An assessment of nuclear power's potential in Denmark

EnergyPLAN-course project

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Starting point

Project Recap

I assess the cost effectiveness of nuclear power in a *RE*-heavy system, mimicking the danish energy system in 2035.

- Concretely, $1GW$ **nuclear power as a substitute for** $2GW$ **off-shore wind capacity (ratio 1:2 in technologically feasible capacities)**.
- In reality, I see many limits hindering free optimization, why I want to base my calculations on a scenario that follows *the Danish climate projection* (KF).
  - *KF* does some optimization, but restricts main decisions to *frozen-policy* and politically feasible solutions.

I run the problem on *EnergyPLAN* as a compliment to a *CGE*-implementation (*GrønREFORM*), as *EnergyPLAN* allows for a classical linear problem set up with a well-behaved energy system.

Adaptation

My *EnergyPLAN*-setup is based on the reference study *Fakta om Atomkraft i Danmark* (FOA) that has also assessed the potential of nuclear power in Denmark (DK) in 2045.

From this, I let the following key elements differ ... ▸ Numbers in Appendix A

1. **Capacities** for *on-* and *off-shore wind*, *PV*, as well as, *PP* to keep a balanced system (*KF*)
2. The aggregate **demand** and its flexible component (*KF*).
3. **Costs** for nuclear power and off-shore wind (*IEA* + *KF*).
4. **Variation patterns** for *on-* and *off-shore wind*, *PV*, *market prices* and *electricity demand* (KF + ENS).

... and of cause nuclear power (with dh). I proceed with *CEEP* = 923457000, which, crucially, places ***nuclear partload* before reduction in *RE*** production, which is consistent with actual marginal costs.

Model dynamics

Figure 1: Comparison of baseline to reference (time series)

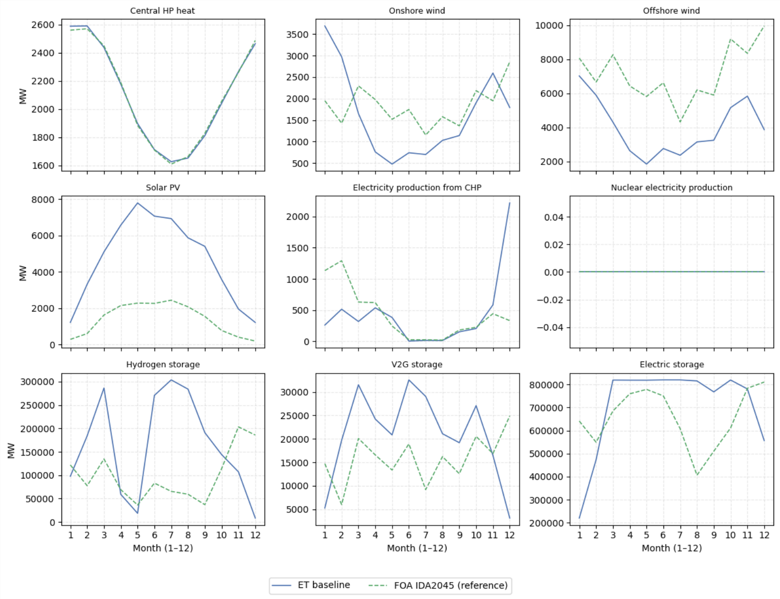


Figure 2: Comparison of baseline to shock (time series)

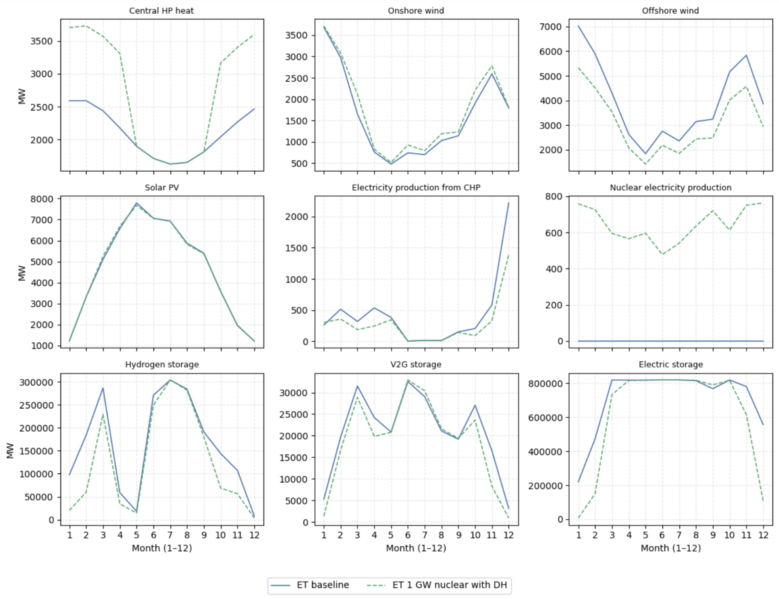


Figure 3: Composition of *Electricity market*

Beyond the time series, I compute the aggregated annual electricity market and, then, decompose it into the main power technologies (Pt):

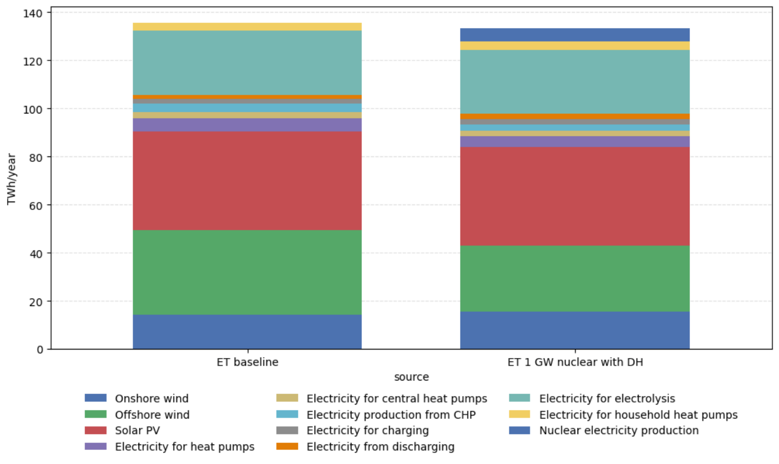


Figure 4: Composition of *Heat market*

I perform a similar exercise for the heat market, with the aggregated production decomposed into the main heat technologies (Ht):

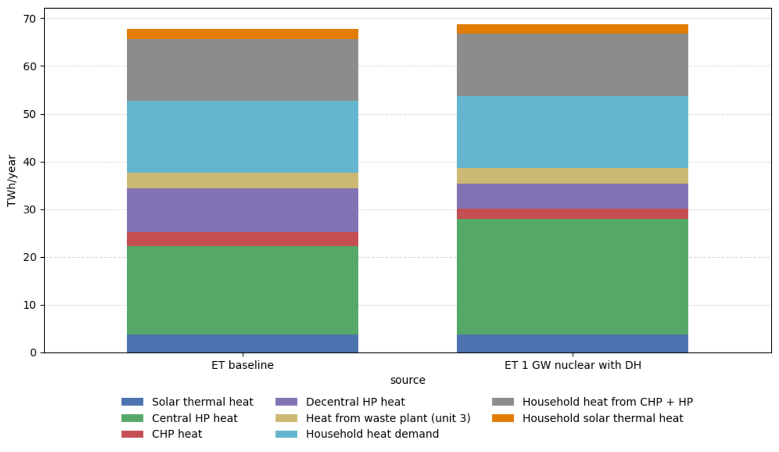


Figure 5: Capture rates of power technologies

Def: Capture rate: Let p_t^{Pt} be *the weighted average sale price of Pt in year, t*, and $\bar{p}_t$ *the average across the technologies*:

$$\text{Capture rate}_t = \frac{p_t^{Pt}}{\bar{p}_t}$$

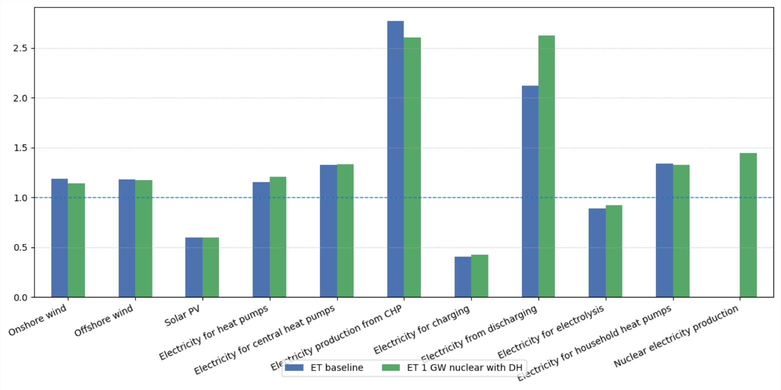
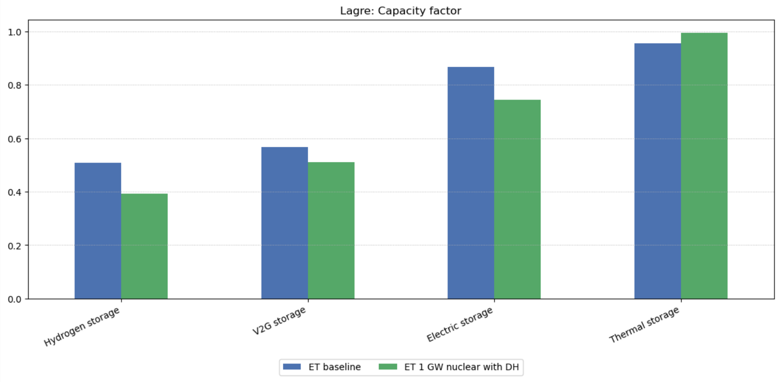


Figure 6: Capacity factor of Storage technologies (St)

Def: Capacity factor: Let $\hat{y}_t^{St}$ be *the actual delivery of energy from St in year*, t, and y_t *the technologically feasible*:

$$\text{Capacity factor}_t = \frac{\hat{y}_t^{Pt}}{y_t^{Pt}}$$



Initial results

Total cost minimization

In total, the effect of replacing $2GW$ *off-shore wind* with $1GW$ *nuclear power* is a slight cost increase in this styalized energy system.

Tabel 1: Annual system costs by case (million EUR)

	Trade		Costs (M EUR)			
Case	Import	Export	Variable	Fixed O&M	Annual investment	Total annual
Base	0.0	0.0	964.0	4330.0	18 337.0	23 631.0
Shock	0.0	0.0	1035.0	4356.0	18 258.0	23 649.0

Both energy systems are balanced as $NX = M = X = 0$. The shock increases the *variable*- and *Fixed O&M* costs, while it lowers the *Annual investment*.

Conclusion

Having completed the initial estimation, I conclude that there is **not a significant difference** in the *Total Annual Costs* between the two scenarios, with the nuclear scenario lying slightly above the base.

... but this was merely the initial estimation. The analysis will, beyond this course, be adapted to account for...

1. *System and transport* costs, which might increase with higher *RE*-production (shadow cost).
2. Key assumptions in the reference scenario, concerning the foreign market.
3. Less *MIT*-style shock, allowing for a higher interplay among the model variables.

... and many more.

Appendix A: Assumptions

EnergyPLAN assumptions (i/ii)

My estimation takes everything as givern per *FOA* except the following as mentioned under *Adaptation*:

Description	Value	Source
Electricity demand [TWh]	31.1	KF25
Additional electricity demand [TWh]	15.6	KF25
Onshore wind capacity [MW]	5150	KF25
Solar PV capacity [MW]	25134	KF25
Power plant capacity [MW]	6000	▸ Explanation in Appendix B
Electricity demand profile	–	ENS 2024
Offshore wind production profile	–	KF25 2035
Onshore wind production profile	–	KF25 2035
Solar PV production profile	–	KF25 2035
Hourly electricity prices	–	KF25 2035
Nuclear electricity dispatch profile	–	FOA
Nuclear heat / central HP profile	–	FOA

Tabel 2: Inputs (i/iii): Generic capacities and variation patterns

EnergyPLAN assumptions (ii/ii)

Tabel 3: Inputs (ii/iii): Pt costs

Description	Value	Source
Nuclear investment cost [M EUR/GW]	4.36	OECD/IEA
Nuclear economic lifetime [years]	60	FOA
Nuclear fixed O&M [M EUR/GW/yr]	2.6	OECD/IEA
Offshore wind investment [M EUR/MW]	2.5	FL
Offshore wind lifetime [years]	30	FOA
Offshore wind fixed O&M [M EUR/MW/yr]	1.9	FOA

Tabel 4: Inputs (iii/iii): Scenario-specific parameters

Description	Base case	Nuclear case
Nuclear capacity [MW]	0	1000
Offshore wind capacity [MW]	8287	6287
CEEP / regulation parameter	234570000	923457000
Nuclear heat capacity [GW]	0.0	5.77

Appendix B: A note on the Power Plant (*PP2*) capacity

The Power Plant (*PP2*) capacity (i/ii)

Currently, I need a massive $6GW$ **of *PP2* to avoid *'critical import needed'* in the last days of December.** The initial results just assume this capacity for both scenarios (ceteris paribus), but, future work should include a more sophisticated implementation.
Below is a short, initial explanation:

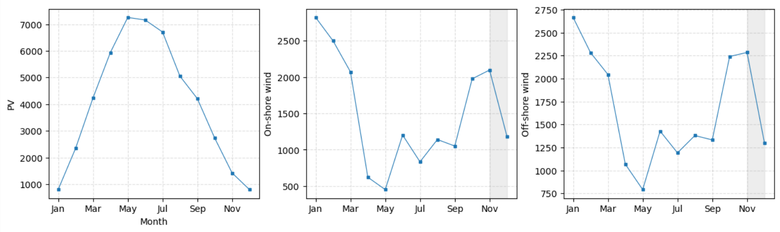
- Hourly time series data show that the import is only needed in very few hours (approx. 190 hours with $M_t > 0MW$).
  - All these hours are placed in late December.
  - Only 2 hours with $M_t > 4000$.

  $\Rightarrow$ Thus, is it really representative to increase *PP2* so much?
- As mentioned, a smaller change in *off-shore wind* production compared to *PV* might also to the trick.

Crucially, a descriptive analysis of the *KF*-distributions for *VE* indicate, that the issue, essentially, is due to heavy *curtailment* in their hourly time series. Figure on next slide

The Power Plant (*PP2*) capacity (ii/ii)

Figure 7 shows how **the production in December is about half that of January**; this is not representative.



Figur 7: *KF* hourly distributions by monthly average

A simple experiment, setting the December production equal to that of January, completely fixes the import-problem $\forall PP2^{\text{cap.}} > 100MW$.

$\Rightarrow$ A proper way to handle this quirk should be implemented in the future.