PPPL PRINCETON PLASMA PHYSICS LABORATORY

Princeton Plasma Control
control.princeton.edu

PRINCETON

PRINCETON UNIVERSITY
ZERO LAB
Zero-carbon Energy Systems Research and Optimization Laboratory

The value of fusion energy to a decarbonized US electric grid

Jacob Schwartz, W. Ricks, E. Kolemen, J. Jenkins

Princeton Plasma Physics Laboratory, Sept 26th, 2022

See full preprint & supplemental information at
https://arxiv.org/abs/2209.09373

Research topic: Characteristics of an attractive fusion reactor for the future US

Optimize for value of fusion plant

[Market size]–[cost thresholds] for fusion plants

Influence of operational parameters on value

Goals: Alongside cost studies,

- Decide among concepts
- Understand tradeoffs

Structure of this talk

1. Methods and model
    a. The electricity system landscape(s)
    b. Fusion plant model
2. Results, analysis
    Study 1: Value of fusion without integrated thermal storage
    Study 2: …with integrated thermal storage
3. Assessment and conclusions

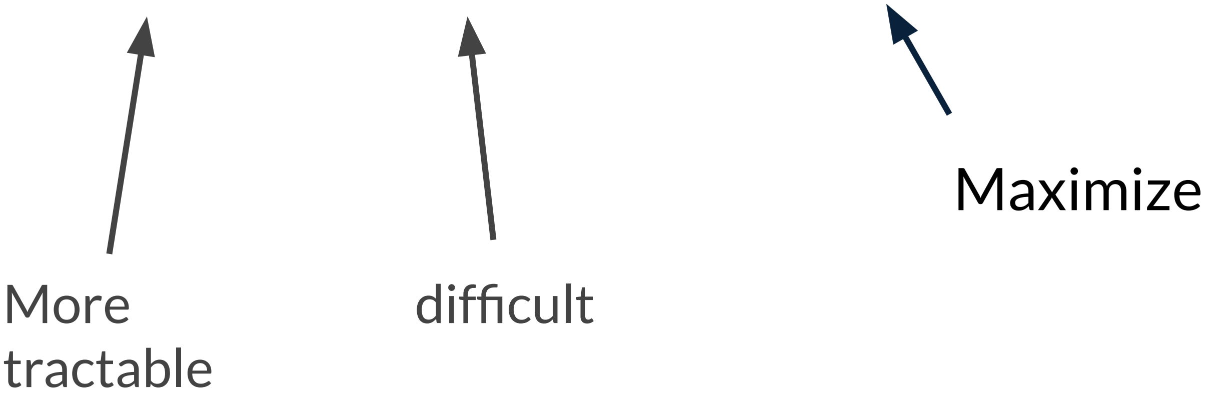
Two parts of the equation: cost and value

Value - cost = net value

Maximize

Two parts of the equation: cost and value

Value - cost = net value



More tractable

difficult

Maximize

Estimate fusion’s value using capacity expansion model

Existing grid ✚ Future loads ✚

Variable Renewables	
Solar	*$*
Onshore wind	*$*
Offshore wind	*$$*
Firm Generation	
Fission	*$$$$*
NG-CCS	*$$$*
Zero-carbon fuel	
Storage	
Li Batteries	
Metal-air	
Refreshments	
Flexible loads	
Transmission	

Estimate fusion’s value using capacity expansion model

Existing grid

+

Future loads

+

Variable Renewables

Solar ....$

Onshore wind ....$

Offshore wind ......$$

Firm Generation

Fission ......$$$$

NG-CCS ......$$$

Zero-carbon fuel

Storage

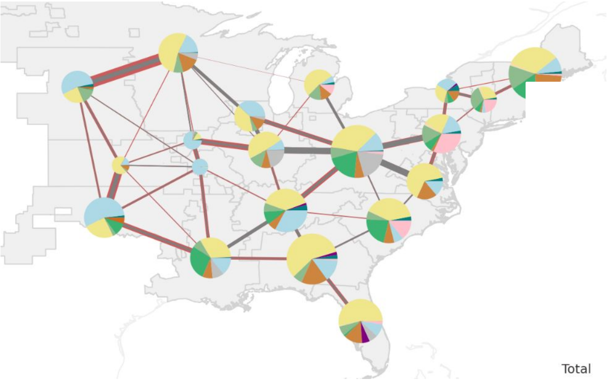
Li Batteries

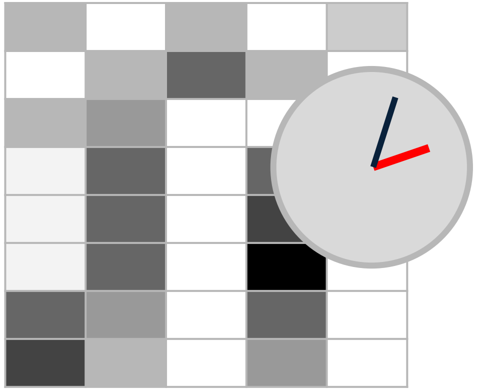
Metal-air

Refreshments

Flexible loads

Transmission

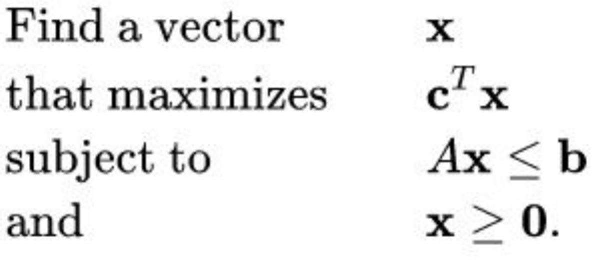




Minimize total annual system cost

Uses a linear programming framework

Uses **LP** or **MILP** models



$$\begin{array}{ll} \text{Find a vector} & \mathbf{x} \\ \text{that maximizes} & \mathbf{c}^T\mathbf{x} \\ \text{subject to} & A\mathbf{x} \le \mathbf{b} \\ \text{and} & \mathbf{x} \ge \mathbf{0}. \end{array}$$

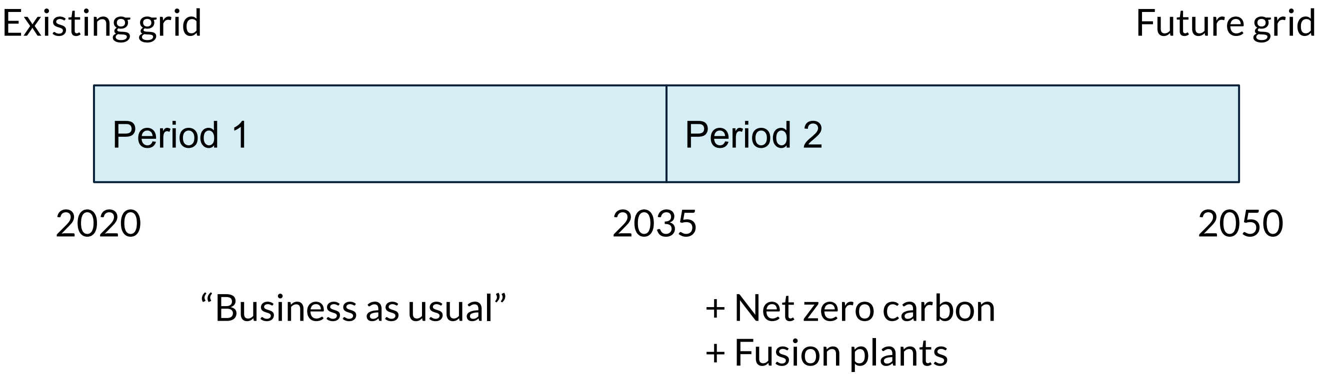
System scale is large

10^7 variables & constraints

Need linearized fusion plant model (later)

“GenX” code, in Julia.
Few dozen core-hours, 200 GB memory

Our model: time periods



Existing grid

Future grid

Period 1

Period 2

2020

2035

2050

“Business as usual”

+ Net zero carbon
+ Fusion plants

Optimize system for equilibrium in each “period”

“Myopic” optimization

Our model: geographic zones

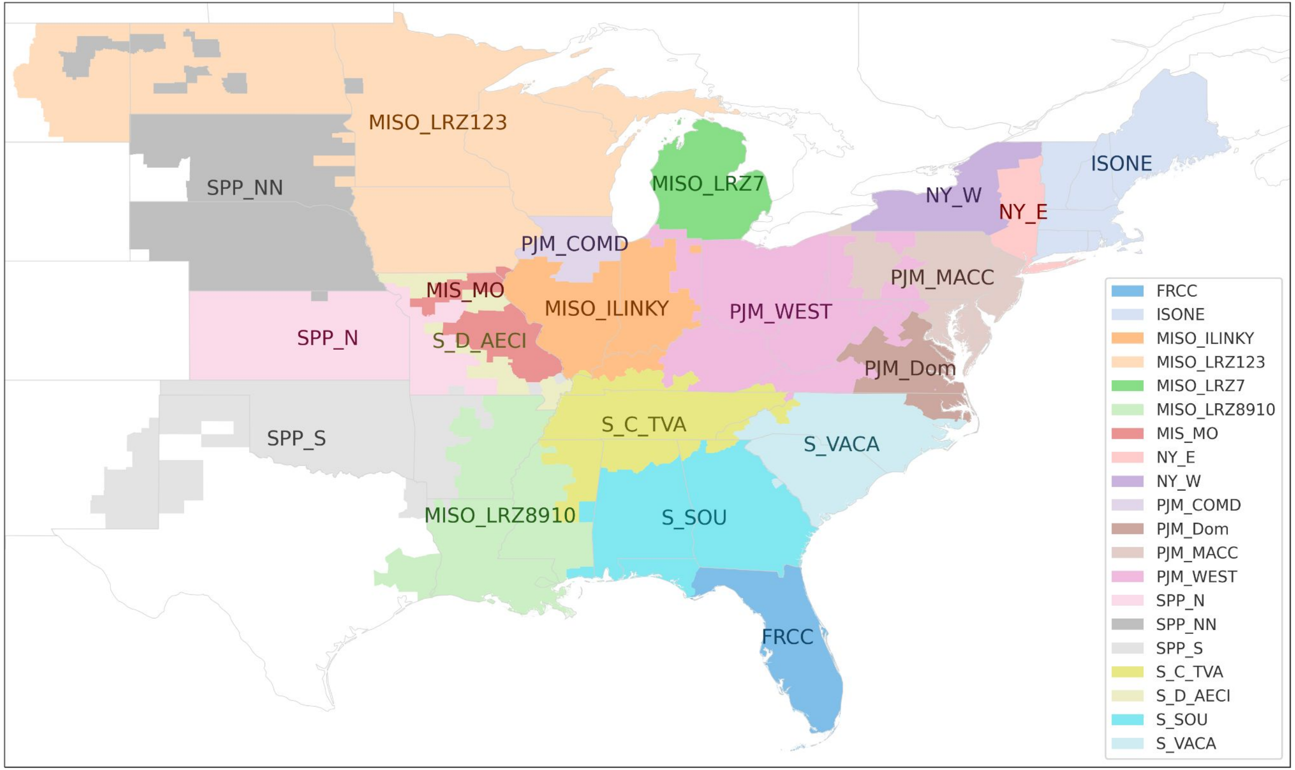
Eastern Interconnect
(Western Interconnect & Texas easier to decarbonize)

20 zones

“Copper-plate” in each zone

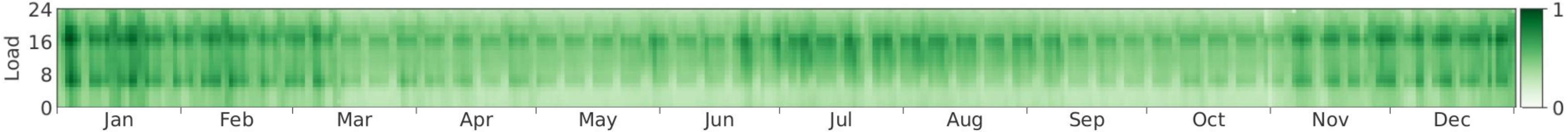
Transmission limits & losses between zones

Zones based on EPA Integrated Planning Model (IPM) regions



Our model: annual time series

1 hour time steps
One (looped) full year: 8760 hours



Example load for one zone

Peak loads of 1100 GW, average 600 GW : roughly double those today

Time series for:

- Solar, wind, hydroelectric availability
- Flexible loads : EV charging & hot water heaters

Our model: generators

Variable renewables
Utility-scale solar
Wind: onshore
Wind: offshore
(Hydroelectric
Distributed solar)

Storage
Li batteries
Metal-air storage
(Pumped hydroelectric)

Firm resources
Fission*
Natural gas with 100% CCS* (NG-CCS)
Closed-cycle gas turbines (ZCF-CC)
Combustion turbines (ZCF-CT)

*Not in all scenarios

Three main Fusion Market Opportunity scenarios

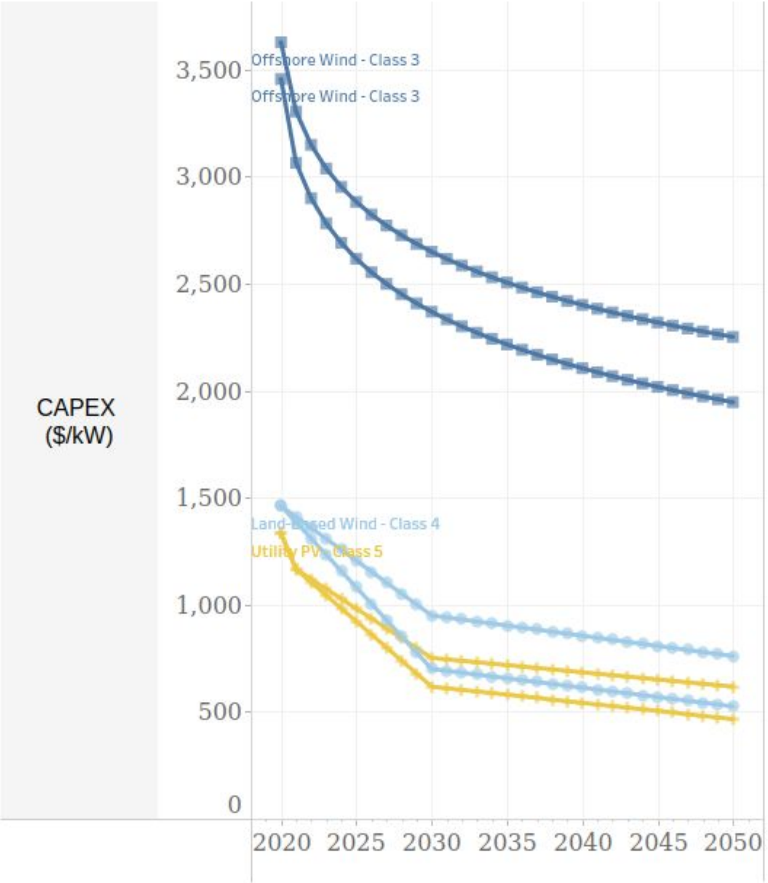
Low, medium, and high “Fusion Market Opportunity” driven by costs of competition

Span a range of futures

- Capital costs: NREL Annual Technology Baseline “advanced” and “moderate”
- % flexibility of EV charging, residential water heating

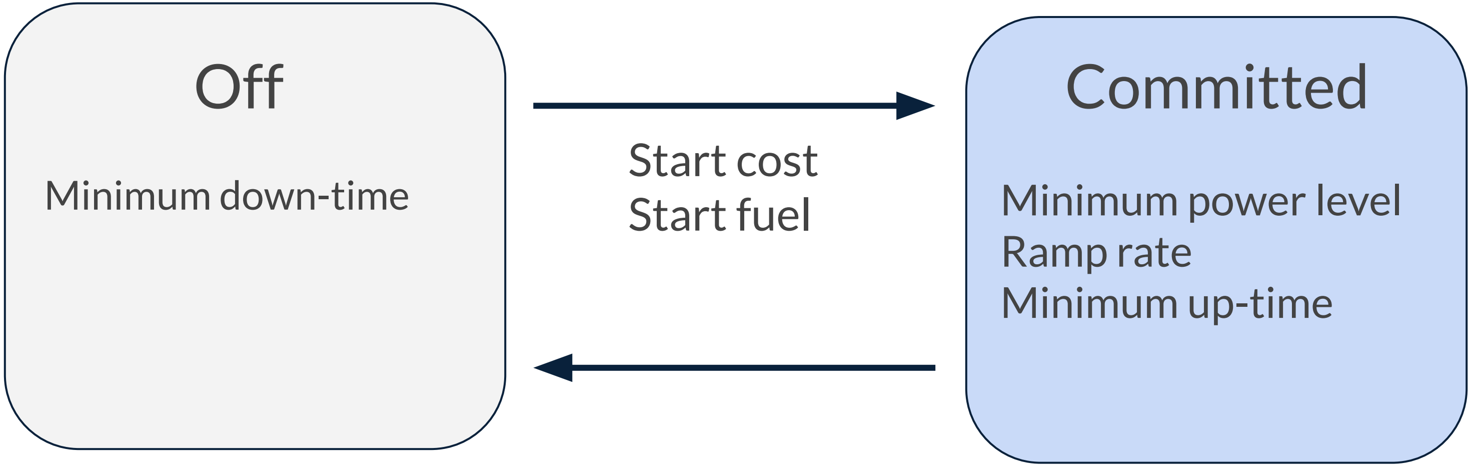
Zero carbon fuel like H_2 at $1.4/kg, $2/kg, $3/kg

Costs are all high / low together



NREL Annual Tech. Baseline data

Thermal generators: linearized unit commitment



Off

Minimum down-time

Start cost
Start fuel

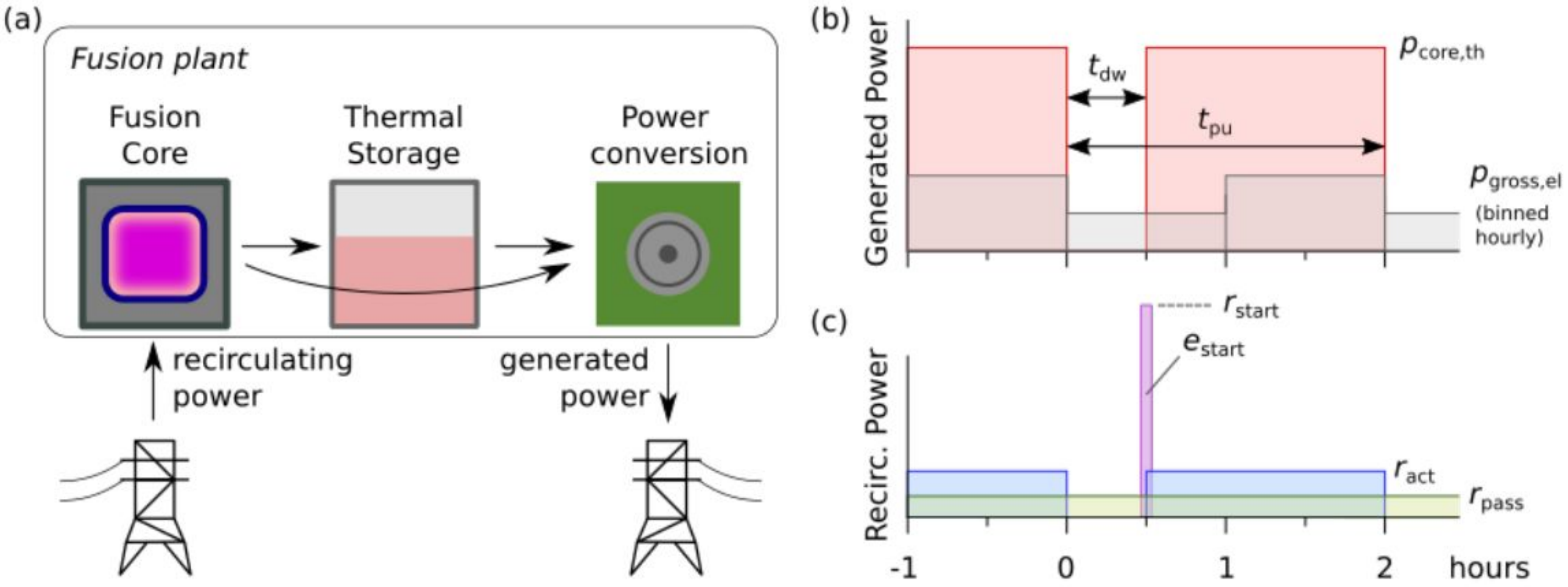
Committed

Minimum power level
Ramp rate
Minimum up-time

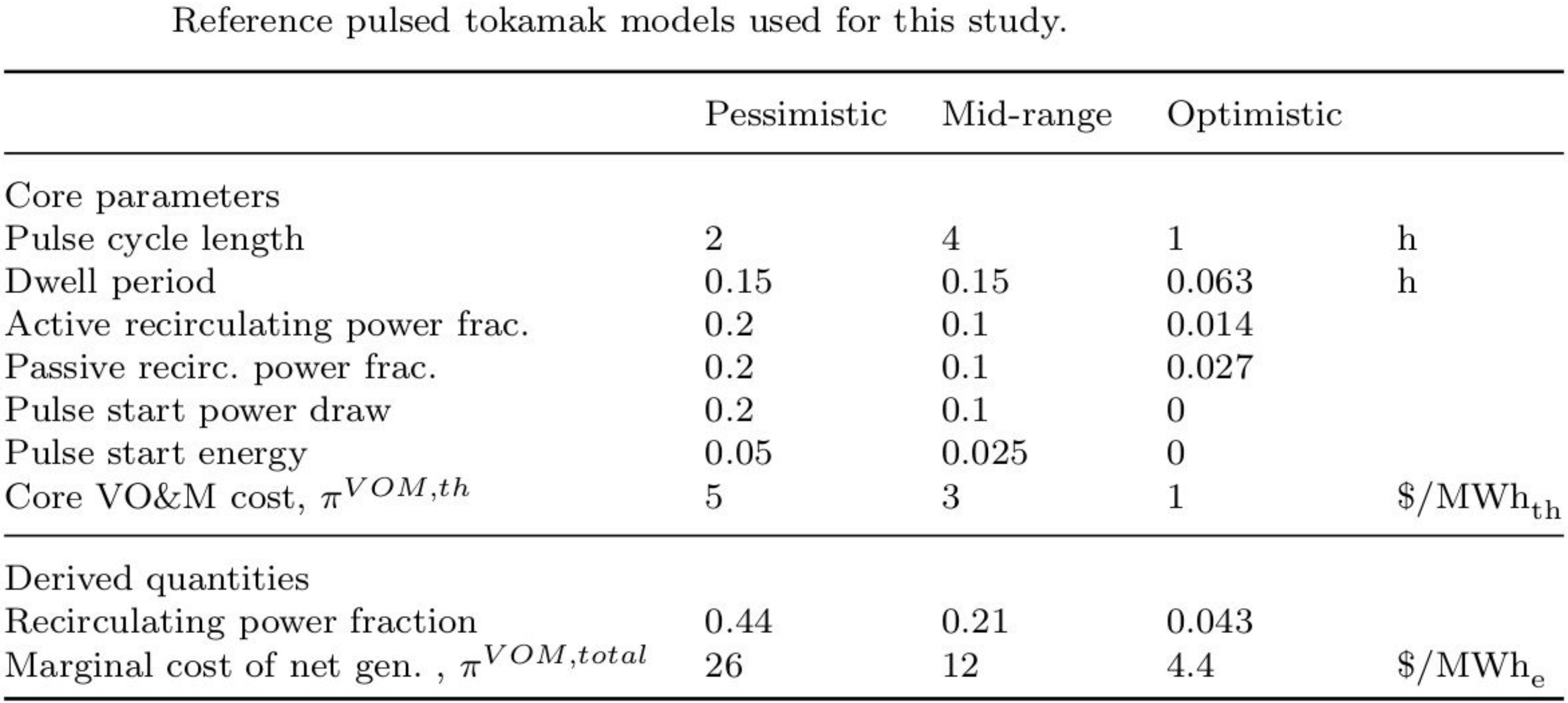
- Fuel costs, Variable O&M cost proportional to energy generated

Linearization: “differential slices” of plants rather than tracking integer plants.
Acceptable when system scale >> unit size

Construct a linearized fusion plant model



Reference tokamaks range from highly pulsed (pessimistic) to quasi-steady state (optimistic)



Reference pulsed tokamak models used for this study.

	Pessimistic	Mid-range	Optimistic	
Core parameters				
Pulse cycle length	2	4	1	h
Dwell period	0.15	0.15	0.063	h
Active recirculating power frac.	0.2	0.1	0.014	
Passive recirc. power frac.	0.2	0.1	0.027	
Pulse start power draw	0.2	0.1	0	
Pulse start energy	0.05	0.025	0	
Core VO&M cost, $\pi^{VOM,th}$	5	3	1	$/MWh$_{th}$
Derived quantities				
Recirculating power fraction	0.44	0.21	0.043	
Marginal cost of net gen. , $\pi^{VOM,total}$	26	12	4.4	$/MWh$_{e}$

Find fusion core's marginal value @ fixed capacity penetration

1. Constrain net fusion capacity, e.g. 100 GW
2. Set core's cost to *zero*
3. Compute optimal solution
4. Find *dual* of the capacity constraint

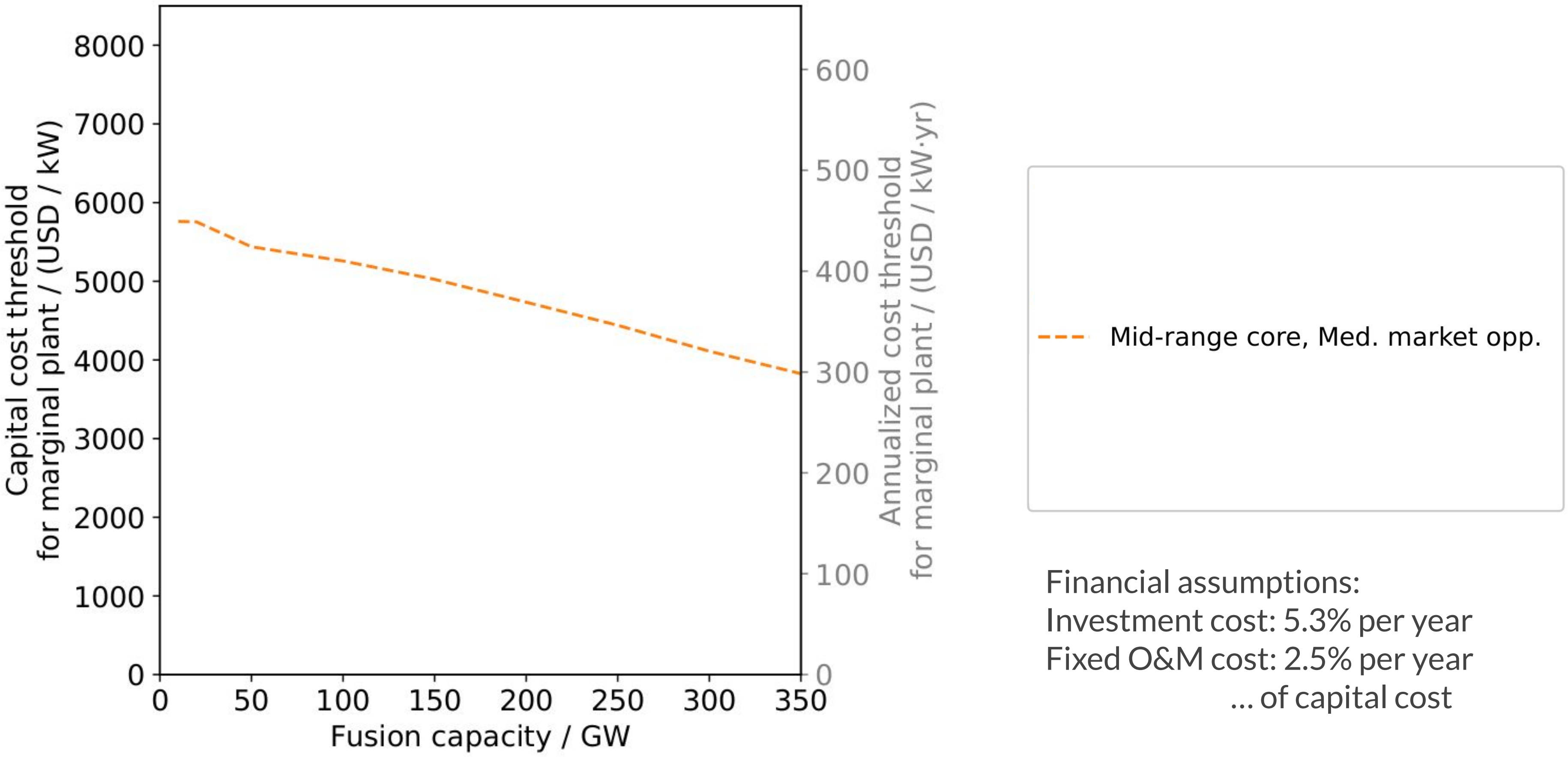
= marginal value of the core at this capacity penetration
= cost threshold to reach this capacity penetration

Plant cost = \$core + \$PCS + \$storage

Studies, results and analysis

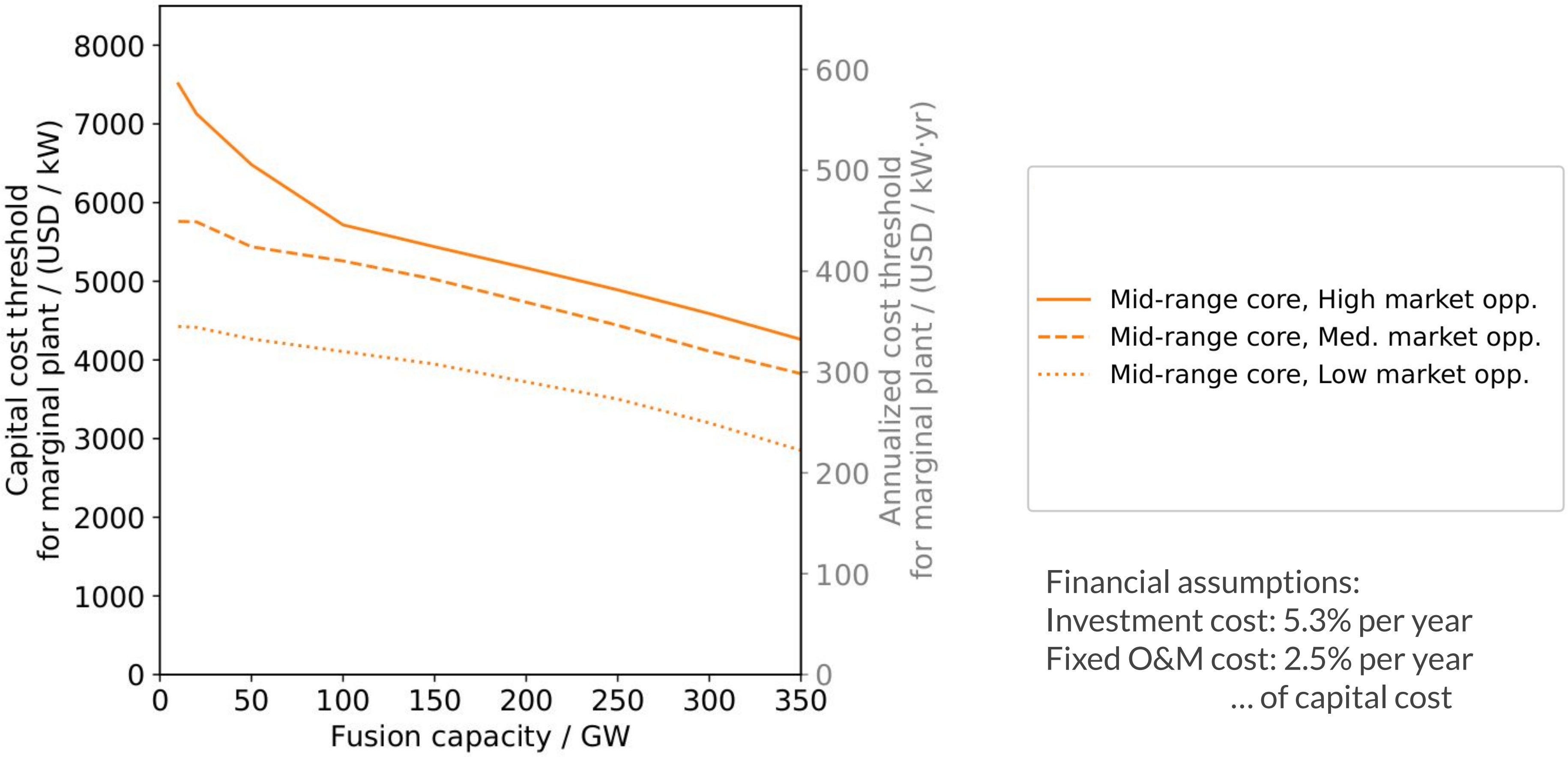
Study 1: fusion plants without thermal storage.

Cost thresholds for reference reactors



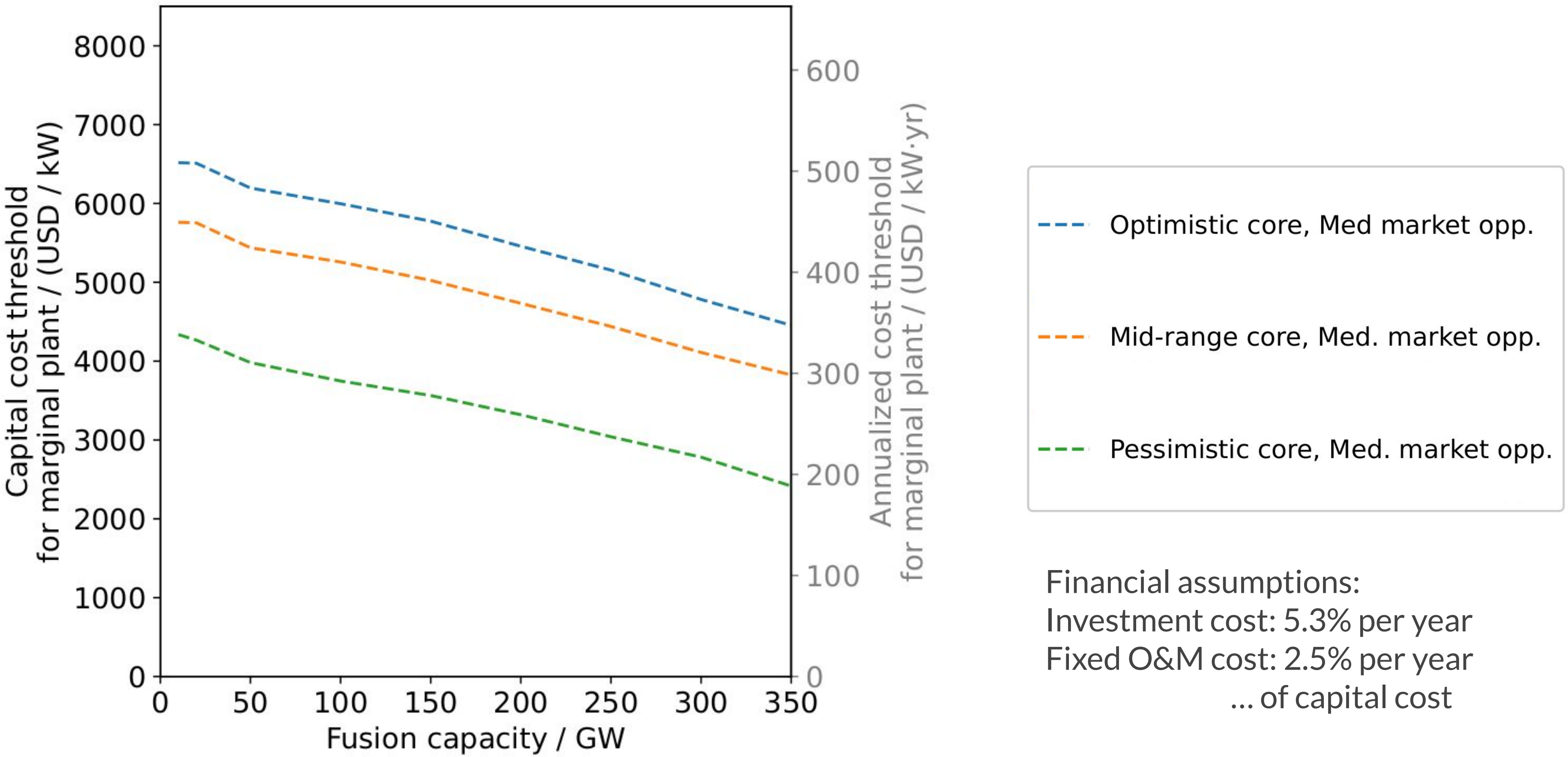
Financial assumptions:
Investment cost: 5.3% per year
Fixed O&M cost: 2.5% per year
... of capital cost

Cost thresholds for reference reactors



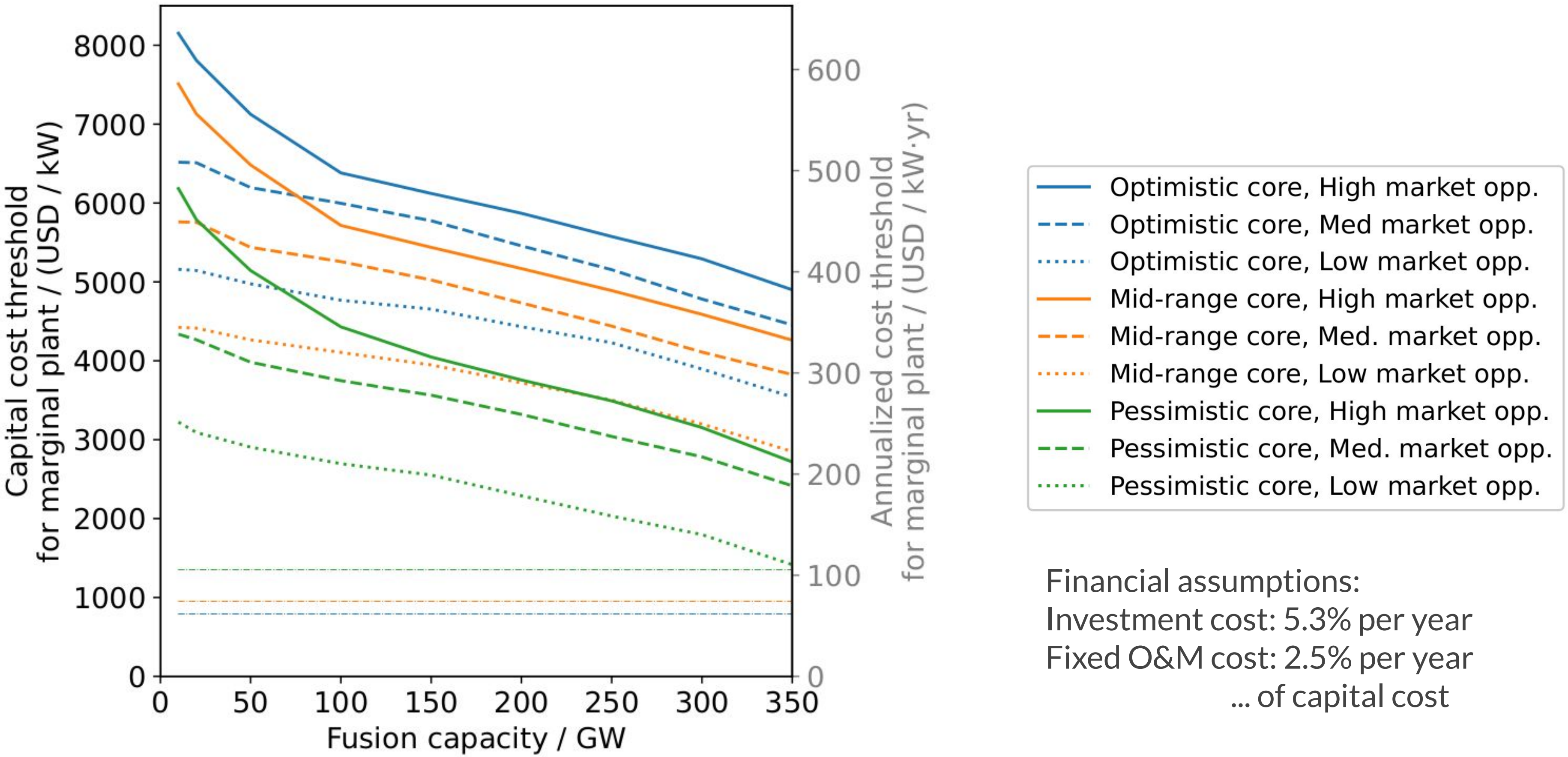
Financial assumptions:
Investment cost: 5.3% per year
Fixed O&M cost: 2.5% per year
… of capital cost

Cost thresholds for reference reactors



Financial assumptions:
Investment cost: 5.3% per year
Fixed O&M cost: 2.5% per year
... of capital cost

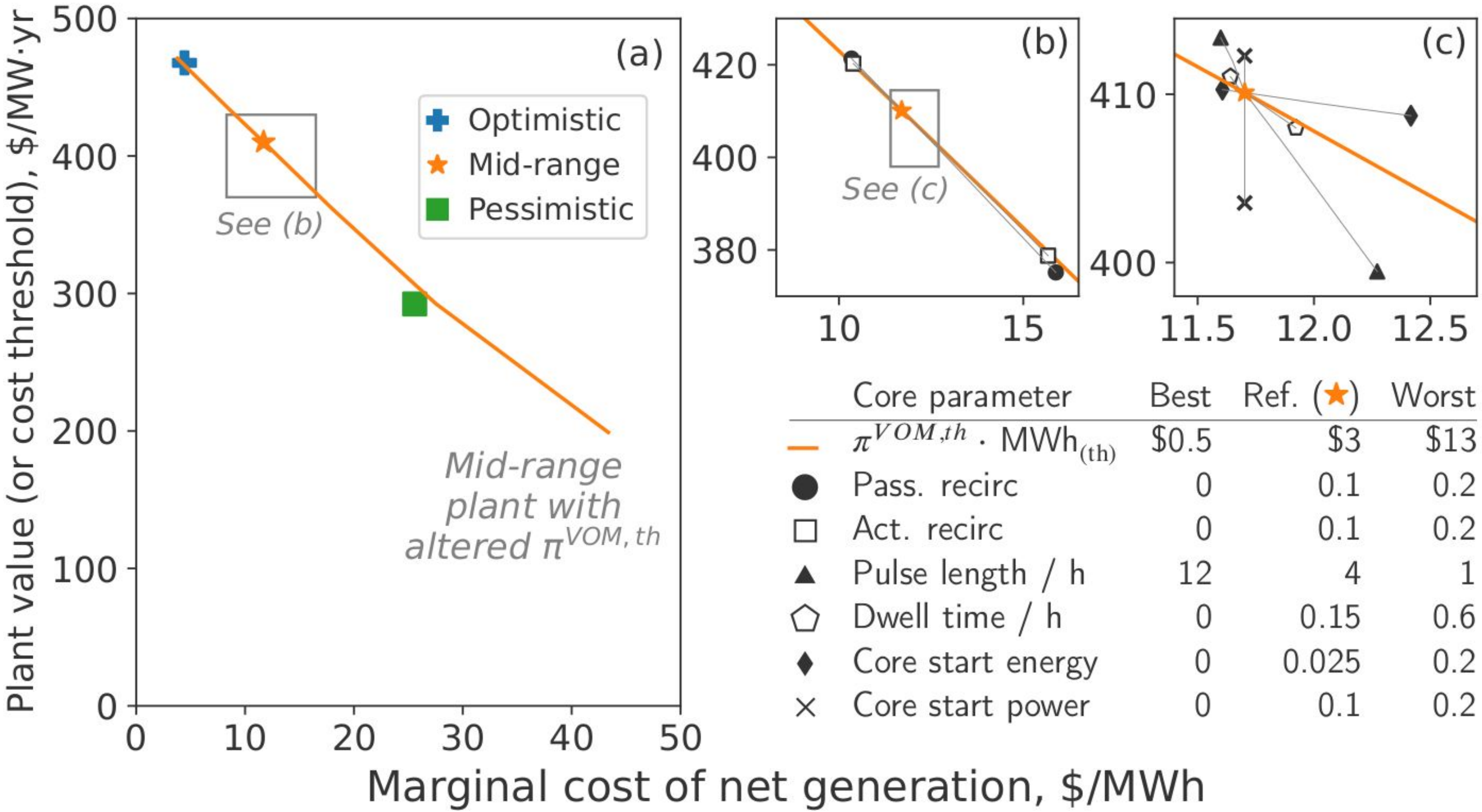
Cost thresholds for reference reactors



Financial assumptions:
Investment cost: 5.3% per year
Fixed O&M cost: 2.5% per year
... of capital cost

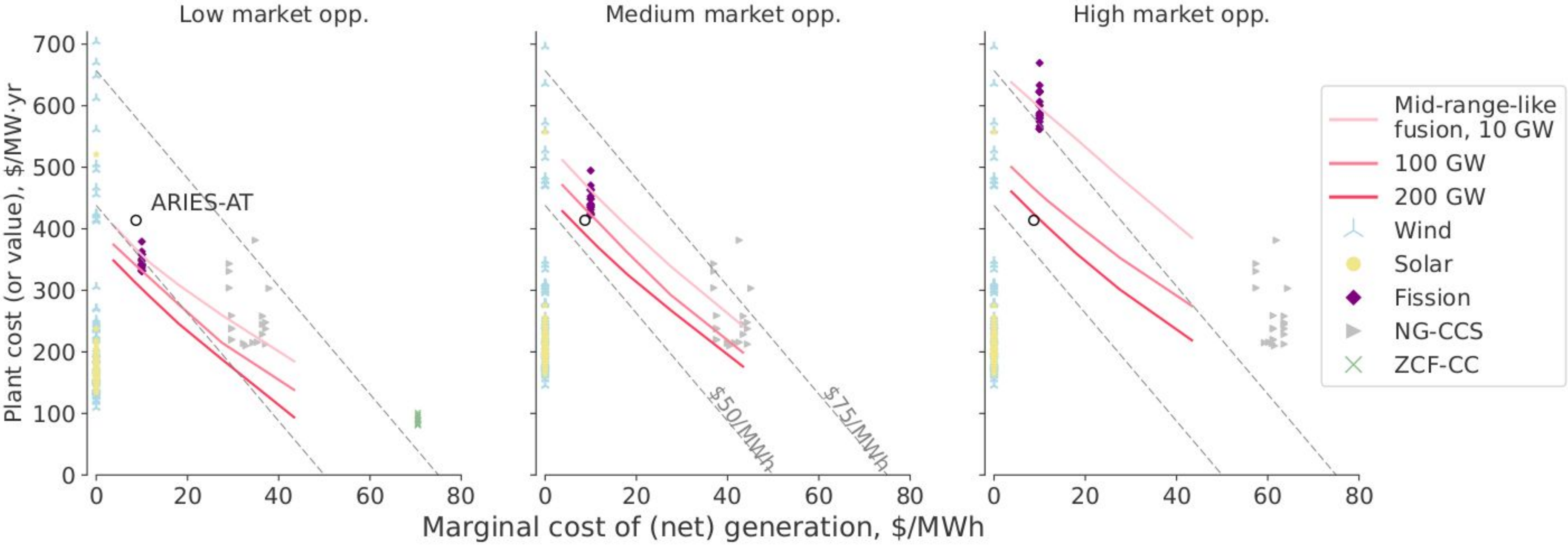
Internal and external drivers of fusion’s value

Differences in cost thresholds caused by variable costs much more than pulse constraints

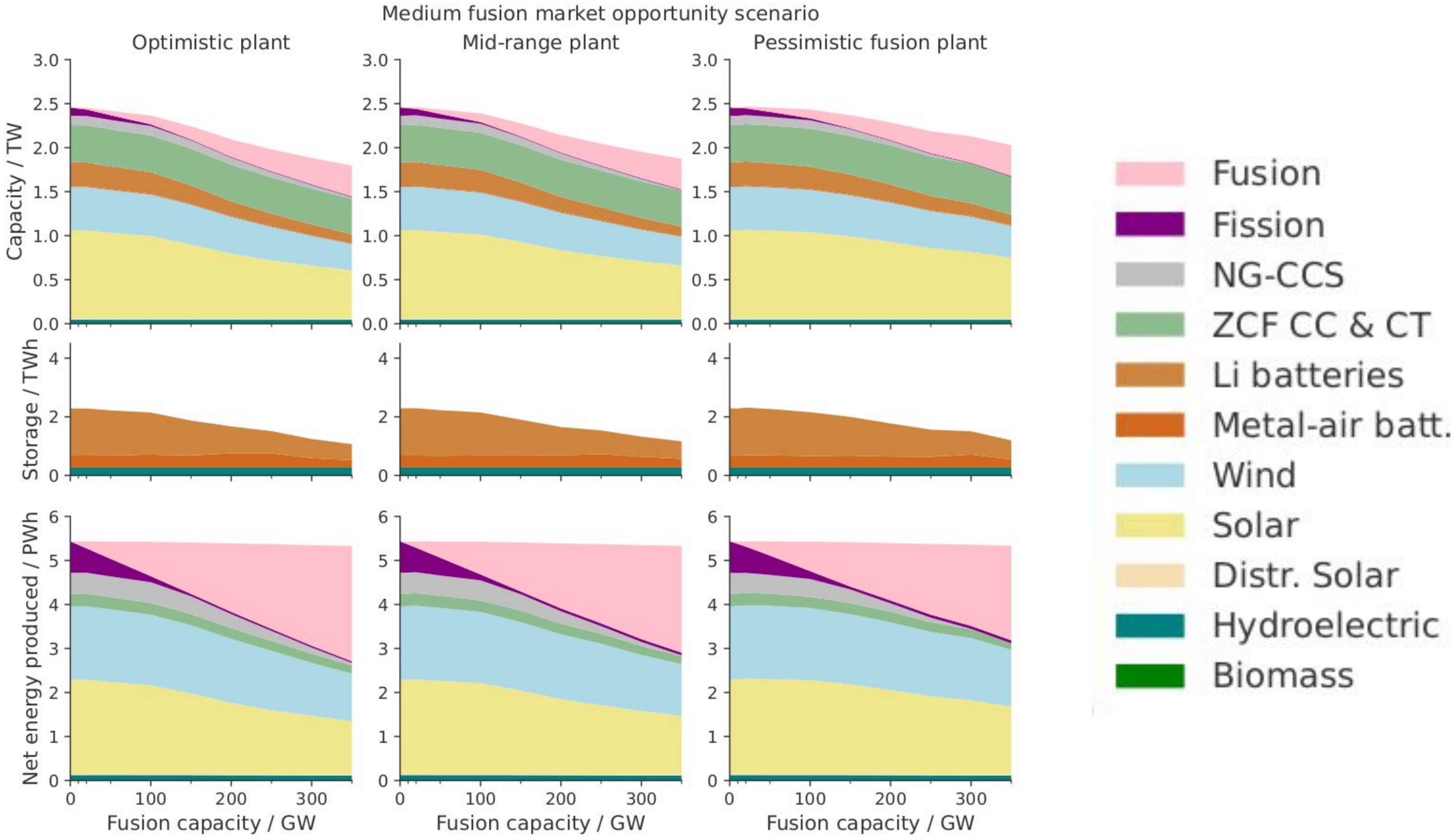


	Core parameter	Best	Ref. (★)	Worst
—	$\pi^{VOM,th}\cdot\text{MWh}_{(th)}$	\$0.5	\$3	\$13
●	Pass. recirc	0	0.1	0.2
□	Act. recirc	0	0.1	0.2
▲	Pulse length / h	12	4	1
⬠	Dwell time / h	0	0.15	0.6
◆	Core start energy	0	0.025	0.2
×	Core start power	0	0.1	0.2

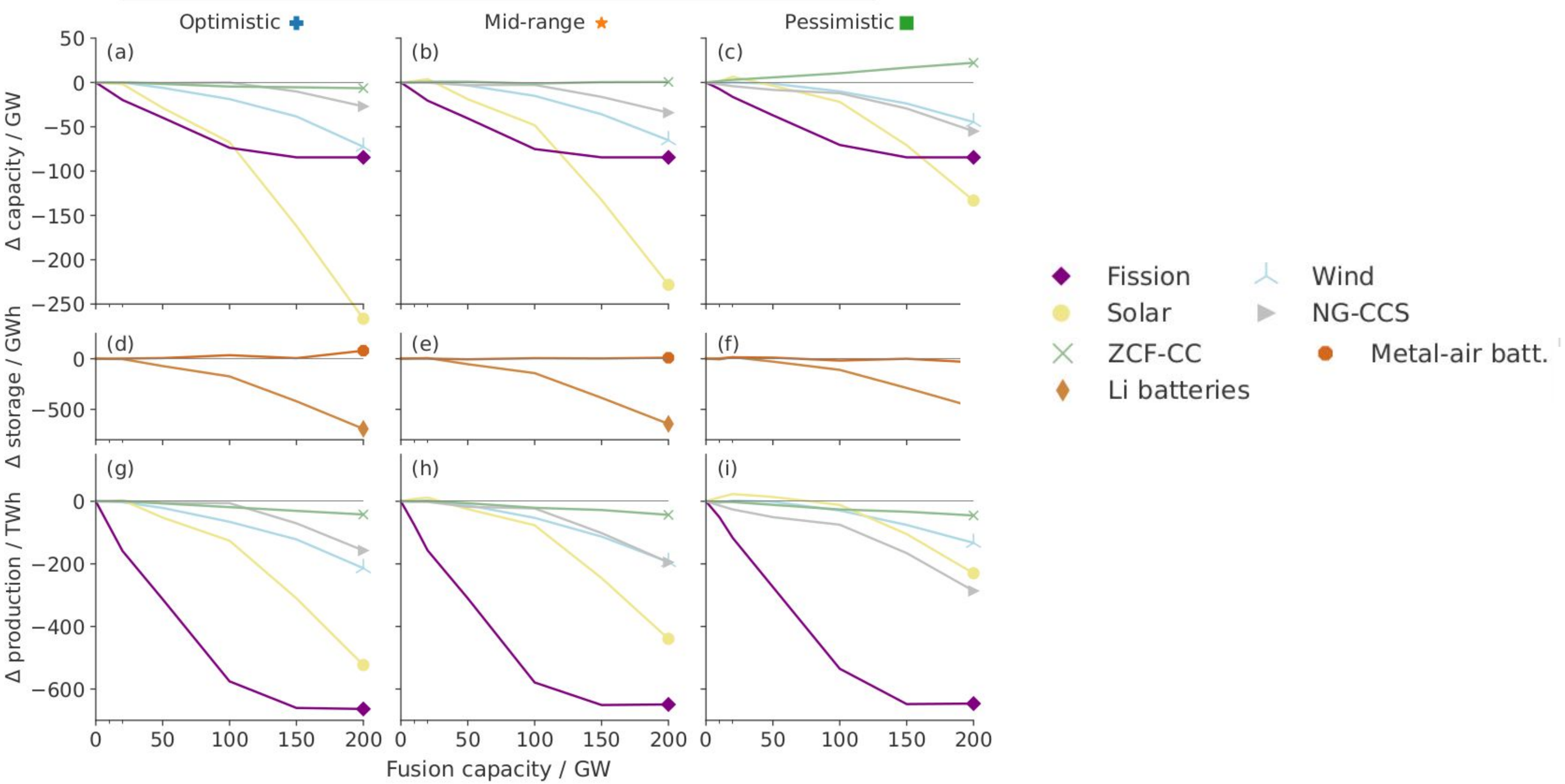
Value of fusion is set by competition



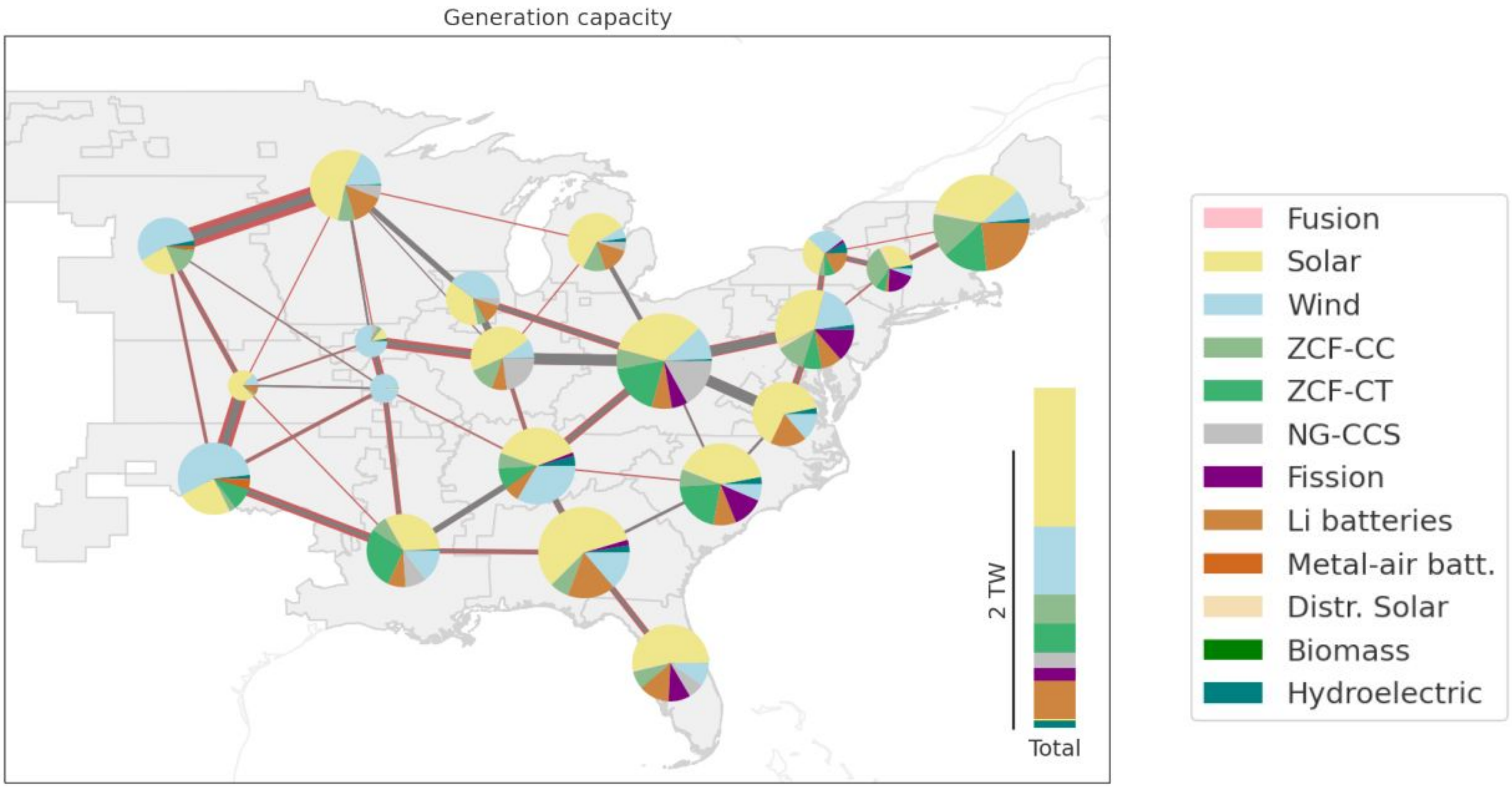
Fusion replaces fission, then other resources



Fusion replaces fission, then other resources

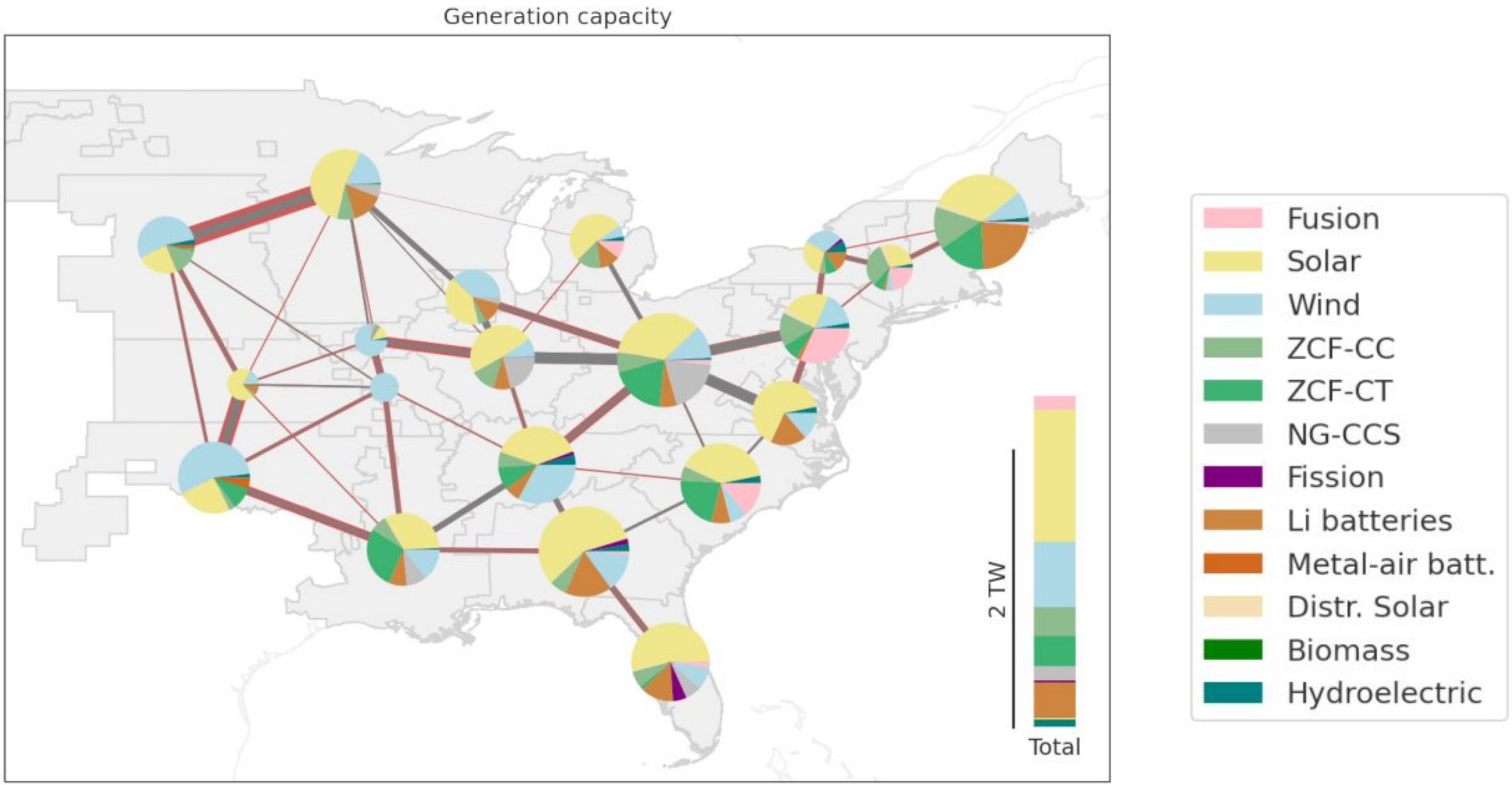


Fusion is generally built to replace fission



Medium market opportunity case without fusion, 100 GW

Fusion is generally built to replace fission



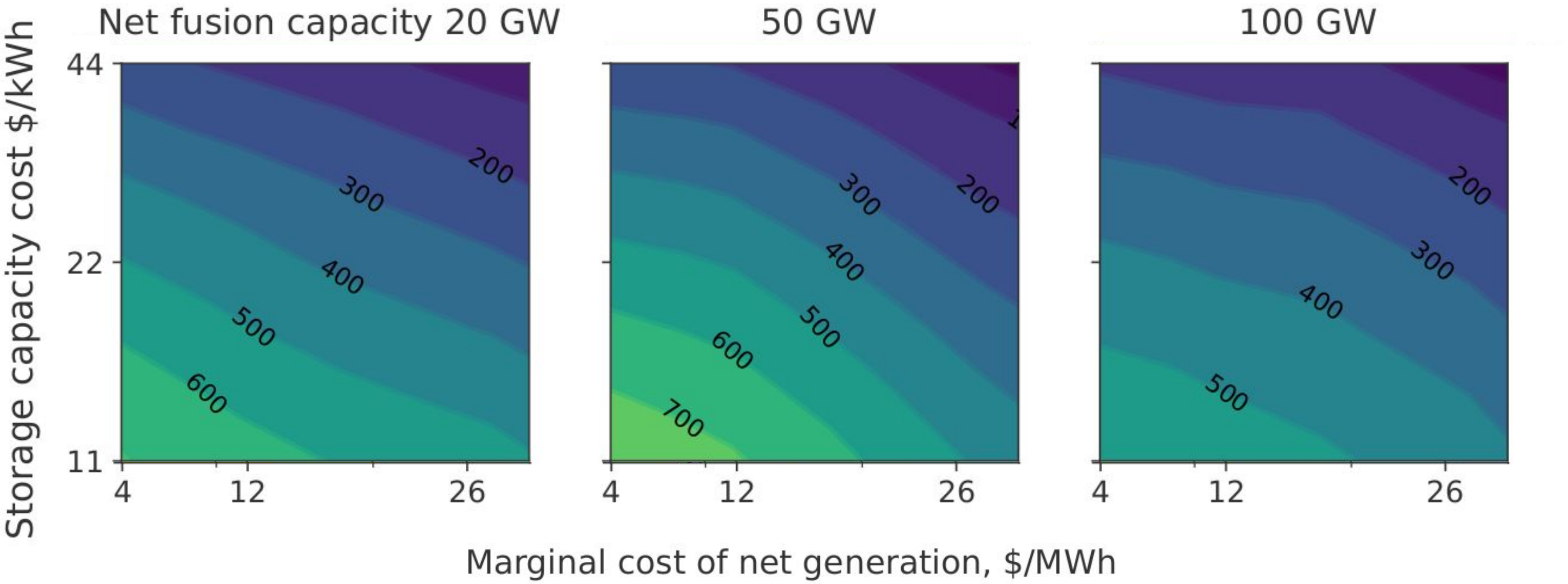
Medium market opportunity case w/ mid-range fusion, 100GW

Study 2: fusion plants with thermal storage

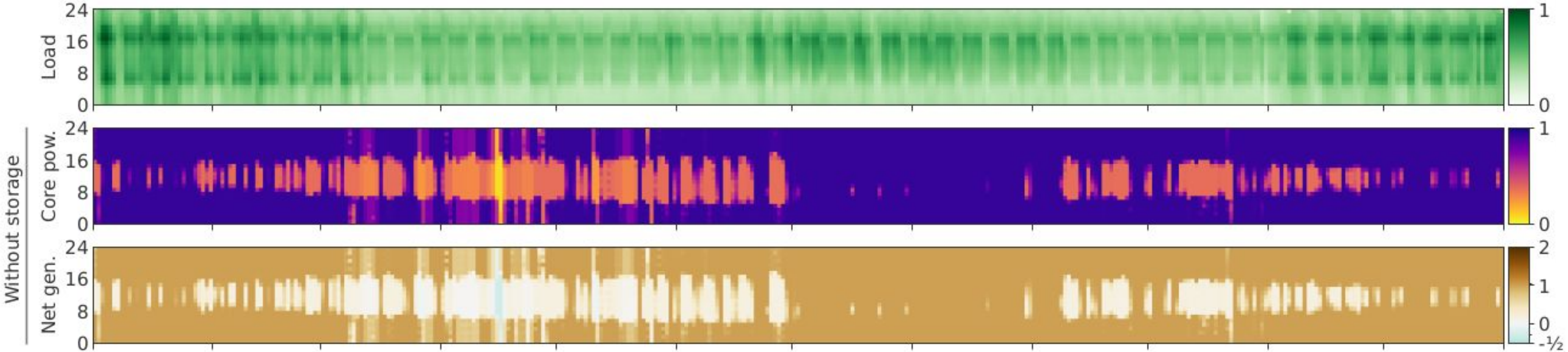
Option to build storage adds value

For the mid-range reactor:

Contours of added value in $/kW

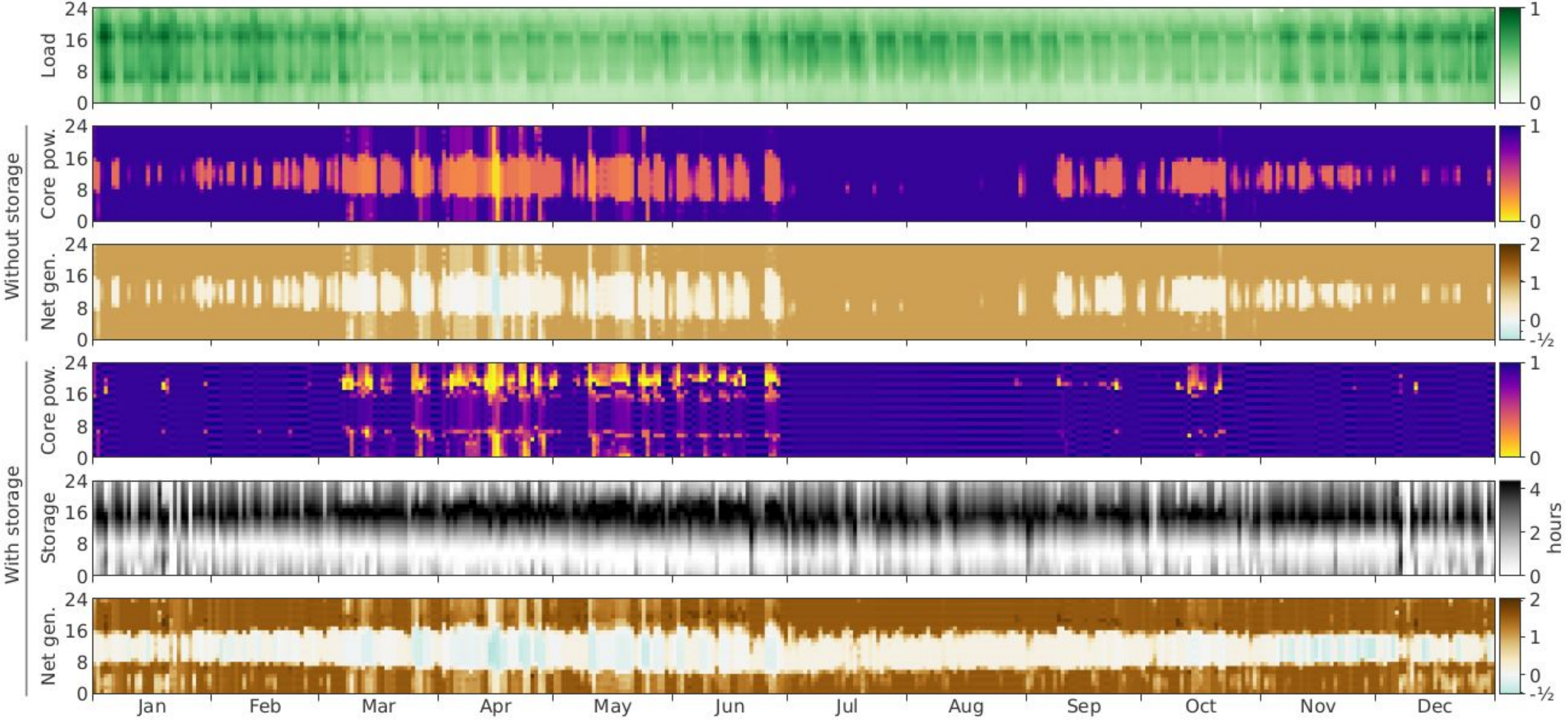


Storage increases utilization & flips core's daily operation



Pessimistic fusion design with 100 GW, Med. market opp. scen.

Storage increases utilization & flips core's daily operation



Pessimistic fusion design with 100 GW, Med. market opp. scen.

Assessment and conclusions

Discussion – how might fusion be useful

1. Fusion could be a major resource for the US, **if** it can reach price targets (and competitors like fission and renewables do not).
   → develop fusion in the US as a hedge for its energy portfolio
   → or develop it for export

2. Pulsed is few % (or less) worse than steady-state.
   → Let engineering & cost will drive this decision.

3. Equilibrium capacity of fusion increases significantly when cost declines
   → May be able to "learning curve" to 100s GW fusion

4. Thermal storage could be helpful, esp. to initial plants

Thank you for your attention.

See full preprint & supplemental information at

https://arxiv.org/abs/2209.09373

Limitations of this study

Which are too favorable to fusion

- Tokamak pulse not time-resolved
- Maintenance not included
- Linearized unit commitment, vs. integer or binary
- Additional costs of pulsing (thermal cycling) not accounted for

- Availability of fusion just as electricity demand grows
- Tritium limitations to growth

- Thermal storage may have lower efficiency than direct coupling
- Fission could also have thermal storage

If considered these could increase value of fusion

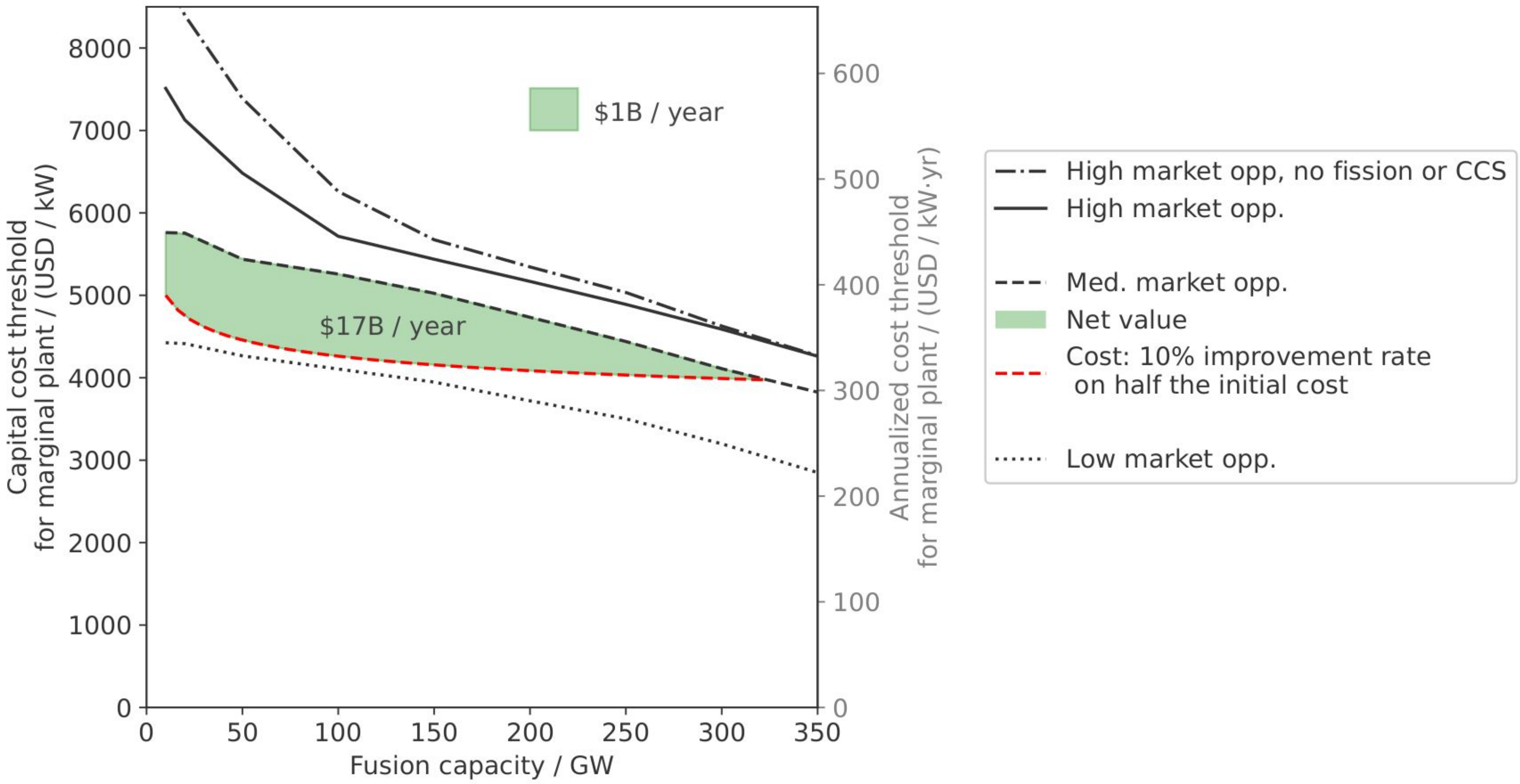
- Industrial heat or co-generation
- Re-powering of existing plants
- Constraints on battery capacity

Uncertain if it helps or hurts fusion

- Electricity system is a “price taker” for fuels; fuel prices not coupled to demand
- Experience-based learning for various technologies
- Finer expansion time periods
- Perfect foresight in optimization

Additional slides

The net value of fusion could be $10B’s / year



Fusion core model is designed to be simple

Not included:
Plasma ramp up or ramp down

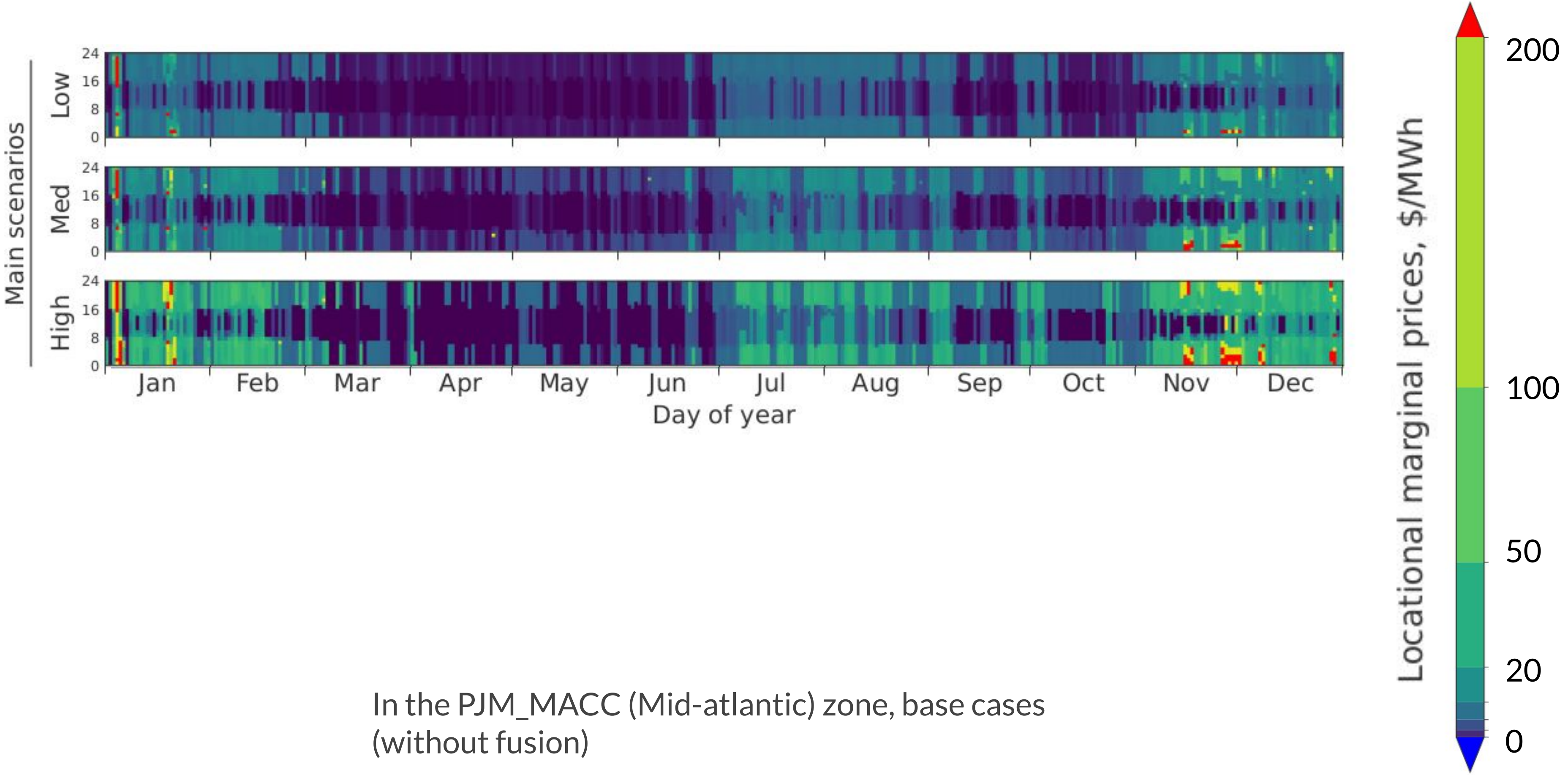
Disruptions / forced outages*

Maintenance periods
- Potential target for follow-up study

Core start costs (thermal cyclic fatigue) or annual start limits

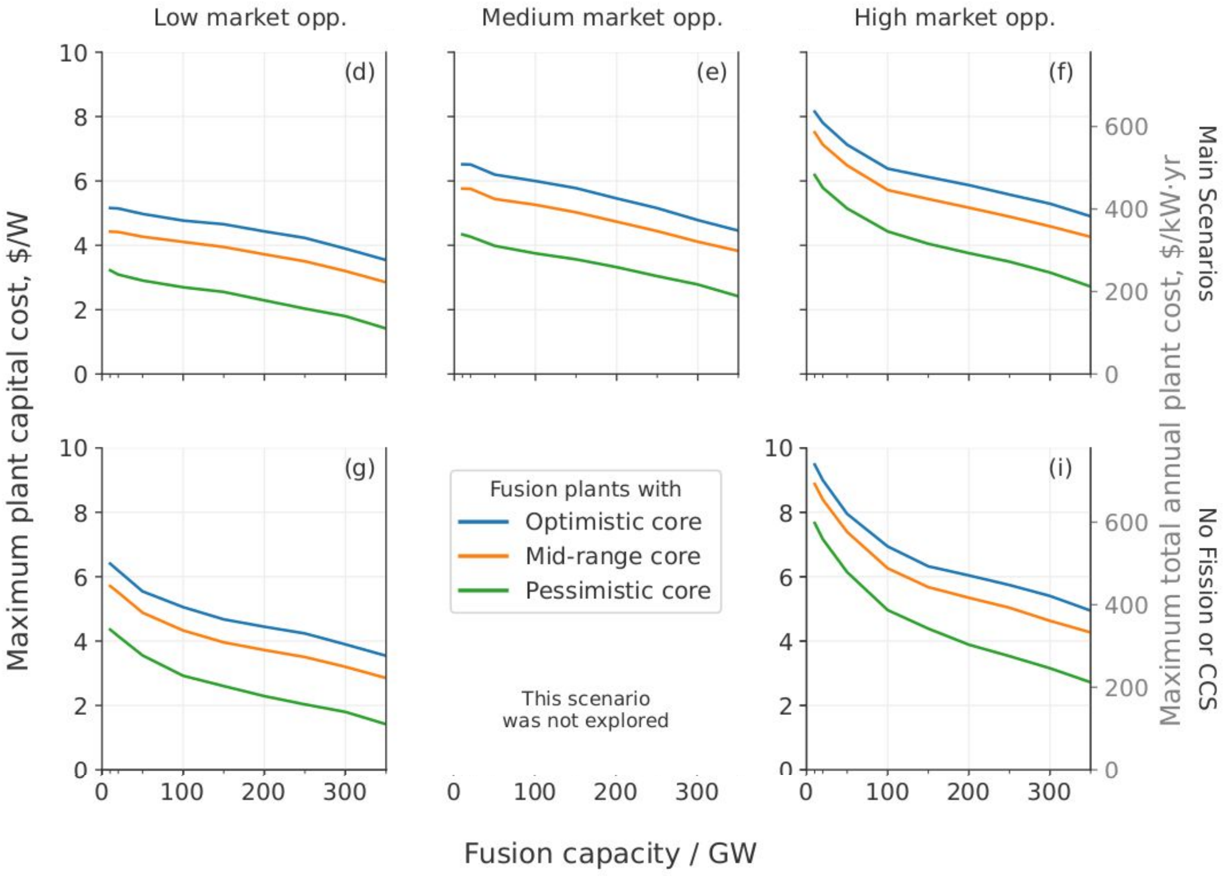
*like other thermal generators, there is a 90% “availability” factor for the plant’s Capacity Reserve Margin constraint

Low prices in spring: good time for maintenance



In the PJM_MACC (Mid-atlantic) zone, base cases (without fusion)

Cost thresholds - additional scenarios



Capital costs for generation

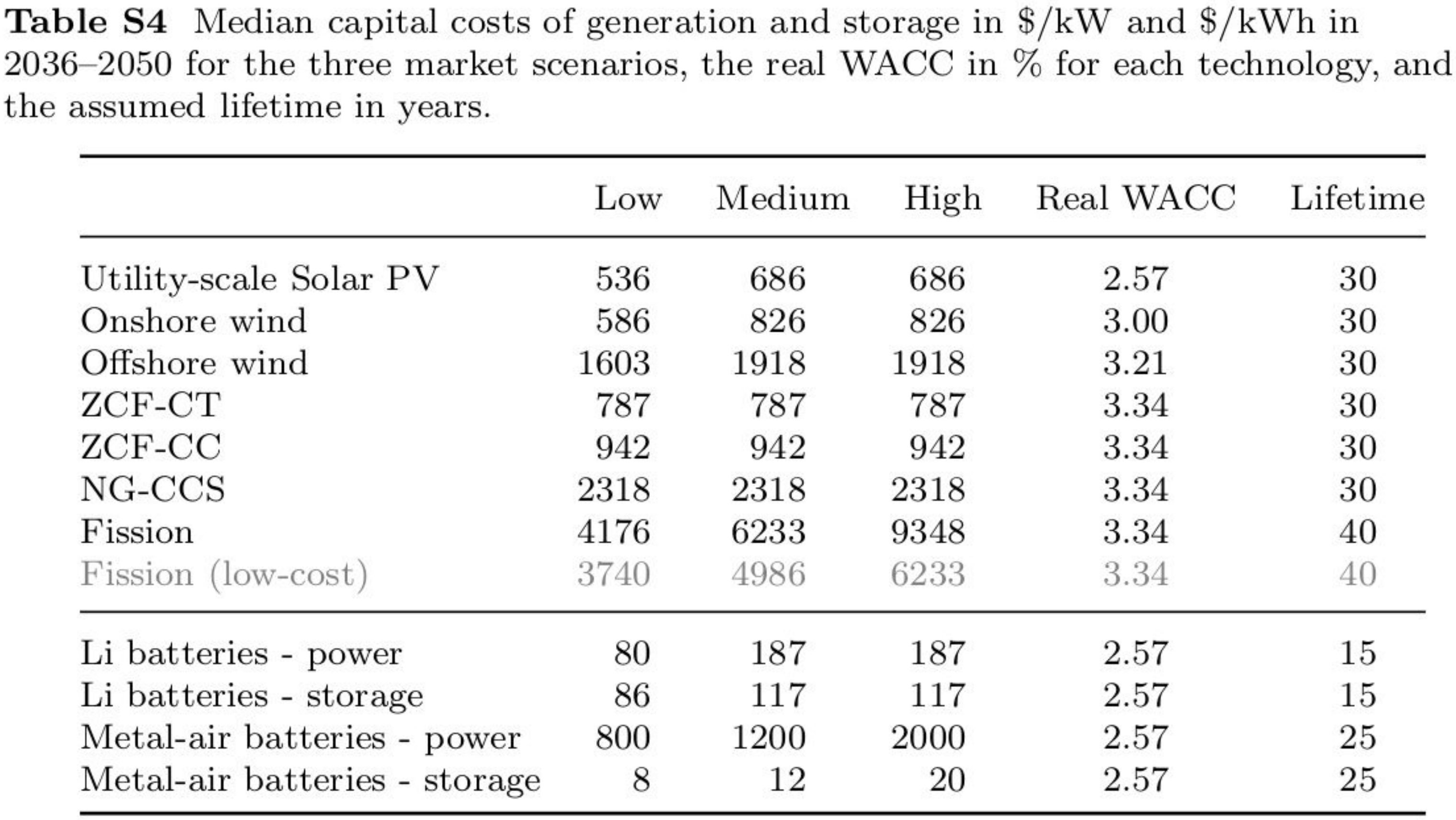


Table S4 Median capital costs of generation and storage in \$/kW and \$/kWh in 2036–2050 for the three market scenarios, the real WACC in % for each technology, and the assumed lifetime in years.

	Low	Medium	High	Real WACC	Lifetime
Utility-scale Solar PV	536	686	686	2.57	30
Onshore wind	586	826	826	3.00	30
Offshore wind	1603	1918	1918	3.21	30
ZCF-CT	787	787	787	3.34	30
ZCF-CC	942	942	942	3.34	30
NG-CCS	2318	2318	2318	3.34	30
Fission	4176	6233	9348	3.34	40
Fission (low-cost)	3740	4986	6233	3.34	40
Li batteries - power	80	187	187	2.57	15
Li batteries - storage	86	117	117	2.57	15
Metal-air batteries - power	800	1200	2000	2.57	25
Metal-air batteries - storage	8	12	20	2.57	25

Fuel costs and variable costs for resources

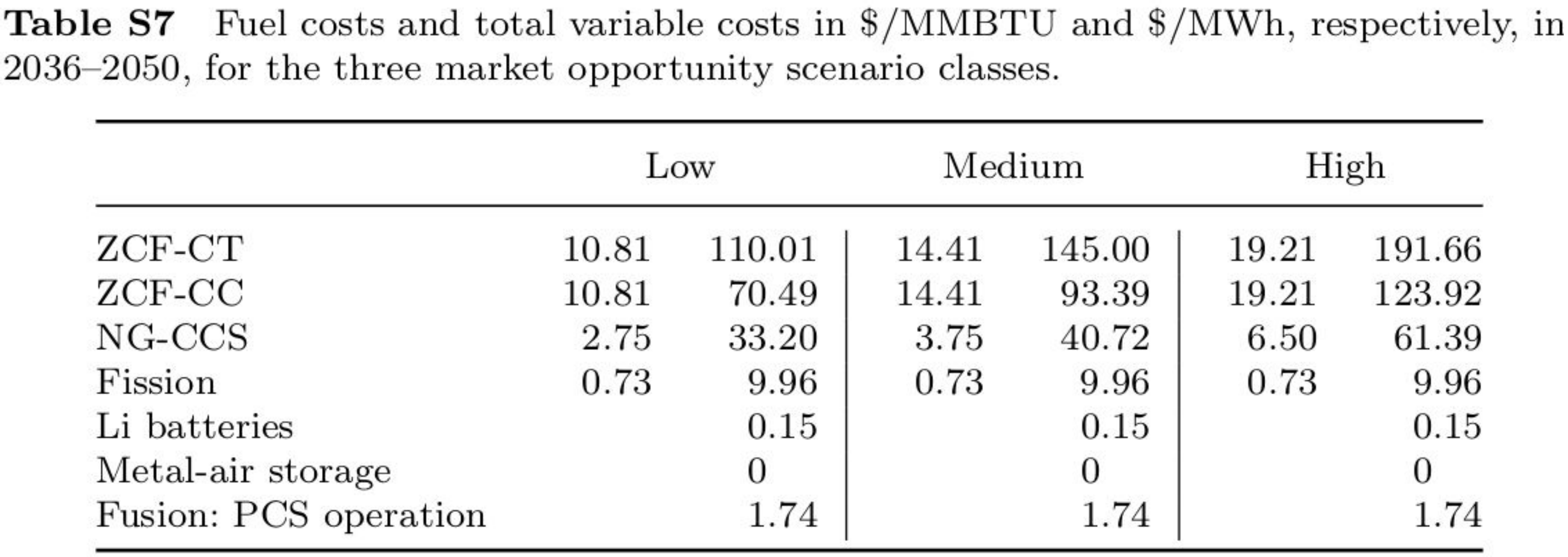


Table S7 Fuel costs and total variable costs in \$/MMBTU and \$/MWh, respectively, in 2036–2050, for the three market opportunity scenario classes.

	Low		Medium		High	
ZCF-CT	10.81	110.01	14.41	145.00	19.21	191.66
ZCF-CC	10.81	70.49	14.41	93.39	19.21	123.92
NG-CCS	2.75	33.20	3.75	40.72	6.50	61.39
Fission	0.73	9.96	0.73	9.96	0.73	9.96
Li batteries		0.15		0.15		0.15
Metal-air storage		0		0		0
Fusion: PCS operation		1.74		1.74		1.74

Conversion table for threshold costs or value

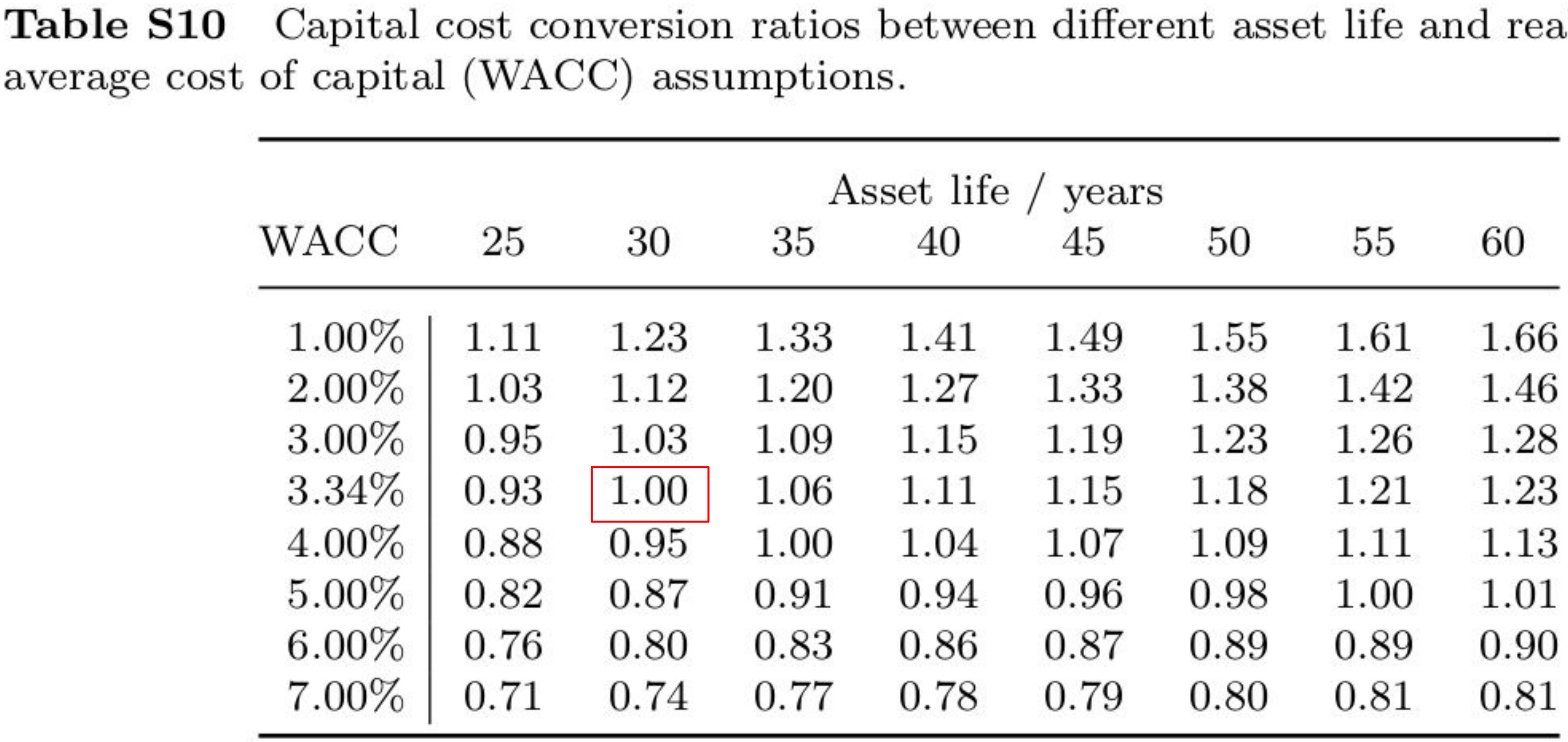
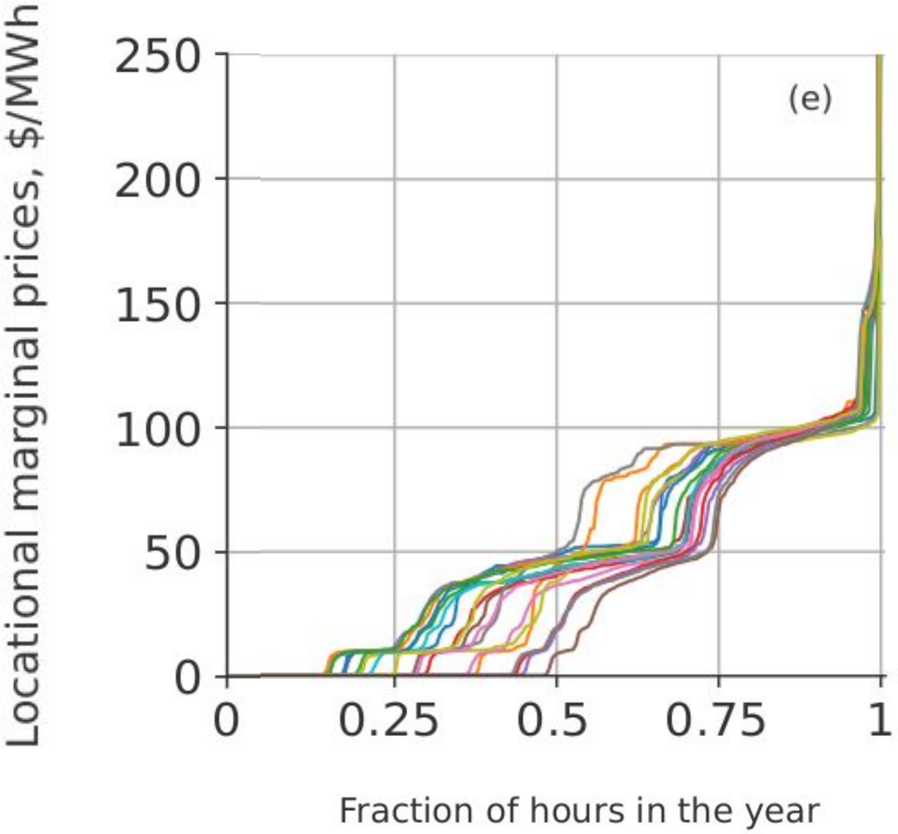


Table S10 Capital cost conversion ratios between different asset life and real weighted average cost of capital (WACC) assumptions.

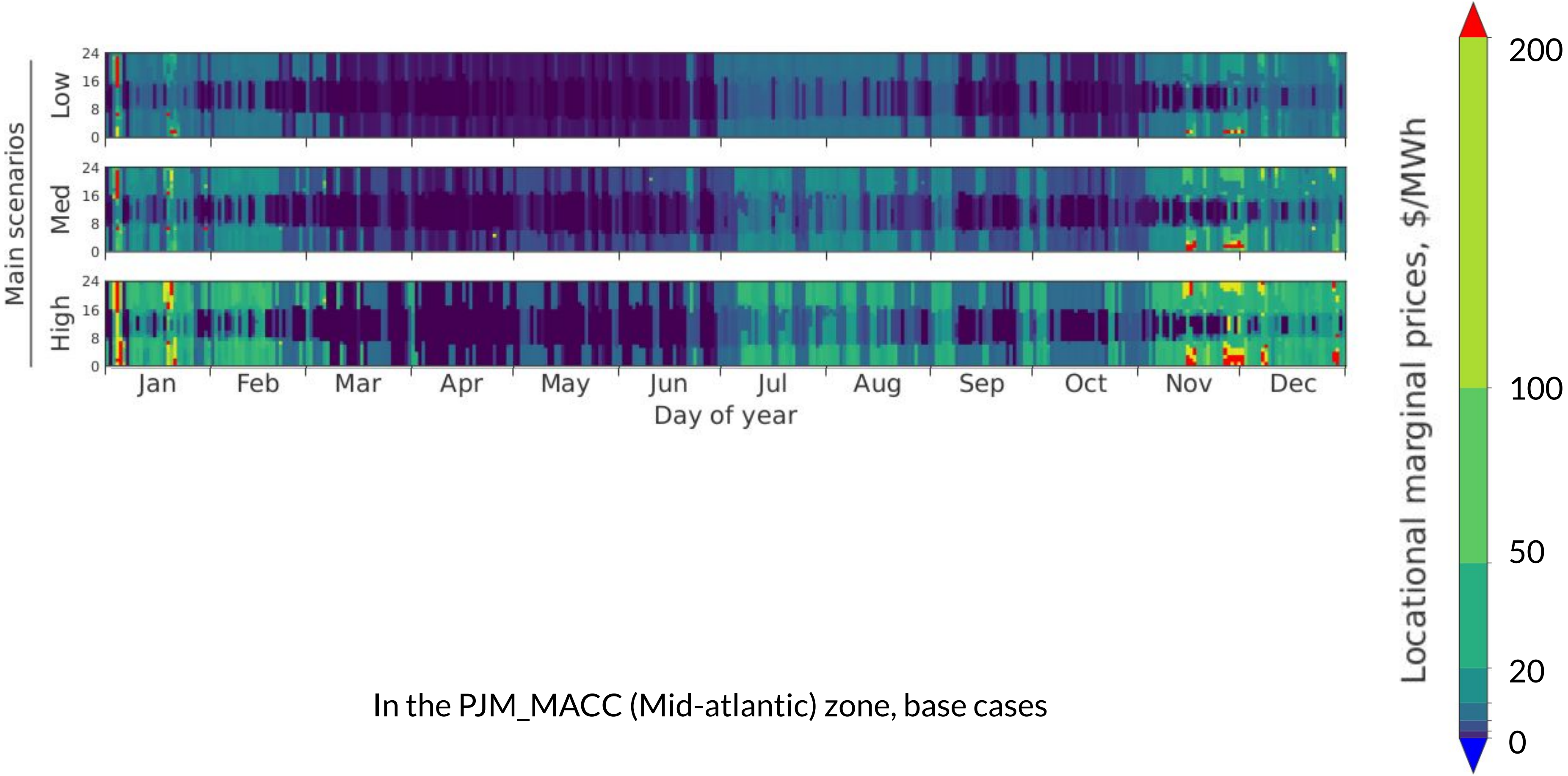
	Asset life / years							
WACC	25	30	35	40	45	50	55	60
1.00%	1.11	1.23	1.33	1.41	1.49	1.55	1.61	1.66
2.00%	1.03	1.12	1.20	1.27	1.33	1.38	1.42	1.46
3.00%	0.95	1.03	1.09	1.15	1.19	1.23	1.26	1.28
3.34%	0.93	1.00	1.06	1.11	1.15	1.18	1.21	1.23
4.00%	0.88	0.95	1.00	1.04	1.07	1.09	1.11	1.13
5.00%	0.82	0.87	0.91	0.94	0.96	0.98	1.00	1.01
6.00%	0.76	0.80	0.83	0.86	0.87	0.89	0.89	0.90
7.00%	0.71	0.74	0.77	0.78	0.79	0.80	0.81	0.81

Example hourly price series for each zone



Medium market
opportunity scenario

Prices throughout the year



In the PJM_MACC (Mid-atlantic) zone, base cases

Reference pulsed tokamaks - full table

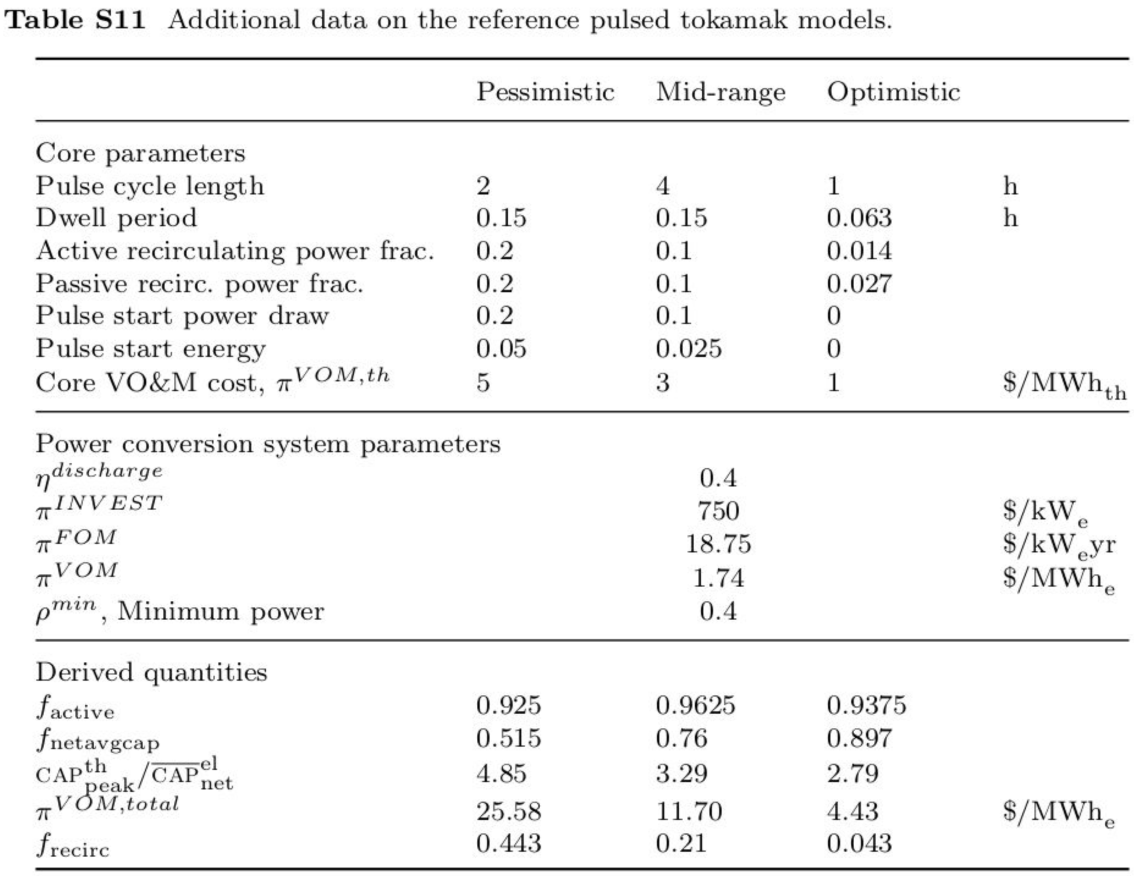
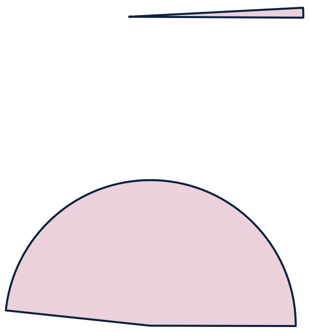


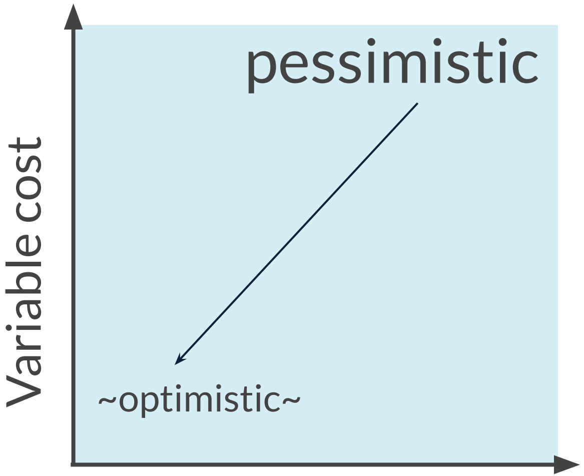
Table S11 Additional data on the reference pulsed tokamak models.

	Pessimistic	Mid-range	Optimistic	
Core parameters				
Pulse cycle length	2	4	1	h
Dwell period	0.15	0.15	0.063	h
Active recirculating power frac.	0.2	0.1	0.014	
Passive recirc. power frac.	0.2	0.1	0.027	
Pulse start power draw	0.2	0.1	0	
Pulse start energy	0.05	0.025	0	
Core VO&M cost, $\pi^{VOM,th}$	5	3	1	$/MWh$_{\mathrm{th}}$
Power conversion system parameters				
$\eta^{discharge}$		0.4		
π^{INVEST}		750		$/kW$_{\mathrm{e}}$
π^{FOM}		18.75		$/kW$_{\mathrm{e}}$yr
π^{VOM}		1.74		$/MWh$_{\mathrm{e}}$
ρ^{min}, Minimum power		0.4		
Derived quantities				
f_{active}	0.925	0.9625	0.9375	
$f_{\mathrm{netavgcap}}$	0.515	0.76	0.897	
$\mathrm{CAP}^{\mathrm{th}}_{\mathrm{peak}}/\overline{\mathrm{CAP}}^{\mathrm{el}}_{\mathrm{net}}$	4.85	3.29	2.79	
$\pi^{VOM,total}$	25.58	11.70	4.43	$/MWh$_{\mathrm{e}}$
f_{recirc}	0.443	0.21	0.043	

Explore space of reactors, markets, capacities



Fusion capacity penetration



Pulse constraints