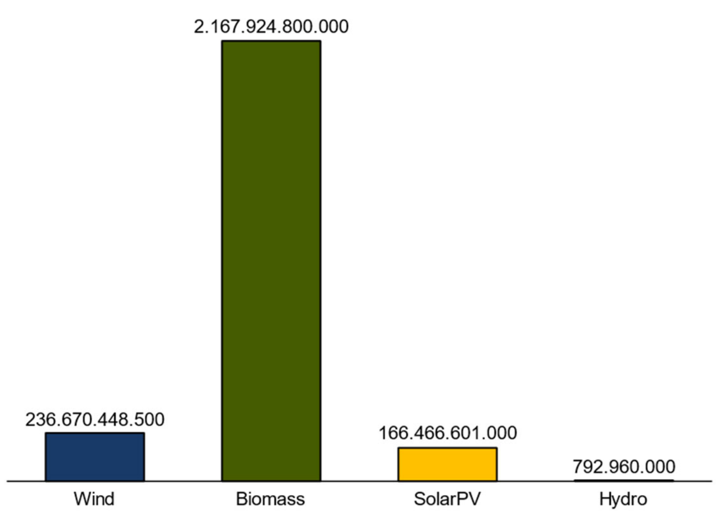


Figure 3: Total emissions by source (gCO2eq)



Discussion

As we have mentioned our goal is to minimize the O&M costs of existing renewable sources and infrastructure in Denmark to produce electricity equal to 2022 based on historical data for electricity production. The result of this objective function shows the minimum operation and maintenance costs of existing renewable energy structures to produce a given MWh defined by the parameter TP. The result of our objective function is 1.219.071.850 DKK.

In this country analysis of electricity dispatch based on 2022 data for Denmark we have used 4 timesteps. Timesteps make our model more flexible and portray an analysis closer to real fluctuations in demand seen in Denmark. If we were to extend the scope of this paper, specialized weather data could be integrated into our model to achieve accurate predictions or simulations of the future capacity. In our case T1 represents the first quarter of 2022 which we see has the clear highest electricity need which will be largely covered by wind, while T3 represents the third quarter of 2022 with the lowest electricity demand covered by mixture of technologies.

As we reported in the Problem Description chapter, constraints (16) – (21) aim to clarify the differentiation in electricity production for the renewable sources that are affected to a significant extent by weather conditions. The "tolerance" price is one millionth *(0.000001)* and we defined this price because we wanted to simulate strict inequality. Furthermore, we wanted the "tolerance" to be so small so it will not affect the results. As far it concerns constraints (12) - (15) Min_Variable_Prod parameter has been set to ensure production for each timestep from every renewable source. Although for every renewable source individually this price differs. Firstly, in regard to wind energy "$Min\_W\_Prod_t = 0.07 * TP$". Secondly, we demonstrate the type to find this price for Biomass "$Min\_B\_Prod_t = 0.03 * TP$". Thirdly, the Solar PV type is "$Min\_PV\_Prod_t = 0.015 * TP$". Lastly, we have Hydro "$Min\_H\_Prod_t = 0.0001 * TP$". As you observe the percentage multiplied with the total production differs for renewable each source. That happens because of differences in capabilities and technological development of each resource, and because of differences in capacity of each resource.

In Figure 2 is illustrated the CO_2 emissions that renewable produces. In this chart we observe the high emissions of Solar PV and Biomass compared to Wind Energy if we take into consideration the amount of electricity produced from each renewable. As described in the Data chapter, the MaxEmissions parameter reflects the CO_2 emissions in 2022 using renewable and non-renewable sources for electricity production. Based on the model we have developed using only renewable sources for the same amount of electricity production we managed to reduce CO_2 emissions by 60% for a total emission of 2,571,854,789,450 CO_2/MWh. Although our primary goal is to minimize operation and maintenance costs to produce 100% renewable electricity, this was an additional benefit. Taking the economic factors (costs) out of our model and setting the left-hand side of constraint (9) as the objective function and finding what the actual minimum CO_2 emissions given the technology and existing infrastructure the result is 963,507,555,000 CO_2/MWh. Which is 60% lower than the emissions of the economic dispatch model we built and almost 85% lower than MaxEmissions. Therefore, the economic efficiency in terms of operations and maintenance cost comes with an additional cost in carbon emissions.

To conclude, an important part of this research and linear programming models is to acknowledge their limitations or weaknesses. In our case we face one major limitation that is also somehow interconnected. The first limitation is the lack of more specialized data like weather data instead of taking assumptions in regard to the weather. Those data are commonly used in timesteps of an hour or per 5 minutes. That also means that we will have to use more computational power to extract results and if those weather data in 5-minute timestep for the whole year combined with other sophisticated data might create a complexity for us, based on the available computational power we have. One weakness in our result is that Solar PV is producing a similar amount of electricity for Timestep 3 and Timestep 4. Although according to theories Solar PV should produce more in Summer (Timestep 3) compared to Autumn (Timestep 4).

Reflections

While our result in its own holds value there are a few key reflections which are important for evaluating the result. There is additional production within the available renewable assets which can be better exploited. This conclusion does not however imply that Denmark could maintain current O&M costs when expanding the network. Currently Denmark has a large installed capacity of onshore wind technology but a larger future offshore wind capacity. Studies such as (Koch, 2019) have looked to study the additional costs associated with acceptance of wind turbines being constructed near people. While the article suggests that onshore wind is still cheaper, it acknowledges that their methodology may undervalue the costs associated with acceptance. If the results of our model are to be extrapolated, we therefore must look at the potential increases in O&M which could be associated with e.g., lesser social acceptance.

The second restriction is sourcing of materials and production equipment. Several wind turbine manufacturers are currently experiencing supply chain issues, and high losses. These issues could influence future O&M pricing and therefore current prices may be a poor representation. Additionally, biomass suffers from a different sourcing problem which is outlined in the 2022 OECD report “Towards net zero emissions in Denmark”, highlighting that Denmark is becoming increasingly reliant on importing biofuels, reducing the sustainability of the process. Denmark imports 45% of the solid biofuels used for district heating and electricity generation. The article implies that it would be hard to imagine biofuels such as wood chips could maintain such a large share of power production in the future as other countries begin to use more biofuels. This dispatchable technology would become increasingly more expensive as more countries begin to use biomass.

Using the result of the dispatch model shows that while there is a huge need for further investment within the energy system, optimizing the use of current capacity would reduce the investments needed. Our model, however, only aims to optimize around the seasonal differences in electricity usage and not the hour-to-hour changes. In order to ensure that there was enough electricity in the system, you would therefore need to even out demand for electricity to match production. In order to get close to this there would need to be investment in storage capacity and regulation of level consumption patterns.

Conclusion

The research conducted on Denmark's transition to 100% renewable electricity production underlines the critical role of economic dispatch models in managing and optimizing energy systems. These models are essential for decision-makers to balance the trade-offs between cost, capacity, and environmental impact. By employing an economic dispatch model, we could identify the most cost-effective mix of renewable energy sources that align with Denmark's infrastructure and environmental goals. This approach provides a framework for other countries that are seeking to optimize their energy systems for cost, efficiency, and sustainability.

Our study further highlights the importance of transitioning to sustainable green electricity with minimal emissions. Denmark's strategy, focusing on wind, hydro, biomass, and solar PV, demonstrates a viable pathway toward achieving a low-carbon energy system. The significant reduction in CO_2 emissions projected in our model, despite being primarily cost-driven, emphasizes the benefits of renewable energy sources. They not only offer a sustainable alternative to fossil fuels but also contribute significantly to reducing the carbon footprint of electricity production.

In conclusion, Denmark's path toward a carbon-neutral future serves as an insightful case study for other countries. The economic dispatch model used in this study provides a valuable tool for optimizing renewable energy mix, and balancing cost, capacity, and environmental objectives. The insights from this research can guide policymakers, energy companies, and stakeholders in making informed decisions as they navigate the complexities of transitioning to a sustainable energy future.

References

1. Boston Consulting Group. 2022. “Denmark’s Path to Net Zero,” April 2022.
2. Chavan, Shantanu, Navaneethakrishnan Raman, and Tamil Rajavel. 2011. “Economic Dispatch and Hydro-Scheduling Using Linear Programming.” https://www.ece.umn.edu/class/ee8725/SAMPLE%20PROJECT%20REPORT%20FROM%20EE5721.pdf.
3. Danish Energy Agency. 2018. “Energistyrelsen.” Energistyrelsen. 2018. https://ens.dk/en.
4. Energy Agency 2023. “Denmark’s Global Climate Impact.” Https://Ens.dk/En/Our-Services/Projections-And-Models/Global-Report. 2023.
5. Energianalyse, EA. 2020. “Roadmap for Elektrificering I Danmark -Ho- Vedrapport.” https://www.ea-energianalyse.dk/wp-content/uploads/2020/03/1865_Roadmap-for-elektrificering-final.pdf.
6. European Commission. 2019. “Denmark’s Long-Term Strategy.” https://ec.europa.eu/clima/sites/lts/lts_dk_en.pdf.
7. Gerbaulet, Clemens, and Casimir Lorenz. 2017. “DynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market.” Www.econstor.eu. 2017. https://www.econstor.eu/handle/10419/161634.
8. Hevia-Koch, Pablo, and Henrik Klinge Jacobsen. 2019. “Comparing Offshore and Onshore Wind Development Considering Acceptance Costs.” *Energy Policy* 125 (125): 9–19. https://doi.org/10.1016/j.enpol.2018.10.019.
9. IRENA. 2022. “Renewable Power Generation Costs in 2021.” /Publications/2022/Jul/Renewable-Power-Generation-Costs-In-2021. July 2022. https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021
10. IRENA. “Technology.” Www.irena.org. https://www.irena.org/Energy-Transition/Technology.
11. Lund, H., and B.V. Mathiesen. 2009. “Energy System Analysis of 100% Renewable Energy Systems—the Case of Denmark in Years 2030 and 2050.” *Energy* 34 (5): 524–31. https://doi.org/10.1016/j.energy.2008.04.003.
12. Mahor, Amita, Vishnu Prasad, and Saroj Rangnekar. 2009. “Economic Dispatch Using Particle Swarm Optimization: A Review.” *Renewable and Sustainable Energy Reviews* 13 (8): 2134–41. https://doi.org/10.1016/j.rser.2009.03.007.
13. Ritchie, Hannah, and Max Roser. 2022. “Energy.” *Our World in Data*, July. https://ourworldindata.org/energy/country/denmark.
14. Smoot, Grace. n.d. “What Is the Carbon Footprint of Fossil Fuels? A Life-Cycle Assessment.” Impactful Ninja. https://impactful.ninja/the-carbon-footprint-of-fossil-fuels/.
15. Smoot, Grace. n.d. “What Is the Carbon Footprint of Renewable Energy? A Life-Cycle Assessment.” Impactful Ninja. https://impactful.ninja/the-carbon-footprint-of-renewable-energy/.
16. Statista Research Department. 2022. “Denmark: Power Production Share by Source 2020.” Statista. 2022. https://www.statista.com/statistics/1235360/denmark-distribution-of-electricity-production-by-source/.