2024 European PVPMC workshop

Curtailment by intrinsic and extrinsic factors - impact on the financial performance.

Jan Vedde – 22nd August 2024

Agenda

1. **Intrinsic curtailment**
2. **Extrinsic curtailment**
3. **Revenue calculation & financial performance**
4. **Conclusion**
5. **Outlook**

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Optimising the grid connection capacity according to financial performance

Intrinsic curtailment

Curtailment according to plant design, imposed by project developer to optimise financial performance of the project.

Four examples discussed:

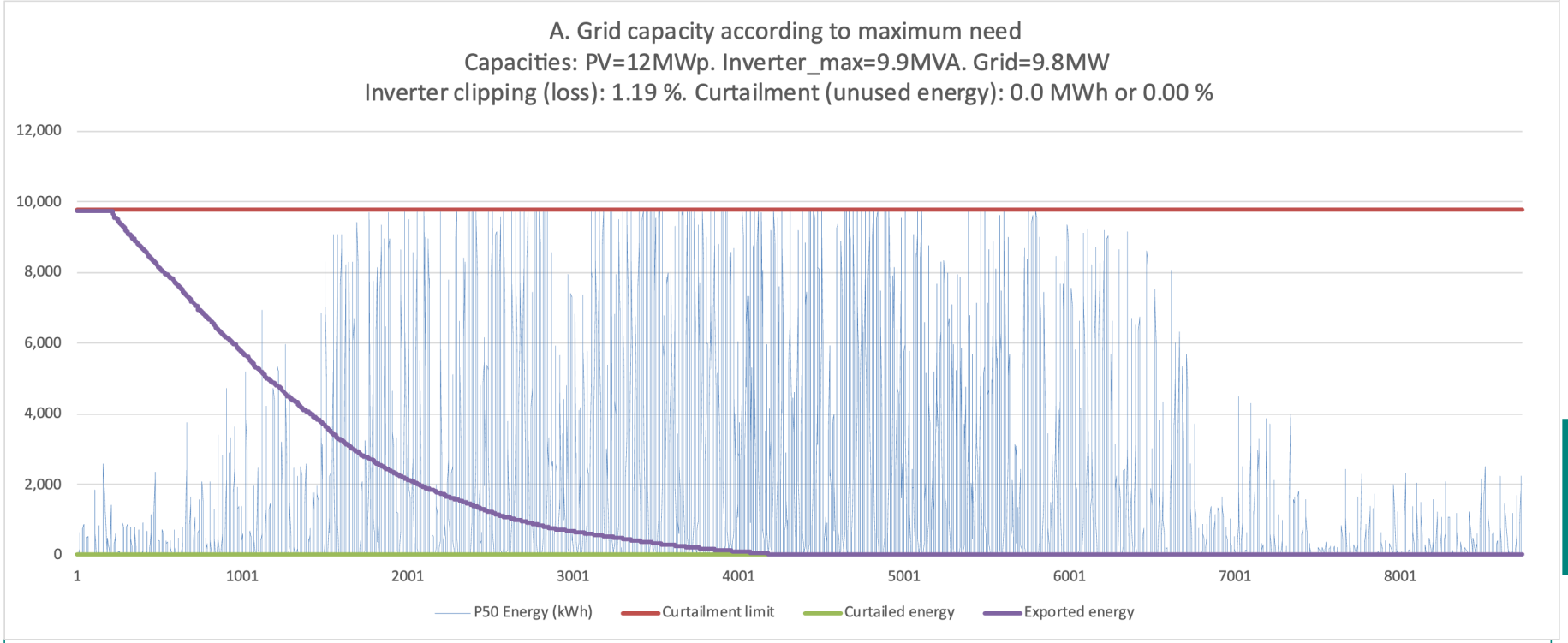
A. Grid capacity according to maximum need (reference = no curtailment)
B. Grid capacity according to RfG compliance
C. Grid capacity peak-shaved below RfG compliant limit
D. Grid capacity for a hybrid PV and wind project

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2

A. Grid capacity according to maximum need (reference without curtailment)

- **Objective**: to ensure energy export of <u>all energy</u> made available in the Point of Connection (POC)
- **Example**: GCA singed with capacity equal to the maximum active power of the inverters

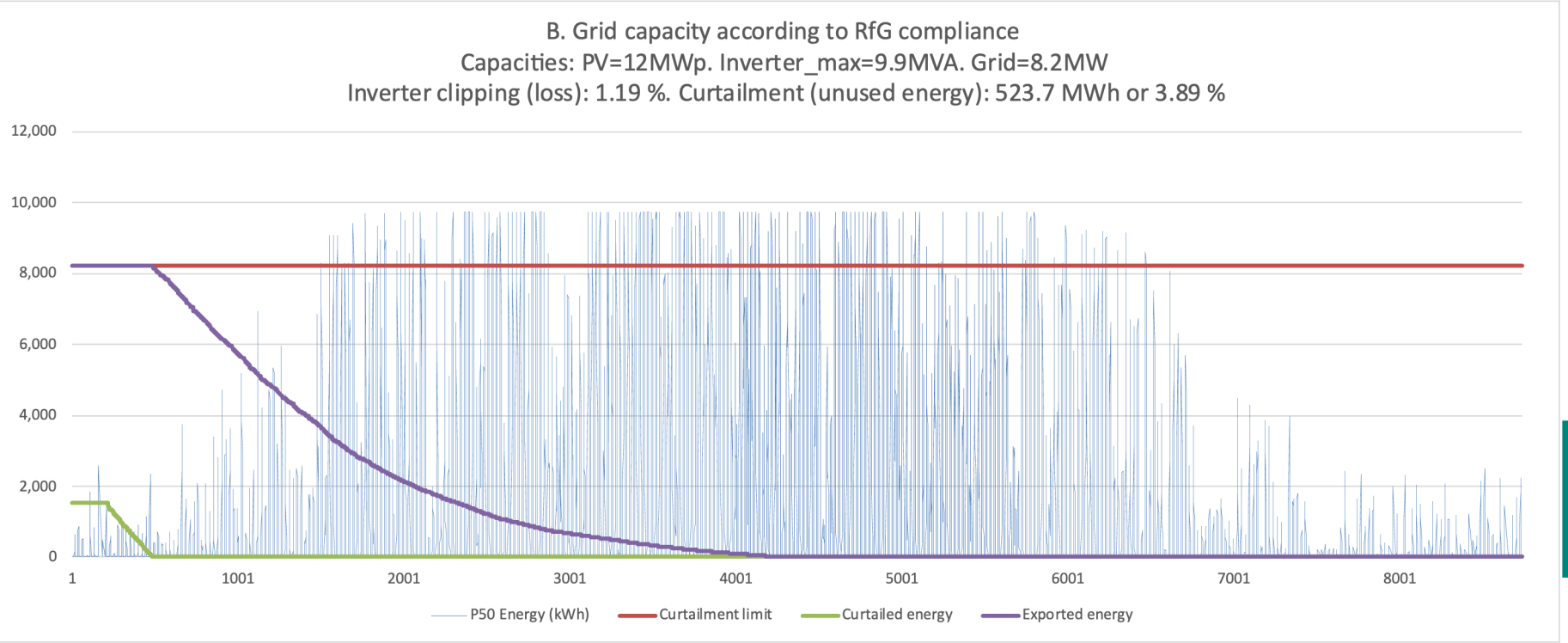


Preferred solution if grid capacity is available and free of charge

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B. Grid capacity according to RfG compliance

- **Objective**: to be compliant with RfG by use of installed inverters only (avoid installation of additional equipment like capacitor banks, reactors, filters etc.).
- **Example**: each Huawei Sun2000-330ktl inverter (nominal power: 300 kW, max power: 330 kVA) is assigned to a RfG compliant capacity of 273 kW in Denmark.

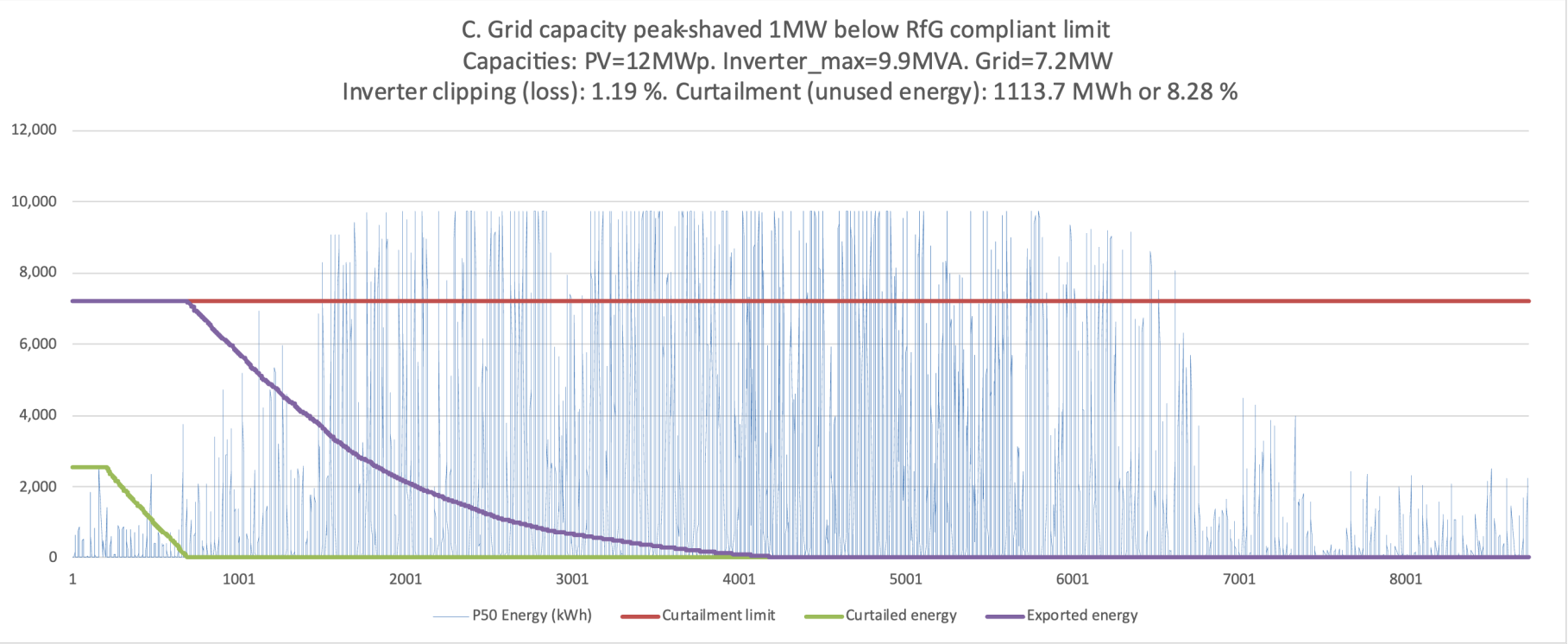


Preferred when simple RfG compliance is critical, and energy produced during peak hours are assigned a low value

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C. Grid capacity peak-shaved 1MW below RfG compliant limit

- **Objective**: cost savings in transformer/hardware as well as connection tariff by limiting the “peak” export capacity which will only be used few hours per year.
- **Example**: connection tariff for a PV project at 10 kV may be up to 400 k€ per MW (red zone) → strong incentive to not contract grid capacity with low utilisation.

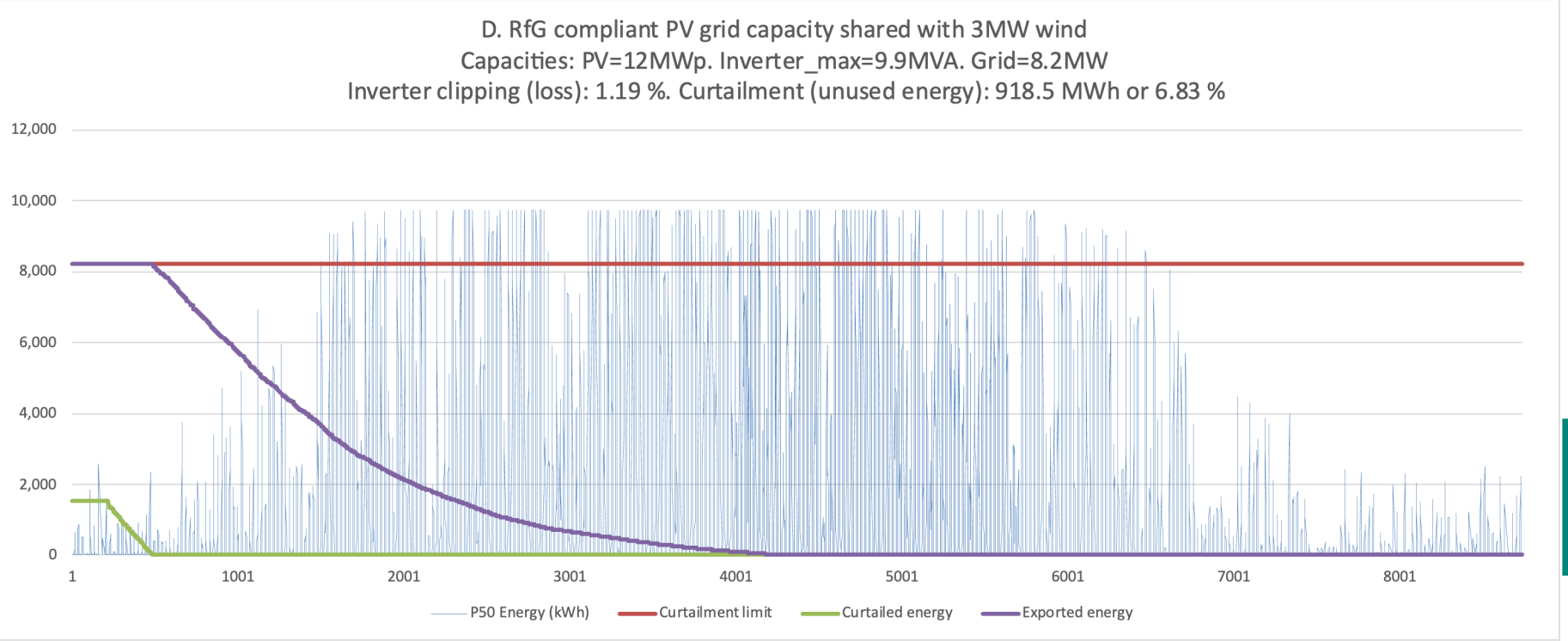


Example of trade-off between up-front payment of a high connection tariff with the value of peak-hour production

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D. RfG compliant PV grid capacity shared with 3MW wind (hybridization)

- **Objective**: cost savings in transformer/hardware and as well as connection tariff by increasing number of Full Load Hours (FLH) by adding an extra generator to POC.
- **Example**: connection of both PV and wind turbines to same grid connection point.



By adding 3MW wind the curtailment increases “only” from 524MWh to 919MWh. Corresponding to 6.8% of PV export or 4.1% of total export.

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Extrinsic curtailment

Curtailment imposed by external factors under conditions which may not be clearly defined.

Two examples discussed:

E. Flexible Grid Connection Agreement with a dynamic emergency clause

~~F. Static Flexible Grid Connection Agreement~~

G. Negative pricing

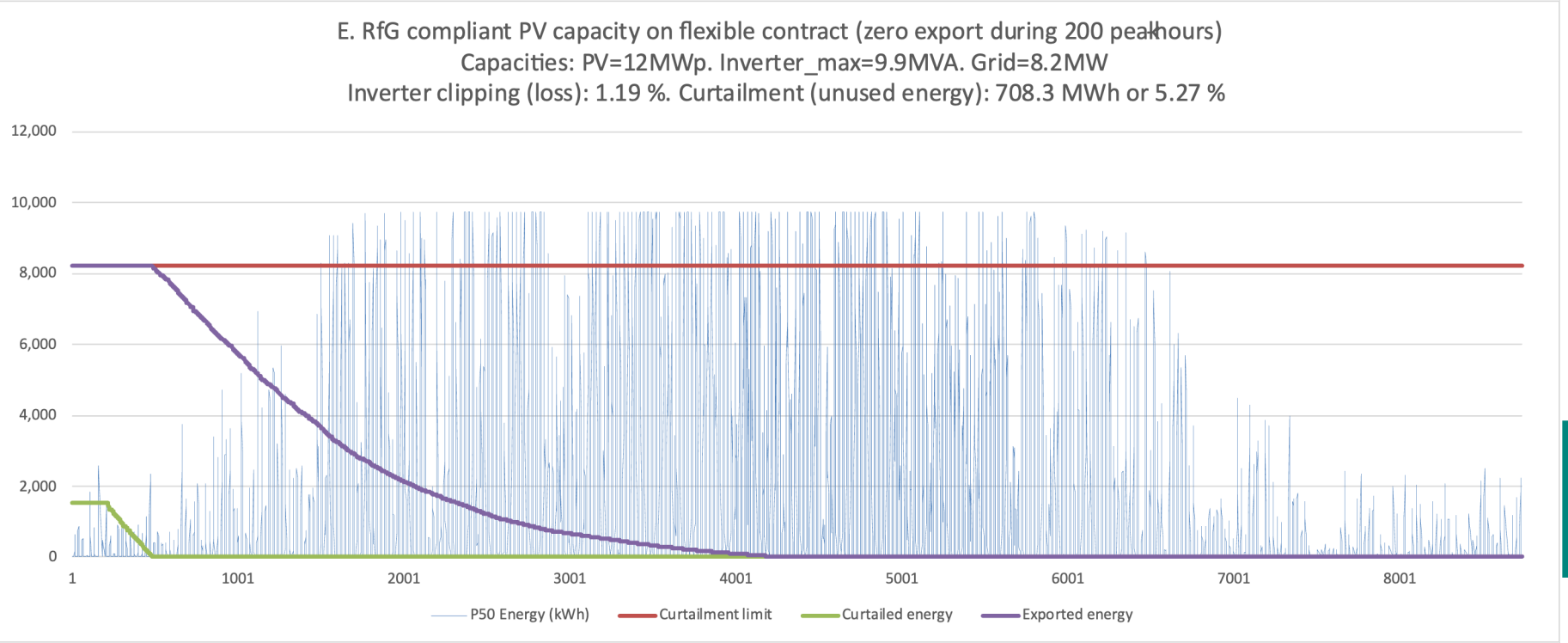
~~H. Ramp-rate restrictions~~

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7

E. Flexible Grid Connection Agreement with a dynamic emergency clause

- **Objective**: Opportunity for fast grid connection, when the project developer accept a risk of full of partly reduction of the export capacity during hours of congestion in the grid. To be compensated by a fast connection and a discounted connection fee.
- **Example:** (permanent flexibility): According to a capacity map of all stations in Denmark, the TSO and DSO disclose details of restriction conditions as:
  - ❖ Estimate on capacity to be curtailed up to 200 hours per year during high load operating conditions
  - ❖ Capacity of stations and interconnectivity among TSO and DSO stations
  - ❖ Existing loading of respectively PV and wind capacity at each station

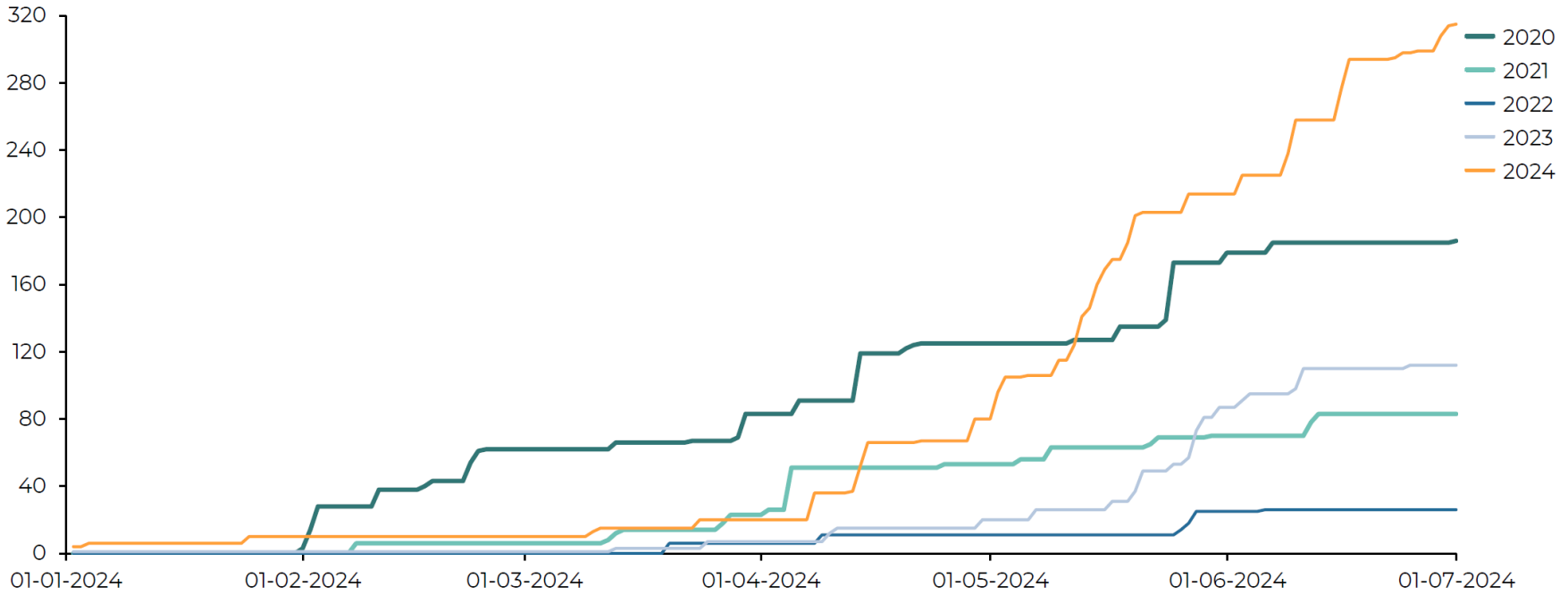


Accepting up to 200-hours with curtailment, the unused energy increases by 184 MWh or 1.4% (from 524 MWh to 708 MWh)

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G. Negative pricing

- Objective: Project developer make a Final Investment Decision despite future operating conditions may be very uncertain.
- Example: Number of negative price-hours has increase from <100 to >300 for H1 over the last 5 years



Already the current amount of 3.7GW of PV in the Danish grid has dramatically changed the amount of negative prices during summer.

Summary of example results: Energy yield

Demo project	Unit	A. Grid capacity according to maximum need	B. Grid capacity according to RfG compliance	C. Grid capacity peak-shaved 1MW below RfG compliant limit	D. RfG compliant PV grid capacity shared with 3MW wind	E. RfG compliant PV capacity on flexible contract (zero export for 200 peak-hours)
1. PV technology concept						
Inverter AC max apparent power	[kVA]	330	330	330	330	330
2. Solar resource & EYA						
GHi estimate used	[kWh/m2/a]	1100	1100	1100	1100	1100
Gross specific energy yield	[kWh/kWp]	1,121	1,121	1,121	1,121	1,121
3. Sizing by area & grid						
No of inverters in project	[#]	30	30	30	30	30
Total installed DC power	[kWp]	12,000	12,000	12,000	12,000	12,000
Grid capacity to be contracted	[MW]	9.8	8.2	7.2	8.2	8.2
Power ratio dc to grid	[kWp/kW]	1.23	1.46	1.66	1.46	1.46
4. Energy export						
Gross energy generation (1st year)	[GWh]	13.5	13.5	13.5	13.5	13.5
Inverter clipping loss	[%]	1.2%	1.2%	1.2%	1.2%	1.2%
Curtailment loss by hourly calculation	[%]	0.00%	3.89%	8.28%	6.83%	5.27%
Net energy export (1st year)	[GWh]	13.45	12.93	12.34	12.53	12.74

$$Net\ energy\ export = Gross\ energy\ generation\ *\ (1 - curtailment)\%$$

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Curtailment from 0% to 8.3% of energy generation presented by in the selected examples

Revenue calculation

Calculating the revenue according to:

$$\boldsymbol{Revenue = Net\ energy\ export\ * Power\ price}$$

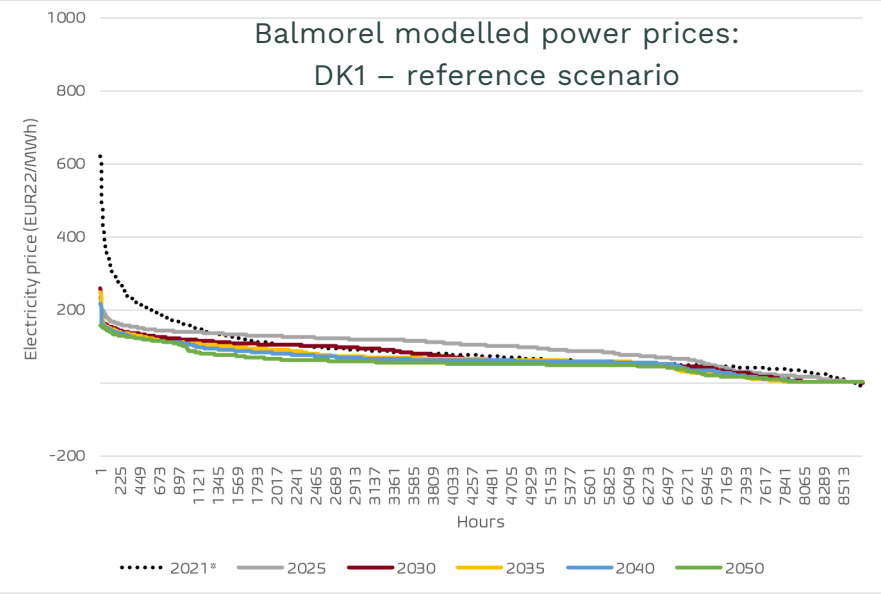
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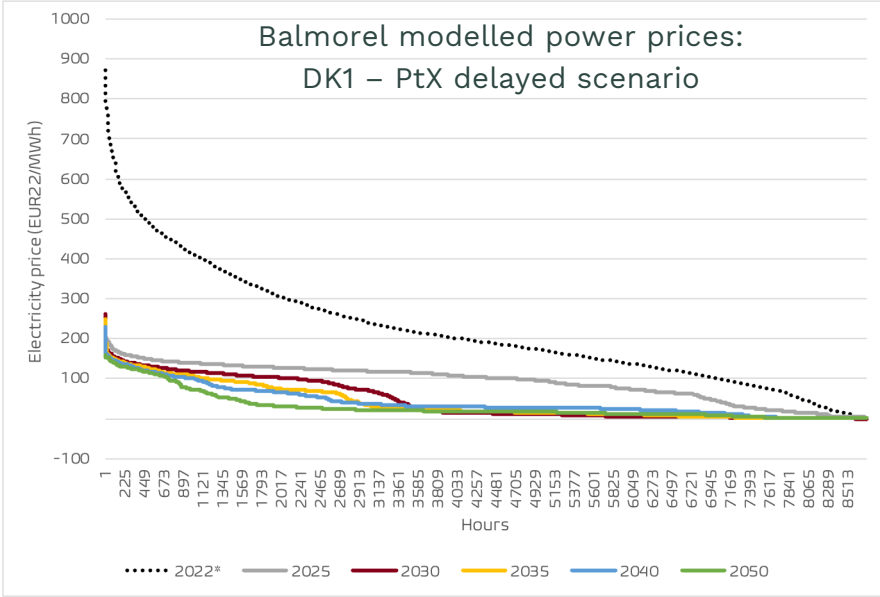
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Power prices taken from the Balmorel power market simulator

Project revenue can easily be calculated from the net energy export, once we have:

- a forecast for the specific bidding zone (DK1) as linked to neighbouring markets,
- a forecast for the full project period (30 years),
- an hourly breakdown of yearly power prices,
- knowledge of the meteorological conditions for the year used in the energy system modelling,
- a forecast reflecting the planned build-out of the power system wrt. generators and interconnectors (reference case)
- forecasts for alternative scenarios describing for example a delayed in deployment of PtX off-take





Calculated capture price and revenue provide the cash-flow which is input to the financial model.

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Summary of results: Revenue and financial performance

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Net energy export (1st year)	[GWh]	13.45	12.93	12.34	12.53	12.74
5. Power sales & revenue						
Capture price (all revenue, net export)	[EUR/MWh]	66.23	66.99	67.88	67.91	67.60
Value Factor (all revenue, lifetimeavg.)	[%]	64.33%	65.08%	65.94%	65.97%	65.68%
Gross lifetime revenue	[mEUR]	25.7	25.3	24.6	24.9	25.2
6. Financial model						
Sum of annual operational costs	[mEUR]	9.1	9.0	8.9	9.0	9.0
CapEx - Hard (on site)	[€/kWp]	300.00	300.00	300.00	300.00	300.00
CapEx - Grid connection	[€/kWp]	325.40	273.70	240.37	273.70	273.70
CAPEX in total	[€/kWp]	*625.40*	*573.70*	*540.37*	*573.70*	*573.70*
Absolute CAPEX in total	[MEUR]	7.50	6.88	6.48	6.88	6.88
7. Business case & conclusion						
Earnings	[mEUR]	0.45	0.84	0.92	0.69	0.79

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Maximum export is less attractive than RfG-compliant, peak-shaved, shared or flexible GCA – when connection tariff is 400k€/MW

Conclusion

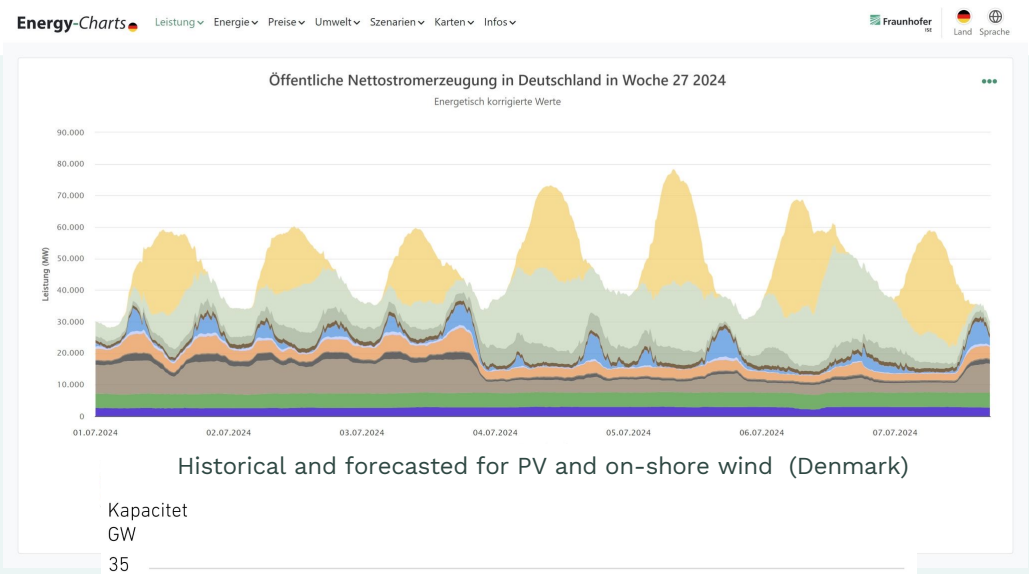
- Annual Energy Yield (alone) is not important…
  -but value of exported energy is…
- Revenue must be evaluated based on forecasted hourly data to calculate the expected capture price
- The capture price of net energy export depends on the specific generation profile, grid constraints and energy market
- Modelling of the future power price and expected amount of curtailment (for flexible grid connection agreements) unfortunately is much more uncertain than the EYA estimate

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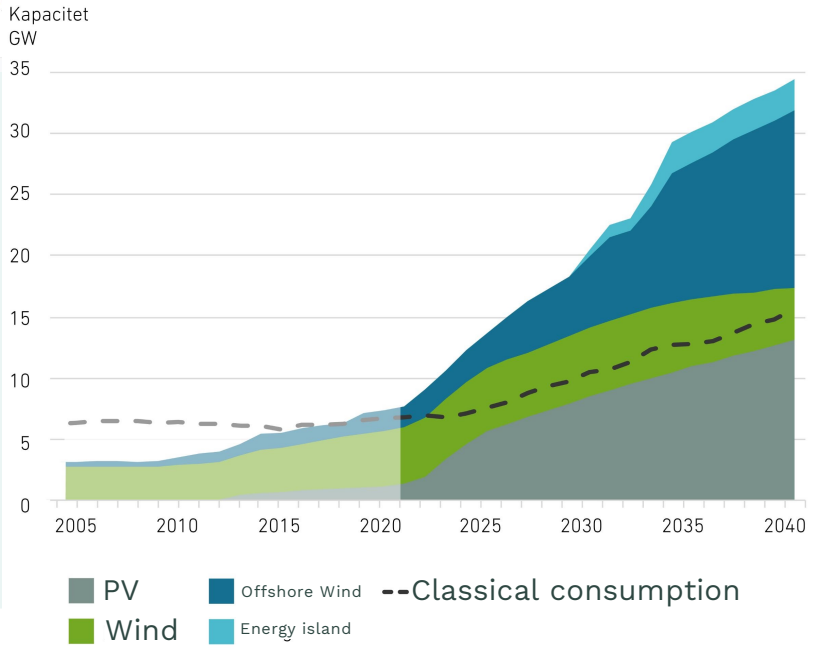
Outlook

Curtailment as here discussed is seen as a contribution to the balancing of generation and demand in the existing *electricity* system.

In the future *energy* system with an 3x increase in generation capacity, curtailment and balancing of the classical electricity consumption shall be seen in a context of sector coupling.



Historical and forecasted for PV and on-shore wind (Denmark)



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