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Opportunities and Limits of CO_2 Recycling in a Circular Carbon Economy

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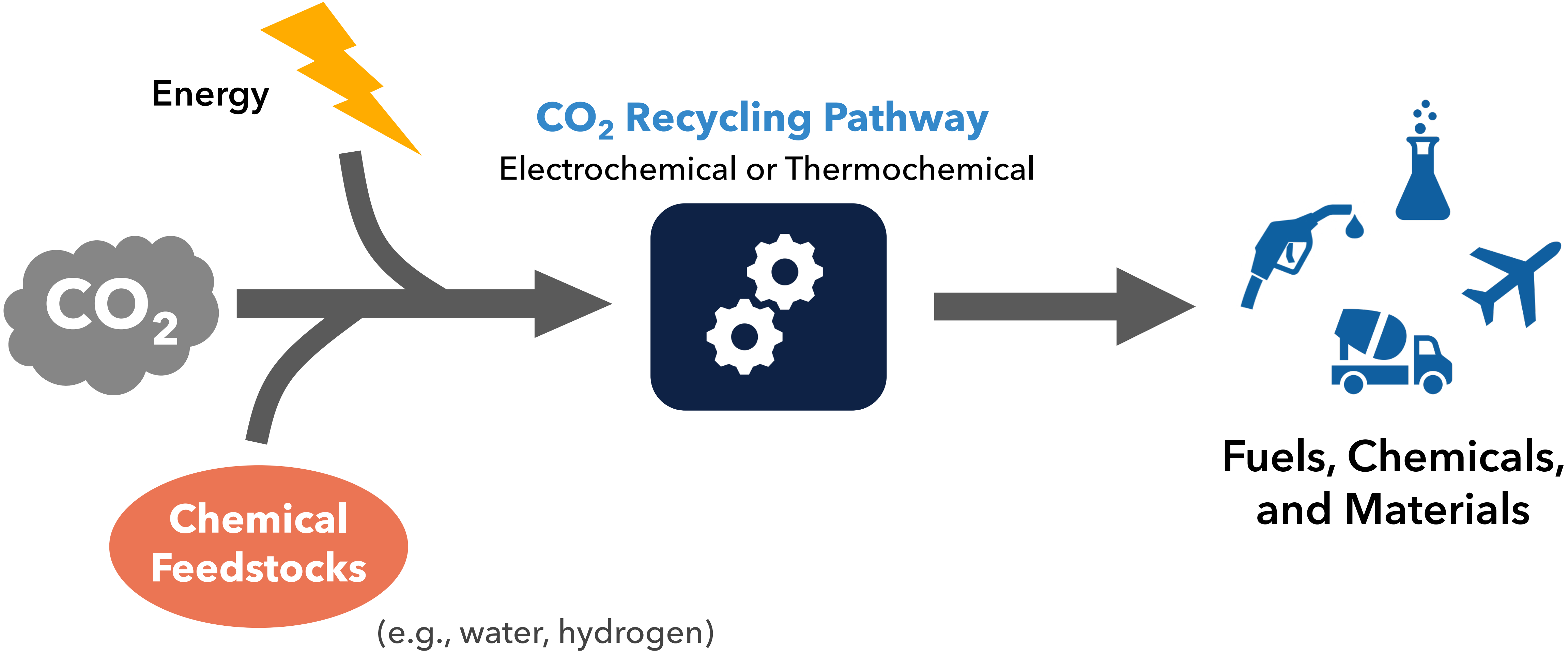
The need for CO_2 recycling

- We rely on many products that are carbon-intensive to produce but have limited alternatives
  - Aviation fuels, concrete, plastics, etc.
- 30% of global CO_2 emissions are in ‘hard to abate’ sectors

CO_2 recycling – converting CO_2 into valuable products



CO_2

Energy

Chemical Feedstocks

(e.g., water, hydrogen)

CO_2 Recycling Pathway

Electrochemical or Thermochemical

Fuels, Chemicals, and Materials

An unrealized opportunity…so far

- Chemical processes that consume CO_2 instead of generating it
- Reduces emissions of production
- Products have economic value in existing markets
- CO_2 recycling has remained difficult to deploy
- Need well-informed policy support

We modeled 19 CO_2 recycling pathways to provide a better understanding of the current state of CO_2 recycling, opportunities, and challenges to reach global scale.

Sections of Analysis

1. Estimated Cost of Production and Cost Sensitivities
2. Life-Cycle Carbon Abatement Potential
3. Effective Carbon Price
4. Critical Infrastructure Needs
5. Policy Recommendations

Eight electrochemical pathways

Product	Process	Feedstocks
Hydrogen	Water electrolysis	H_2O
Carbon monoxide (CO)	Electrochemical CO_2 reduction	CO_2, H_2O
Methane		
Methanol		
Ethylene		
Ethane		
Ethanol		
Syngas		

Eleven thermochemical pathways

Product	Process	Feedstocks
Light olefins incl. ethylene	CO_2 hydrogenation	CO_2, H_2
	Fischer-Tropsch (F-T) synthesis	CO, H_2
Methane	Sabatier process	CO_2, H_2
Methanol	CO_2 hydrogenation	CO_2, H_2
Ethanol	Lignocellulosic biomass fermentation	Lignocellulosic biomass
Syngas	Reverse water-gas shift (RWGS) reaction	CO_2, H_2
Jet fuel	CO_2 hydrogenation	CO_2, H_2
	Fischer-Tropsch synthesis	CO, H_2
Urea	Bosch-Meiser process	CO_2, NH_3
Precast concrete	Concrete carbonation curing	CO_2, concrete
All concretes	CarbonCure process	CO_2, concrete

Analysis design

- Pathways consume low-carbon inputs
  - Renewable electricity and chemical feedstocks that are made electrochemically with renewable power
- Pathways scaled to supply current global demand for their product
- Globally representative cost estimates
- Market parity: cost of production equals selling price

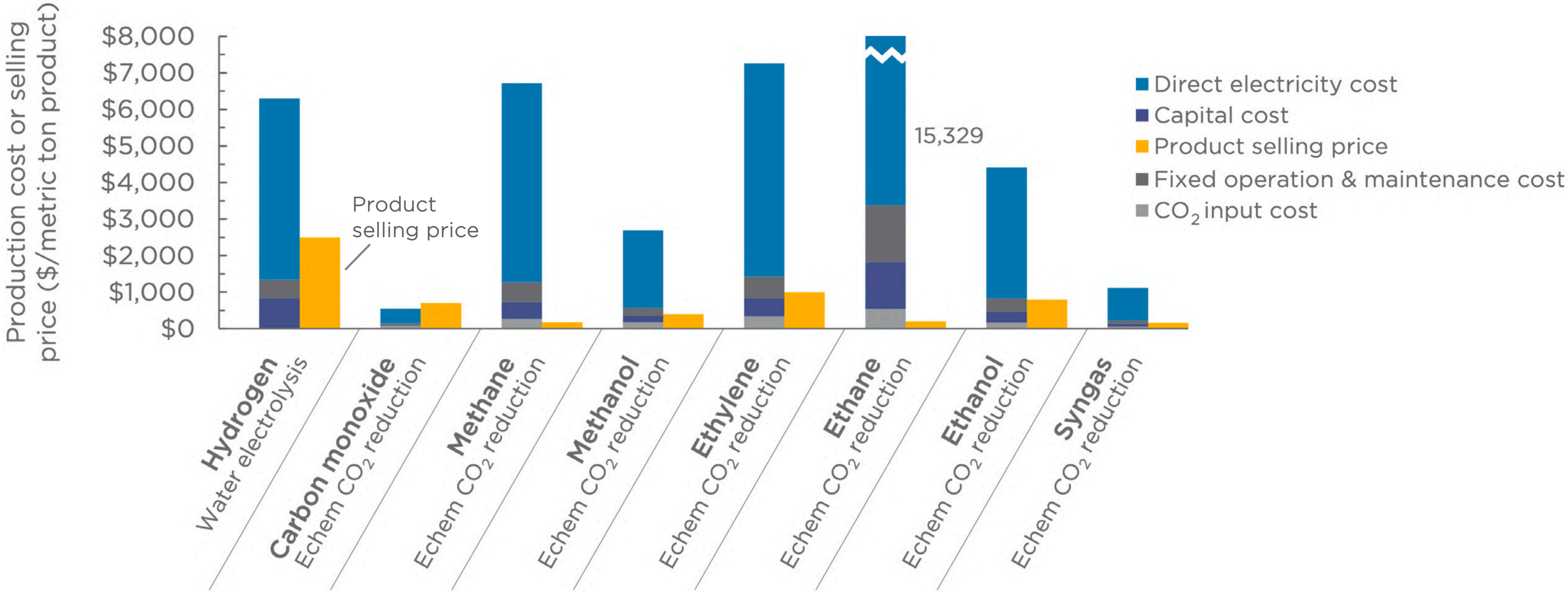
Key numerical assumptions

Parameter	Value
Renewable electricity price	\$0.095/kWh
Green hydrogen feedstock price	\$6.3/kg H_2
CO_2 feedstock price	\$50/tCO_2
Electrolyzer capital cost	\$1,000/kW

- Electricity price is globally representative and includes non-generation costs
- CO_2 feedstock is from point-source carbon capture
- Input prices may fall significantly over time and lower costs are available today in limited contexts

1. Estimated Cost of Production (ECOP)

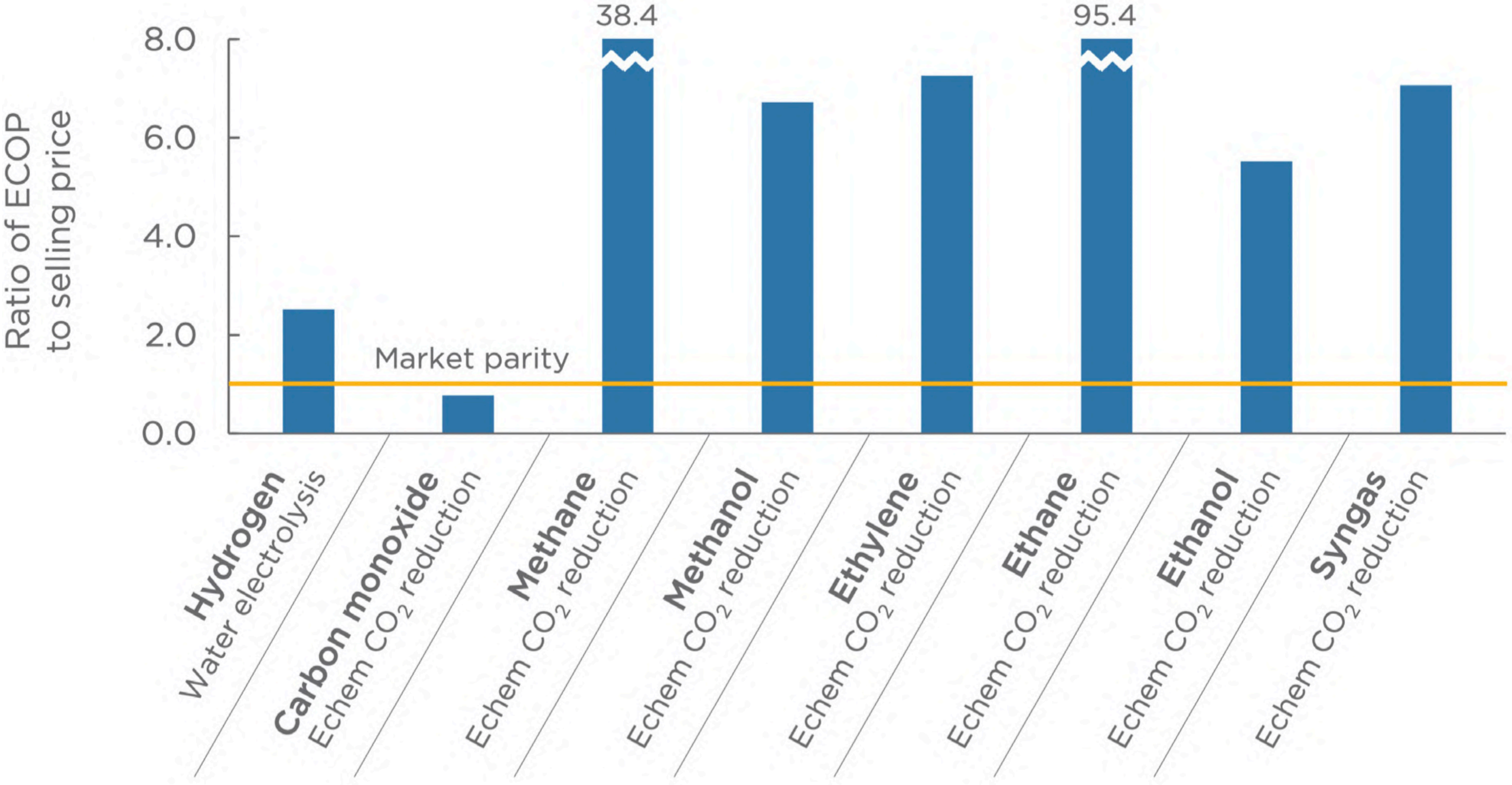
Costs of electrochemical pathways are high, and dominated by electricity costs



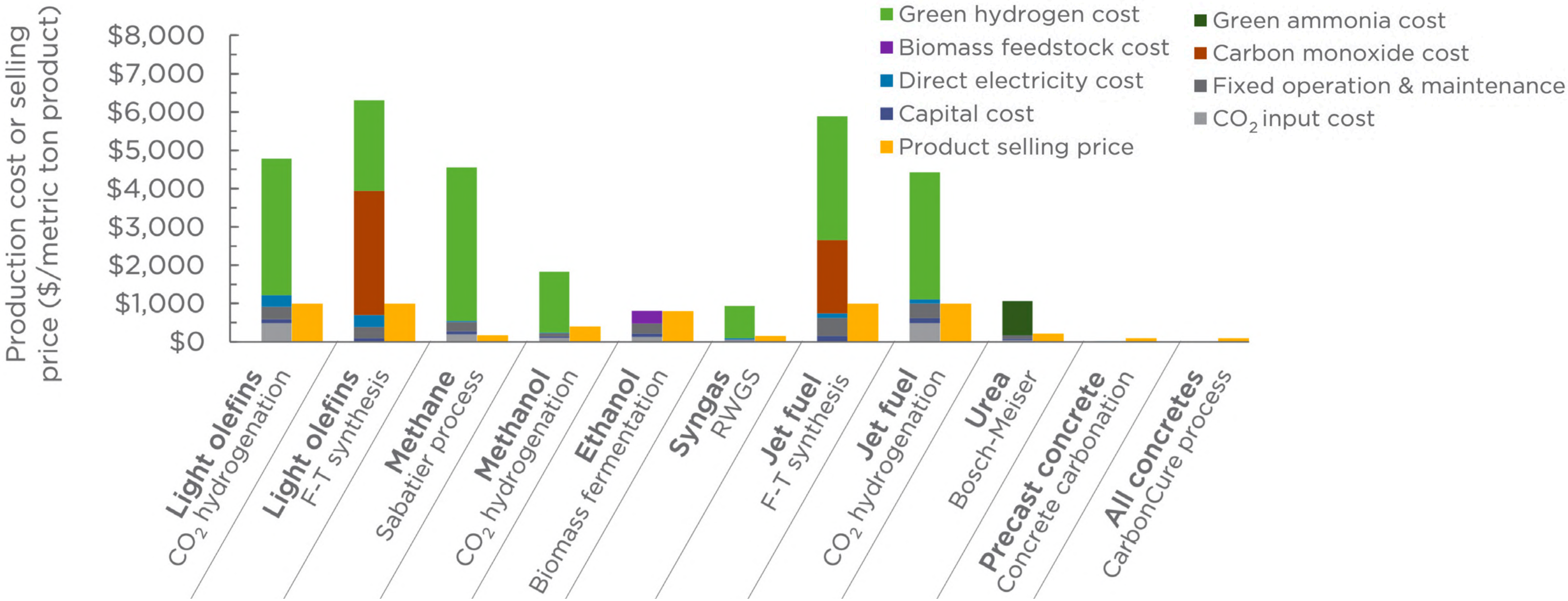
- But capital cost and fixed operation & maintenance alone are greater than selling price for many pathways

Ratio of ECOP to selling price for electrochemical pathways demonstrates distance from market parity

- Market parity: Electrochemical (Echem) CO production
- Water electrolysis ratio is 2.5
- Others are below 7



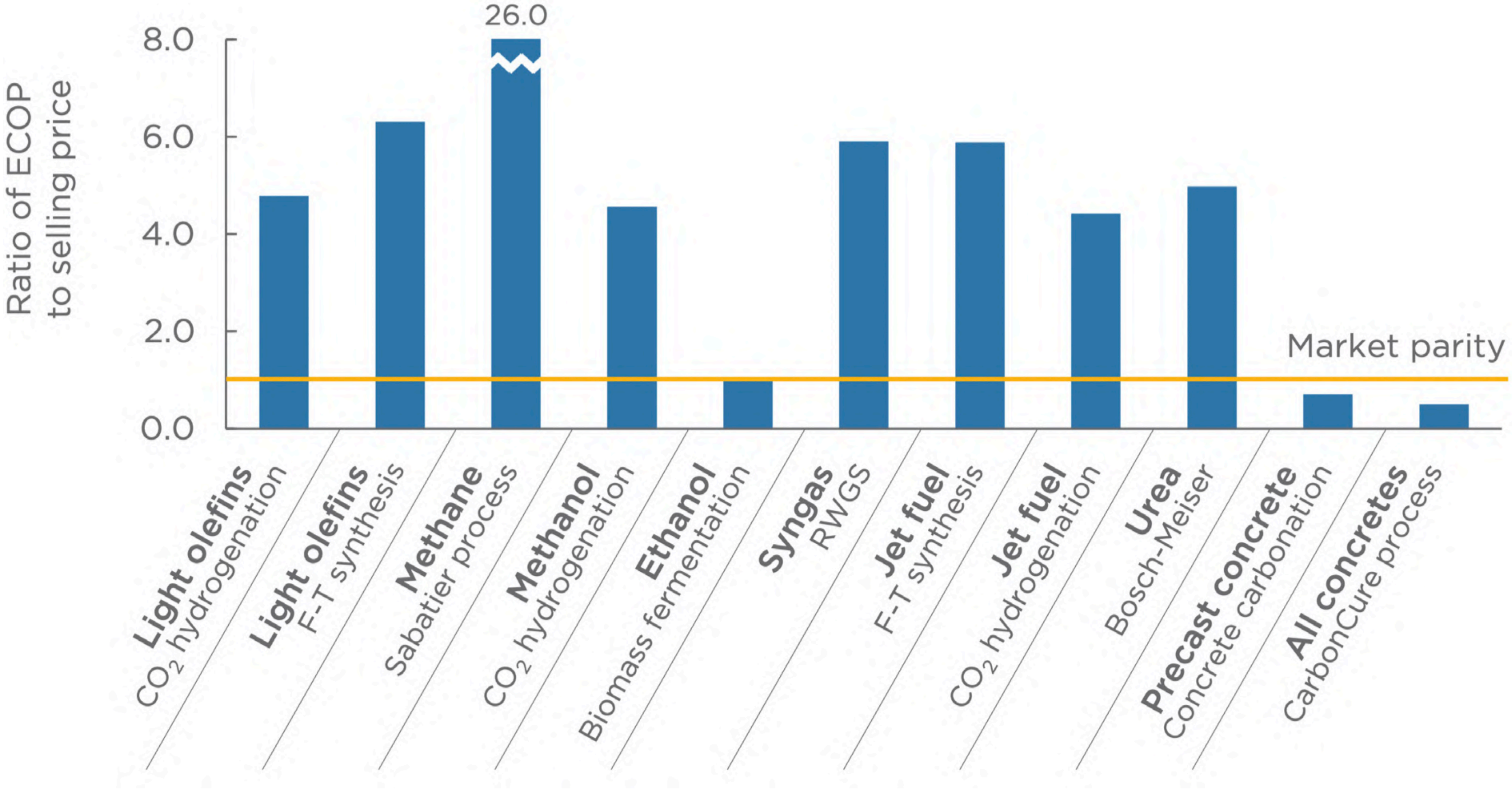
Costs of thermochemical pathways are slightly lower, and main component is green hydrogen feedstock cost



- Non-hydrogen costs exceed selling price for many pathways

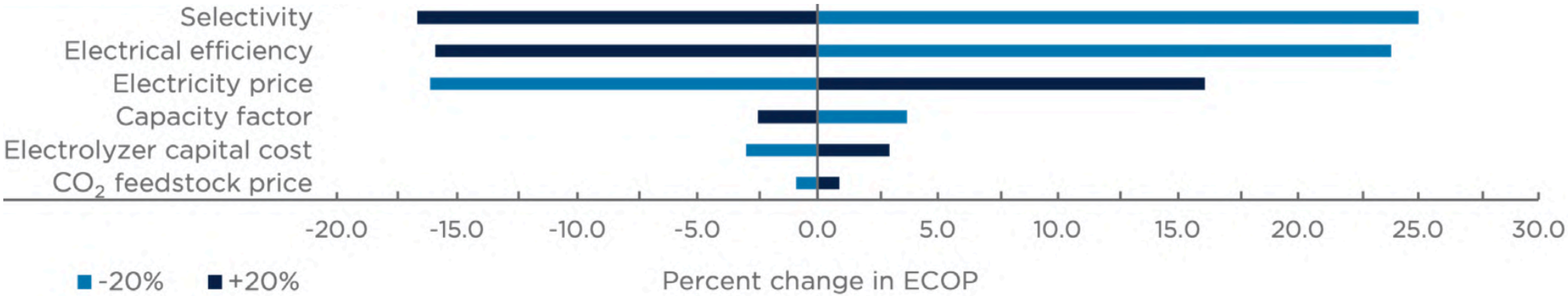
Ratio of ECOP to selling price for thermochemical pathways is lower, but far exceeds market parity

- Market parity: Ethanol from lignocellulosic biomass and the concrete production pathways
- Others have ratio below 6



Sensitivity analysis shows key cost drivers

Percent change in ECOP as a result of a 20% change in an input value



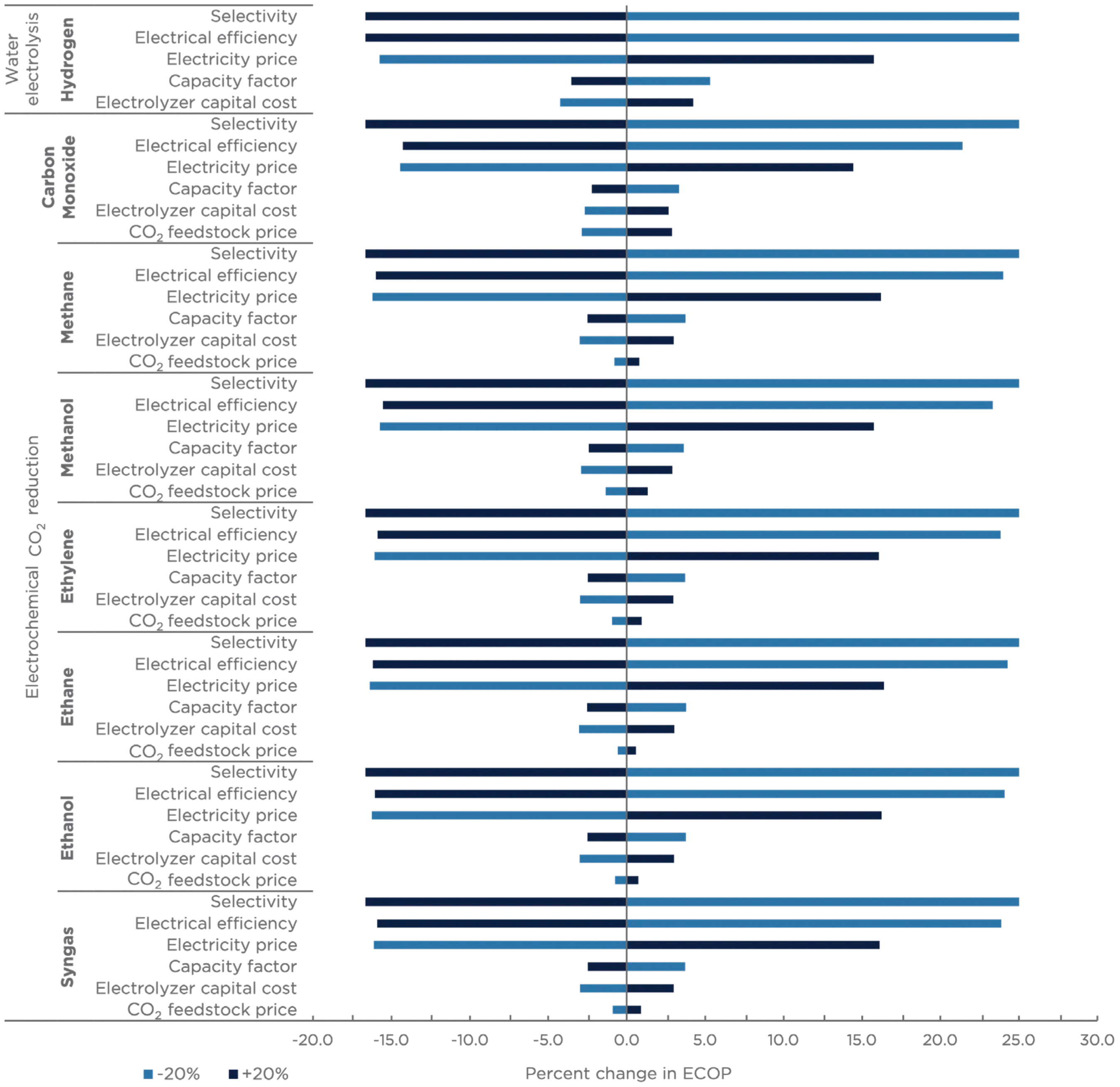
Electrochemical pathways

Key cost drivers:

- **Selectivity** (ability to avoid unwanted side reactions)
- **Electrical energy efficiency**
- **Electricity price**
  - Slower to improve

Weaker cost drivers:

- **Capacity factor**
- **Electrolyzer capital cost**
- **CO_2 feedstock price**
  - DAC would have small effect on ECOP



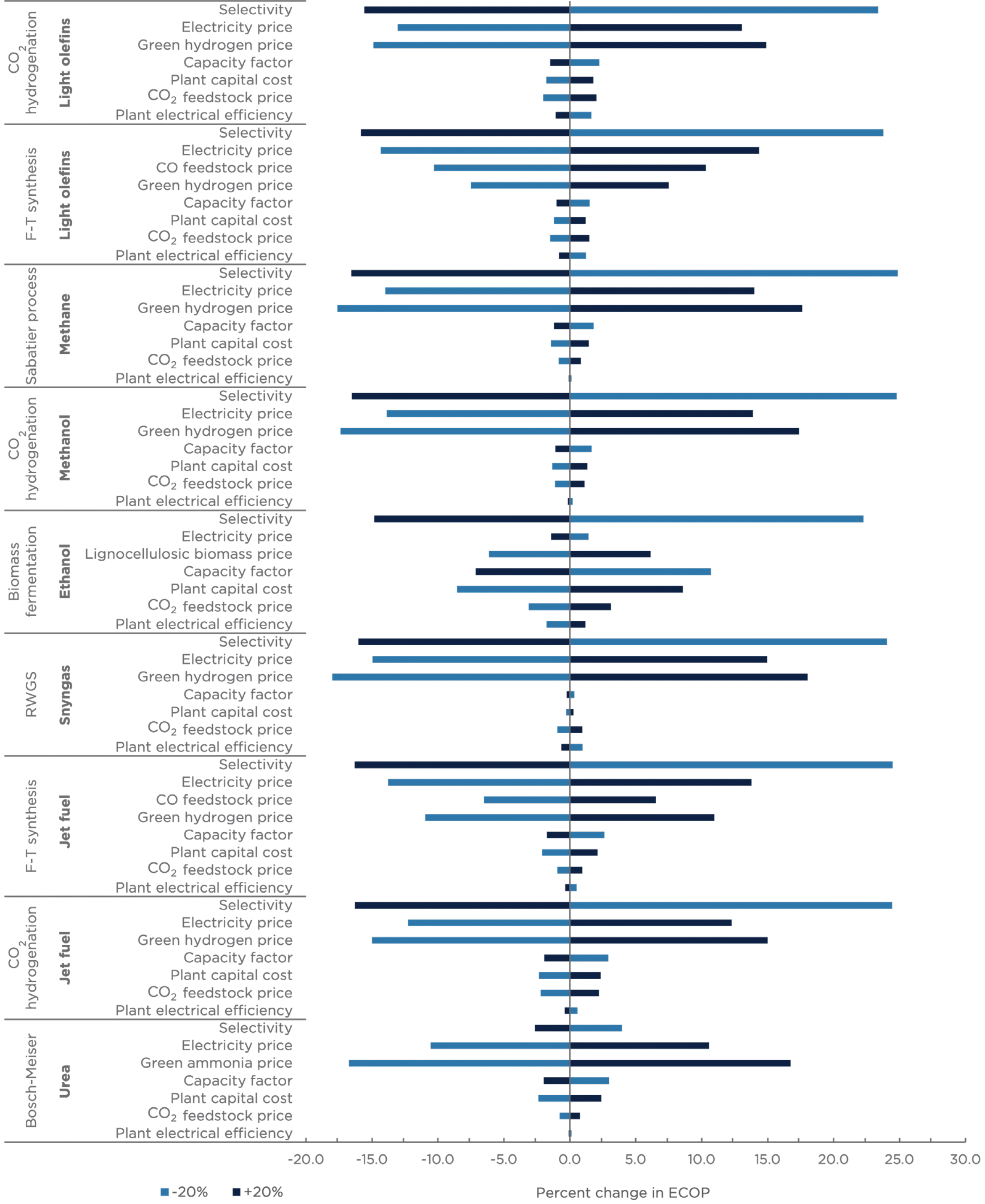
Thermochemical pathways

Key cost drivers:

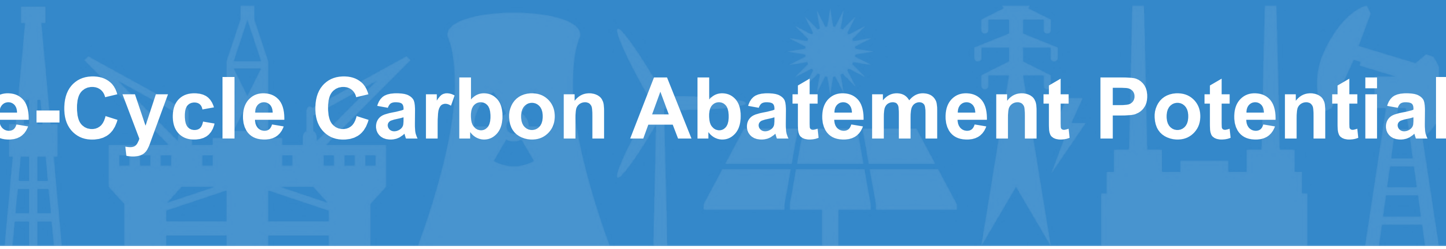
- Selectivity
- Electricity price
- Hydrogen price

Weaker cost drivers:

- Capacity factor
- Capital cost
- CO_2 feedstock price

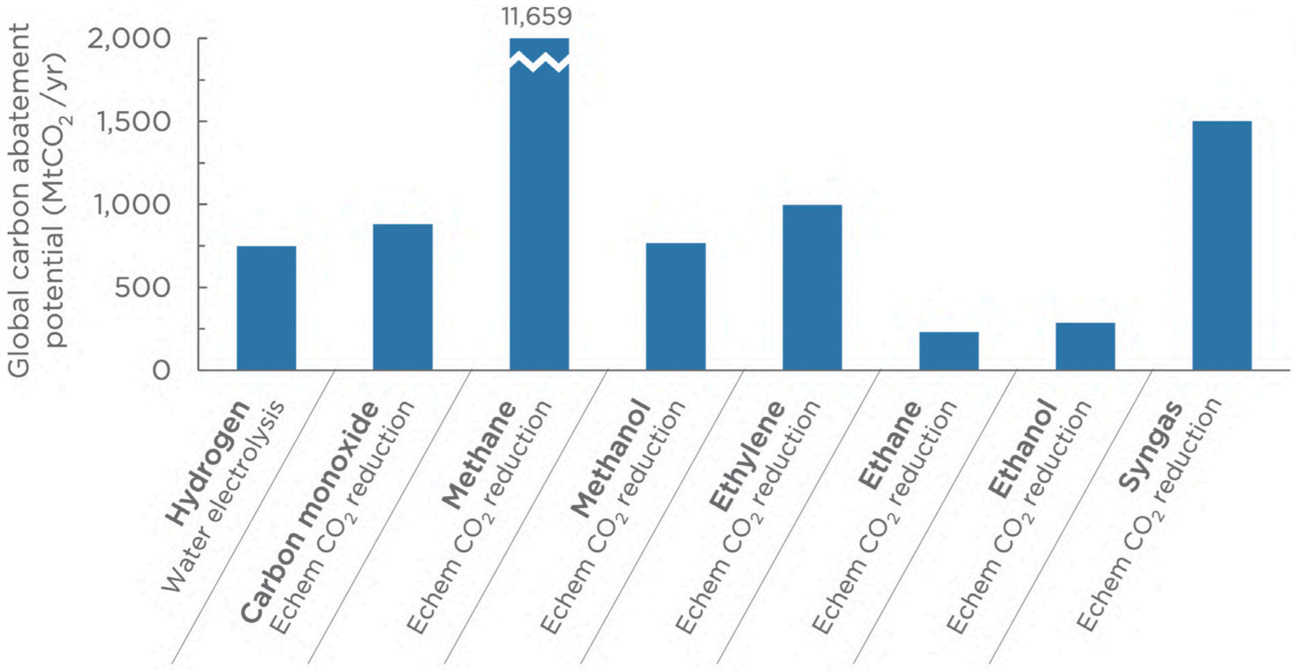


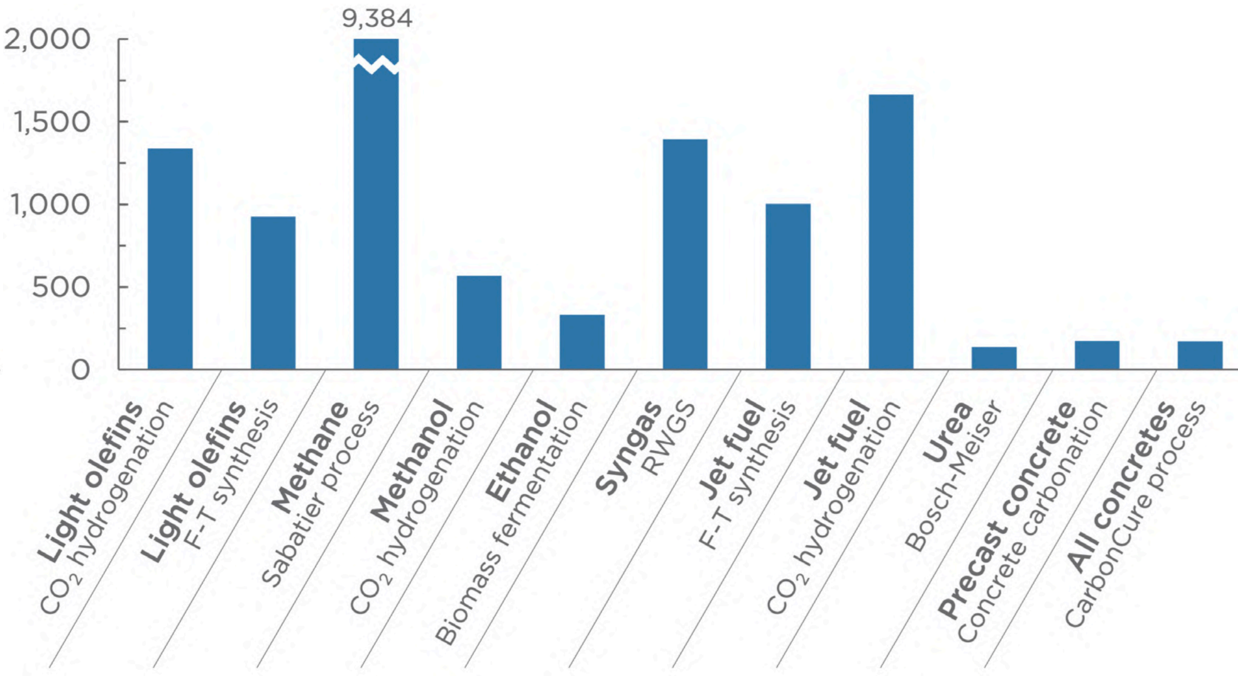
2. Life-Cycle Carbon Abatement Potential



Pathways have a combined carbon abatement potential of 6.8 $GtCO_2$/yr

Contingent on use of low-carbon electricity and feedstocks

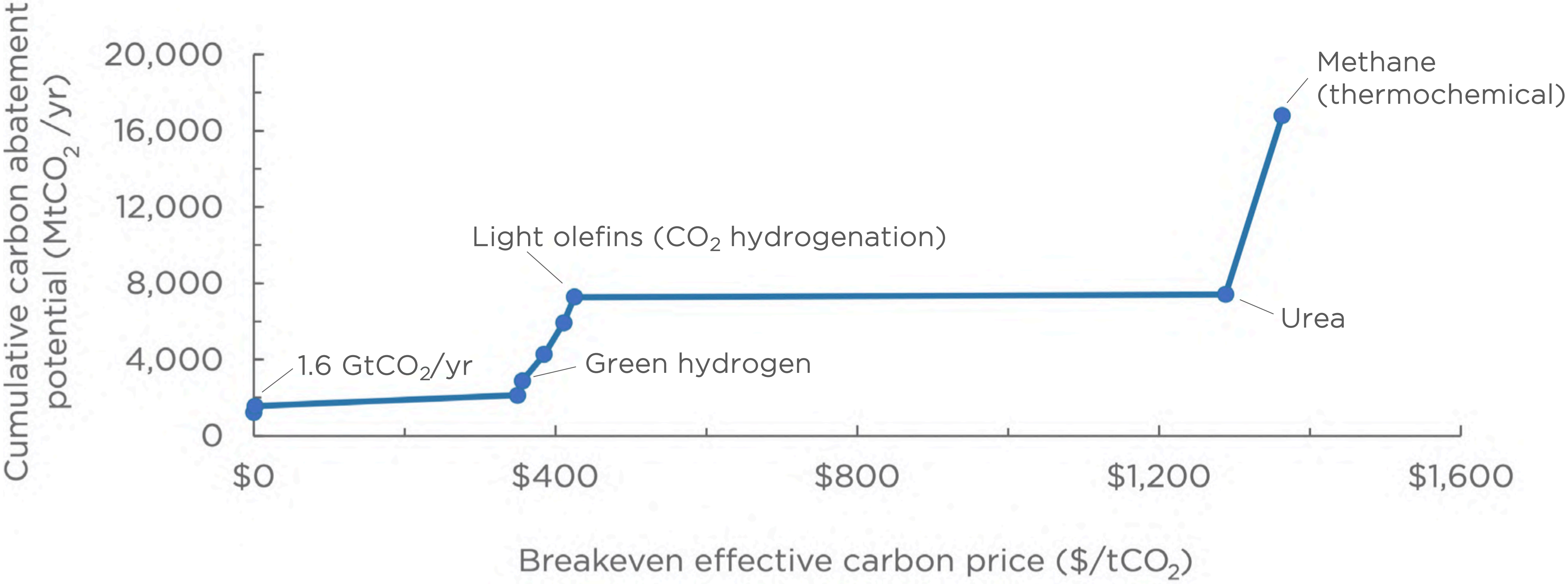


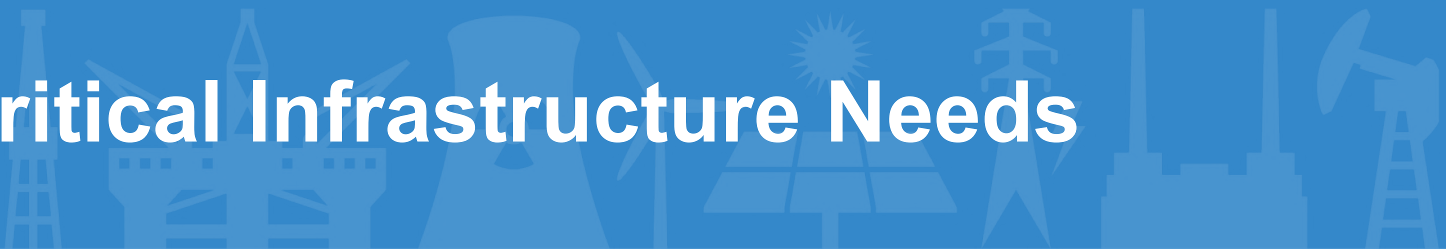


- **Carbon abatement is emissions reduction of displacing conventional production with CO_2 recycling**

3. Effective Carbon Price and Gross Subsidies

Cumulative abatement potential available at market parity as a function of effective carbon price



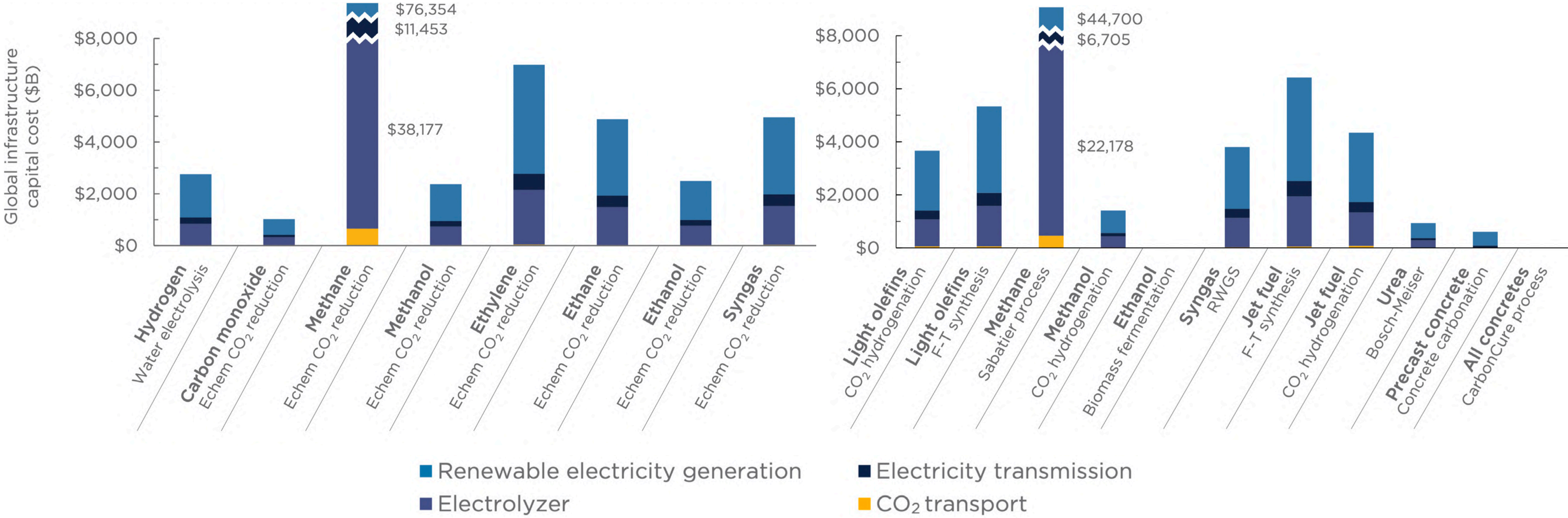


4. Critical Infrastructure Needs

Pathways have massive global consumption of electricity and feedstocks

- Pathways consume a combined **36,700 TWh/yr** of low-carbon electricity at global scale
  - Current global electricity consumption: ~26,000 TWh/yr
- Most thermochemical pathways consume **~80 MtH_2/yr each** as feedstock low-carbon hydrogen
  - IEA NZE in 2030: 140 MtH_2/yr global low-carbon hydrogen supply
- Pathways consume a combined **5.3 $GtCO_2$/yr** as feedstock CO_2
  - Currently ~0.2 $GtCO_2$/yr consumed globally in CO_2 recycling

Trillions of dollars of capital investment in global critical infrastructure needed

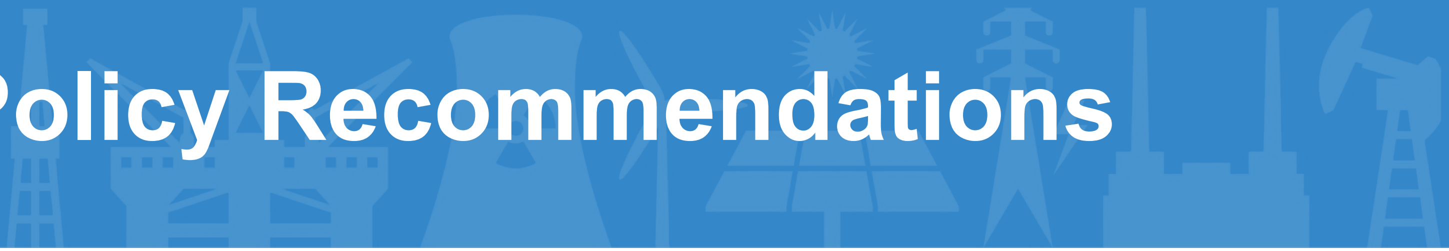


- **Majority renewable electricity capacity (8,400 GW total)**
- **CO_2 transport capital costs comparatively negligible**

Key findings

- Costs of CO_2 recycling are high and dominated by input costs (electricity and feedstocks)
- Pathways can be classified by ratio of ECOP to selling price
- Main cost drivers are catalyst selectivity, catalyst energy efficiency, and prices of inputs
- Pathways have a combined carbon abatement potential of 6.8 $GtCO_2$/yr
- High effective carbon price consistent with market parity
- Trillions of dollars of critical infrastructure needed per pathway, mainly renewables and electrolyzers

5. Policy Recommendations



Ensure CO_2 recycling pathways consume low-carbon inputs

High carbon abatement can only be achieved using low-carbon electricity and low-carbon H_2, syngas, and/or ammonia feedstocks.

- Can use CO_2 from direct air capture or biomass

Prioritize pathways strategically

For market scale: (market parity)

- Electrochemical CO production
- Ethanol from lignocellulosic biomass
- Precast concrete carbonation curing
- CarbonCure concrete process

For early market entry: (ECOP to selling price ratio < 5)

- Green hydrogen
- CO_2 hydrogenation to light olefins, methanol, and jet fuel
- CO_2 recycling urea production

For further technological innovation: (ratio < 8)

- All pathways (incl. Echem CO_2 reduction, F-T synthesis, RWGS)

Deprioritize: (ratio > 25)

- Electrochemical methane and ethane production
- Sabatier process methane production

Use RD&D agenda focused on catalyst innovation to bring down costs

Improving the activity and selectivity of catalysts will reduce electricity/feedstock costs and alleviate demand on critical infrastructure.

Catalyst performance is an efficiency lever

Create demand pull for early market CO_2 recycling products

Demand pull policies can create early markets for CO_2 recycling and help achieve scale.

- **Public procurement, financial incentives, milestone payments**

Promote buildout of critical infrastructure

Accelerated buildout of low-carbon electricity, transmission, electrolyzers, and CO_2 transport infrastructure is needed to enable CO_2 recycling at scale.

- **Remove barriers to infrastructure projects and provide/enable investment**

Our findings can provide granularity for American Jobs Plan

Initial plan included $35 billion in climate innovation and public procurement of cleaner cement.

- **Use findings to guide CO_2 recycling innovation funding and define public procurement standards**

Include demonstration of market-ready CO_2 recycling pathways in American Jobs Plan

Initial plan included $15 billion in climate demonstration (CO_2 recycling not listed) + 15 low-carbon hydrogen demonstration and 10 carbon capture retrofits

Include the following CO_2 recycling pathways:

- Electrochemical CO production
- CO_2 hydrogenation to light olefins, methanol, and jet fuel
- CO_2 recycling urea production

Thank You

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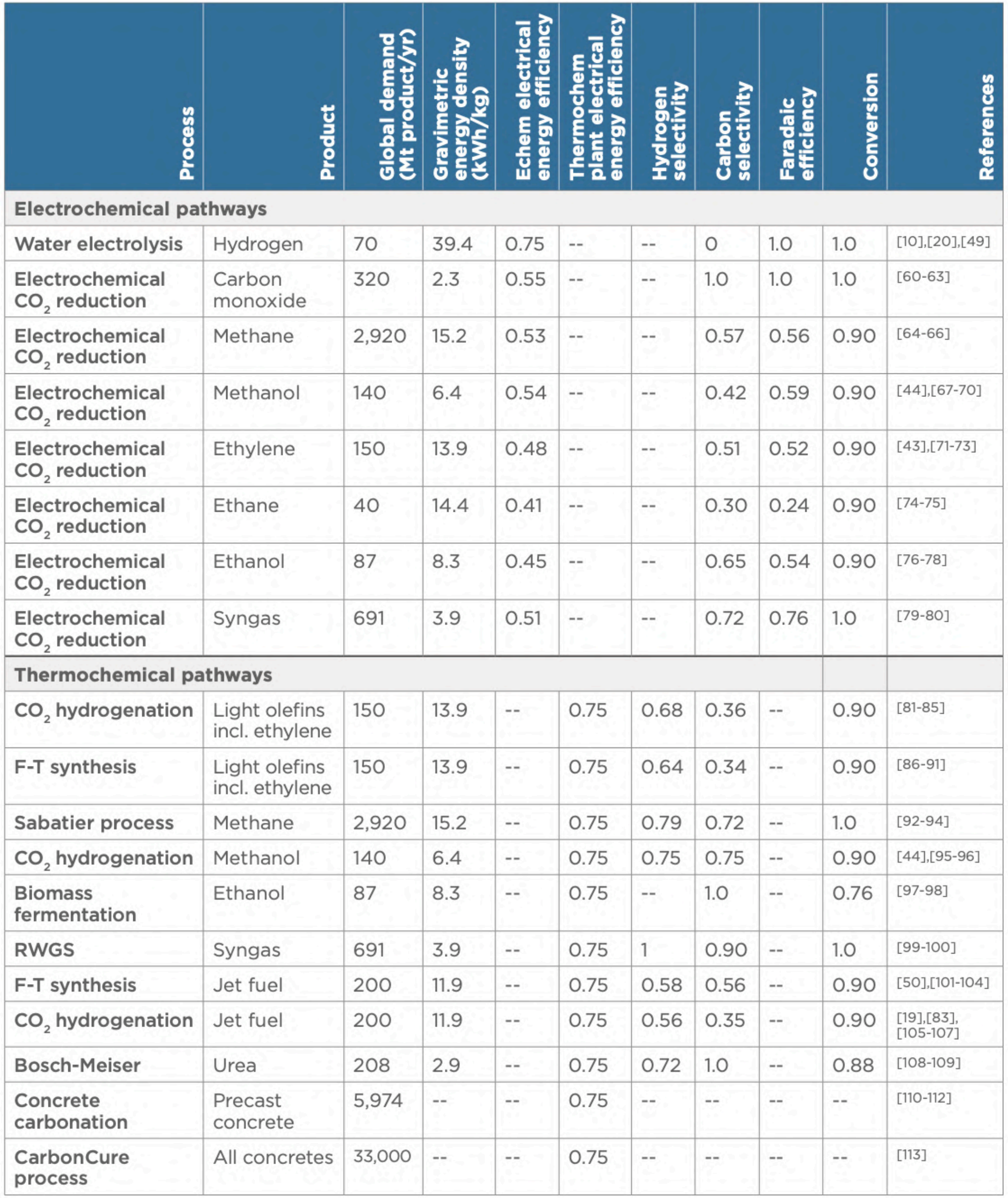
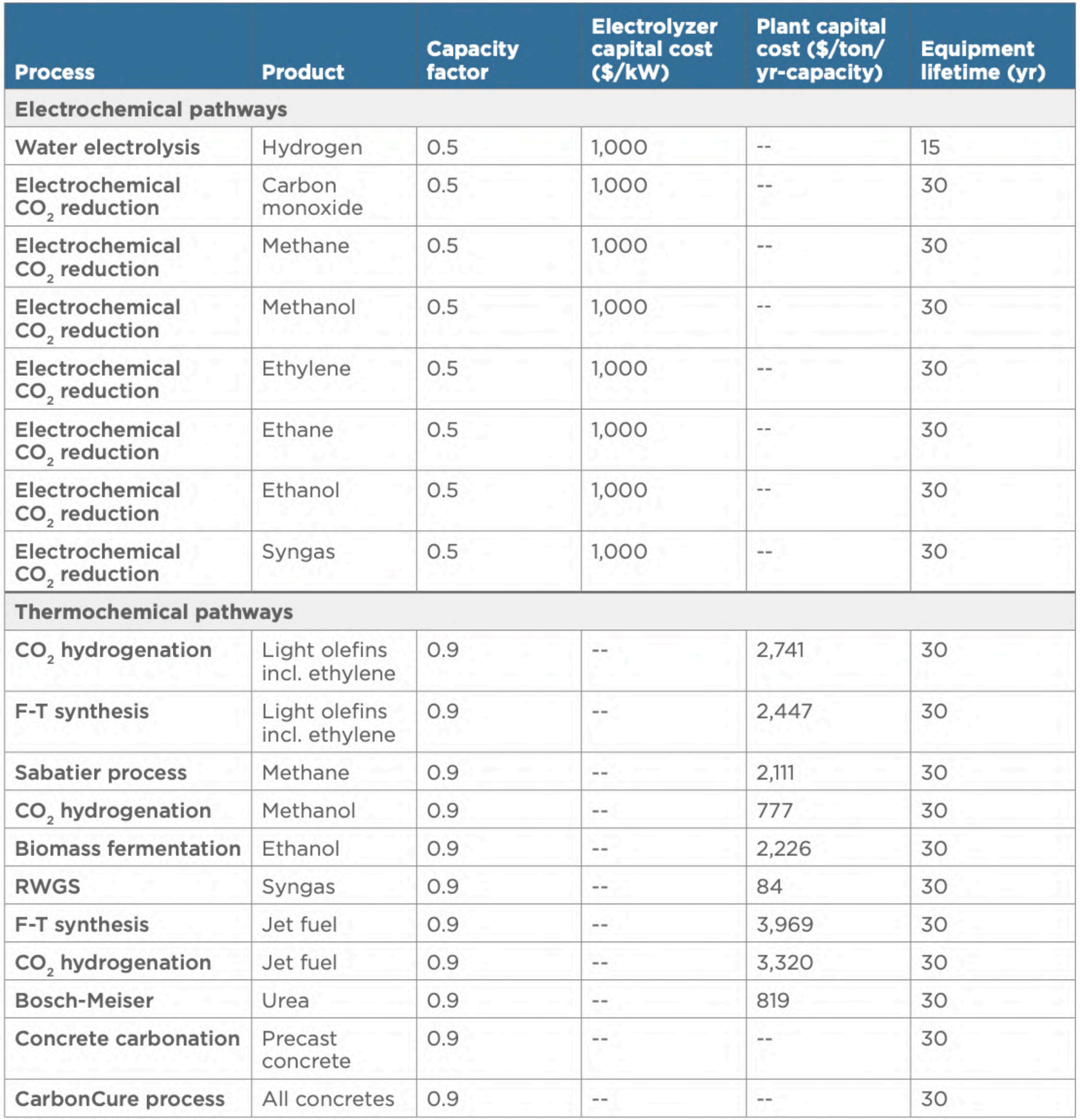
6. Appendix

Technical inputs and assumptions



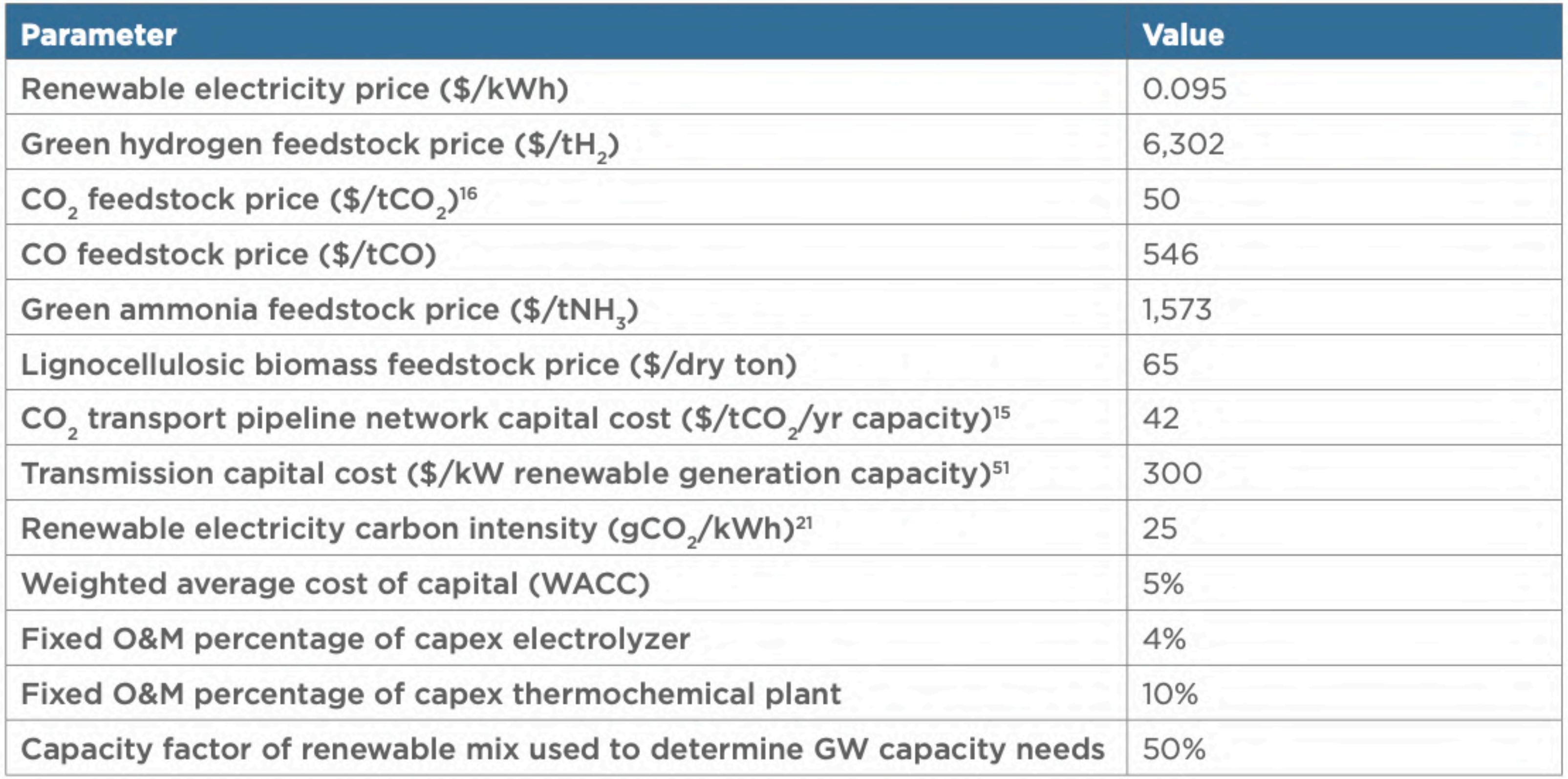
Process	Product	Global demand (Mt product/yr)	Gravimetric energy density (kWh/kg)	Echem electrical energy efficiency	Thermochem plant electrical energy efficiency	Hydrogen selectivity	Carbon selectivity	Faradaic efficiency	Conversion	References
Electrochemical pathways										
Water electrolysis	Hydrogen	70	39.4	0.75	--	--	0	1.0	1.0	[10],[20],[49]
Electrochemical CO_2 reduction	Carbon monoxide	320	2.3	0.55	--	--	1.0	1.0	1.0	[60-63]
Electrochemical CO_2 reduction	Methane	2,920	15.2	0.53	--	--	0.57	0.56	0.90	[64-66]
Electrochemical CO_2 reduction	Methanol	140	6.4	0.54	--	--	0.42	0.59	0.90	[44],[67-70]
Electrochemical CO_2 reduction	Ethylene	150	13.9	0.48	--	--	0.51	0.52	0.90	[43],[71-73]
Electrochemical CO_2 reduction	Ethane	40	14.4	0.41	--	--	0.30	0.24	0.90	[74-75]
Electrochemical CO_2 reduction	Ethanol	87	8.3	0.45	--	--	0.65	0.54	0.90	[76-78]
Electrochemical CO_2 reduction	Syngas	691	3.9	0.51	--	--	0.72	0.76	1.0	[79-80]
Thermochemical pathways										
CO_2 hydrogenation	Light olefins incl. ethylene	150	13.9	--	0.75	0.68	0.36	--	0.90	[81-85]
F-T synthesis	Light olefins incl. ethylene	150	13.9	--	0.75	0.64	0.34	--	0.90	[86-91]
Sabatier process	Methane	2,920	15.2	--	0.75	0.79	0.72	--	1.0	[92-94]
CO_2 hydrogenation	Methanol	140	6.4	--	0.75	0.75	0.75	--	0.90	[44],[95-96]
Biomass fermentation	Ethanol	87	8.3	--	0.75	--	1.0	--	0.76	[97-98]
RWGS	Syngas	691	3.9	--	0.75	1	0.90	--	1.0	[99-100]
F-T synthesis	Jet fuel	200	11.9	--	0.75	0.58	0.56	--	0.90	[50],[101-104]
CO_2 hydrogenation	Jet fuel	200	11.9	--	0.75	0.56	0.35	--	0.90	[19],[83], [105-107]
Bosch-Meiser	Urea	208	2.9	--	0.75	0.72	1.0	--	0.88	[108-109]
Concrete carbonation	Precast concrete	5,974	--	--	0.75	--	--	--	--	[110-112]
CarbonCure process	All concretes	33,000	--	--	0.75	--	--	--	--	[113]

Plant assumptions



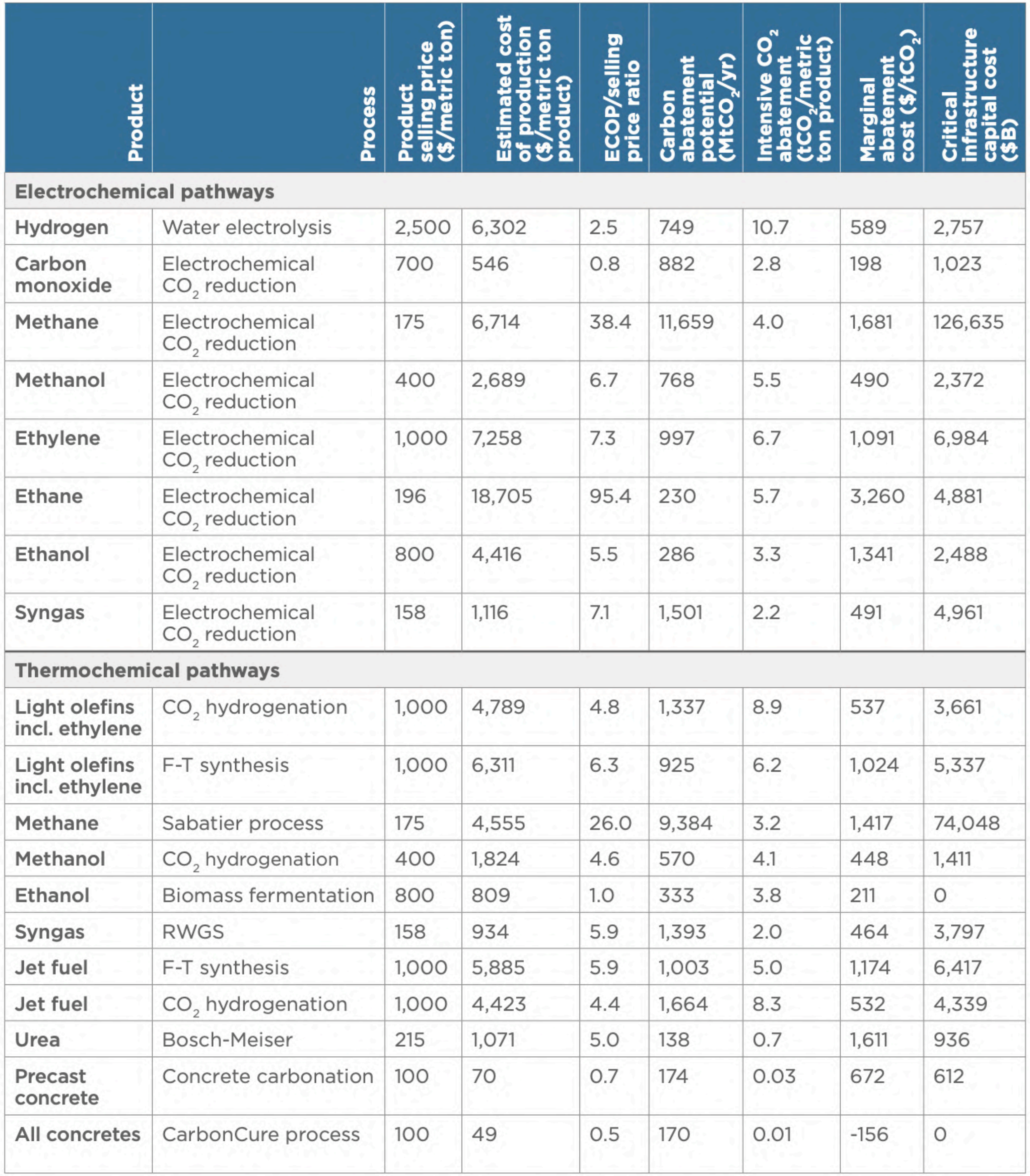
Process	Product	Capacity factor	Electrolyzer capital cost ($/kW)	Plant capital cost ($/ton/yr-capacity)	Equipment lifetime (yr)
Electrochemical pathways					
Water electrolysis	Hydrogen	0.5	1,000	--	15
Electrochemical CO_2 reduction	Carbon monoxide	0.5	1,000	--	30
Electrochemical CO_2 reduction	Methane	0.5	1,000	--	30
Electrochemical CO_2 reduction	Methanol	0.5	1,000	--	30
Electrochemical CO_2 reduction	Ethylene	0.5	1,000	--	30
Electrochemical CO_2 reduction	Ethane	0.5	1,000	--	30
Electrochemical CO_2 reduction	Ethanol	0.5	1,000	--	30
Electrochemical CO_2 reduction	Syngas	0.5	1,000	--	30
Thermochemical pathways					
CO_2 hydrogenation	Light olefins incl. ethylene	0.9	--	2,741	30
F-T synthesis	Light olefins incl. ethylene	0.9	--	2,447	30
Sabatier process	Methane	0.9	--	2,111	30
CO_2 hydrogenation	Methanol	0.9	--	777	30
Biomass fermentation	Ethanol	0.9	--	2,226	30
RWGS	Syngas	0.9	--	84	30
F-T synthesis	Jet fuel	0.9	--	3,969	30
CO_2 hydrogenation	Jet fuel	0.9	--	3,320	30
Bosch-Meiser	Urea	0.9	--	819	30
Concrete carbonation	Precast concrete	0.9	--	--	30
CarbonCure process	All concretes	0.9	--	--	30

Financial assumptions



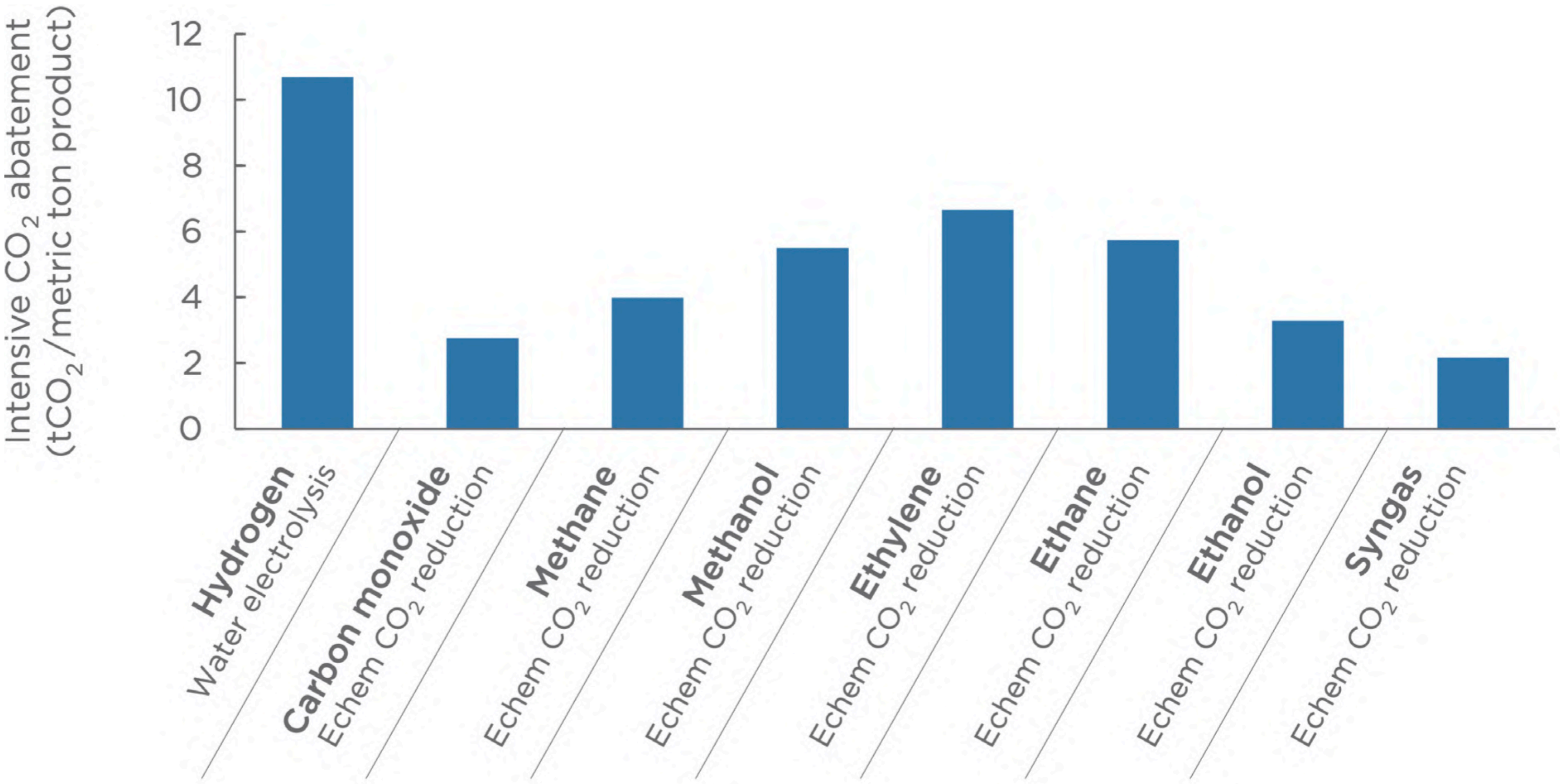
Parameter	Value
Renewable electricity price (\$/kWh)	0.095
Green hydrogen feedstock price (\$/tH_2)	6,302
CO_2 feedstock price (\$/tCO_2)[16]	50
CO feedstock price (\$/tCO)	546
Green ammonia feedstock price (\$/tNH_3)	1,573
Lignocellulosic biomass feedstock price (\$/dry ton)	65
CO_2 transport pipeline network capital cost (\$/tCO_2/yr capacity)[15]	42
Transmission capital cost (\$/kW renewable generation capacity)[51]	300
Renewable electricity carbon intensity (gCO_2/kWh)[21]	25
Weighted average cost of capital (WACC)	5%
Fixed O&M percentage of capex electrolyzer	4%
Fixed O&M percentage of capex thermochemical plant	10%
Capacity factor of renewable mix used to determine GW capacity needs	50%

Results summary

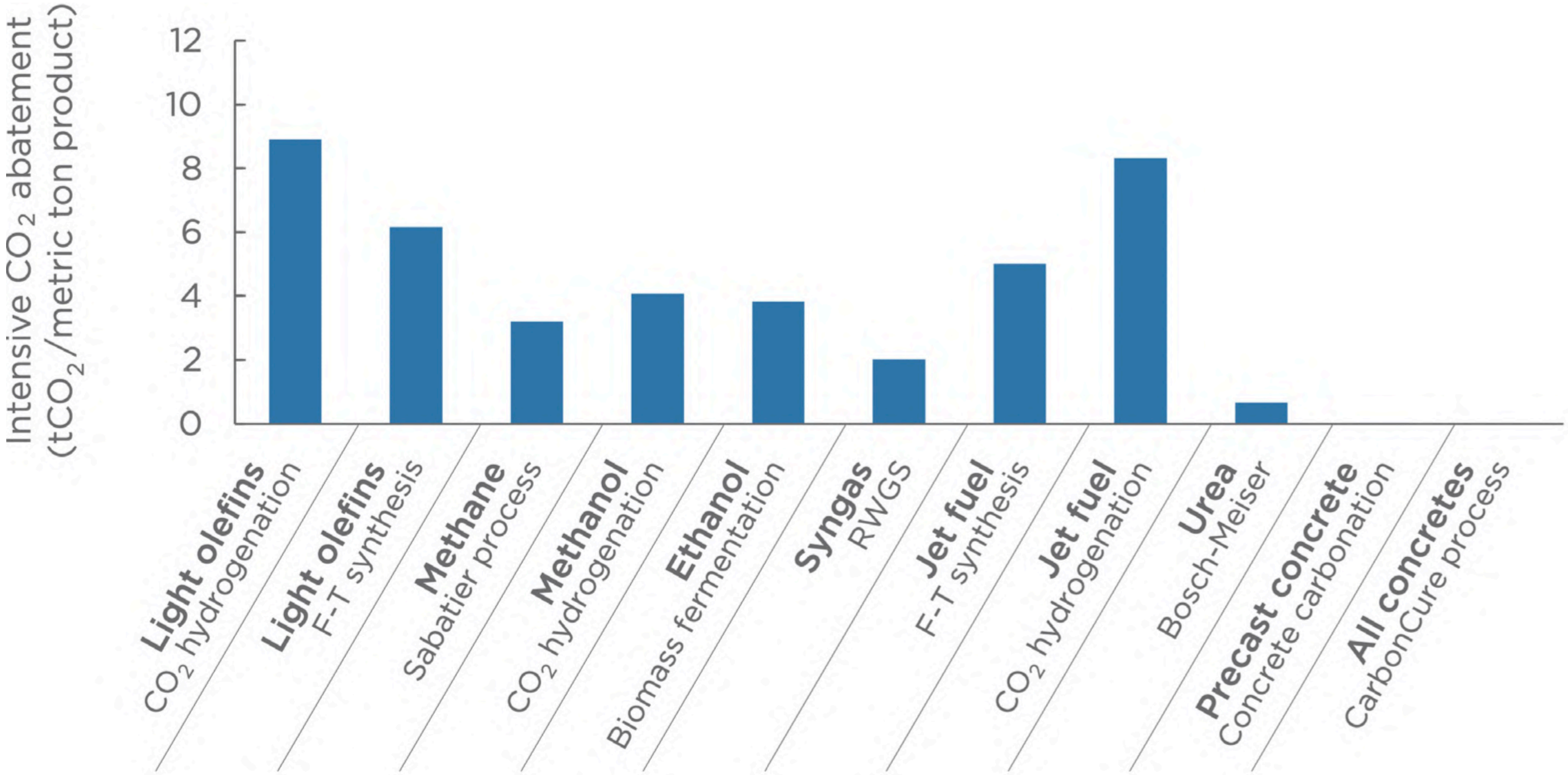


Product	**Process**	**Product selling price ($/metric ton)**	**Estimated cost of production ($/metric ton product)**	**ECOP/selling price ratio**	**Carbon abatement potential ($MtCO_2$/yr)**	**Intensive CO_2 abatement (tCO_2/metric ton product)**	**Marginal abatement cost ($/$tCO_2$)**	**Critical infrastructure capital cost ($B)**
Electrochemical pathways								
Hydrogen	Water electrolysis	2,500	6,302	2.5	749	10.7	589	2,757
Carbon monoxide	Electrochemical CO_2 reduction	700	546	0.8	882	2.8	198	1,023
Methane	Electrochemical CO_2 reduction	175	6,714	38.4	11,659	4.0	1,681	126,635
Methanol	Electrochemical CO_2 reduction	400	2,689	6.7	768	5.5	490	2,372
Ethylene	Electrochemical CO_2 reduction	1,000	7,258	7.3	997	6.7	1,091	6,984
Ethane	Electrochemical CO_2 reduction	196	18,705	95.4	230	5.7	3,260	4,881
Ethanol	Electrochemical CO_2 reduction	800	4,416	5.5	286	3.3	1,341	2,488
Syngas	Electrochemical CO_2 reduction	158	1,116	7.1	1,501	2.2	491	4,961
Thermochemical pathways								
Light olefins incl. ethylene	CO_2 hydrogenation	1,000	4,789	4.8	1,337	8.9	537	3,661
Light olefins incl. ethylene	F-T synthesis	1,000	6,311	6.3	925	6.2	1,024	5,337
Methane	Sabatier process	175	4,555	26.0	9,384	3.2	1,417	74,048
Methanol	CO_2 hydrogenation	400	1,824	4.6	570	4.1	448	1,411
Ethanol	Biomass fermentation	800	809	1.0	333	3.8	211	0
Syngas	RWGS	158	934	5.9	1,393	2.0	464	3,797
Jet fuel	F-T synthesis	1,000	5,885	5.9	1,003	5.0	1,174	6,417
Jet fuel	CO_2 hydrogenation	1,000	4,423	4.4	1,664	8.3	532	4,339
Urea	Bosch-Meiser	215	1,071	5.0	138	0.7	1,611	936
Precast concrete	Concrete carbonation	100	70	0.7	174	0.03	672	612
All concretes	CarbonCure process	100	49	0.5	170	0.01	-156	0

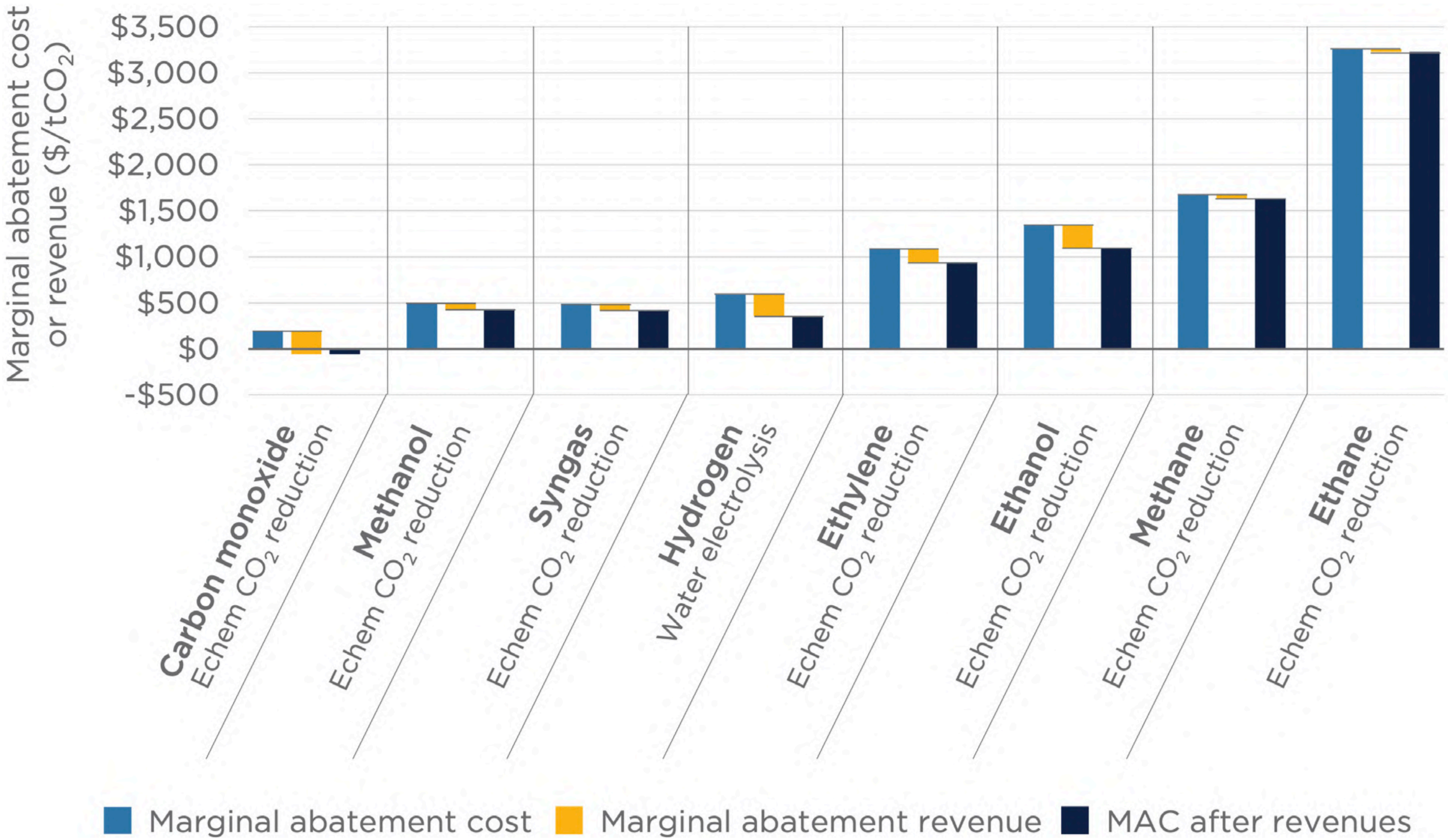
Intensive CO_2 abatement of **electrochemical** pathways



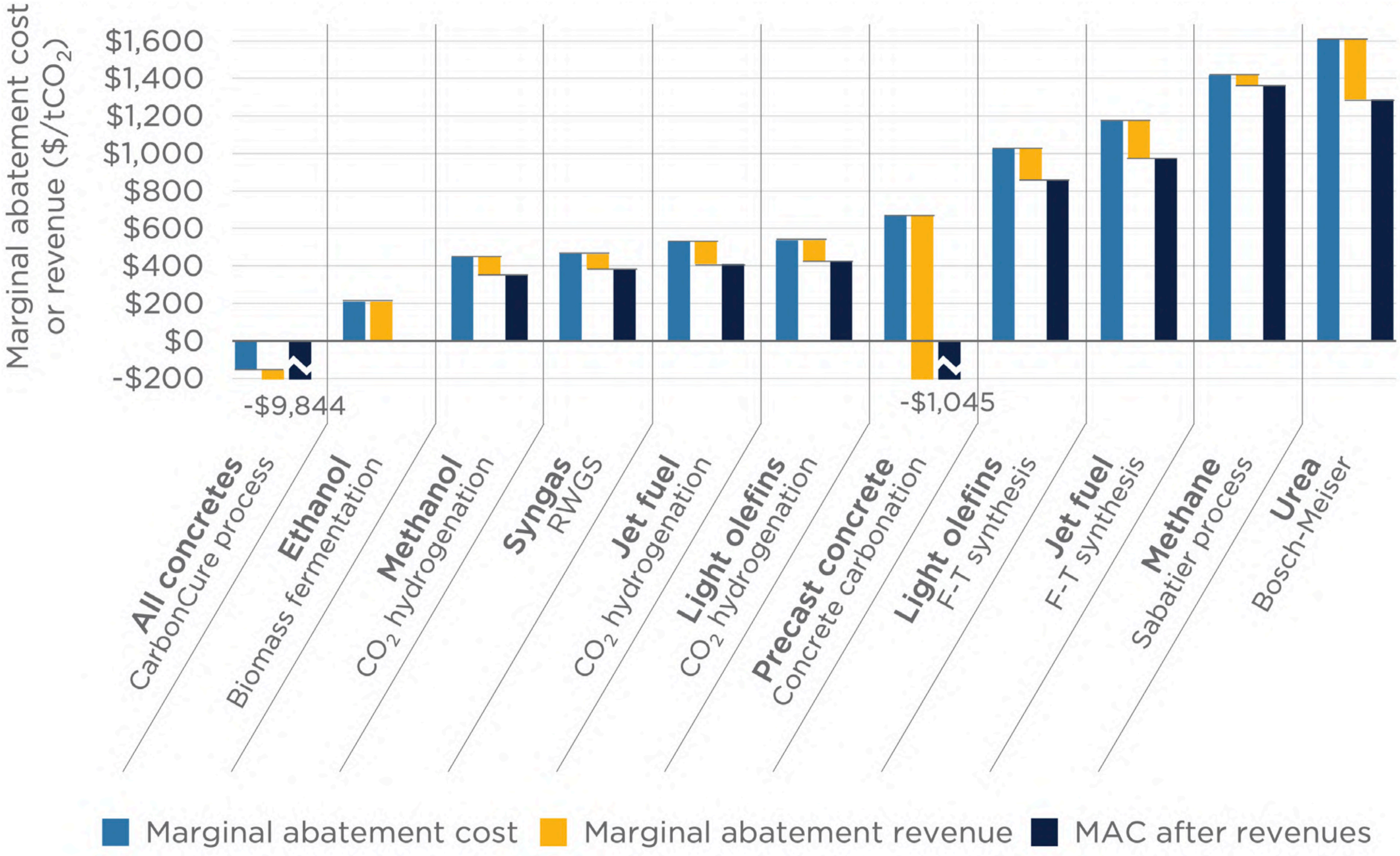
Intensive CO_2 abatement of thermochemical pathways



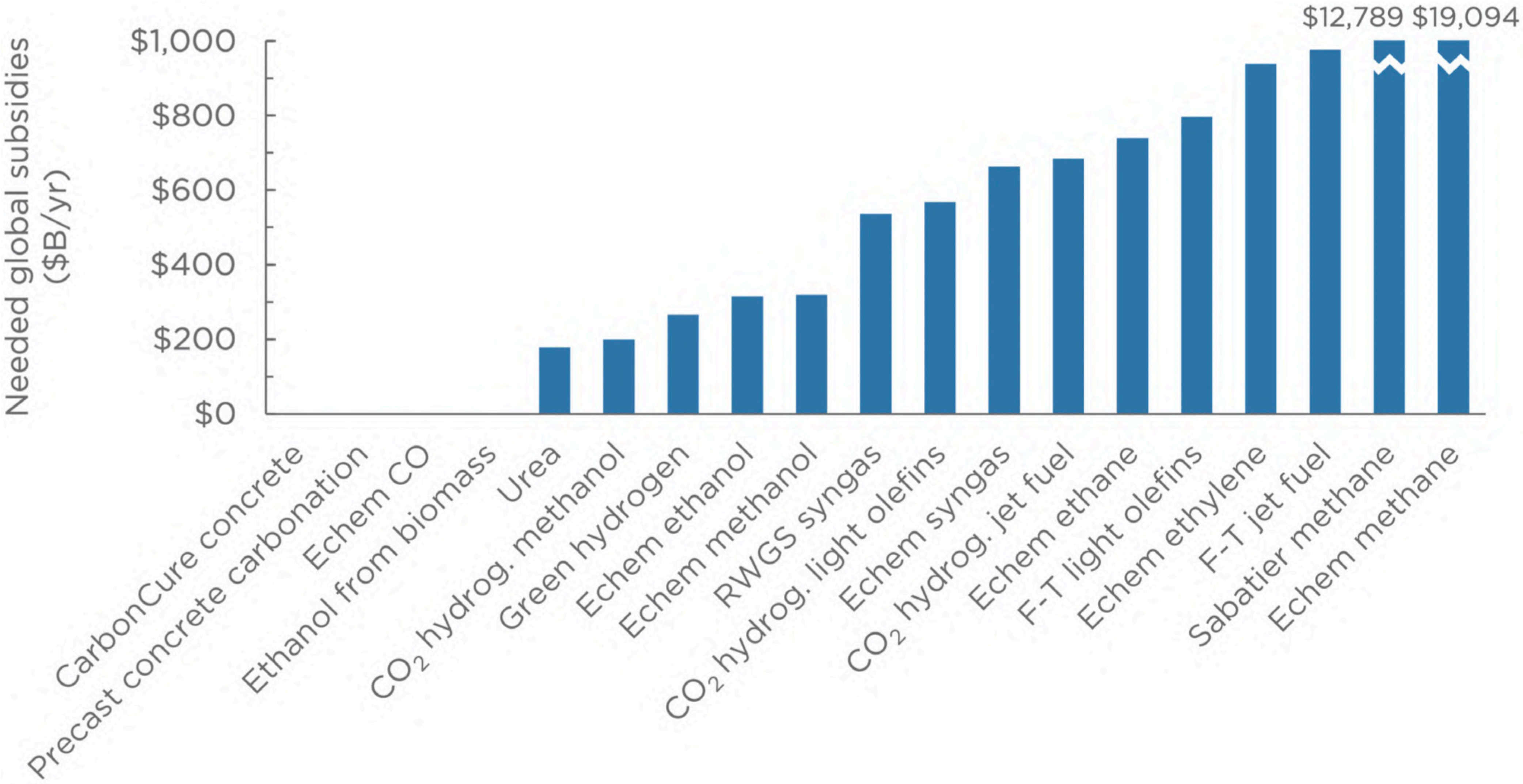
Marginal abatement cost and revenues for electrochemical pathways



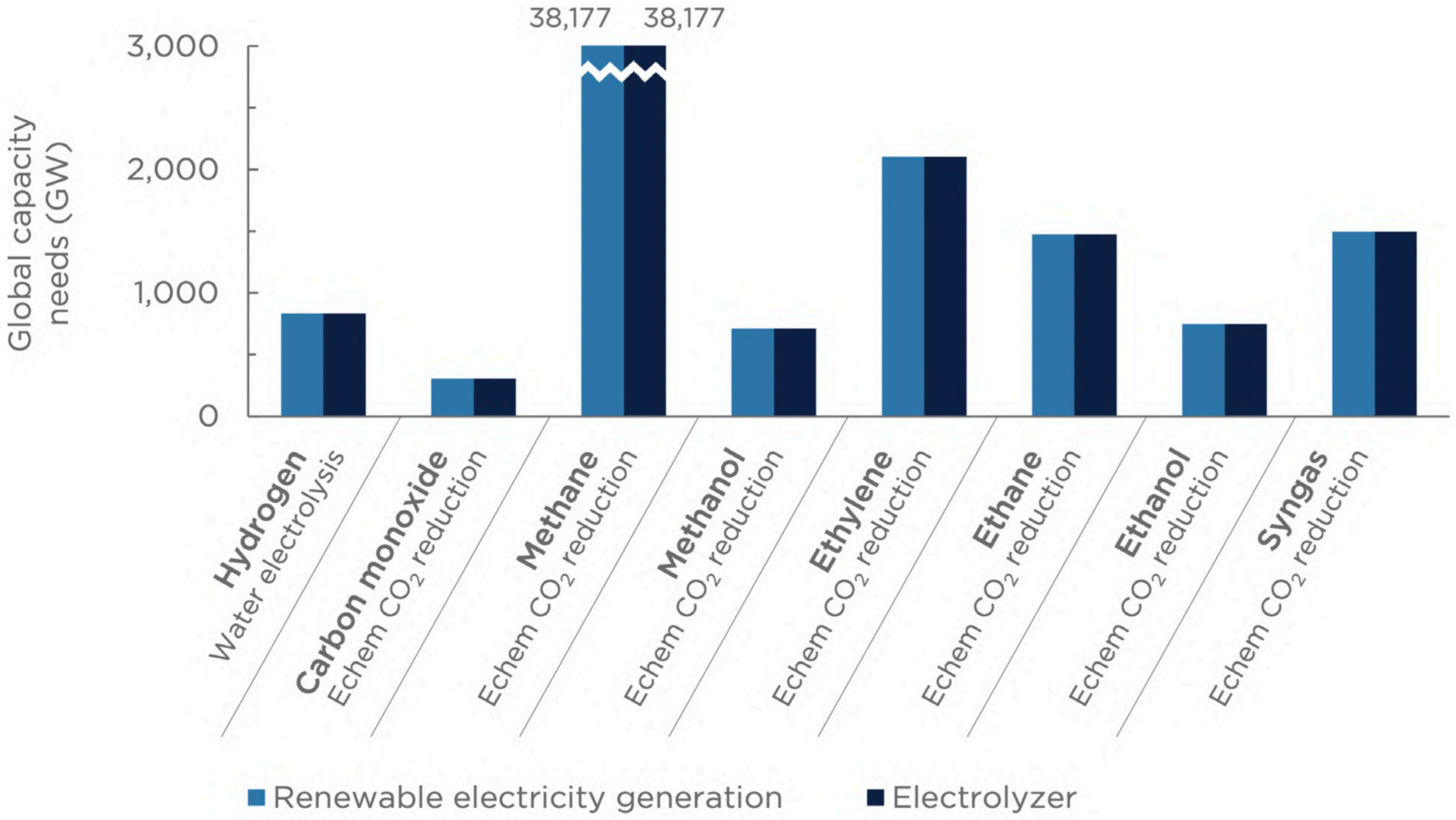
Marginal abatement cost and revenues for thermochemical pathways



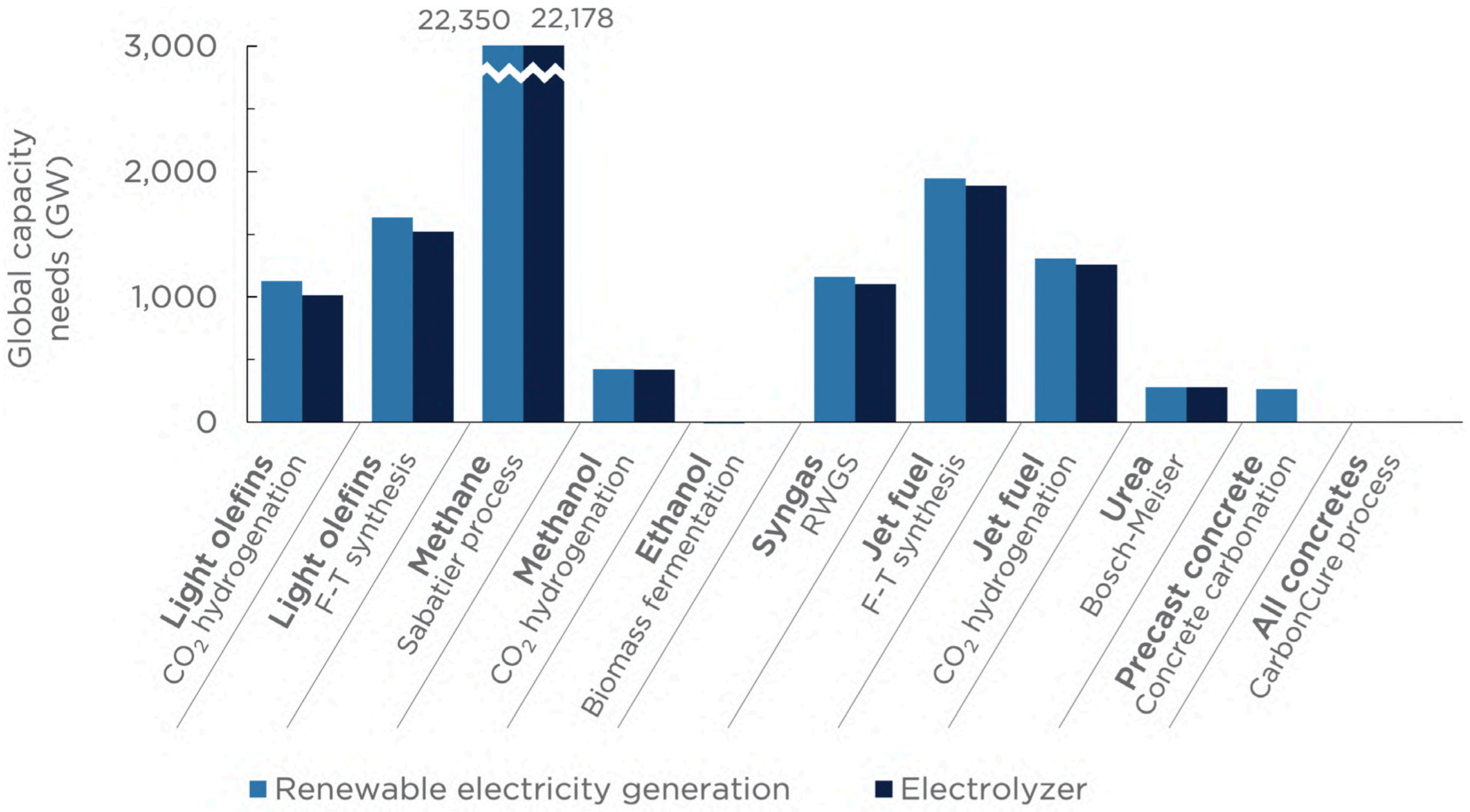
Hundreds of billions of dollars in gross global subsidies needed to close cost-price gap



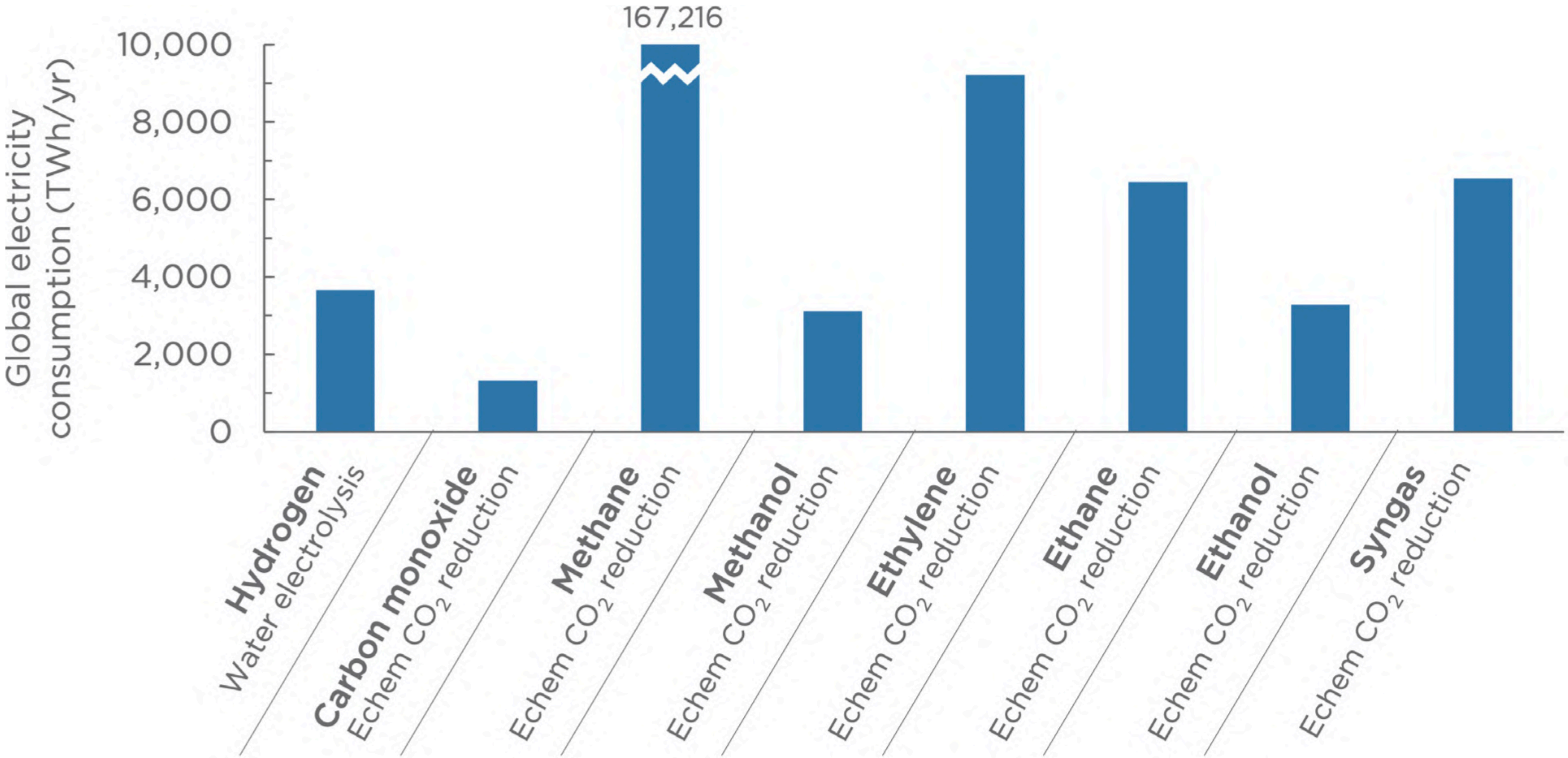
Global renewables and electrolyzer capacity for electrochemical pathways



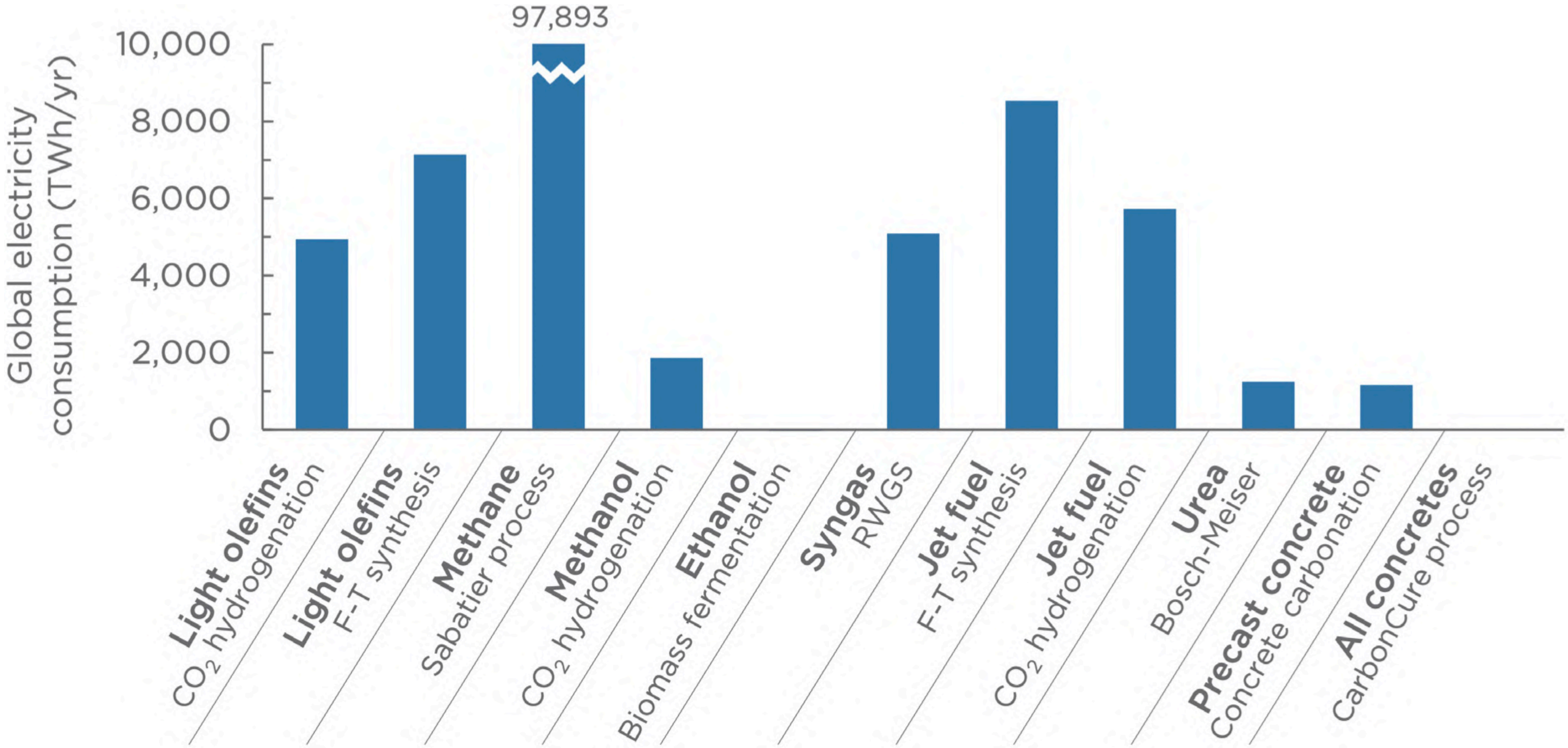
Global renewables and electrolyzer capacity for thermochemical pathways



Global electricity consumption of electrochemical pathways



Global electricity consumption of thermochemical pathways



Global hydrogen consumption of thermochemical pathways