Renewable NH_3 for grid-scale sustainable energy:
Sector coupling for economic competitiveness

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November 9th, 2021

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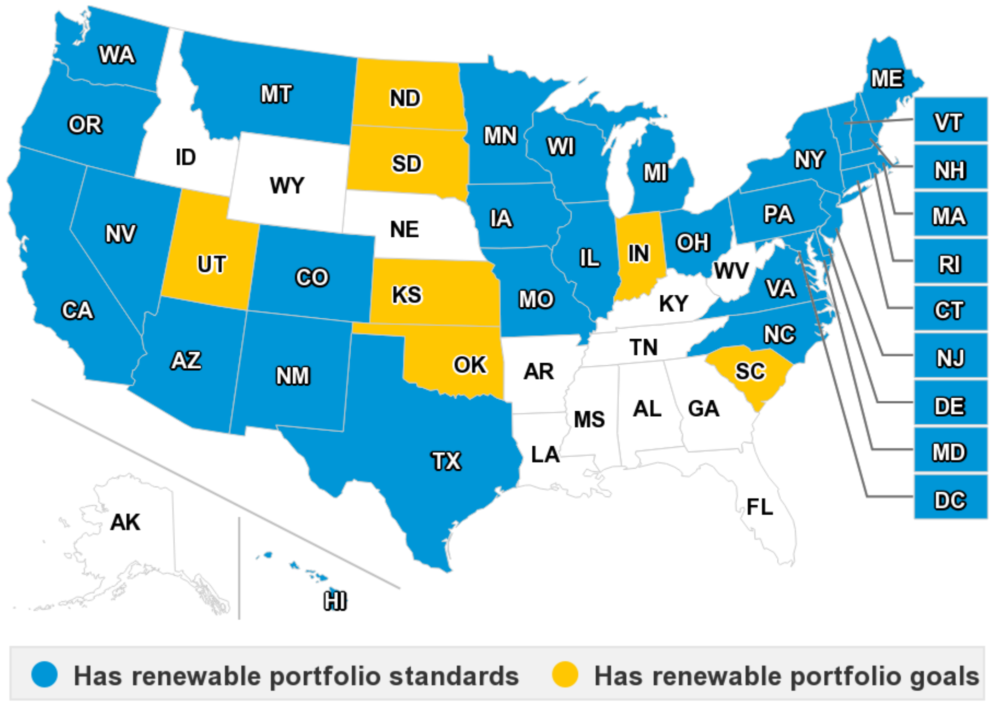
Renewable energy transition: Energy storage?

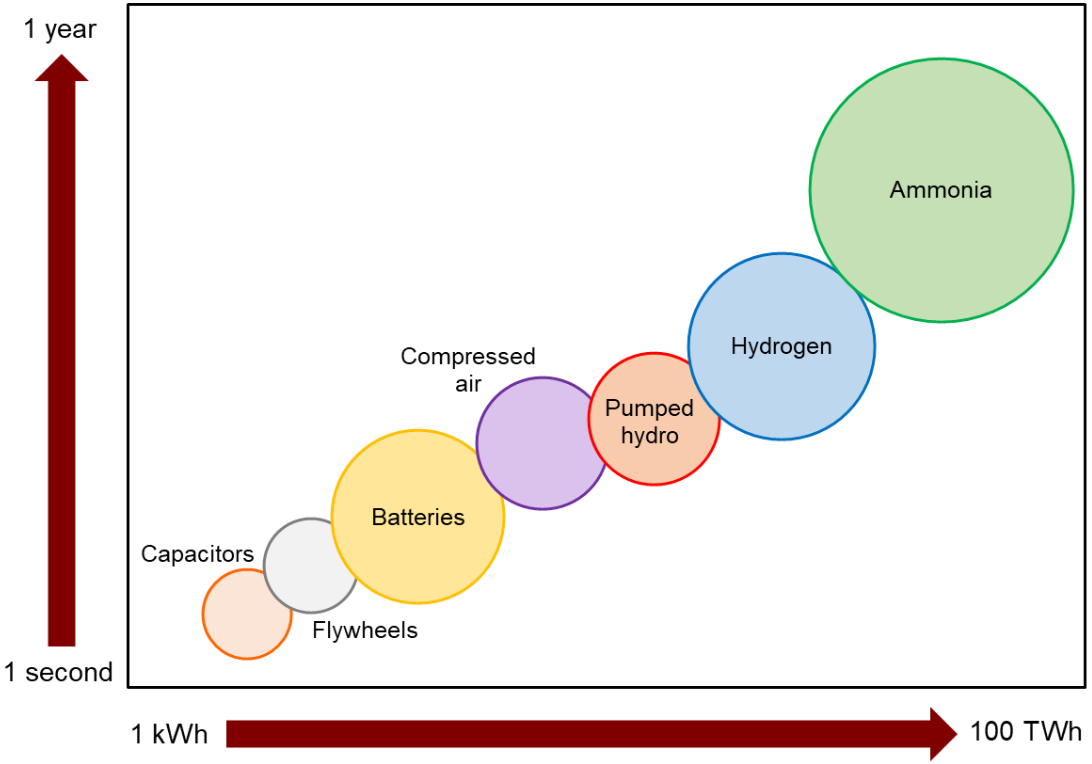
- Transition to renewables underway
  - Renewable portfolio standards: 32 states[1]
  - Need seasonal energy storage needed for high penetrations[2-4]: Renewable NH_3

U.S. renewable portfolio standards by state



Source: EIA (2020). Database of State Incentives for Renewable Energy and Efficiency.

Energy storage technology capacity and duration

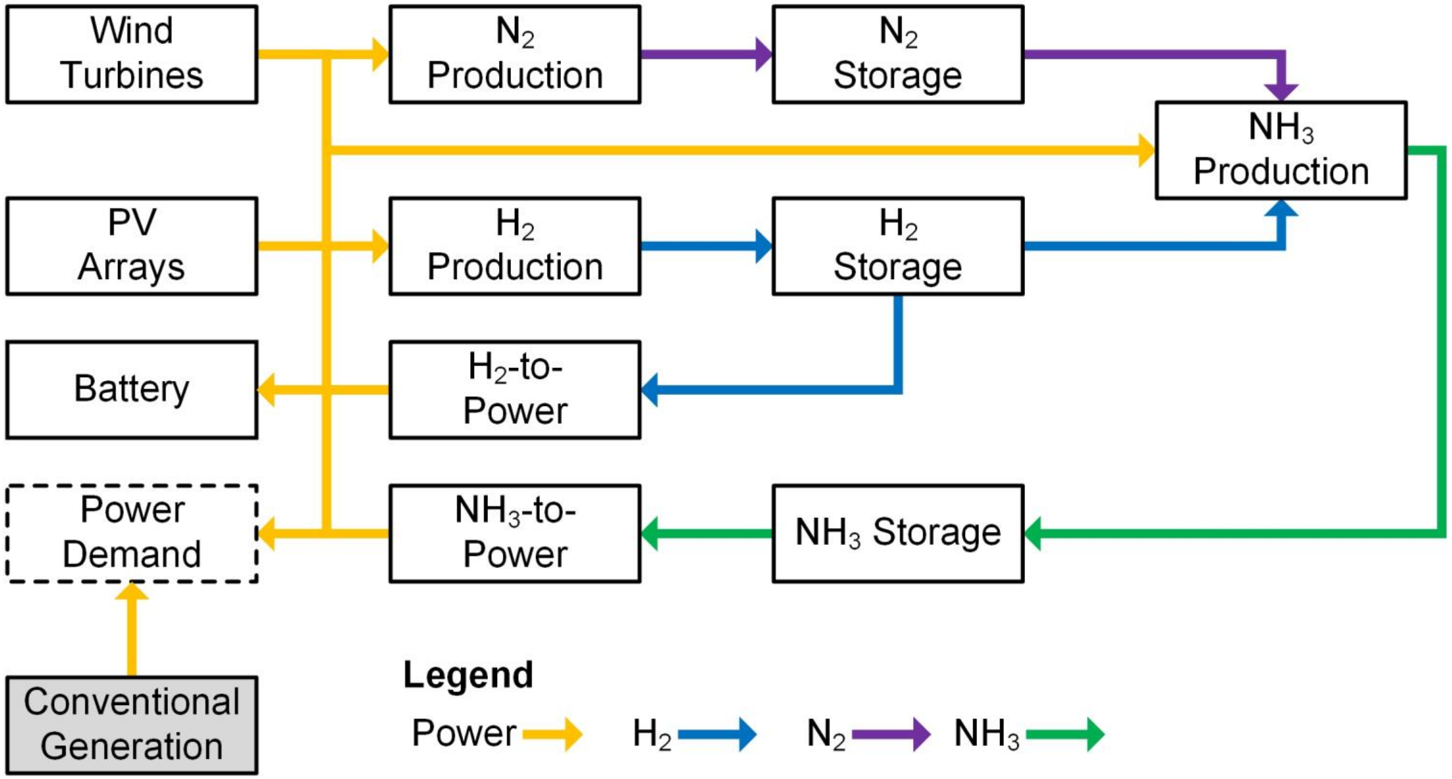


[1] EIA (2021). Renewable energy explained - Portfolio standards.
[2] Rouwenhurst et al. (2019). *Renew. Sust. Energ. Rev. 114*, 109339.
[3] Sánchez et al. (2021). *Appl. Energy 293*, 116956.
[4] Cesaro et al. (2021). *Appl. Energy 282*, 116009.

Renewable H_2 and NH_3 as energy storage

Our previous work: **H_2 and NH_3 for small-scale 100% renewable energy storage**

- Lowest cost systems use both in combination: Efficiency vs. storage cost[1]
- Seasonal storage for competitive renewable CHP in remote locations[2]



[1] Palys et al. (2020). *Comput. Chem. Eng. 136*, 106785.
[2] Palys et al. (2021). *Optim. Contr. Appl. Meth.* DOI:10.1002/oca.2793.

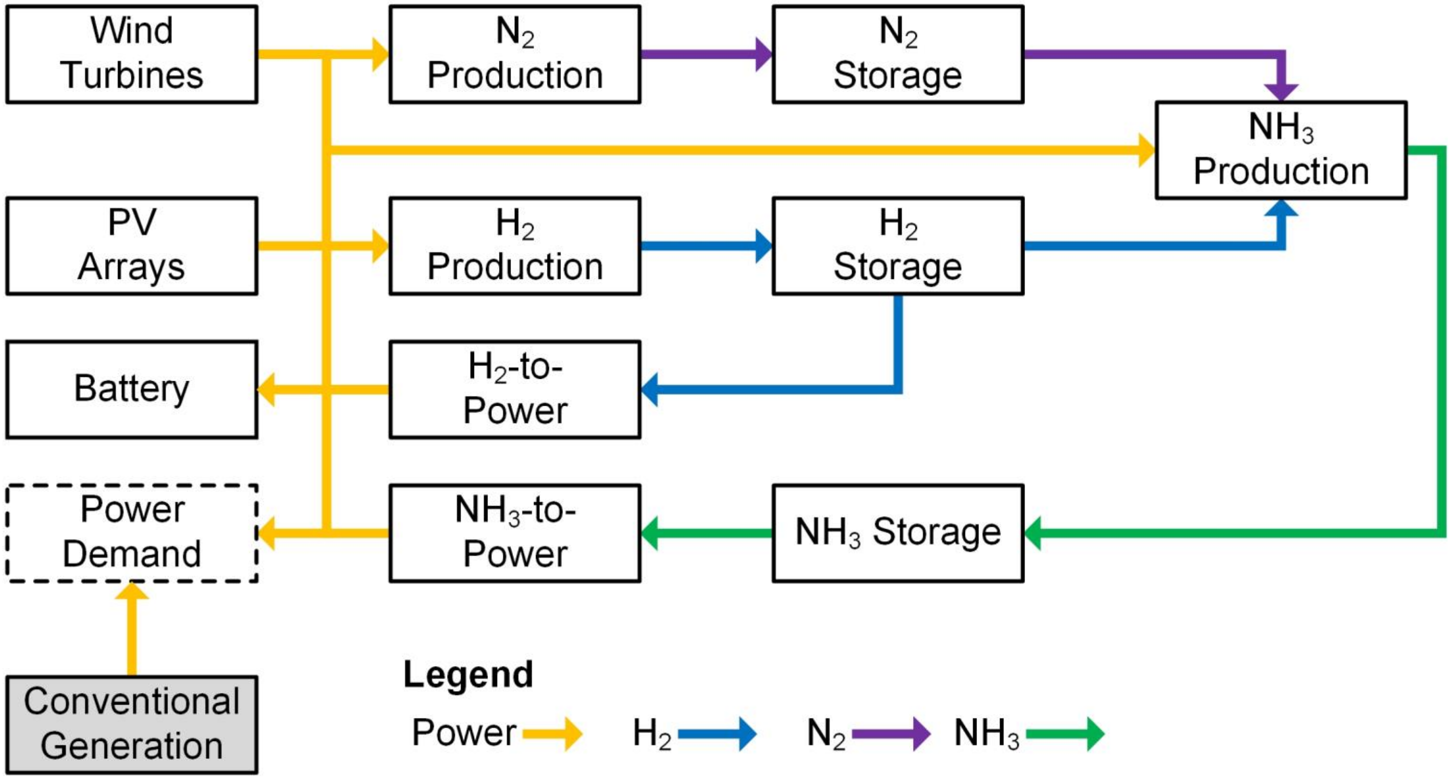
This work: Energy transition with renewable H_2 and NH_3

Cost and performance improvement?

Renewable portfolio standards?

Demand growth?

Fuel cost increase?



What role does renewable NH_3 play in energy transition?

Combined planning and scheduling model for energy transition

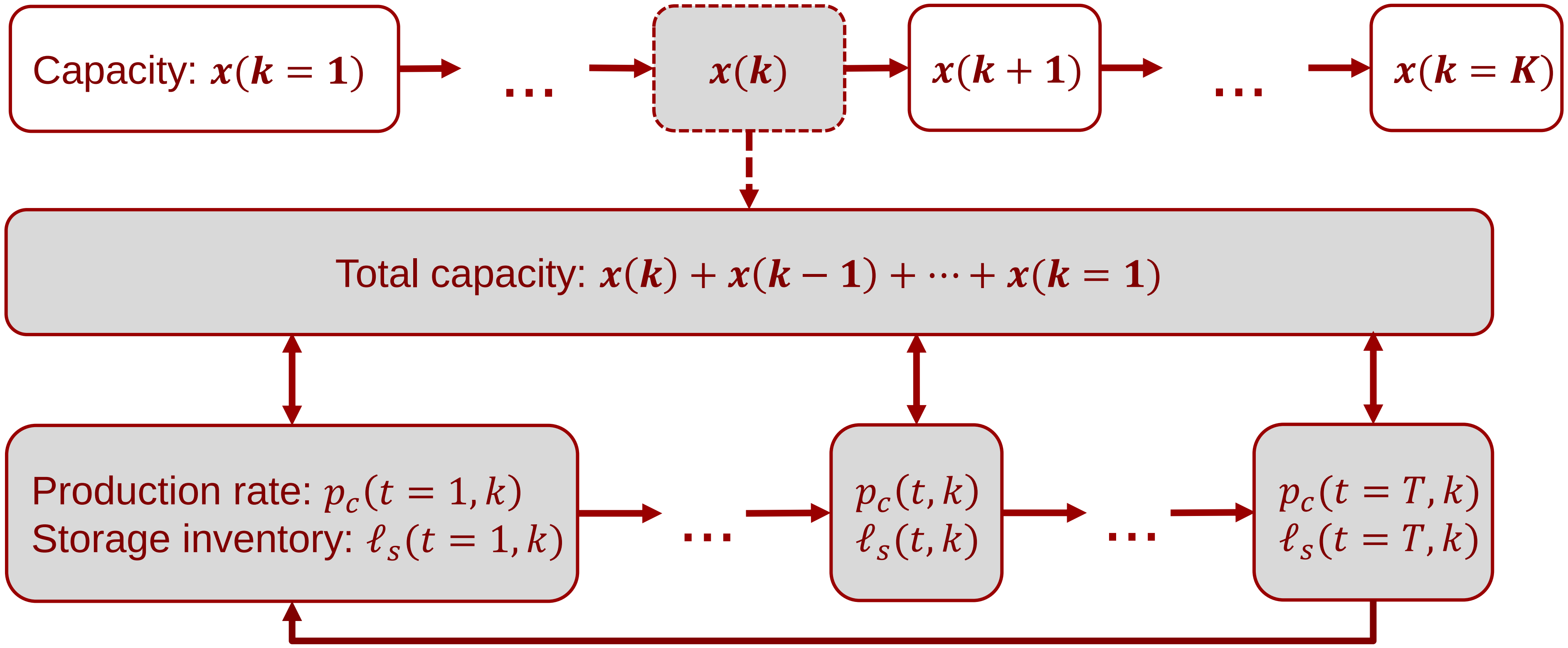
Plan installation of renewable generation and storage in each investment period

Capacity: $\boldsymbol{x}(\boldsymbol{k}=\mathbf{1})$ → … → $\boldsymbol{x}(\boldsymbol{k})$ → $\boldsymbol{x}(\boldsymbol{k}+\mathbf{1})$ → … → $\boldsymbol{x}(\boldsymbol{k}=\boldsymbol{K})$

Combined planning and scheduling model for energy transition

Plan installation of renewable generation and storage in each investment period

Schedule operation of new and previously installed renewable generation and storage



Account for renewable intermittency without oversizing[1,2]

[1] Palys et al. (2020). *Comput. Chem. Eng. 136*, 106785.
[2] Palys et al. (2021). *Optim. Contr. Appl. Meth.* DOI:10.1002/oca.2793.

Combined planning and scheduling model for energy transition

Minimize: Net present cost

Decisions

- Planning - Made once for each investment period
- Scheduling - Made for each operating period in each investment period

Constraints

- Installed capacity continuity between investment periods
- Renewable energy standards
- Power generation + storage discharge > Power demand + storage charge
- Storage inventory balances
- Production rate/inventory bounds
- Production ramping bounds

} *Relates planning and scheduling*

Mixed integer linear programming (MILP) model

Energy transition case study: Southern California

- Planning from 2025 to 2040
  - 5-year investment periods

- 500 MW in 2025
- 160 MW, 340 MW existing wind and PV[1]
  - 7% and 14% energy supply
- $35/MWh conventional generation in 2025[2]

- Scheduling: Wind and PV capacity factors, demand data
  - Synthesized from 10 cities
  - Open access[3,4]
  - Demand: 50% commercial, 50% residential

[1] U.S. EIA (2020). State electricity profiles.
[2] U.S. EIA (2021). Annual energy outlook 2021.
[3] NREL (2019). NSRDB, 1991-2005 Update: Typical Meteorological Year 3.
[4] EERE (2019). OpenEI Commerical and Residential Hourly Load Profiles for TMY3.

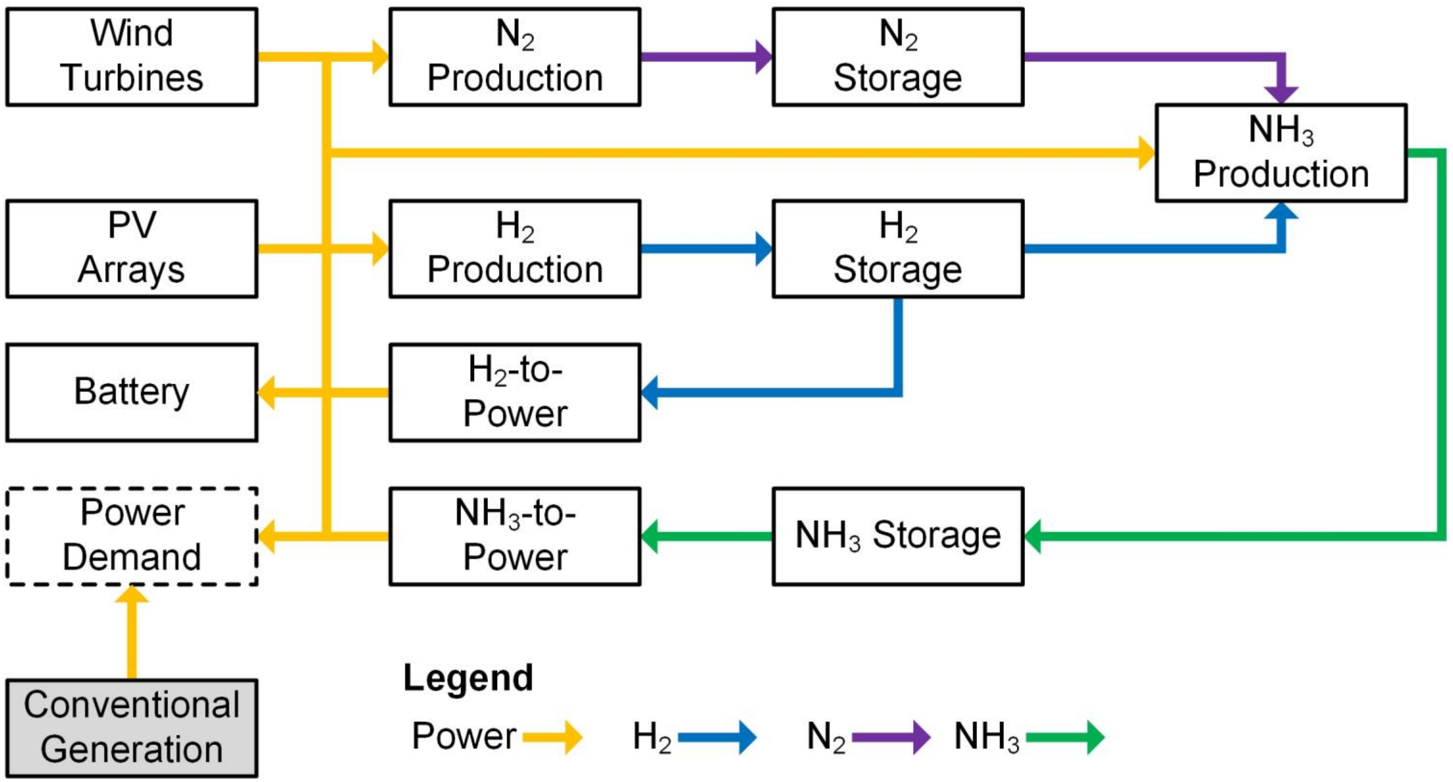
Energy transition case study: Southern California

Cost and performance projections
EU JRC ETRI[2]

Renewable portfolio standards
40% in 2025
4% increase per year

Demand growth
1% per year[1]

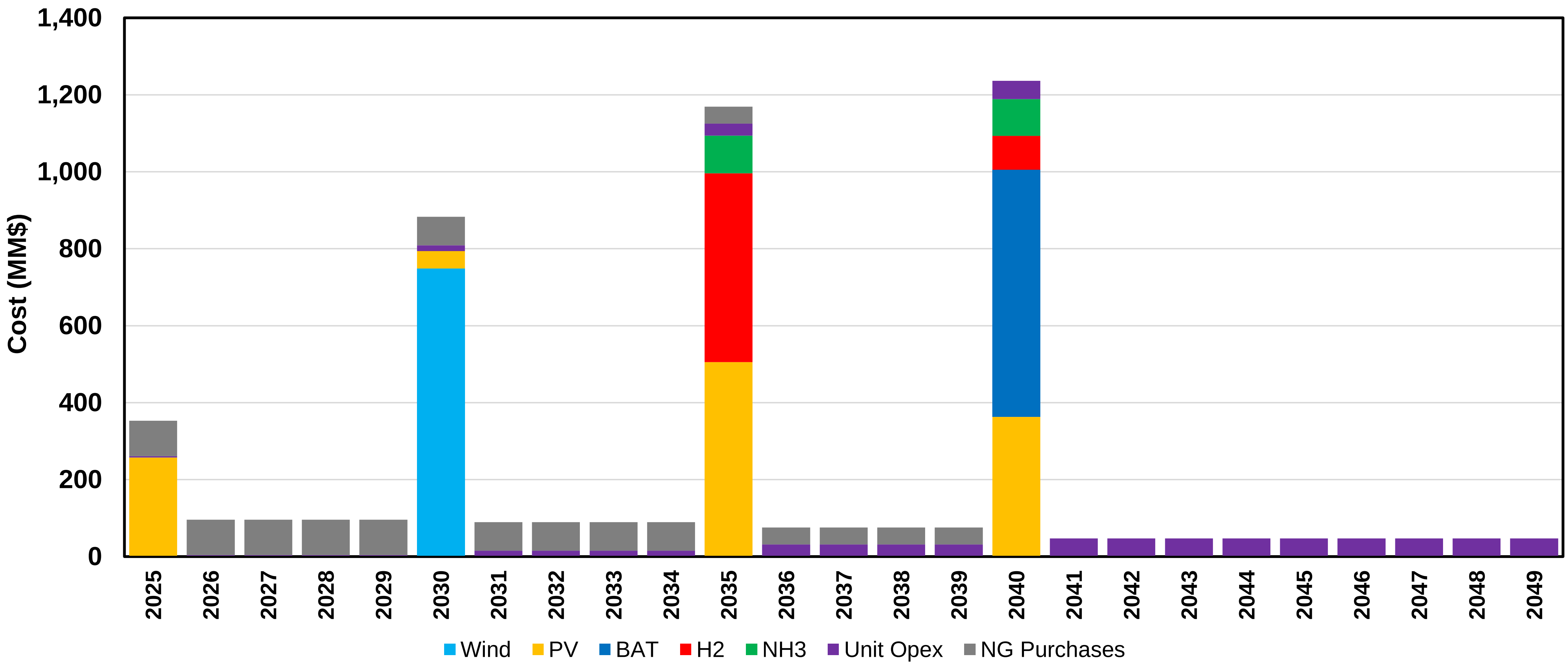
Fuel cost increase
2% per year[1]



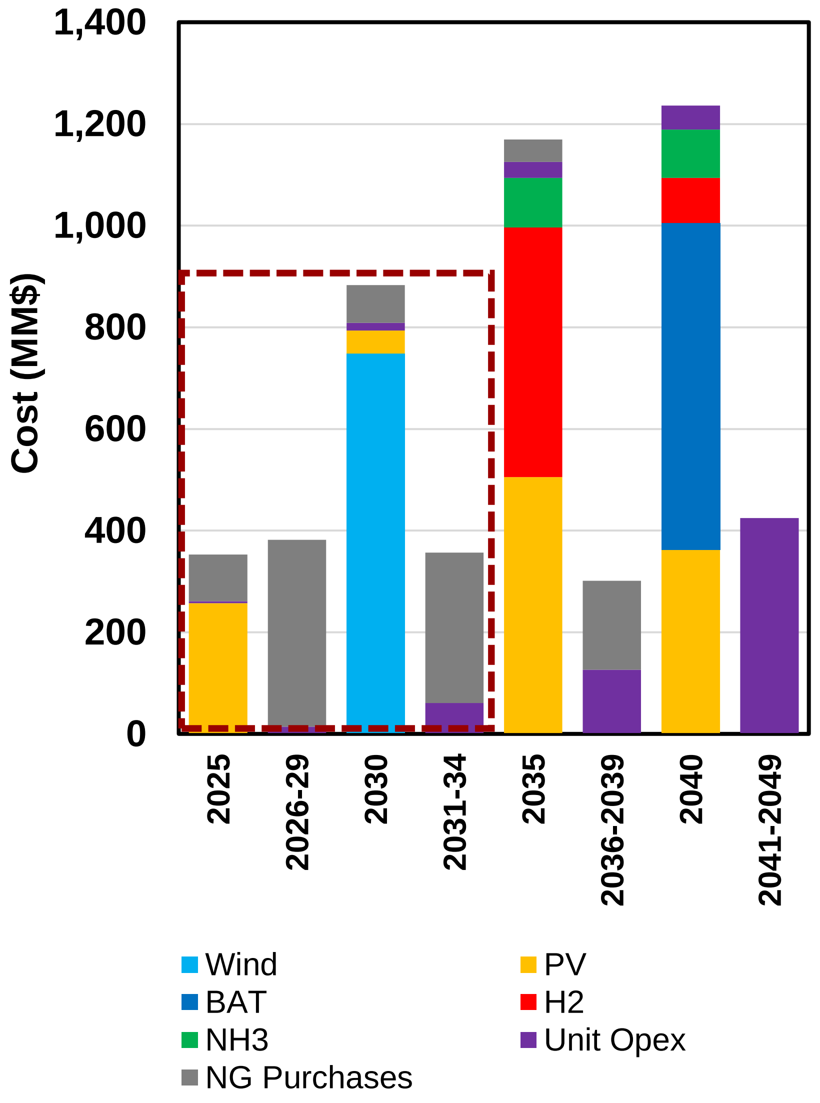
[1] U.S. EIA (2021). Annual energy outlook 2021.
[2] EU JRC. (2014). ETRI 2014: Energy technology reference indicator projections for 2010-2050.

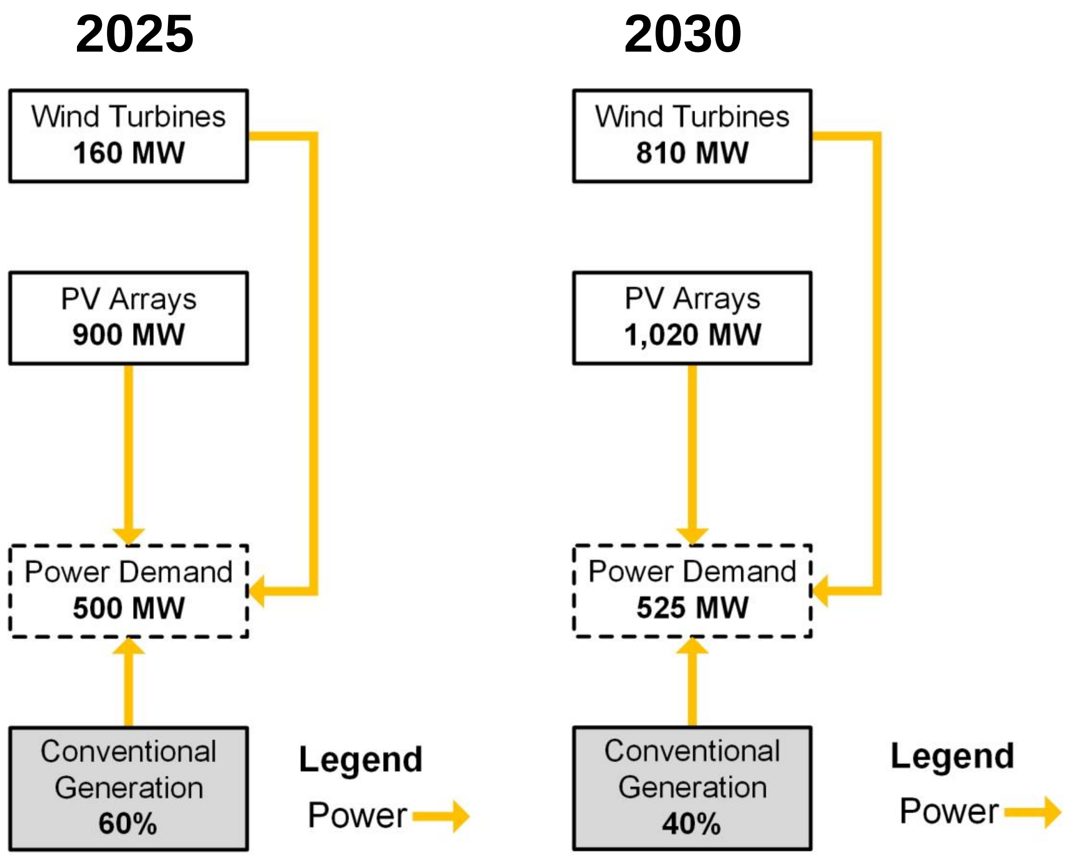
Southern California optimal economics

NPC: 2,790 MM$ (25-year project lifetime, 7.5% discount rate)



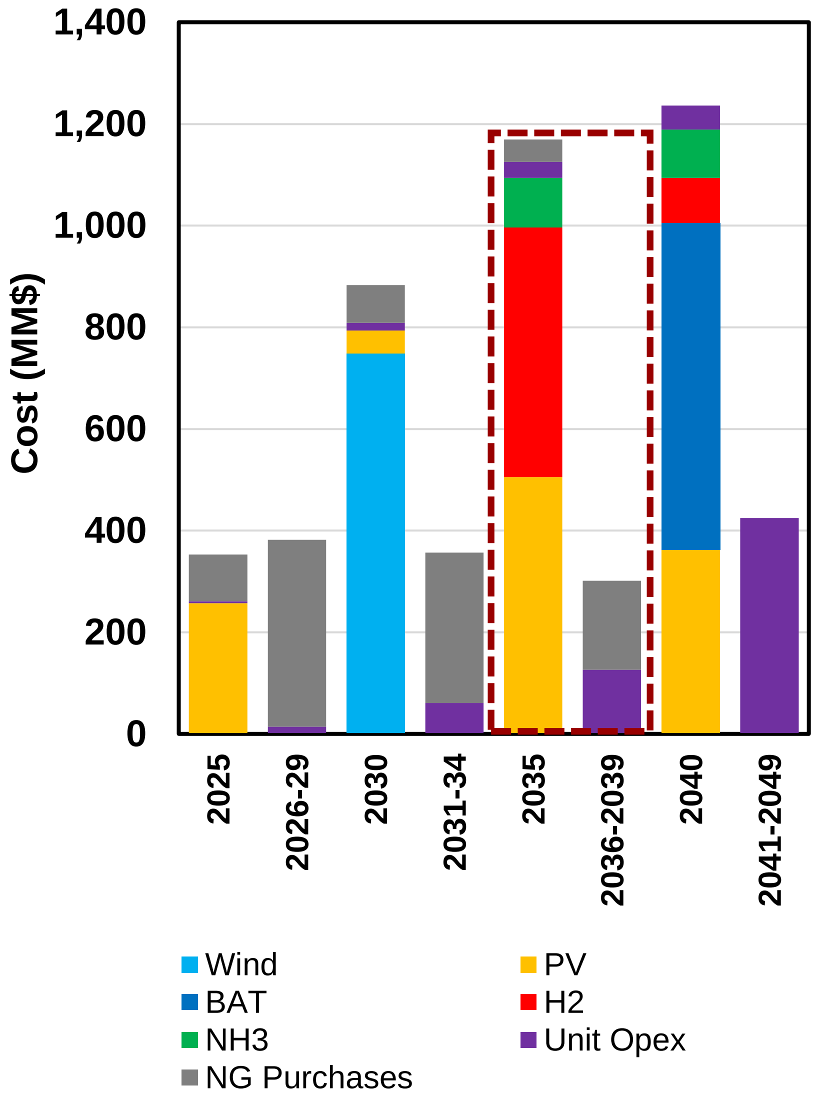
Southern California energy systems in 2025 and 2030

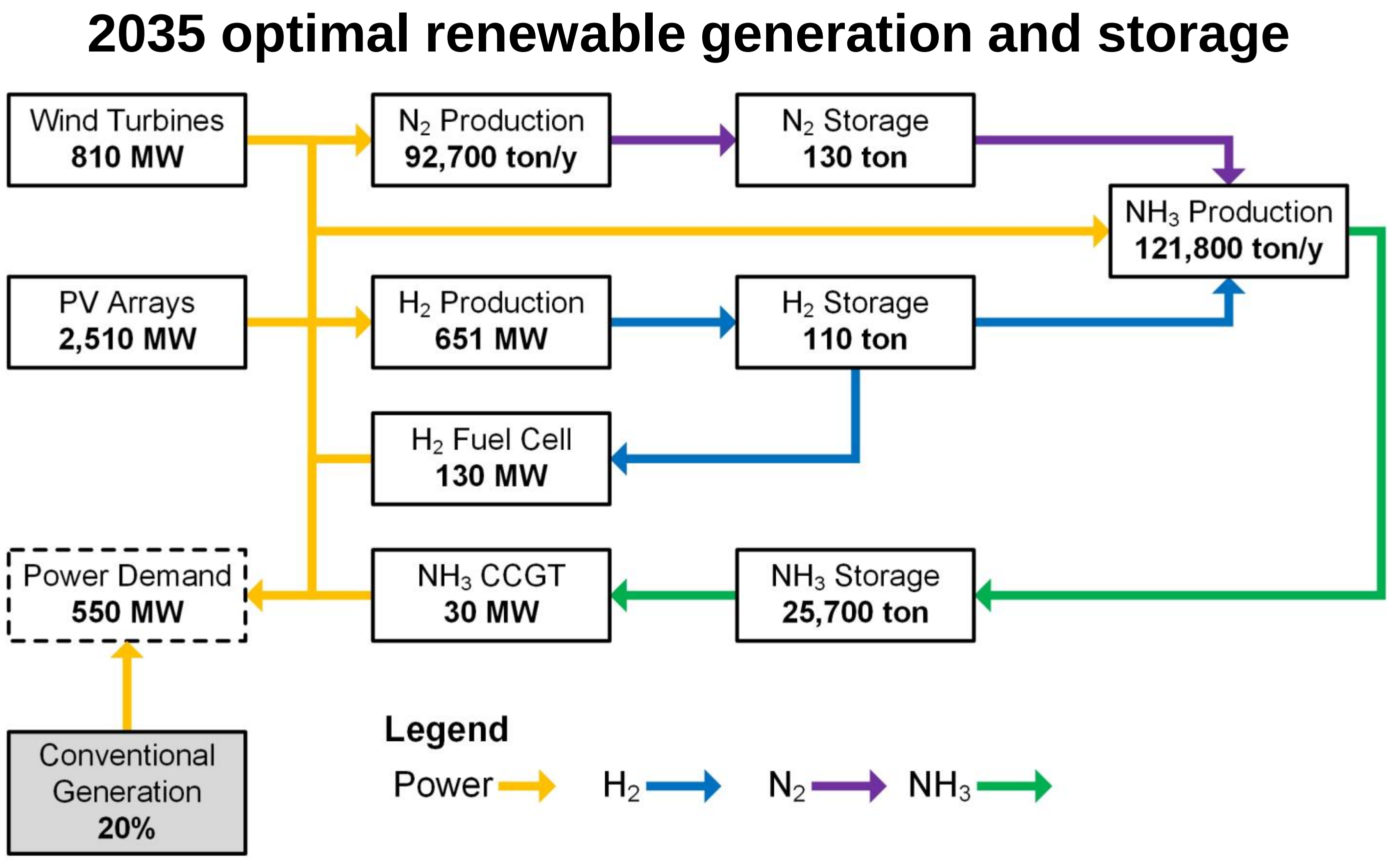




- Maximum allowable conventional generation
- No storage at lower renewable penetrations
- 2030: Wind investment for night generation

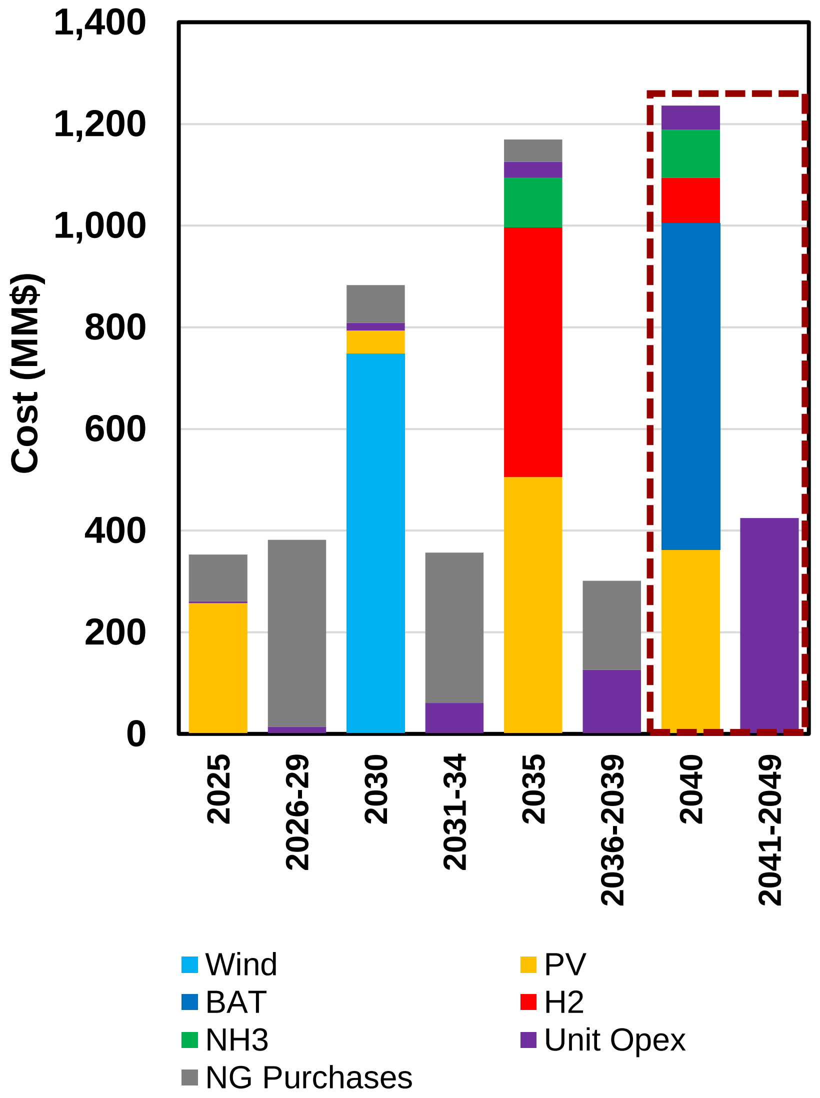
Southern California energy system in 2035

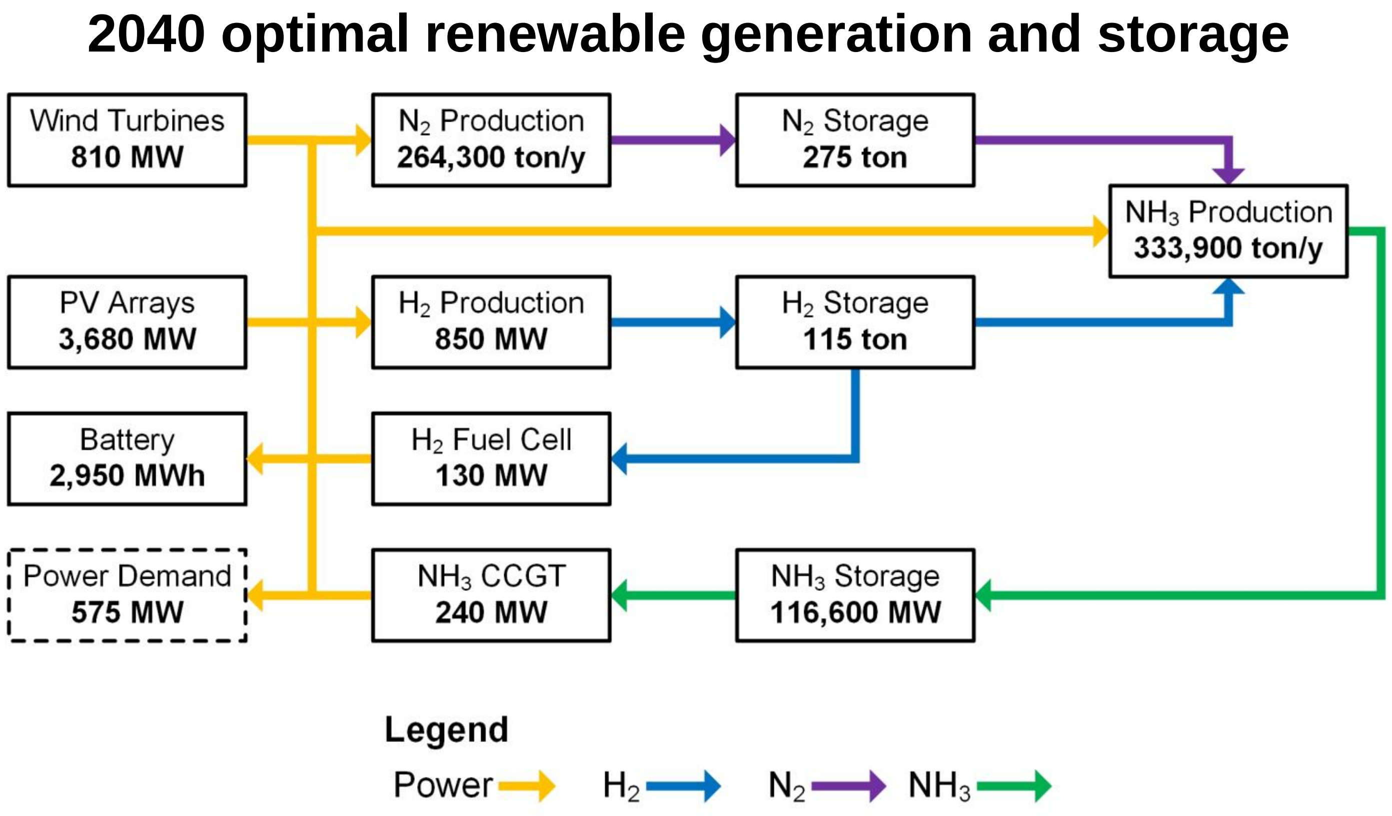




- Considerable PV capacity increase
- H_2 and small NH_3 storage added

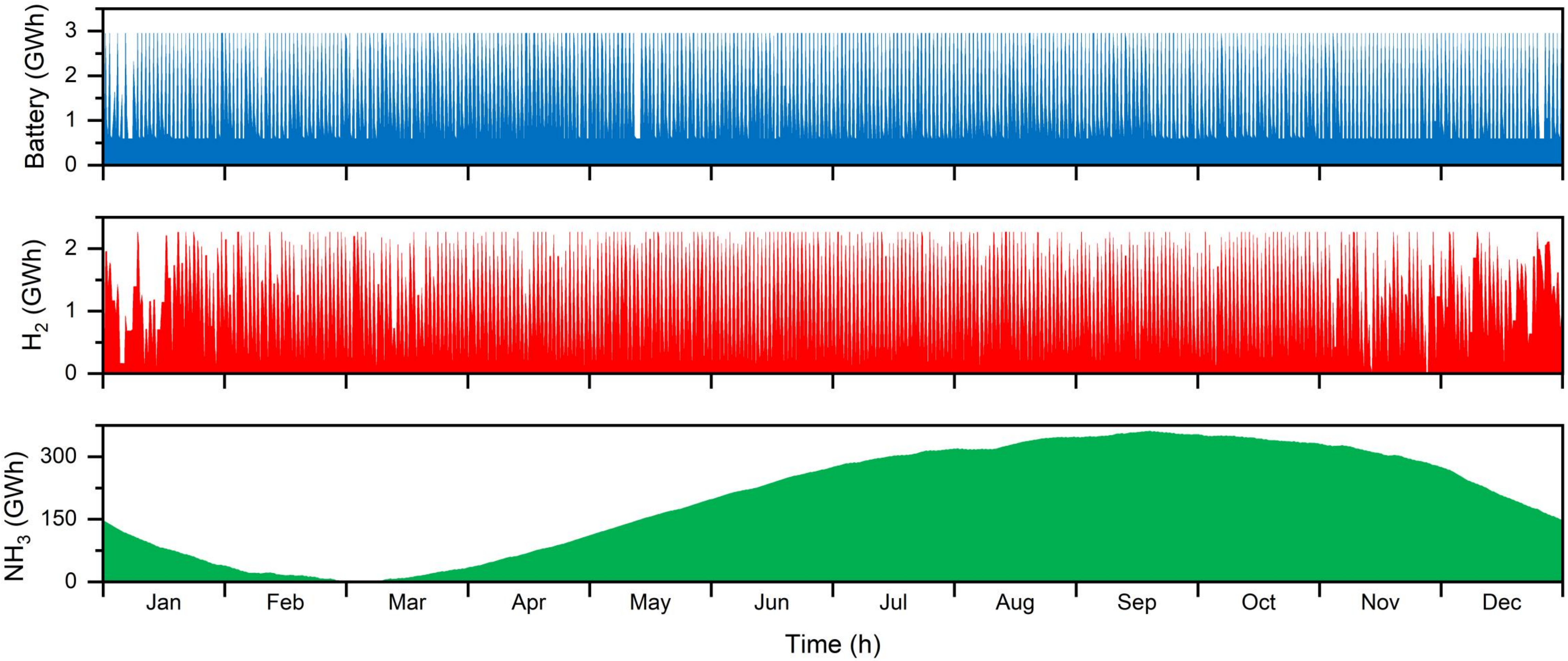
Southern California energy system in 2040





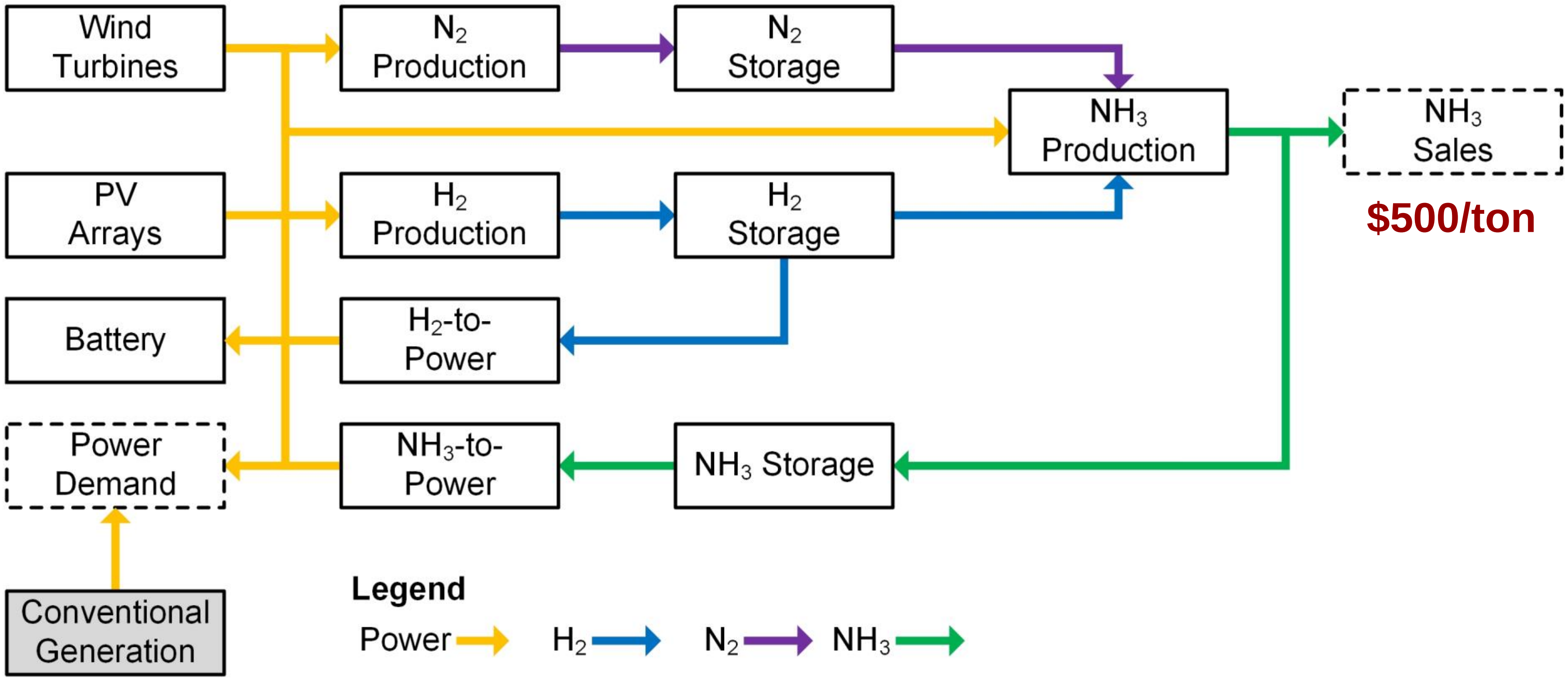
- NH_3 capacity increased
  - 3x production, 5x storage, 8x generation
- Battery storage included

Southern California energy storage schedules in 2040



Renewable NH_3 for seasonal energy storage

Sector coupling with renewable NH_3

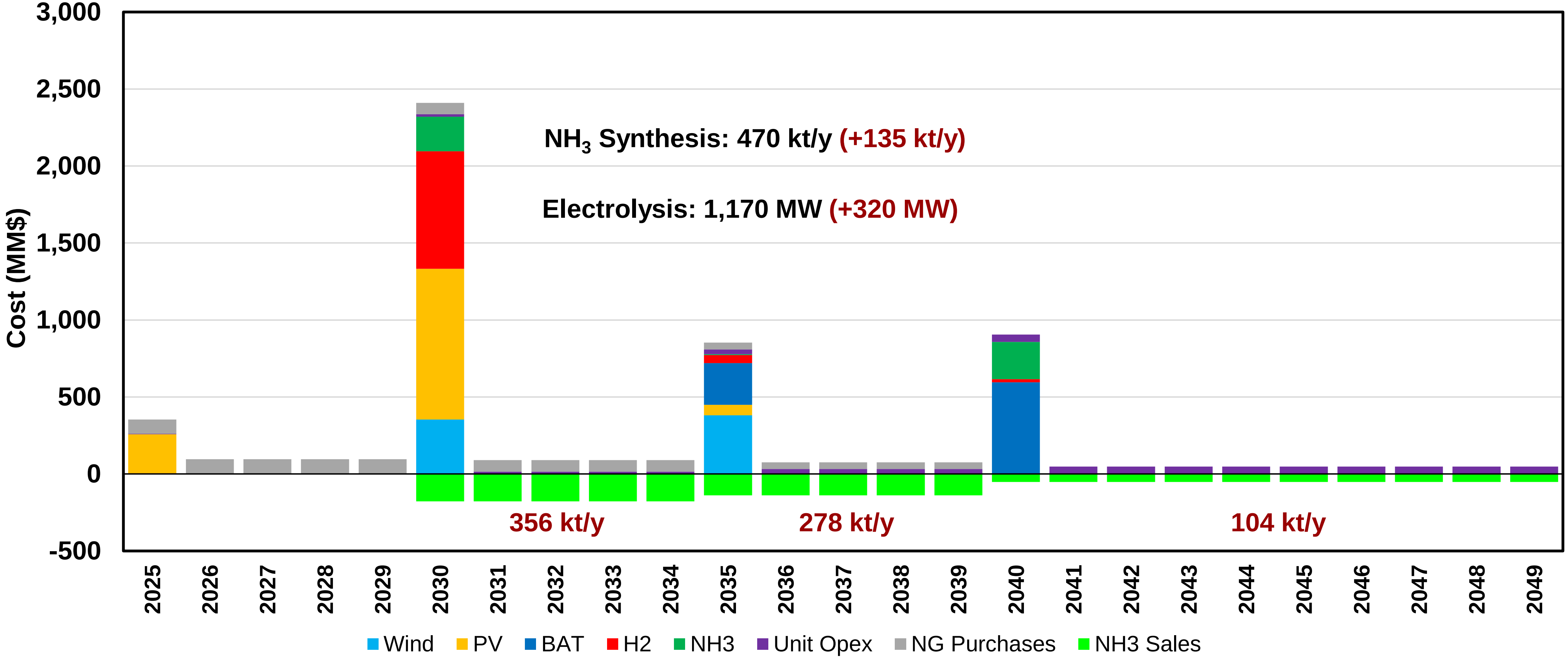


$500/ton

- Fertilizer to agriculture sector
- Hydrogen carrier for fuel cell vehicle sector

Southern California sector coupling economics

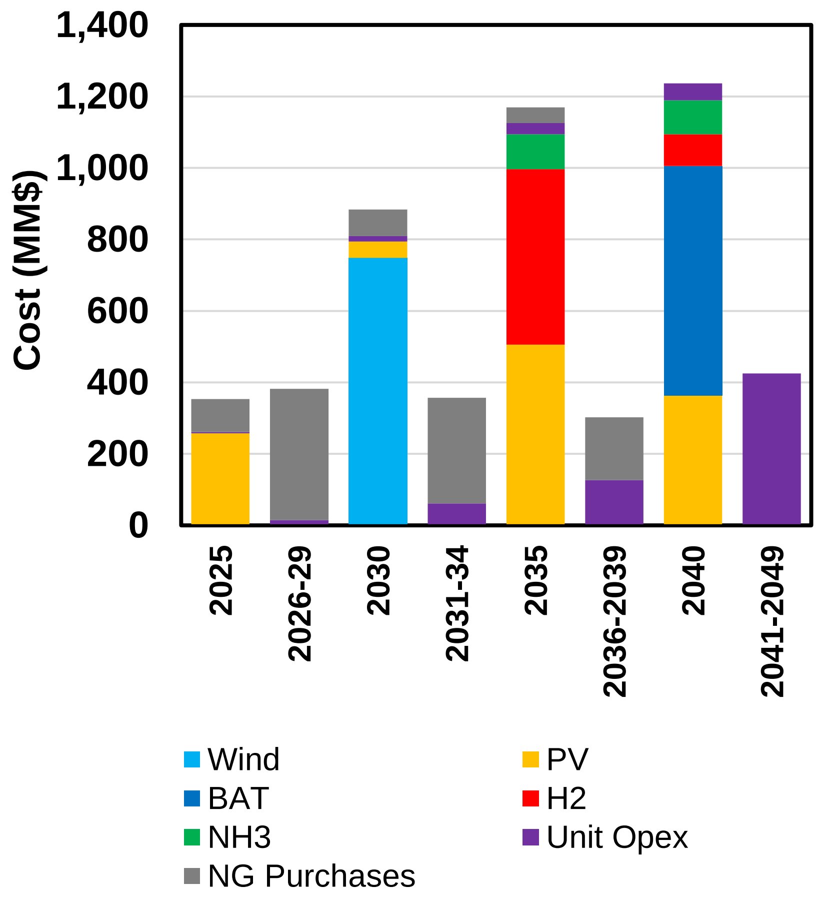
NPC: 2,680 MM$ NPC ← **110 MM$ reduction**

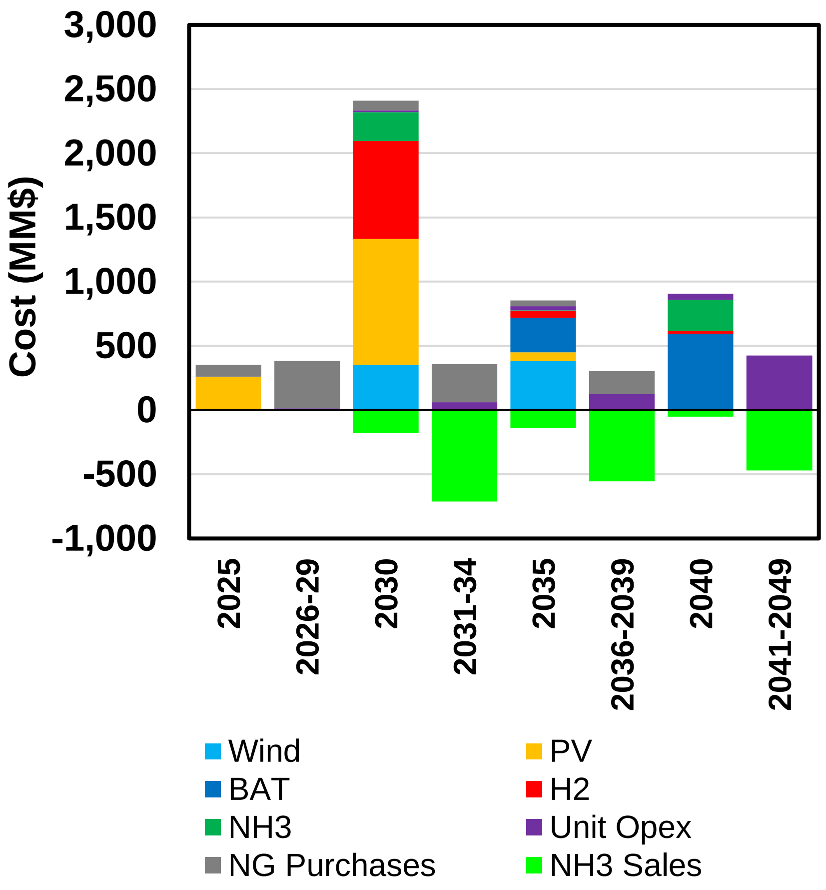


Conclusions

Conceptual case study with publicly available data

- Renewable NH_3 for seasonal storage grid-scale energy transition
- Sector coupling accelerates renewable NH_3 adoption





Conclusions

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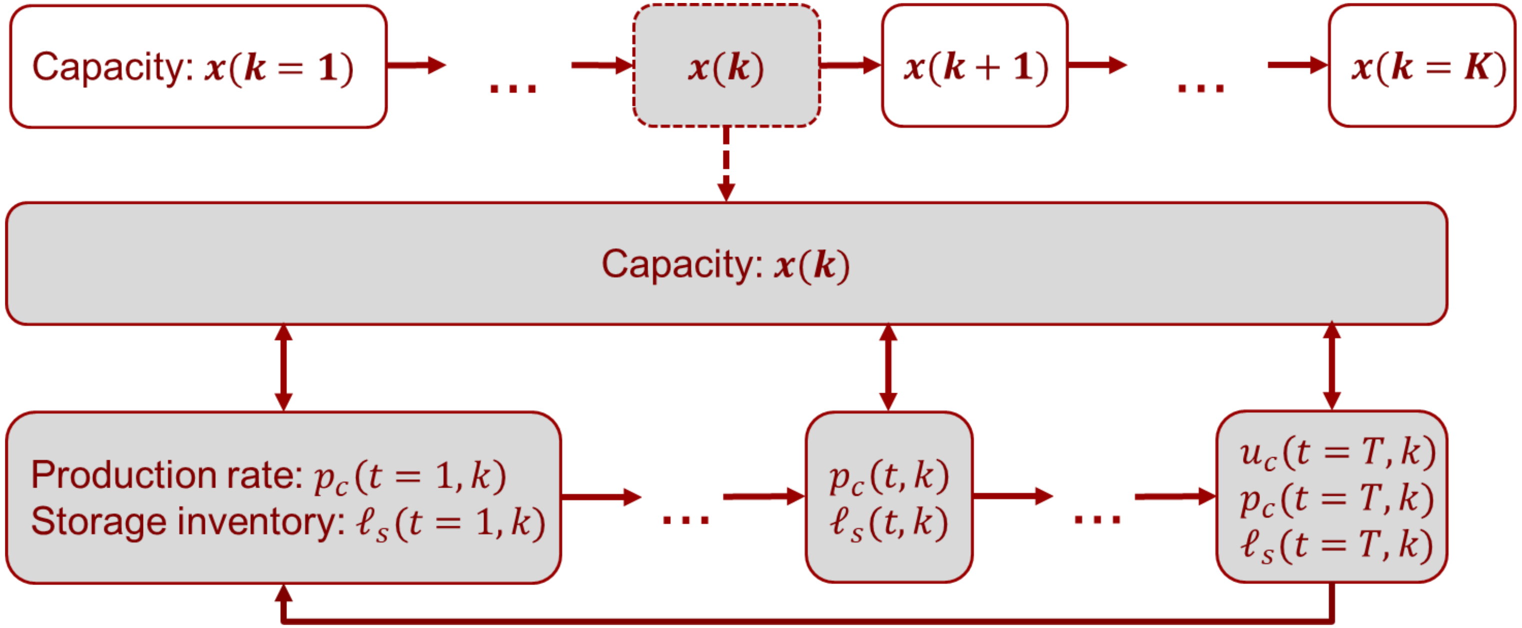


Combined investment planning-scheduling model for renewable energy transition

- Can be easily customized: Demands, technologies, policy
- **Want to analyze real scenarios!**

Acknowledgements

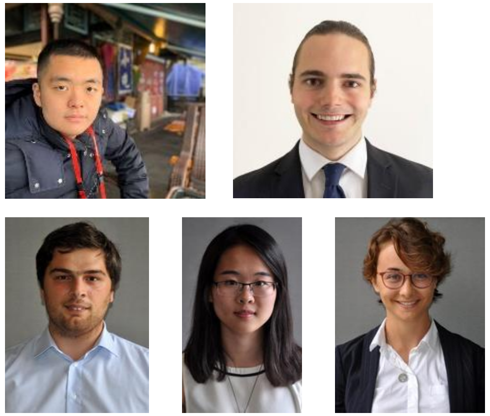
Xcel Energy

ARPA-E Refuel

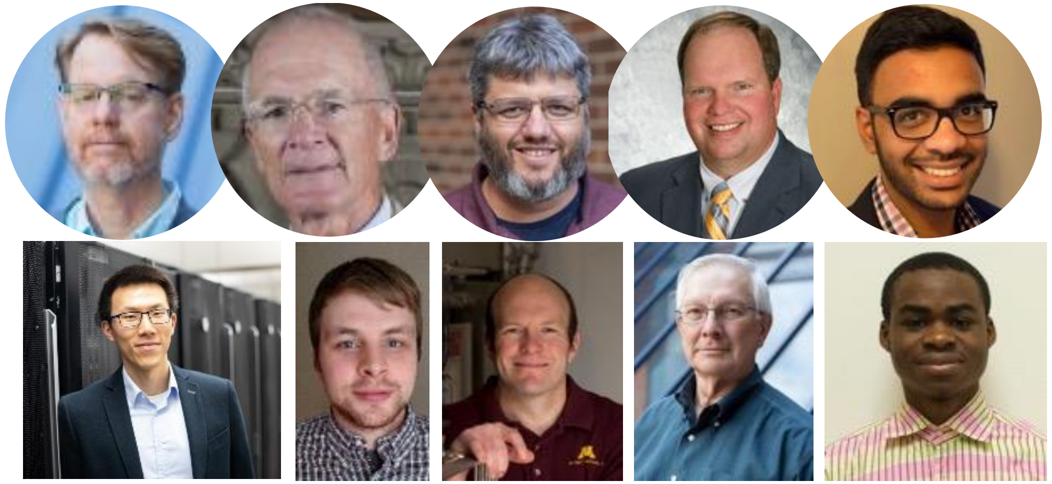
Grant USDOE / DE-AR0000804

UMN Office of the Vice President for Research

Daoutidis research group



UMN renewable NH_3 project team



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Literature review: Renewable NH_3 and H_2 as energy storage

Our previous work: **Renewable H_2 and NH_3 for small-scale energy storage**

- Both in combination optimal for islanded storage systems @ 1-10 MW scale[1]
- NH_3 enables economical 100% renewable CHP in remote locations[2]

Large-scale renewable NH_3 for energy

- Competitive by 2040 in systems with high renewable penetration[3,4]
  - Fuel for combustion turbines
- Best chemical storage medium for durations > 3 months at state scale[5]
- Best seasonal energy storage at continental scale in 2050[6]

[1] Palys et al. (2020). *Comput. Chem. Eng. 136*, 106785.
[2] Palys et al. (2021). *Optim. Contr. Appl. Meth.* DOI:10.1002/oca.2793.
[3] Sánchez et al. (2021). *Appl. Energy 293*, 116956.
[4] Cesaro et al. (2021). *Appl. Energy 282*, 116009.
[5] Tso et al. (2019). *Comput. Aided Chem. Eng. 47*, 1-6.
[6] Ikäheimo et al. (2018). *Int. J. Hydrogen Energy 43*(36), 17295-17308.

Generation and storage cost and performance projections

	Capital investment (MM$)				Operating cost - % of capital				Energy efficiency	Production/storage lower bound
	2025	*2030*	*2035*	*2040*	*2025*	*2030*	*2035*	*2040*		
Wind turbines (MW)	1.22	1.15	1.11	1.08	1.38	1.51	1.54	1.57	-	-
PV arrays (MW)	0.46	0.38	0.34	0.31	1.38	1.51	1.54	1.57	-	-
Electrolysis (MW)	0.7	0.53	0.46	0.42	1.50	1.50	1.50	1.50	75%	5%
Air separation (kt/y)	0.18	0.17	0.16	0.16	3.50	3.50	3.50	3.50	0.12 MWh/t	50%
NH_3 synthesis (kt/y)	0.38	0.36	0.34	0.32	3.50	3.50	3.50	3.50	0.48 MWh/t	50%
H_2 fuel cell (MW)	1	0.79	0.7	0.63	2.00	2.00	2.00	2.00	55%	5%
NH_3 CCGT (MW)	0.8	0.79	0.78	0.77	2.50	2.50	2.50	2.50	60%	20%
Battery power inteface (MW)	0.25	0.19	0.15	0.12	1.60	2.00	2.40	2.80	-	20%
Battery storage (MWh)	0.39	0.29	0.24	0.2	1.88	2.00	2.13	0.25	90%	20%
H_2 Storage (t)	0.96	0.87	0.74	0.62	0	0	0	0	-	1%
N_2 Storage (t)	5.0E-03	5.0E-03	5.0E-03	5.0E-03	0	0	0	0	-	1%
NH_3 Storage (t)	7.0E-04	7.0E-04	7.0E-04	7.0E-04	0	0	0	0	-	0%

Southern California power balance schedule in 2040