

THE FUTURE OF LOW-CARBON POWER

From intermittent to indispensable



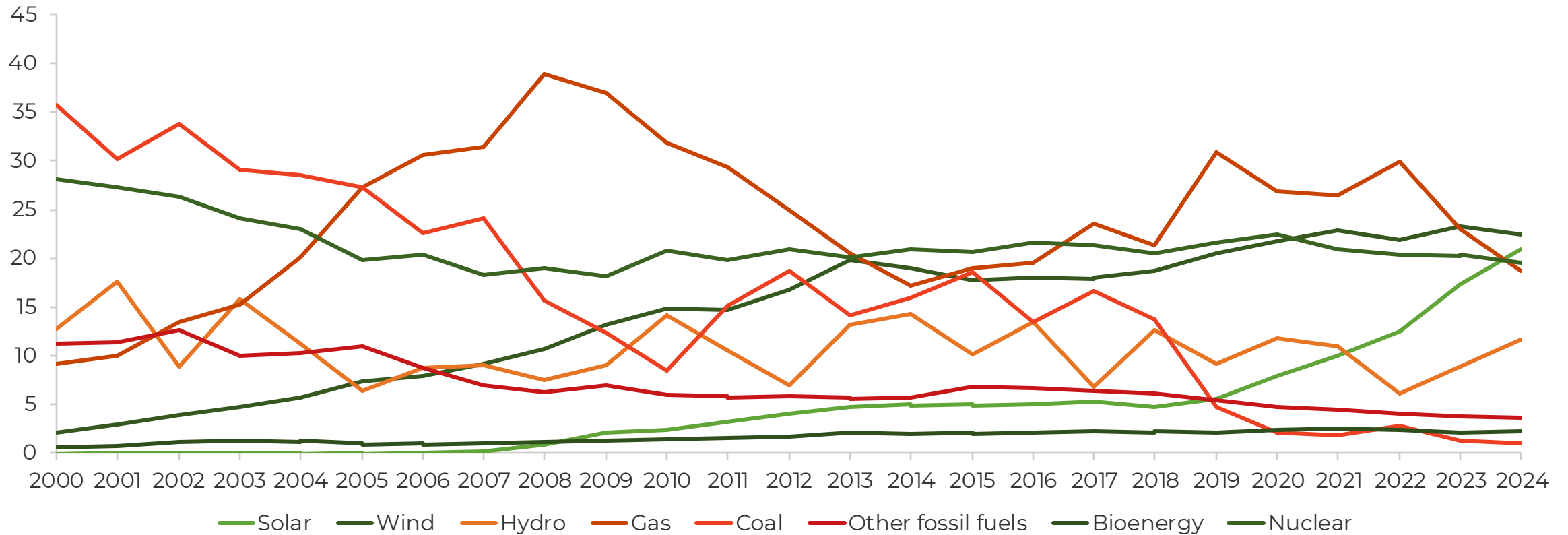
Anirudh Bhoopalam, Ph.D.
Analyst

IBERIAN PENINSULA WENT DARK



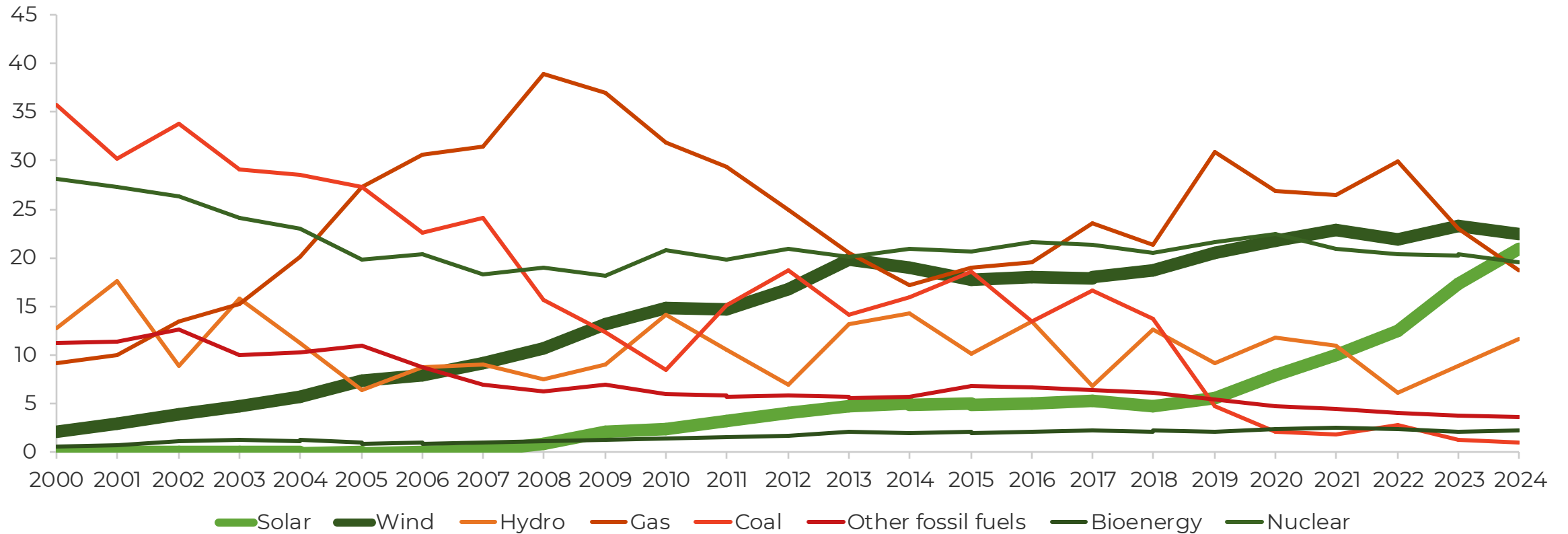
RENEWABLES HAVE BEEN RISING

Share of Electricity Generation per Energy Source in Spain (%)



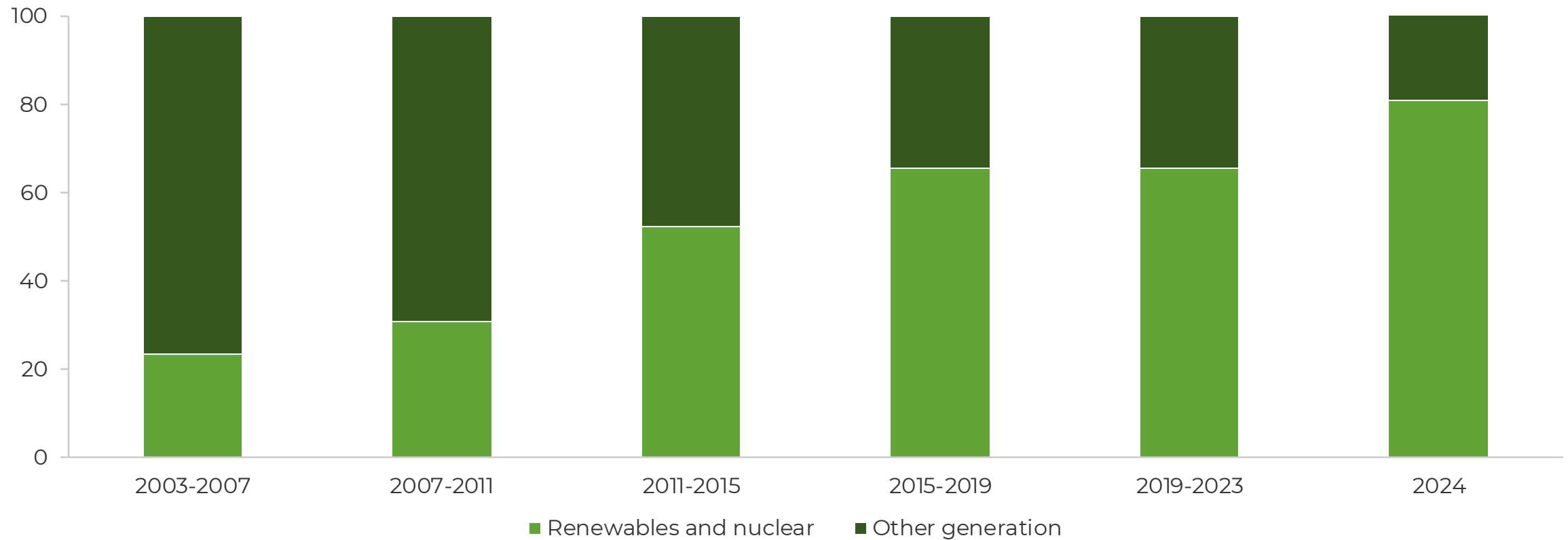
SOLAR AND WIND LEAD

Share of Electricity Generation per Energy Source in Spain (%)



RENEWABLES ARE GROWING GLOBALLY

Share of increase in global electricity generation (%)



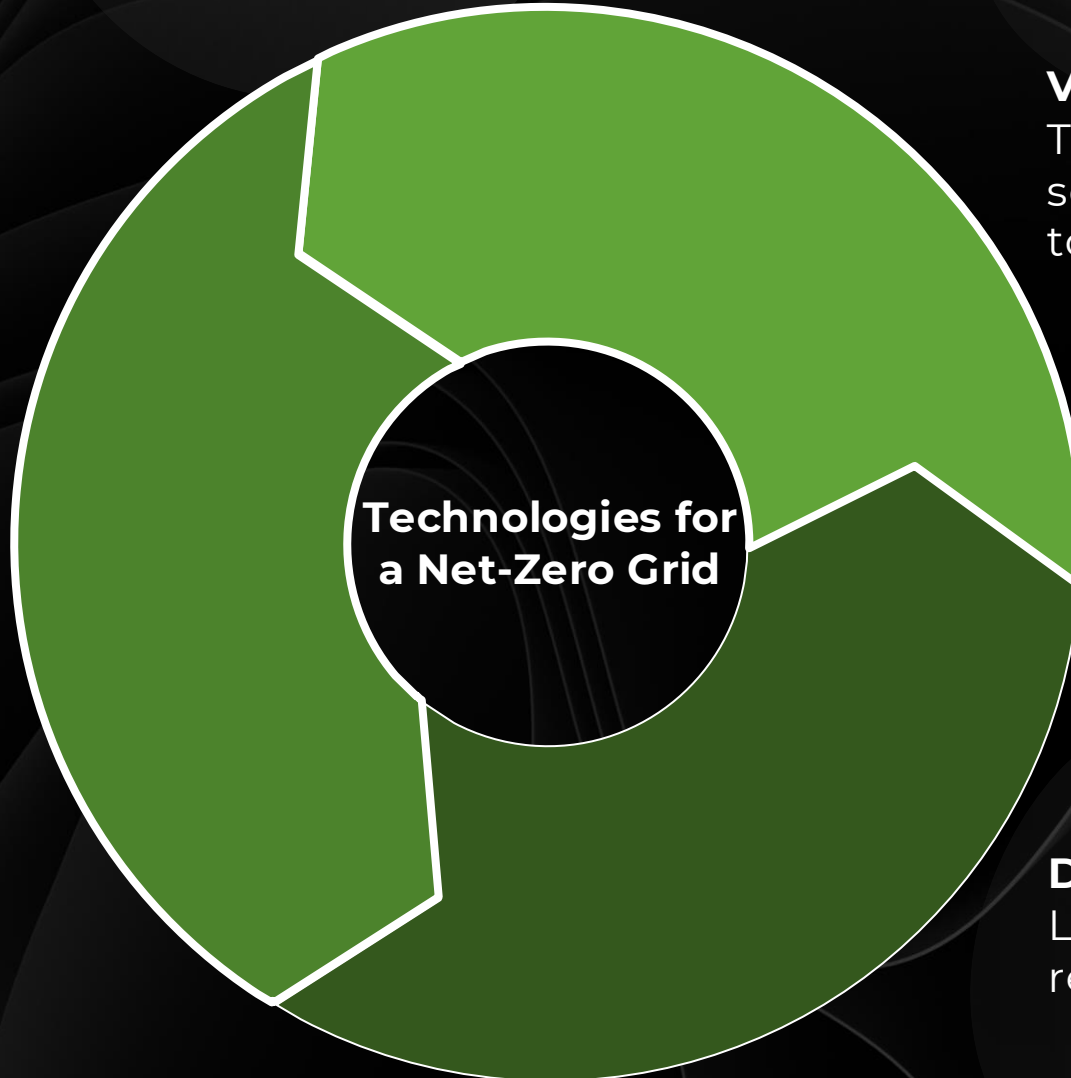
RENEWABLES ALONE ARE NOT ENOUGH

**Technologies for
a Net-Zero Grid**

RENEWABLES ALONE ARE NOT ENOUGH

Long-Duration Energy Storage

The ability to store electricity for days, weeks, or even months at a time



Variety of Generation

Tapping into a variety of sources of generation to improve reliability

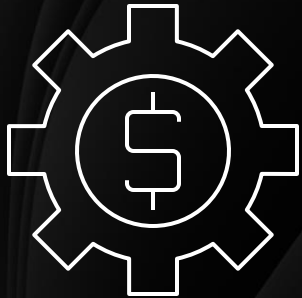
Demand Flexibility

Leveraging flexibility to reduce peak load

UTILITIES INNOVATION PRIORITIES



**Innovating at
the Grid Edge**



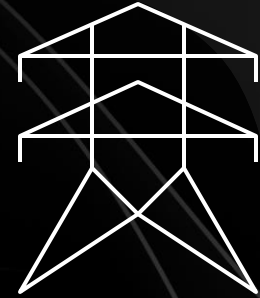
**Asset
Management**



Low-Carbon Electrons



**Meeting Demand
for Power**



**Enhancing Resilience
and Reliability**



Policy and Regulations

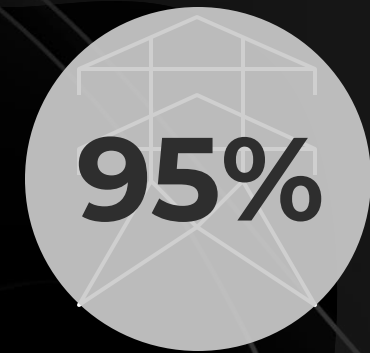
UTILITIES INNOVATION PRIORITIES



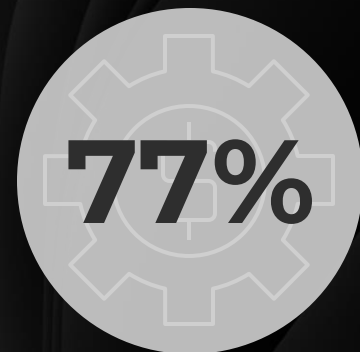
**Innovating at
the Grid Edge**



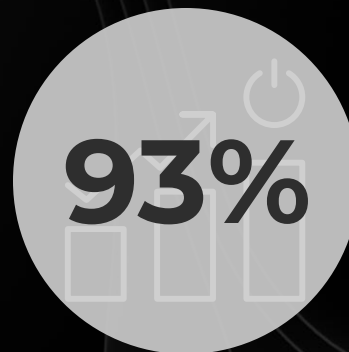
Low-Carbon Electrons



**Enhancing Resilience
and Reliability**



**Asset
Management**



**Meeting Demand
for Power**



Policy and Regulations

WHAT TO EXPECT

01 | **Characteristics of renewables with use-cases**

02 | Analysis of economics and reliability

03 | Outlook

RENEWABLES CAN PROVIDE CONTINUOUS POWER



Sage Geosystems to provide 150 MW of geothermal power to Meta's data centers



Google signs a PPA with Kairos Power to deployed SMRs for data centers

SOLAR AND WIND ARE INTERMITTENT

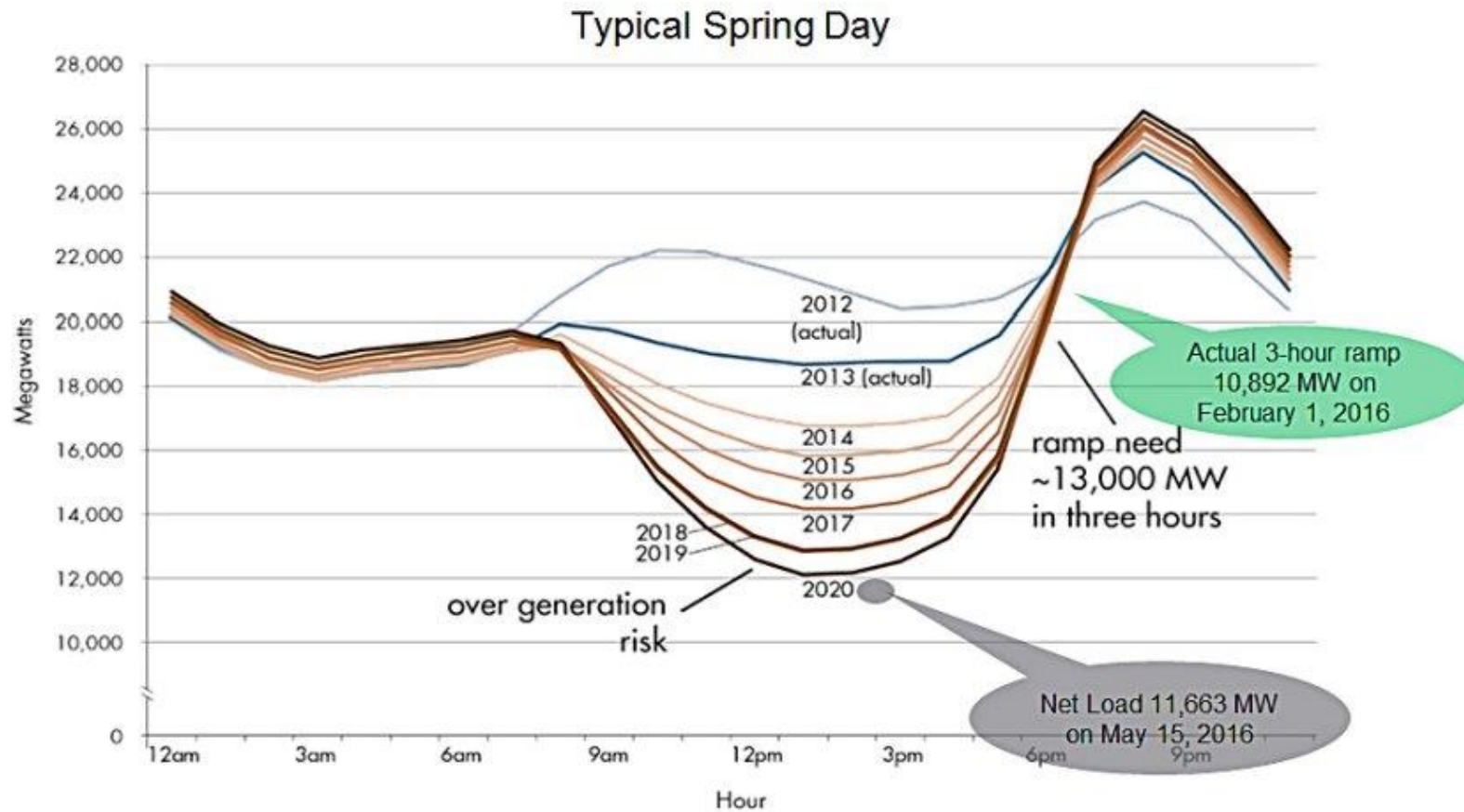


Meta signs 200-MW solar PPA with RWE in Texas



Google signs PPA for 79.3 MW of onshore wind power in Virginia

INTERMITTENCY BRINGS CHALLENGES



RELIABILITY REQUIRES OVERSIZING



Masdar: 1-GW baseload from 5.2-GW solar and 19.2 GWh of storage



ReNew Power: 400-MW baseload from 400 MW of solar, 900 MW of wind, and 100 MWh of storage

HOW DO THESE RENEWABLES COMPARE?

€

£

\$

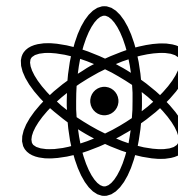
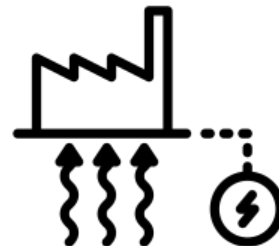
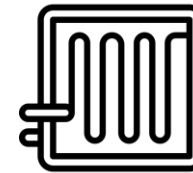
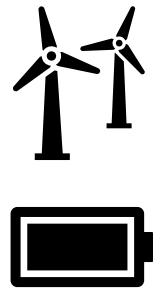
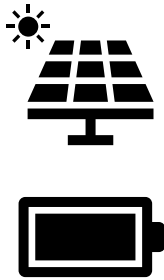
WHAT TO EXPECT

01 | Characteristics of renewables with use-cases

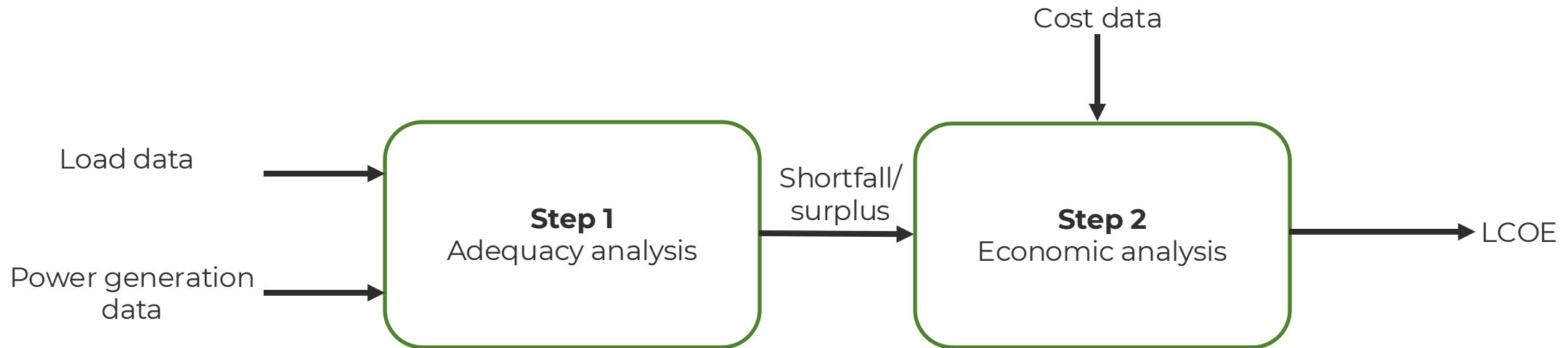
02 | **Analysis of economics and reliability**

03 | Outlook

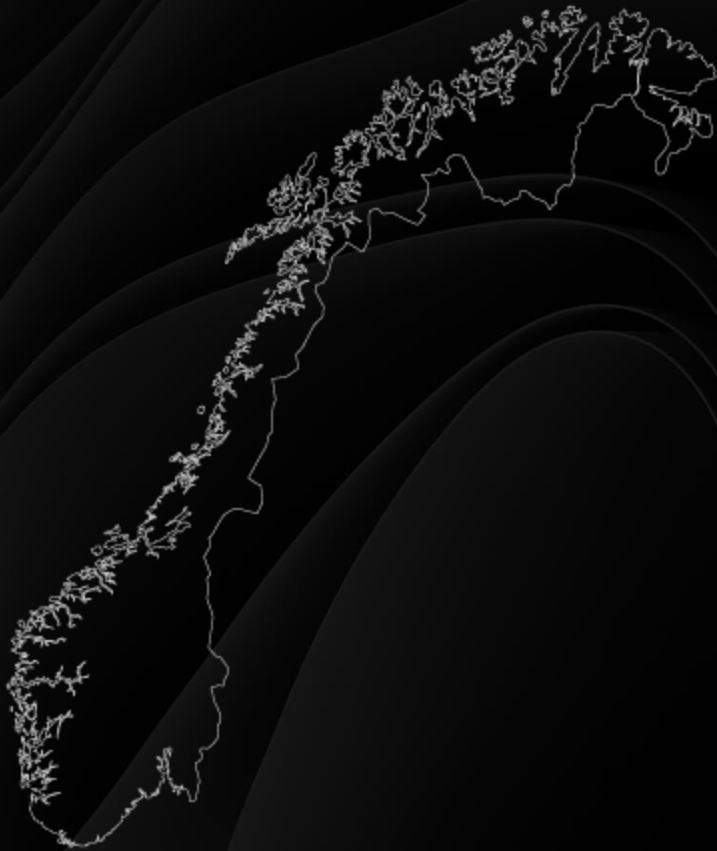
POWER-GENERATION OPTIONS



ANALYSIS – CALCULATING LCOE

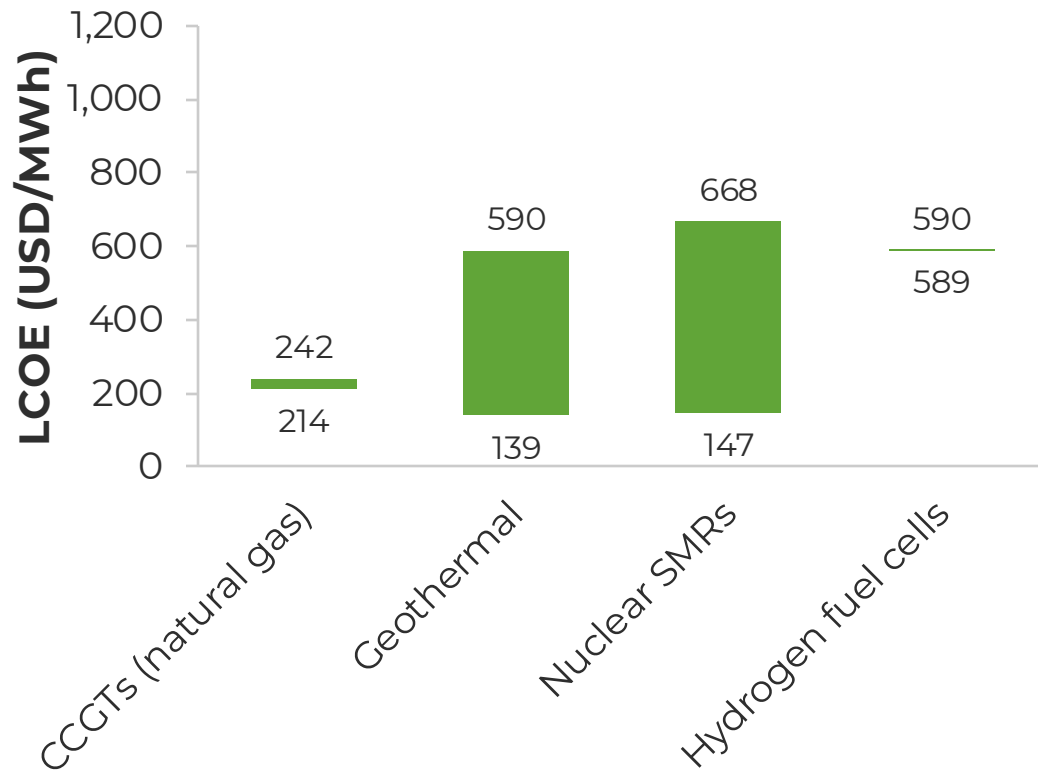


REGIONS CONSIDERED

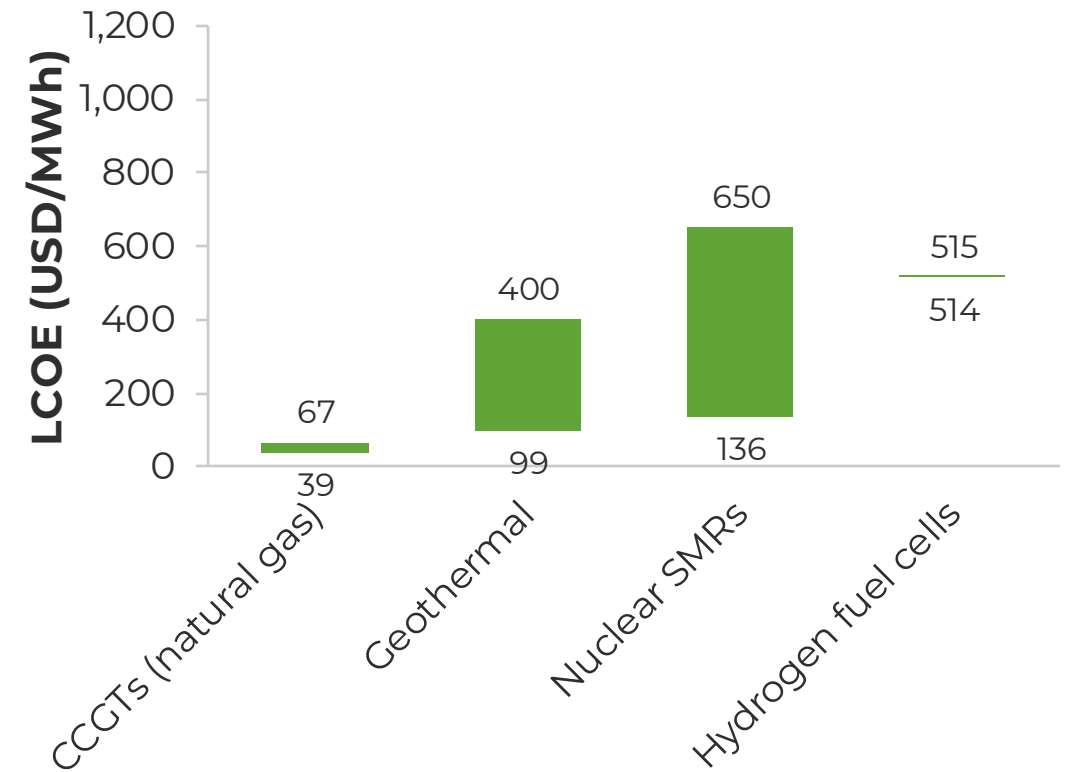


ECONOMICS OF CONTINUOUS POWER

10 MW to 10 GW – Norway



10 MW to 10 GW – Saudi



ASSESSING INTERMITTENT RELIABILITY

Reliability: Percentage of load served

SOLAR RELIABILITY BY REGION

Norway

Solar Capacity (multiple of load)

	1x	2x	3x	4x	5x	6x	7x	8x	9x	10x	11x	12x	13x	14x	15x	16x	17x	18x	19x	20x	21x	22x	23x	24x	25x
1x	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
2x	22	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
3x	27	28	30	31	31	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
4x	29	31	33	34	36	37	37	38	39	39	40	40	40	40	40	40	40	40	40	41	41	41	41	41	41
5x	31	33	35	37	38	39	41	42	43	44	44	45	46	46	46	47	47	47	47	47	47	47	47	48	48
6x	32	34	36	38	40	41	43	44	45	46	47	48	49	50	50	51	52	52	53	53	53	53	53	53	54
7x	33	35	37	39	41	43	44	46	47	48	49	51	51	52	53	54	55	55	56	56	57	57	58	58	58
8x	34	36	38	40	41	43	45	47	48	50	51	52	53	54	55	56	57	58	59	59	60	60	60	61	61
9x	35	37	39	41	42	44	46	48	49	51	52	54	55	56	57	58	59	60	61	62	62	62	63	63	63
10x	36	38	40	41	43	45	47	48	50	52	53	55	56	57	58	60	61	62	63	63	64	64	65	65	65
11x	36	38	40	42	44	46	47	49	51	52	54	55	57	58	59	61	62	63	64	65	65	66	66	67	67
12x	37	39	41	43	44	46	48	50	51	53	55	56	58	59	60	62	63	64	65	66	67	67	68	68	68
13x	37	39	41	43	45	47	48	50	52	53	55	57	58	60	61	62	64	65	66	67	68	68	69	69	69
14x	38	40	41	43	45	47	49	51	52	54	55	57	59	60	62	63	64	66	67	68	68	69	70	70	70
15x	38	40	42	44	46	47	49	51	53	54	56	58	59	61	62	64	65	66	67	68	69	70	71	71	71
16x	38	40	42	44	46	48	50	51	53	55	56	58	59	61	63	64	66	67	68	69	70	71	71	72	72
17x	39	41	42	44	46	48	50	52	53	55	57	58	60	62	63	65	66	67	68	69	70	71	72	72	73
18x	39	41	43	45	46	48	50	52	54	55	57	59	60	62	63	65	66	68	69	70	71	72	72	73	73
19x	39	41	43	45	47	49	50	53	54	56	58	59	61	62	64	65	67	68	69	70	71	72	73	73	74
20x	39	41	43	45	47	49	51	53	55	56	58	60	61	63	64	65	67	68	70	71	72	72	73	74	74
21x	40	42	44	46	47	49	51	53	55	57	58	60	61	63	64	66	67	69	70	71	72	73	74	74	75
22x	40	42	44	46	48	49	51	53	55	57	59	60	62	63	65	66	68	69	70	71	72	73	74	74	75
23x	40	42	44	46	48	50	51	53	55	57	59	61	62	63	65	67	68	69	70	72	73	73	74	75	75
24x	40	42	44	46	48	50	51	53	55	57	59	61	62	64	65	67	68	70	71	72	73	74	74	75	76
25x	40	42	44	46	48	50	52	54	55	57	59	61	63	64	66	67	69	70	71	72	73	74	75	75	76

Saudi Arabia

Solar Capacity (multiple of load)

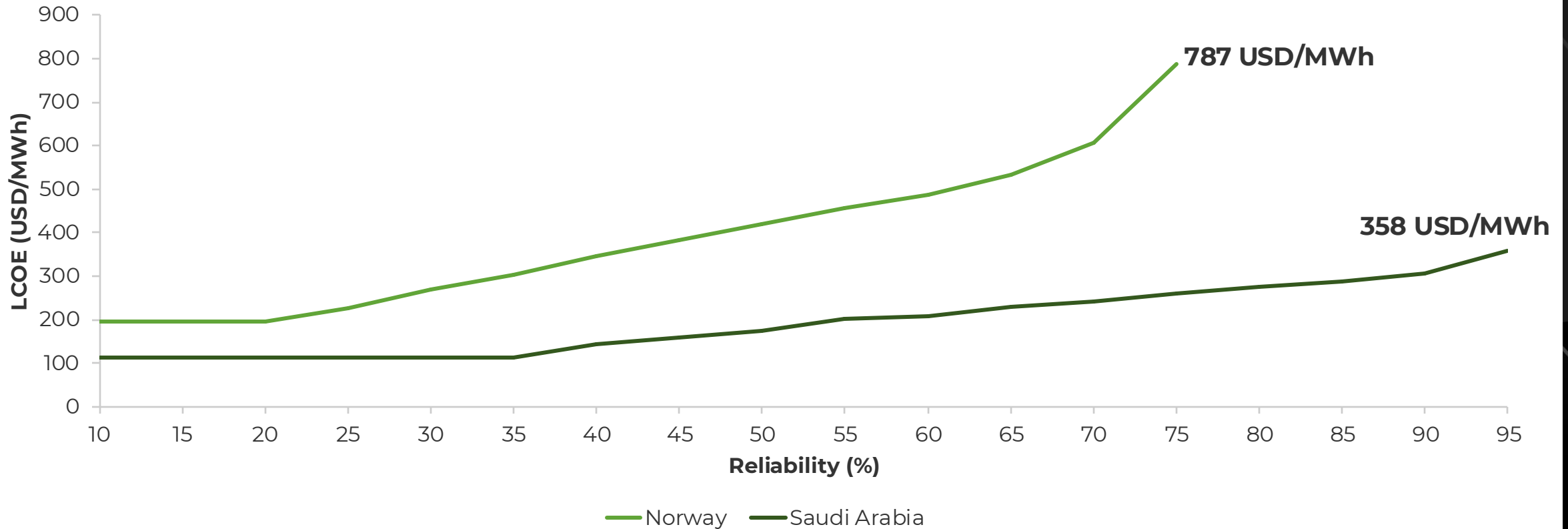
	1x	2x	3x	4x	5x	6x	7x	8x	9x	10x	11x	12x	13x	14x	15x	16x	17x	18x	19x	20x	21x	22x	23x	24x	25x
1x	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
2x	38	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
3x	41	44	47	50	52	53	54	55	55	55	55	55	55	55	55	56	56	56	56	56	56	56	56	56	56
4x	43	46	49	52	54	55	56	57	58	58	58	58	58	58	58	59	59	59	59	59	59	59	59	59	59
5x	44	47	50	53	55	56	57	58	59	59	59	59	59	59	59	60	60	60	60	60	60	60	60	60	60
6x	45	48	50	53	55	56	57	58	59	59	59	59	59	59	59	60	60	60	60	60	60	60	60	60	60
7x	46	48	50	53	55	56	57	58	59	59	59	59	59	59	59	60	60	60	60	60	60	60	60	60	60
8x	46	49	51	53	55	56	57	58	59	59	59	59	59	59	59	60	60	60	60	60	60	60	60	60	60
9x	47	49	51	54	56	58	61	64	67	70	72	74	76	78	81	83	85	86	88	90	92	93	94	95	95
10x	47	49	52	54	56	58	61	64	67	70	72	74	76	78	81	83	85	87	89	91	92	94	94	95	96
11x	47	50	52	55	57	59	61	63	66	69	72	74	76	78	80	83	85	87	89	91	93	94	95	96	96
12x	48	50	52	55	57	59	61	63	66	69	72	74	77	79	81	82	85	87	89	91	93	95	96	96	97
13x	48	50	53	55	57	60	62	64	66	68	71	74	77	79	81	83	85	87	89	91	93	95	96	97	97
14x	48	50	53	55	58	60	62	64	66	68	71	74	76	79	81	83	85	87	89	91	92	94	96	97	97
15x	48	51	53	55	58	60	62	64	67	69	71	73	76	78	81	83	85	87	89	91	92	94	95	96	97
16x	48	51	53	56	58	60	63	65	67	69	71	73	75	78	81	83	85	87	89	91	92	94	95	96	97
17x	48	51	53	56	58	60	63	65	67	69	71	73	75	78	80	83	85	87	89	91	93	94	95	96	97
18x	48	51	53	56	58	61	63	65	67	69	71	73	75	78	80	82	85	87	89	91	93	94	95	96	97
19x	49	51	53	56	58	61	63	65	67	69	71	73	75	78	80	82	84	87	89	91	93	94	96	96	97
20x	49	51	53	56	58	61	63	65	67	69	71	73	75	78	80	82	84	86	89	91	93	95	96	96	97
21x	49	51	53	56	58	61	63	65	67	69	71	73	75	78	80	82	84	86	88	90	93	94	96	97	97
22x	49	51	53	56	58	61	63	65	67	69	71	73	75	78	80	82	84	86	88	90	92	94	95	96	97
23x	49	51	53	56	58	61	63	65	67	69	71	73	75	78	80	82	84	86	88	90	92	94	95	96	97
24x	49	51	54	56	58	61	63	66	68	70	72	74	76	78	80	82	84	86	88	90	92	93	95	96	97
25x	49	51	54	56	58	61	63	66	68	70	72	74	76	78	80	82	84	86	88	90	92	93	95	96	97

Storage boosts reliability, but with diminishing returns

Heavy oversizing does not guarantee reliability

SOLAR RELIABILITY COSTS A PREMIUM

Minimum LCOE to Achieve a Certain Reliability



WIND REQUIRES MUCH LESS OVERSIZING

Norway

		Wind Capacity (multiple of load)														
		1x	2x	3x	4x	5x	6x	7x	8x	9x	10x	11x	12x	13x	14x	15x
Storage capacity (multiples of load)	1x	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	2x	49	49	49	49	49	49	49	49	49	49	49	50	50	50	50
	3x	62	63	63	63	64	64	64	64	64	64	64	65	65	65	65
	4x	71	72	72	73	73	73	73	73	73	73	73	74	74	74	75
	5x	77	78	78	79	79	79	79	79	79	79	79	80	81	81	81
	6x	81	82	83	83	83	84	84	84	84	85	85	85	85	85	85
	7x	84	85	86	86	86	87	87	87	87	88	88	88	88	89	89
	8x	87	87	88	88	89	89	89	89	90	90	90	91	91	91	91
	9x	88	89	90	90	91	91	91	91	92	92	92	92	92	93	93
	10x	90	90	91	92	92	92	93	93	93	93	94	94	94	94	94
	11x	91	92	92	93	93	94	94	94	94	95	95	95	95	95	95
	12x	92	93	93	94	94	94	95	95	95	95	96	96	96	96	96
	13x	93	93	94	94	95	95	95	96	96	96	96	96	97	97	97
	14x	93	94	95	95	95	96	96	96	96	97	97	97	97	97	97
	15x	94	95	95	96	96	96	97	97	97	97	97	97	98	98	98

Requires less
oversizing than
solar

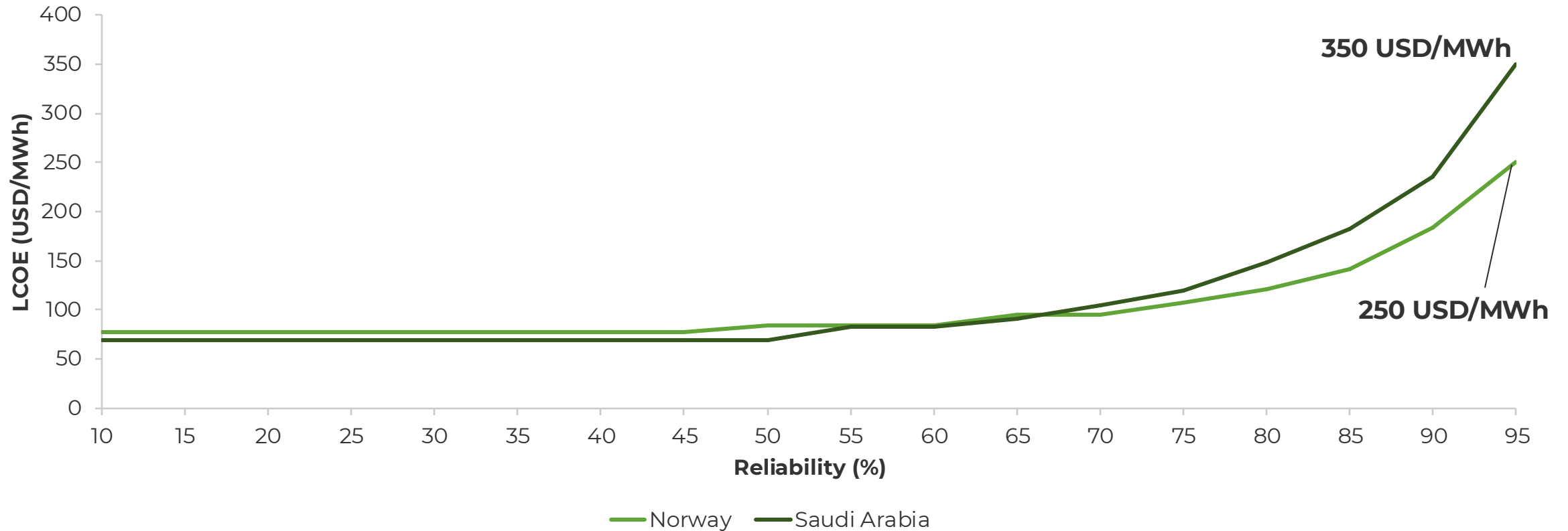
Saudi Arabia

		Wind Capacity (multiple of load)														
		1x	2x	3x	4x	5x	6x	7x	8x	9x	10x	11x	12x	13x	14x	15x
Storage capacity (multiples of load)	1x	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	2x	54	54	55	55	55	55	56	56	56	56	56	56	56	56	56
	3x	64	65	66	67	68	68	69	69	69	70	70	70	70	70	71
	4x	70	71	72	73	74	75	76	76	77	77	78	78	78	78	79
	5x	74	75	76	78	78	78	79	79	80	82	82	83	83	83	84
	6x	76	78	79	80	81	81	82	82	83	85	85	86	86	87	87
	7x	78	80	81	82	83	83	84	84	85	87	87	88	88	89	89
	8x	80	82	83	84	85	86	87	87	88	89	89	89	90	90	91
	9x	81	83	84	85	86	87	88	89	89	90	90	91	91	91	92
	10x	83	84	85	86	87	88	89	89	90	91	91	92	92	92	93
	11x	83	85	86	87	88	89	89	90	90	91	91	92	92	93	93
	12x	84	86	87	88	89	90	90	91	92	92	92	93	93	94	94
	13x	85	86	87	88	89	90	91	92	92	93	93	93	94	94	94
	14x	85	87	88	89	90	91	92	92	93	93	93	94	94	94	95
	15x	86	87	89	90	90	91	92	93	93	94	94	94	95	95	95

Requires less
oversizing even
in sun-rich
countries

WIND'S PREMIUM IS NOT AS HIGH

Minimum LCOE to Achieve a Certain Reliability



OFFSHORE WIND SHINES IN NORWAY

Norway

Wind Capacity (multiple of load)

1x 2x 3x 4x 5x 6x 7x 8x 9x 10x 11x 12x 13x 14x 15x

Storage capacity (multiples of load)	1x	2x	3x	4x	5x	6x	7x	8x	9x	10x	11x	12x	13x	14x	15x
1x	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
2x	87	87	88	88	88	88	88	88	89	89	90	90	90	90	90
3x	92	92	93	93	93	93	93	94	94	94	94	94	95	95	95
4x	94	94	95	95	95	95	95	96	96	96	96	96	96	96	97
5x	95	96	96	96	96	96	96	97	97	97	97	97	97	97	97
6x	96	96	96	97	97	97	97	97	97	98	98	98	98	98	98
7x	97	97	97	97	97	98	98	98	98	98	98	98	98	98	98
8x	97	97	97	98	98	98	98	98	98	98	98	98	98	98	99
9x	97	98	98	98	98	98	98	98	98	99	99	99	99	99	99
10x	98	98	98	98	98	98	98	99	99	99	99	99	99	99	99
11x	98	98	98	98	98	99	99	99	99	99	99	99	99	99	99
12x	98	98	98	98	99	99	99	99	99	99	99	99	99	99	99
13x	98	98	98	99	99	99	99	99	99	99	99	99	99	99	99
14x	98	98	99	99	99	99	99	99	99	99	99	99	99	99	99
15x	98	99	99	99	99	99	99	99	99	99	99	99	99	99	99

>90% reliability;
1x wind
capacity and 3x
storage

99% reliability
achievable

Saudi Arabia

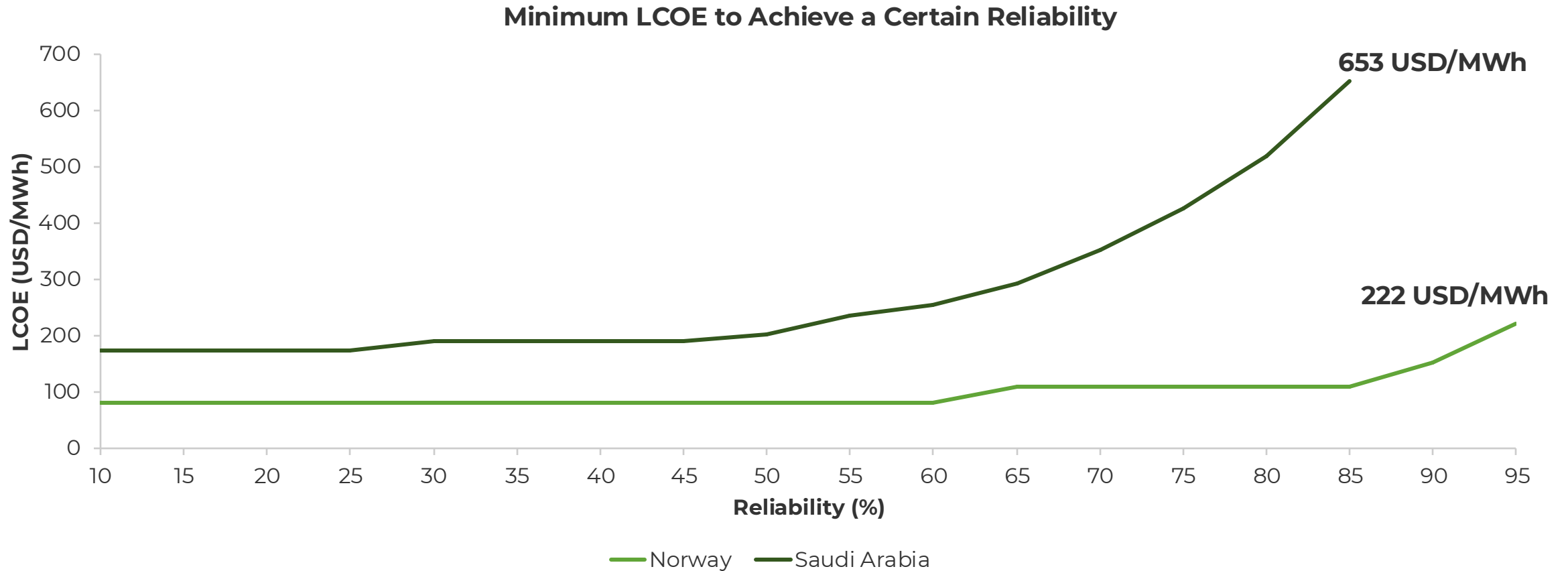
Wind Capacity (multiple of load)

1x 2x 3x 4x 5x 6x 7x 8x 9x 10x 11x 12x 13x 14x 15x

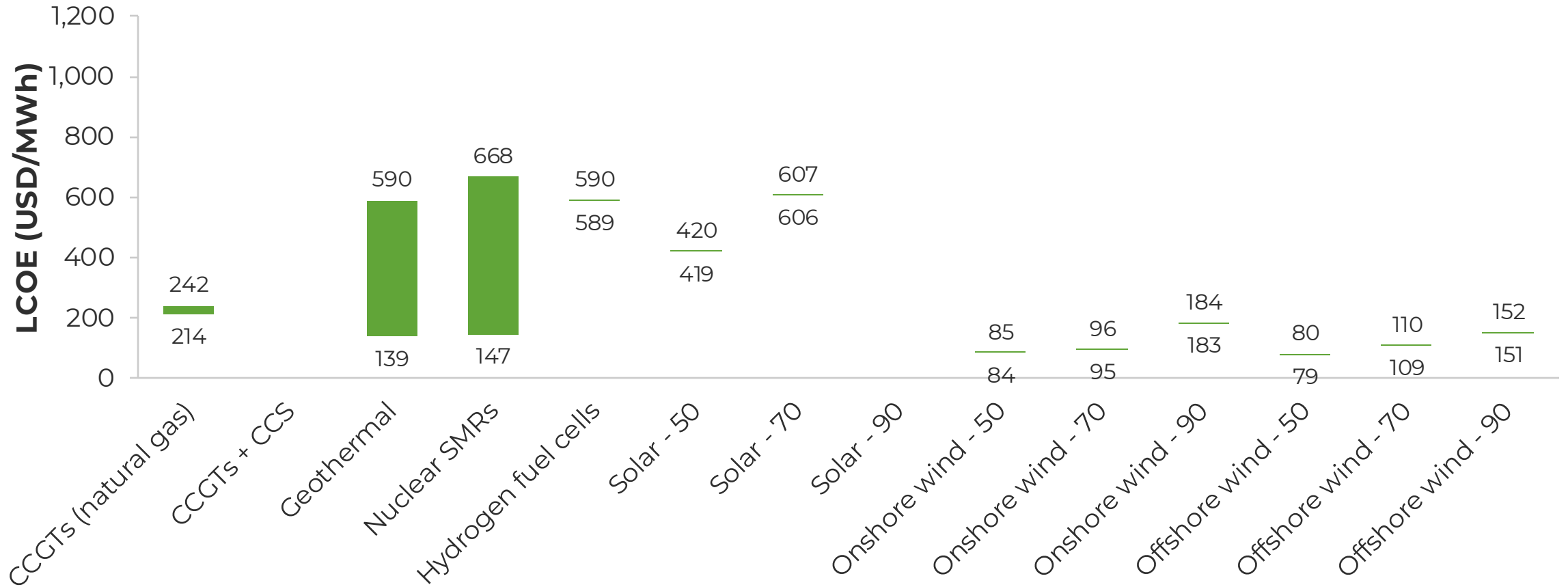
Storage capacity (multiples of load)	1x	2x	3x	4x	5x	6x	7x	8x	9x	10x	11x	12x	13x	14x	15x
1x	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
2x	50	50	51	51	51	51	51	51	52	52	52	52	52	52	52
3x	59	60	60	61	61	61	62	62	62	62	62	62	63	63	63
4x	64	65	66	66	67	67	68	68	68	68	69	69	69	69	69
5x	68	69	70	71	71	71	72	72	72	73	73	73	73	73	74
6x	71	72	73	73	74	75	75	75	76	76	76	76	77	77	77
7x	73	74	75	76	76	77	77	78	78	79	79	79	79	80	80
8x	75	76	77	78	78	79	79	80	80	81	81	81	81	82	82
9x	76	78	79	79	80	81	81	82	82	82	83	83	83	83	84
10x	78	79	80	81	81	82	83	83	83	84	84	84	85	85	85
11x	79	80	81	82	83	83	84	84	85	85	85	85	86	86	86
12x	80	81	82	83	84	84	85	85	86	86	86	86	87	87	87
13x	81	82	83	84	84	85	86	86	87	87	87	87	88	88	88
14x	81	83	84	85	85	86	87	87	87	88	88	88	89	89	89
15x	82	83	84	85	86	87	87	88	88	89	89	89	89	89	90

90% in Saudi
requires
more
oversizing

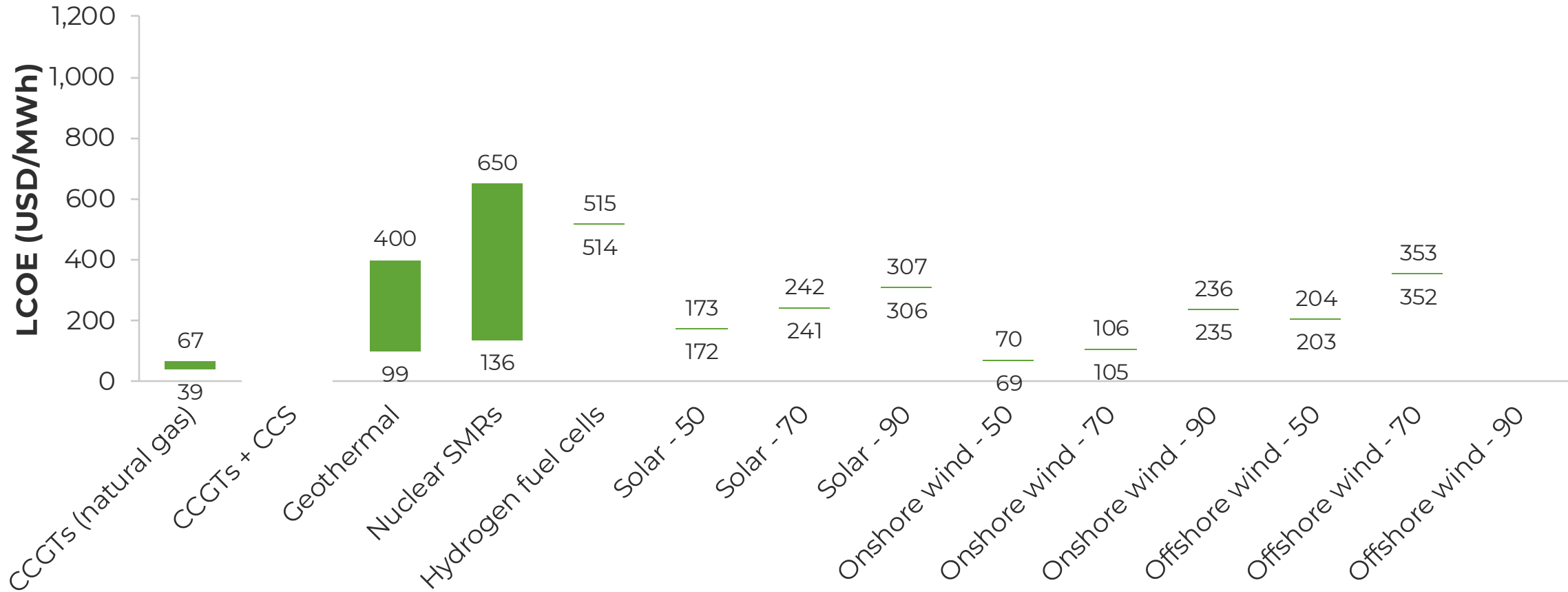
OFFSHORE WIND RELIABILITY COSTS MORE IN SAUDI ARABIA



WIND PERFORMS WELL IN NORWAY



CHEAP GAS WINS IN SAUDI ARABIA





**In chasing reliability, intermittent
renewables may lose their cost
edge**

WHAT TO EXPECT

01 | Characteristics of renewables with use-cases

02 | Analysis of economics and reliability

03 | **Outlook**

INTERMITTENTS NEED EXTERNAL STABILITY

Firming raises solar and wind
LCOE to premium levels

Best used as low-cost
complements

Need investment in grid inertia
and demand flexibility

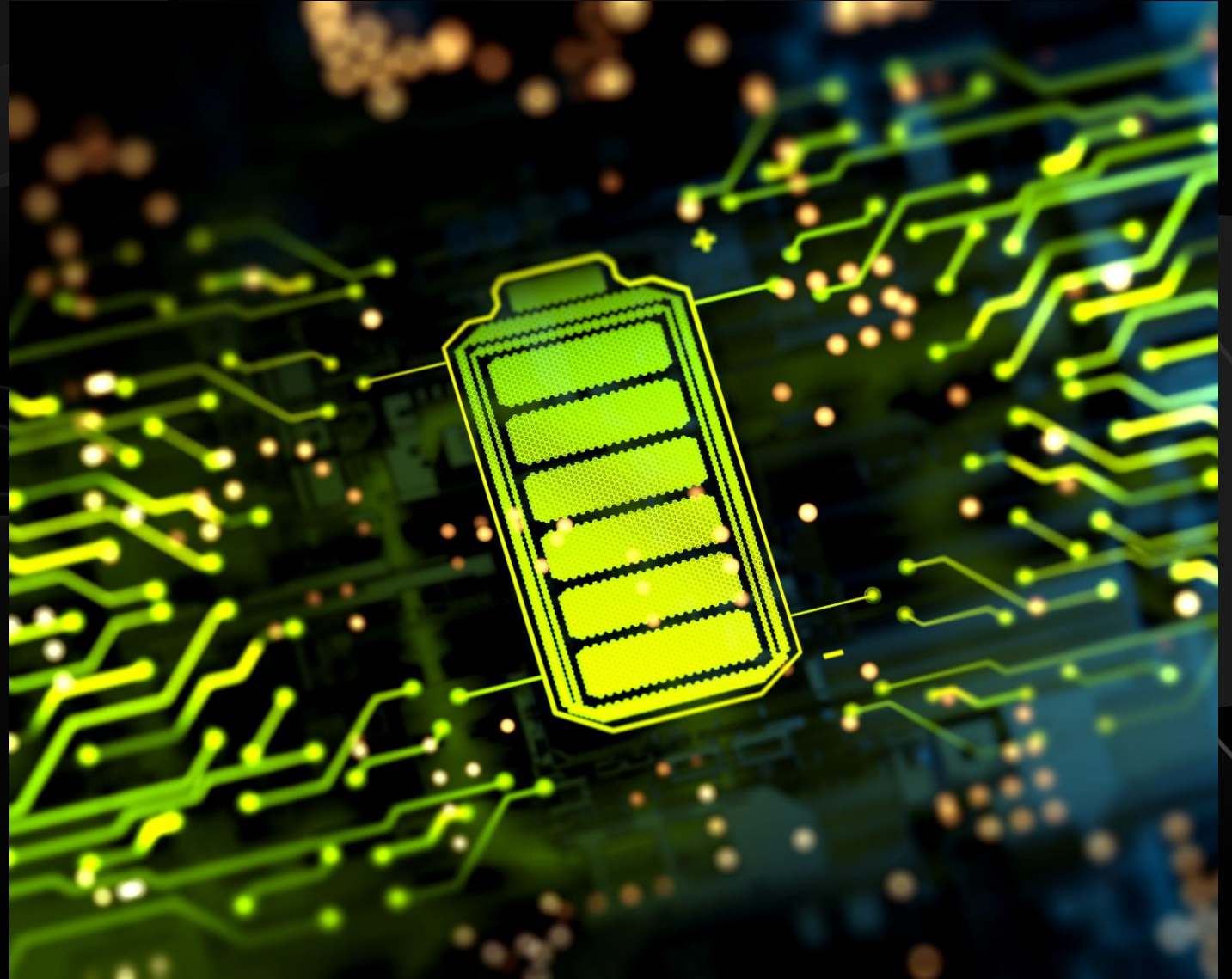


LONG-DURATION STORAGE

Batteries boost reliability but add cost

8-h systems emerging, still Li-ion based (2x4 h)

New tech better suited for 10–12-h needs



CARBON CAPTURE TECHNOLOGY

Segmented by capture medium and desorption mechanism

- Amine solvent

Efficiency

Degradation

Energy Consumption

Cost

Corrosiveness

CARBON CAPTURE TECHNOLOGY

Segmented by capture medium and desorption mechanism

- Solvent
- Sorbent
- Membrane
- Cryogenic
- Electroswing

Efficiency

Degradation

Energy Consumption

Cost

Corrosiveness

DISPATCHABLES FOR THE LONG HAUL

High capex but competitive LCOE for large projects with high reliability requirements

Gaining traction with more projects amid data center boom

Delays persist, but long-term potential is strong





THANK YOU



READ

<http://www.luxresearchinc.com/blog/>



LISTEN

[Innovation Matters Podcast - Spotify](#)



VISIT

www.luxresearchinc.com



EMAIL

questions@luxresearchinc.com



FOLLOW

[@LuxResearch](#)



CONNECT

[LuxResearch](#)

ABOUT LUX

Our mission is to advise leaders about commercially viable science and technology to enable sustainable innovation. We deliver research and advisory services to inspire, illuminate, and ignite innovative thinking that reshapes and grows businesses. Using quality data derived from primary research, fact-based analysis, and opinions that challenge traditional thinking, our experts focus on finding truly disruptive innovations that are also realistic and make good business sense.

The “Lux Take” is trusted by innovation leaders around the world, many of whom seek our advice directly before placing a bet on a startup or partner — our clients rely on Lux insights to make decisions that generate fantastic business outcomes. We pride ourselves on taking a rigorous, scientific approach to avoid the hype and generate unique perspectives and insights that innovation leaders can’t live without.



READ

<http://www.luxresearchinc.com/blog/>



LISTEN

[Innovation Matters Podcast - Spotify](#)



VISIT

www.luxresearchinc.com



EMAIL

questions@luxresearchinc.com



FOLLOW

[@LuxResearch](#)



CONNECT

[LuxResearch](#)