THE EFFECT OF PV GENERATION'S HOURLY VARIATIONS ON ISRAEL'S SOLAR INVESTMENT

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MOTIVATION

- **The sharp expansion in renewable energy, such as photovoltaic cells (PV) and wind, in electricity generation compels researchers to develop optimal capacity mix models that account for the intermittent nature of these technologies.**
- **The cost of PV has been reduced dramatically during the last decade, and this cost may further be reduced to $30 per MWh in 2030 (Jones-Albertus et al., 2018; PUA, 2018; Wanner, 2019; Milstein et al. 2024).**
- **Government policies enhance the use of renewable energy in electricity production. These policies include tax credits, net energy metering, carbon trading, low-cost financing, and more (Zarnikau et al., 2019).**

RESEARCH QUESTIONS

1. **How to model the intermittent nature of the PV technology in optimal capacity mix models?**
2. **Is it essential, due to the intermittent nature of the PV technology, to employ capacity mix models that account for the seasons of the year?**
3. **What is the impact of an increase in the productivity of PV's effective capacity, due to R&D (say), on the optimal capacity mix, electricity prices, and industry profits?**

MODEL

- Two generation technologies: PV and natural gas (NG)
- Market structure:
  - *N* identical firms (IPPs) employing PV technology
  - *M* identical firms (IPPs) employing NG technology
- Electricity demand varies across the hours of the day and over the seasons.
- Effective PV's capacity (i.e., actual electricity generation by one MW of installed PV capacity) is zero during the nighttime hours; it is high during midday hours, but low and variable in other daytime hours.

MODEL

- Firms that employ **PV (PV IPPs)** and firms that use **NG (NG IPPs)** participate in the generation market during the daytime hours.
- We assume, and later verify empirically for Israel's electricity market, that the M **NG IPPs** will not reach, at the optimal solution, full capacity during any daytime hour.

MODEL

- Let K_i^S be the PV capacity of the *i*'s PV IPP.
- One installed MW of photovoltaic (PV) capacity can only produce ω_t MWh of electricity in daytime hour *t*, where ω_t = positive fraction that we call PV's *hourly effective capacity* (HEC); the *effective capacity constraint* (ECC) of PV IPP *i* at daytime hour *t* is $\omega_t \cdot K_i^S$.
- Let K_j^G be the optimal NG capacity of the *i*'s NG IPP;
- The optimal capacity mix (K_i^S and K_j^G) may be calculated for any number of HEC during the daytime hours (i.e., the number of ω_t may be 1, 2, 3, 4, 5,…, 10,…3650).
- The optimal capacity mix (optimal values of K_i^S and K_j^G) is computed for annual and for four seasonal daytime and nighttime demand functions.

MODEL (two stage game)

First stage

In the first stage, PV and NG IPPs know the distribution function of the random hourly electricity demands and respectively build K_i^S and K_j^G MW of capacities, where $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, M$.

Second stage

In the second stage the actual electricity demand in hour *t* becomes known to all IPPs. PV and NG IPPs determine their profit maximizing production quantities which are made possible by generation capacities already installed.

This stage is replicated *T* independent times during the planning horizon, with *T* = 8760 in a 1-year horizon.

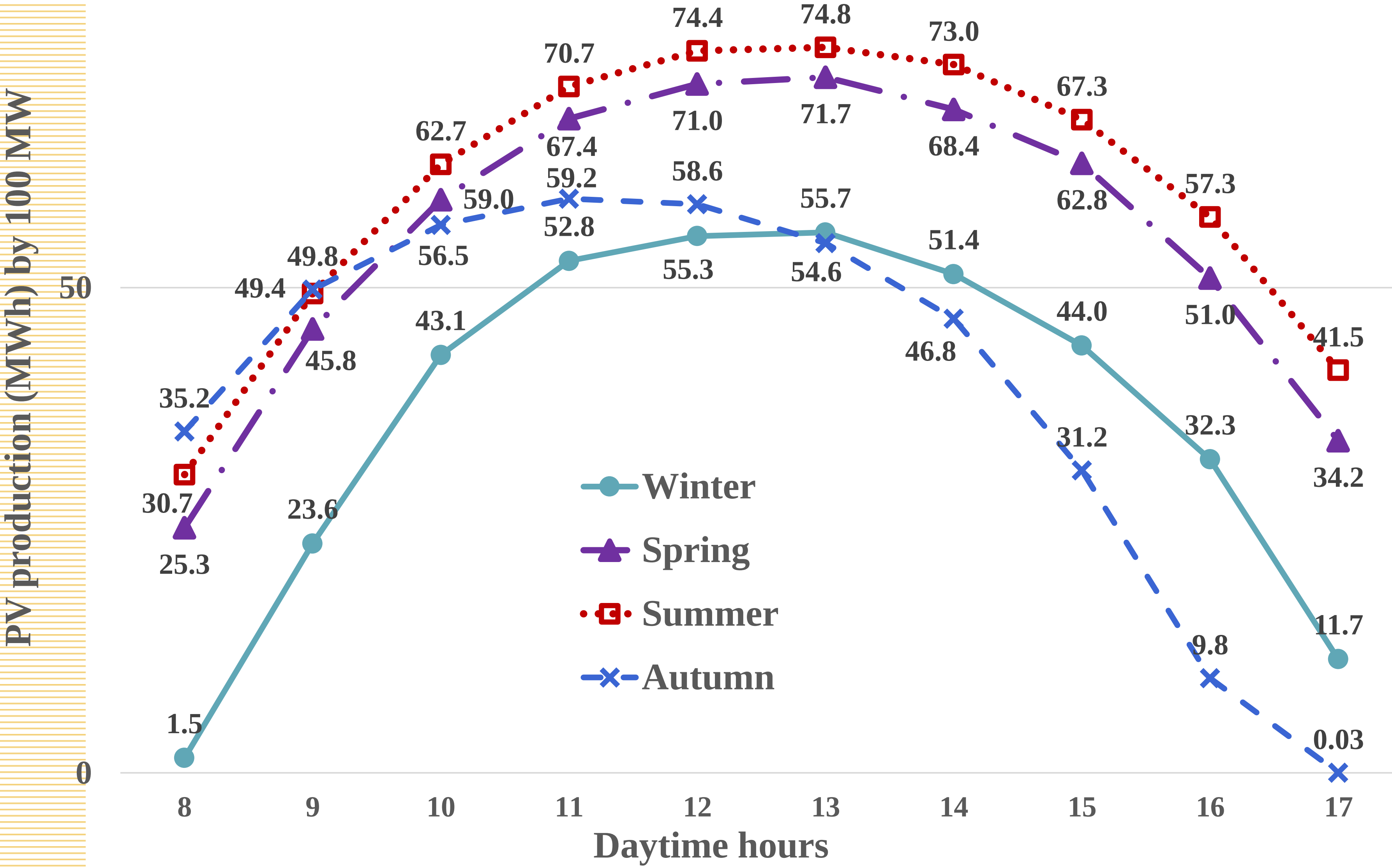
EMPIRICS

- **Our projection of Israel's hourly electricity demands in 2030 is the actual 2022 hourly electricity loads adjusted by 2.8% annually during 2023-2030**
- **The summer months: June-September, the spring months: March-May; the autumn months: October-November; the winter months: December-February**
- **We partition the 24 hours of the day into 10 daytime hours (8:00 -18:00) and 14 nighttime hours (00:00-8:00, 18:00-24:00)**
- **The average electricity price in 2030 is $93/MWh**
- **The short-run price elasticity is -0.1**
- $N = 50$, $M = 20$

DATA: Israel's projected hourly loads in 2030 (GWh)

Descriptive statistics	Daytime				Nighttime			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Mean	**11.4**	**10.8**	**14.9**	**11.1**	**10.5**	**9.6**	**12.2**	**9.6**
Median	**11.1**	**10.5**	**15.1**	**11.2**	**9.9**	**9.3**	**11.9**	**9.3**
Standard deviation	**1.6**	**1.3**	**2.2**	**1.1**	**2.4**	**1.6**	**2.1**	**1.4**
Minimum	**7.8**	**7.8**	**9.0**	**7.9**	**7.2**	**7.0**	**8.0**	**7.3**
Maximum	**16.5**	**15.4**	**19.2**	**13.9**	**17.4**	**15.5**	**17.7**	**13.1**
No. of hours	**900**	**920**	**1220**	**610**	**1260**	**1288**	**1708**	**854**

Seasonal averages of actual electricity production by 100MW of nominal PV capacity from 8:00 to 18:00 in 2022



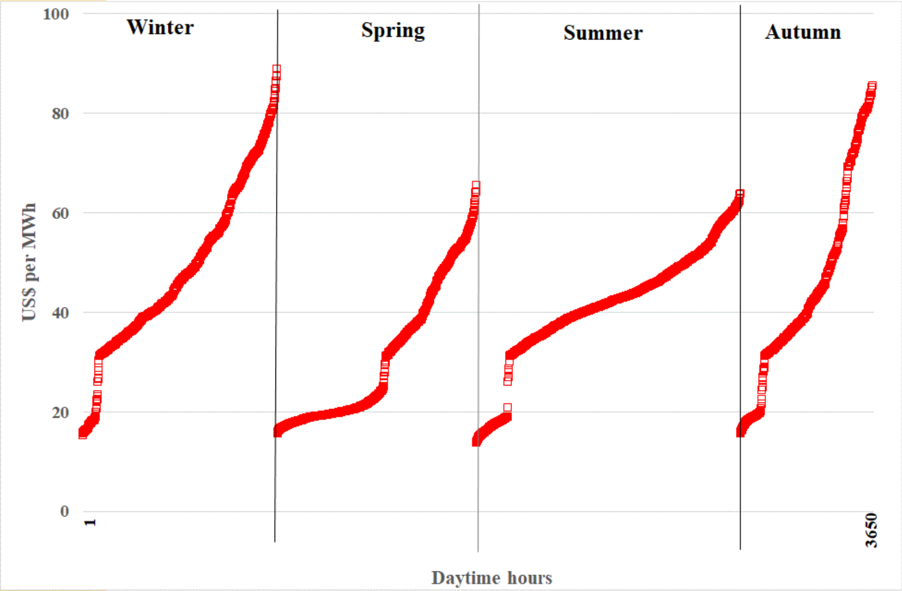
OPTIMAL PV CAPACITY (K^G=12.92GW)

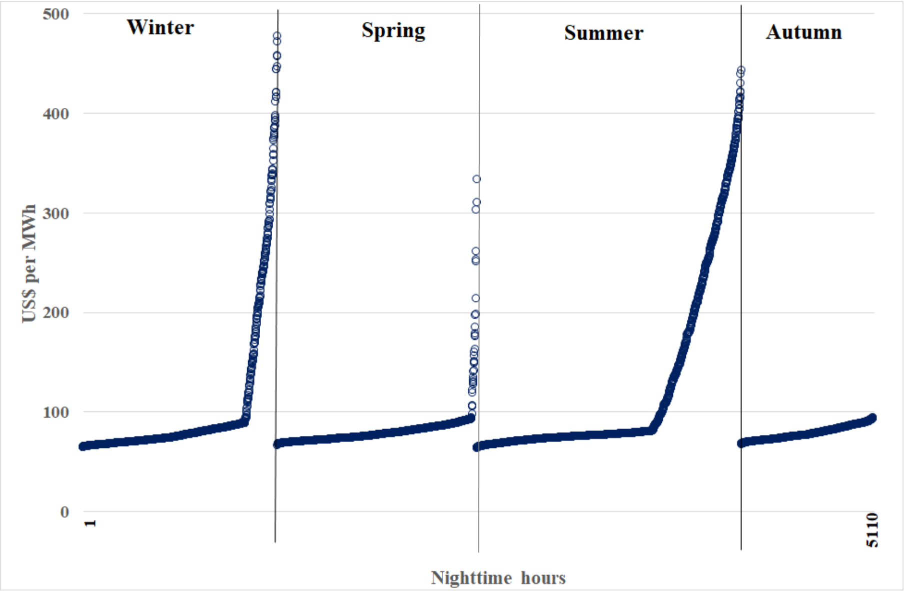
Effective daytime PV output of one MW nominal capacity: annual model										K^S
8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	
0.31		0.60						0.31		21.45
0.23	0.4	0.60						0.4	0.23	21.27
0.23	0.4	0.53	0.63				0.53	0.4	0.23	21.18
0.23	0.4	0.53	0.61	0.65		0.61	0.53	0.4	0.23	21.17
0.23	0.42	0.55	0.63	0.65	0.64	0.60	0.51	0.38	0.22	20.73

OPTIMAL PV CAPACITY (K^G=13.05GW)

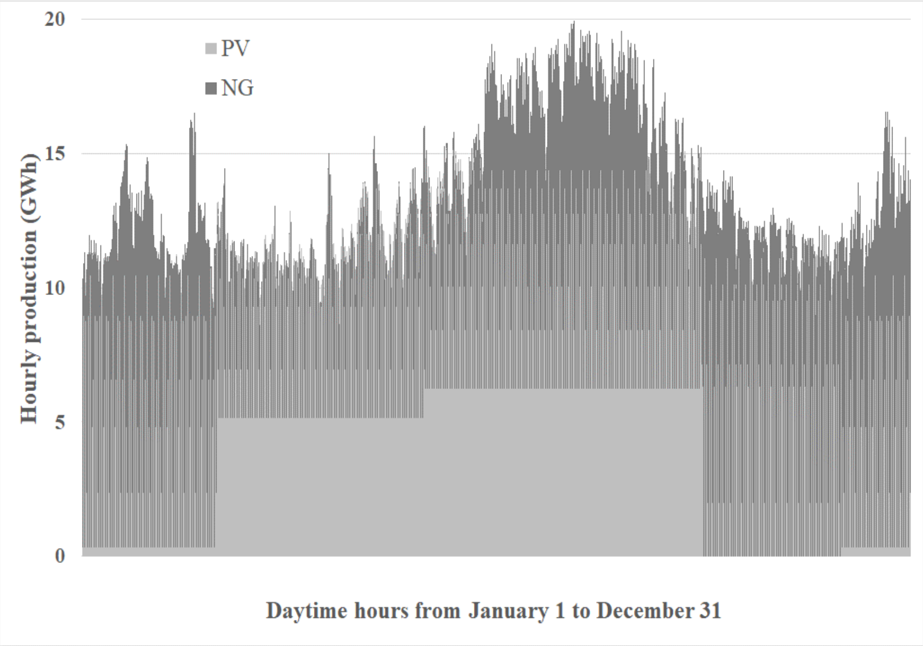
	Effective daytime PV output of one MW nominal capacity: Four-seasons model										K^S
	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	
W	0.17		0.50						0.17		21.02
Sp	0.39		0.67						0.39		
Sm	0.45		0.70						0.45		
A	0.24		0.51						0.24		
W	0.07	0.28	0.60						0.28	0.07	20.79
Sp	0.30	0.48	0.50						0.48	0.30	
Sm	0.36	0.53	0.67						0.53	0.36	
A	0.18	0.30	0.70						0.30	0.18	
W	0.07	0.28	0.44	0.54				0.44	0.28	0.07	20.63
Sp	0.30	0.48	0.61	0.70				0.61	0.48	0.30	
Sm	0.36	0.53	0.65	0.73				0.65	0.53	0.36	
A	0.18	0.30	0.44	0.55				0.44	0.30	0.18	
W	0.07	0.28	0.44	0.52	0.55		0.52	0.44	0.28	0.07	20.61
Sp	0.30	0.48	0.61	0.68	0.71		0.68	0.61	0.48	0.30	
Sm	0.36	0.53	0.65	0.72	0.75		0.72	0.65	0.53	0.36	
A	0.18	0.30	0.44	0.53	0.57		0.53	0.44	0.30	0.18	
W	0.02	0.24	0.43	0.53	0.55	0.56	0.51	0.44	0.32	0.12	20.32
Sp	0.25	0.46	0.59	0.67	0.71	0.72	0.68	0.63	0.51	0.34	
Sm	0.31	0.49	0.63	0.71	0.74	0.75	0.73	0.67	0.57	0.41	
A	0.35	0.50	0.56	0.59	0.59	0.55	0.47	0.31	0.10	0.0003	

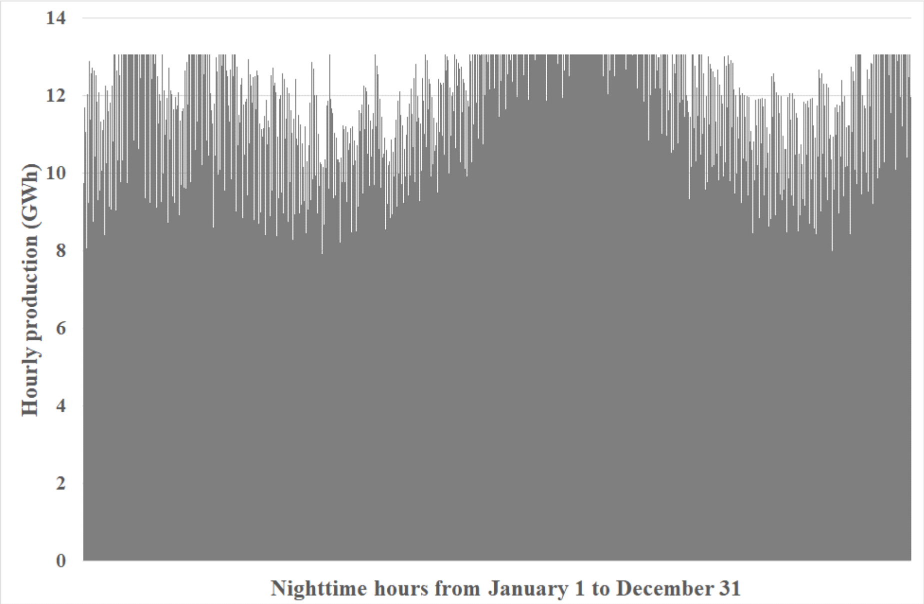
PRICE DISTRIBUTIONS OVER THE YEAR





DISTRIBUTIONS OF HOURLY PRODUCTION

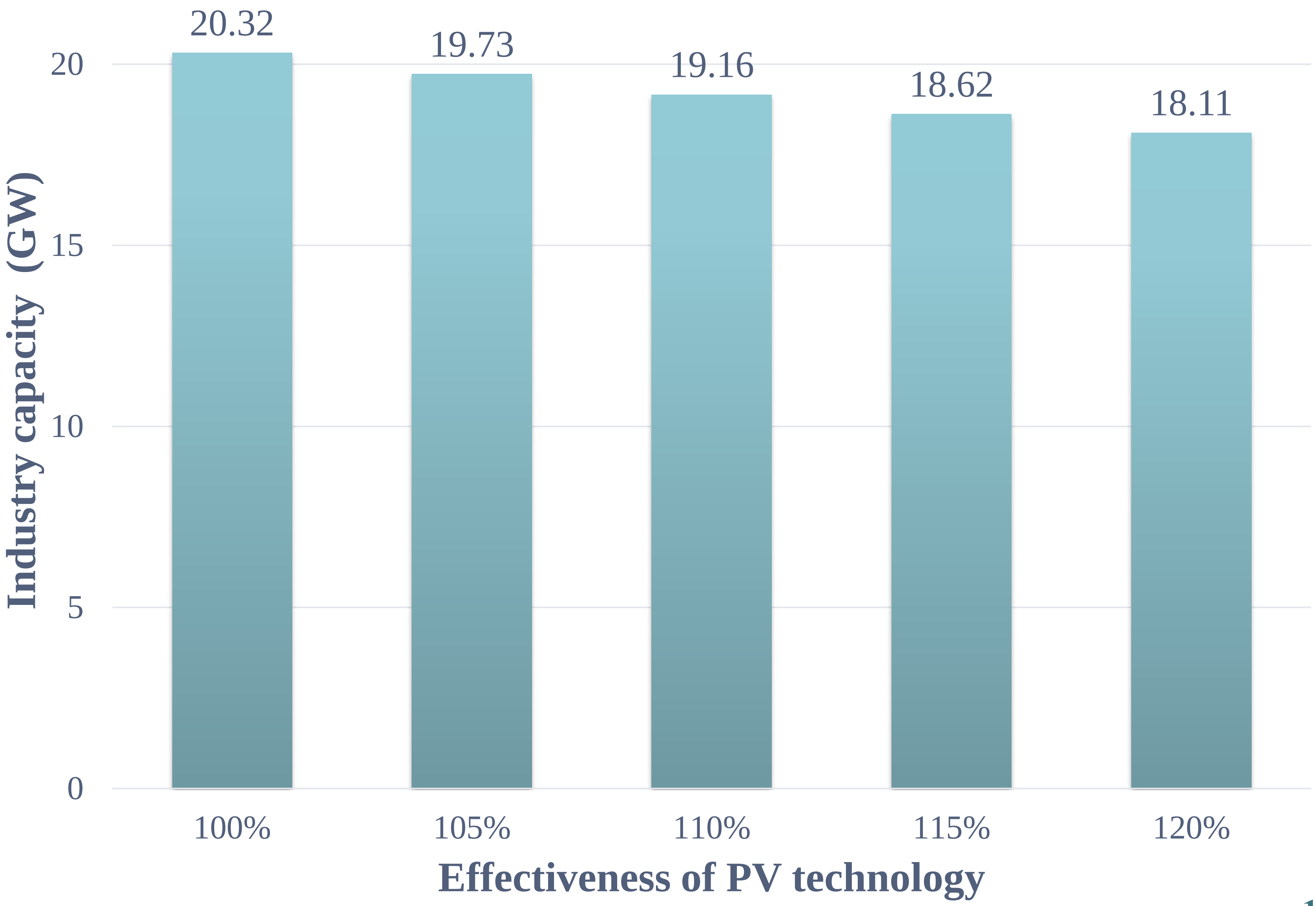




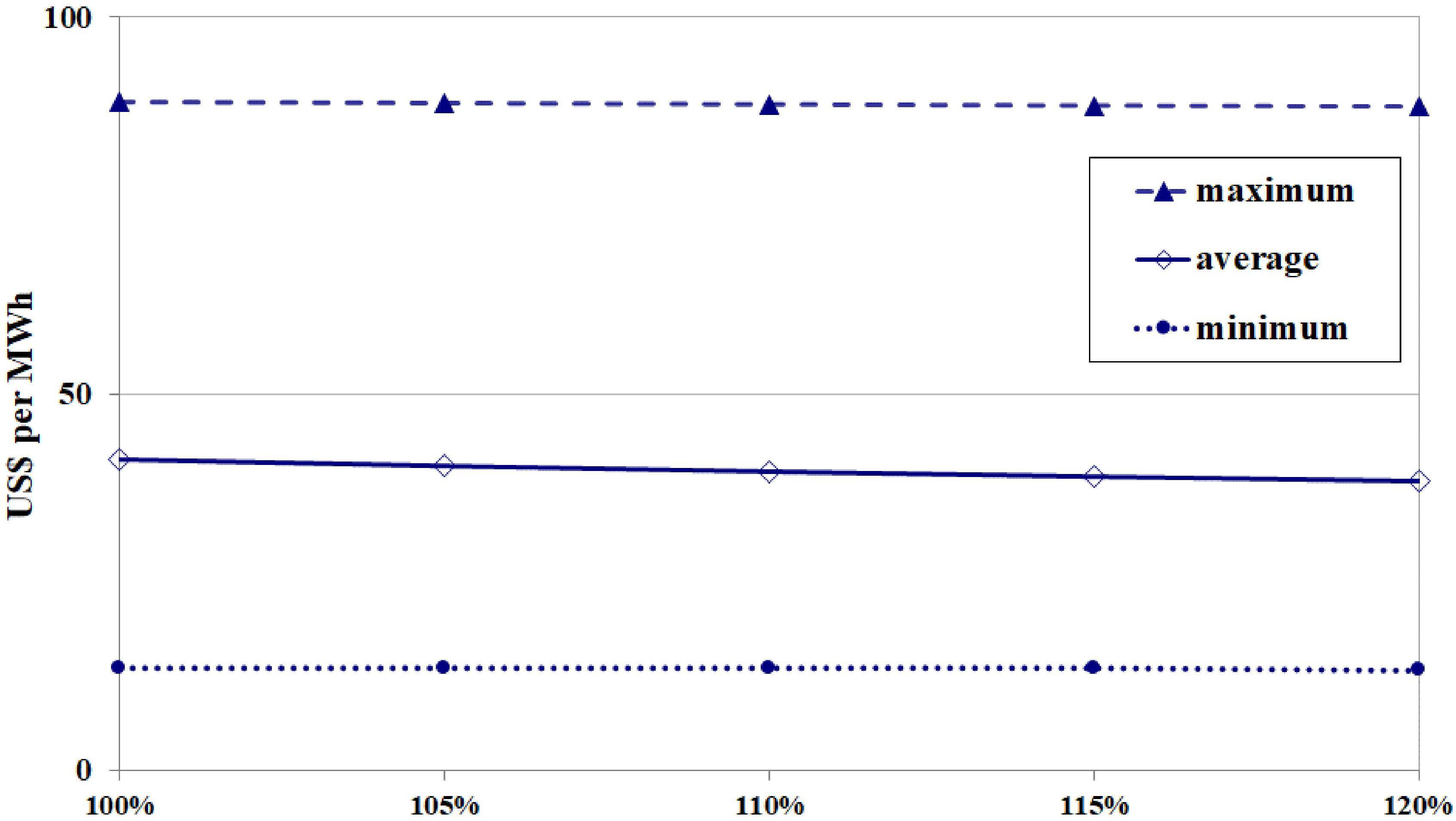
- **NG never reach full capacity**

- **NG production reaches full capacity in only 16% of the nighttime hours in summer and winter and is rarely at full capacity during spring or autumn.**

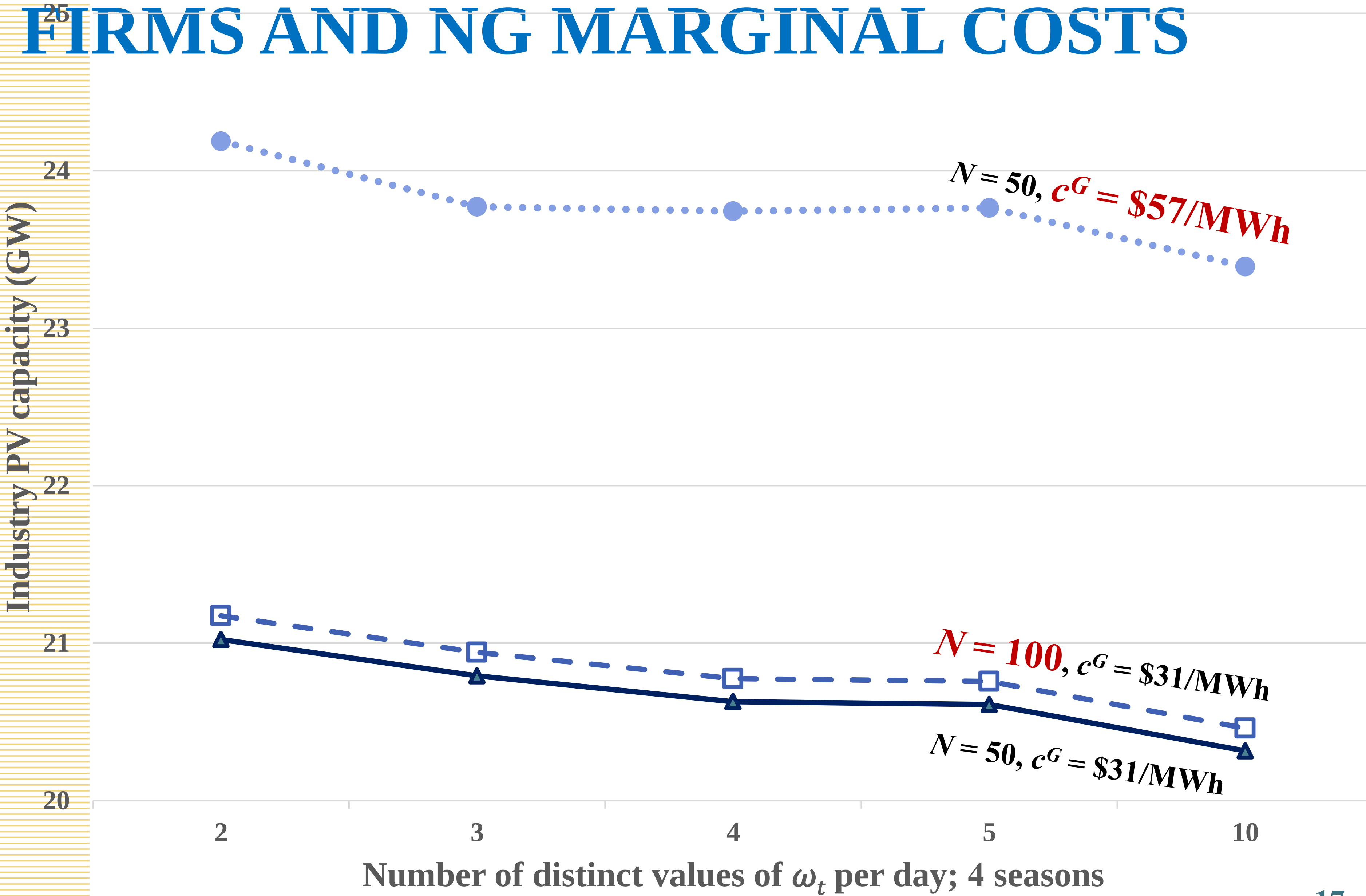
EFFECT OF PV PRODUCTIVITY ON CAPACITY



EFFECT OF PV PRODUCTIVITY ON MARKET DAYTIME PRICES



EFFECT OF THE NUMBER OF PV FIRMS AND NG MARGINAL COSTS



SUMMARY

- **Our two-stage model reveals how the optimal capacity mix and production in a Cournot wholesale electricity market may move with the representation of the variability of HEC.**

- **The representation of PV's effective capacity variability during the day-hours (2 or 3 or 4 or 5 or 10 values of HEC) does not materially change the optimal mix of PV and NG capacities.**

- **An improvement in PV effective capacity has modest effects on the optimal PV and NG capacities, daytime market prices and output levels, and PV and NG profits.**

- **We can use only two daily values of HEC with annual demand function to assess the optimal capacity mix, generation levels and prices in models with several generation technologies, including batteries, when assessing Israel's electricity market**