An introduction to energy systems modeling in IAMs

Volker Krey

15 October 2024

Based on material by Oliver Fricko, Siddharth Joshi, Measrainsey Meng, Fei Guo

NTNU course: Integrated Assessment Modelling (EP8900)

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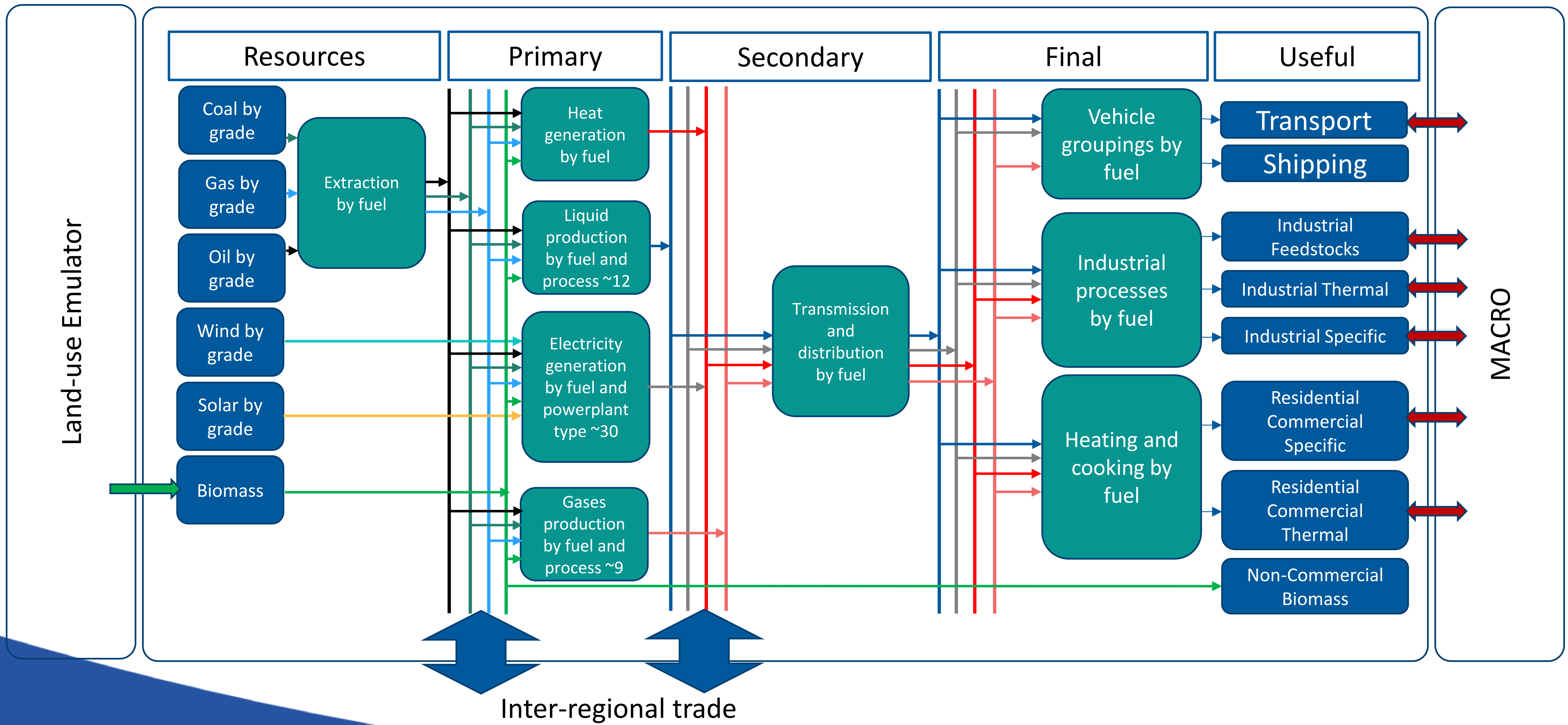
Reference Energy System: MESSAGEix-GLOBIOM



Key Parametric Assumptions

- Resource availability
  - ⇒ Fossil energy supply curves
  - ⇒ Renewable energy potentials
- Techno-economic parameters
- Demand projections
  - ⇒ Mostly econometric analysis
- Base year calibration
  - ⇒ Capacity (by vintage)
  - ⇒ Activity

Reserves, Resources and Occurrences

- No consensus on the exact meanings of the terms reserves, resources, and occurrence.
- McKelvey box presents resource categories in a matrix that shows increasing degrees of geological assurance and economic feasibility (USGS)
- Production costs of reserves are usually supported by actual production experience and feasibility analyses, while cost estimates for resources are often inferred from current production experience

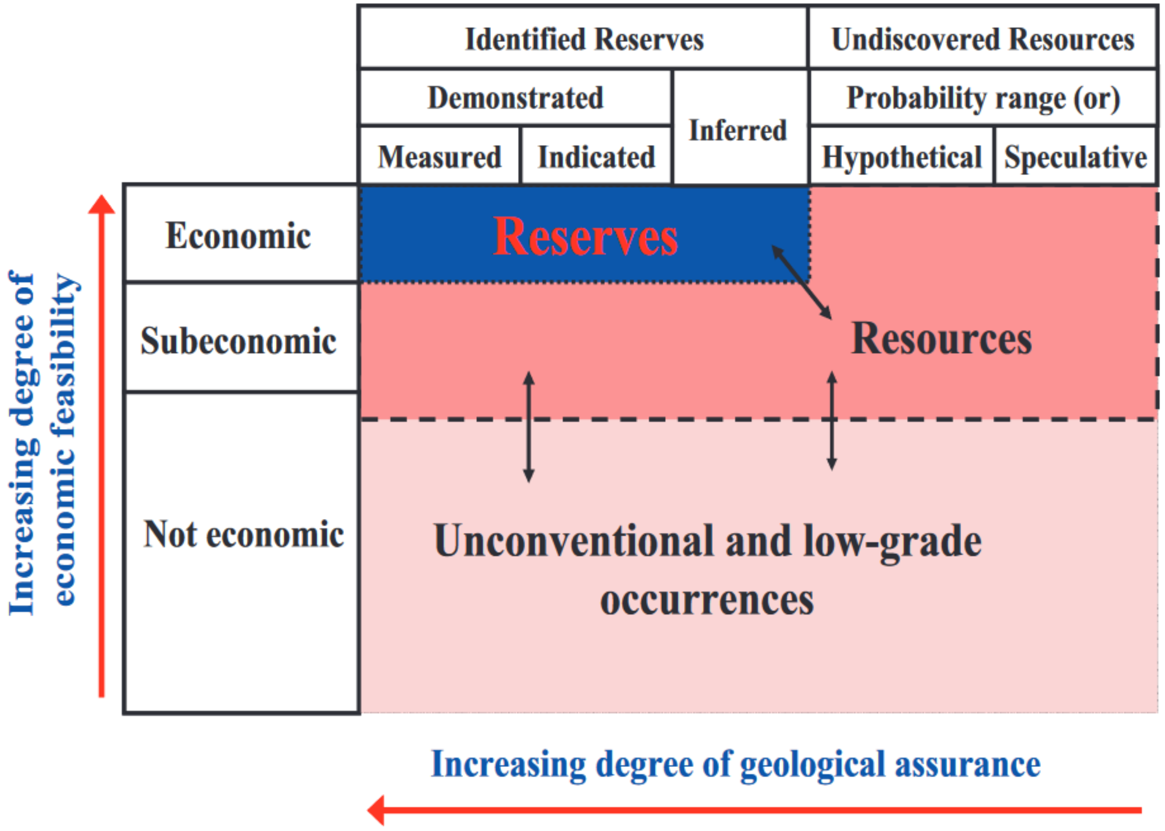


Figure 7.1 | Principles of resource classification. Source: McKelvey, 1967.

Rogner et al. (2012)

Exhaustible resources

Table 7.1 | Fossil and uranium reserves, resources, and occurrences.[a]

	Historical production through 2005	Production 2005	Reserves	Resources	Additional occurrences
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
Conventional oil	6069	147.9	4900–7610	4170–6150	
Unconventional oil	513	20.2	3750–5600	11,280–14,800	> 40,000
Conventional gas	3087	89.8	5000–7100	7200–8900	
Unconventional gas	113	9.6	20,100–67,100	40,200–121,900	> 1,000,000
Coal	6712	123.8	17,300–21,000	291,000–435,000	
Conventional uranium[b]	1218	24.7	2400	7400	
Unconventional uranium	34	n.a.		7100	> 2,600,000

[a] The data reflect the ranges found in the literature; the distinction between reserves and resources is based on current (exploration and production) technology and market conditions. Resource data are not cumulative and do not include reserves.

[b] Reserves, resources, and occurrences of uranium are based on a once-through fuel cycle operation. Closed fuel cycles and breeding technology would increase the uranium resource dimension 50–60 fold. Thorium-based fuel cycles would enlarge the fissile-resource base further.

Rogner et al. (2012)

Exhaustible resources: Conventional Oil

Table 7.6 | Conventional oil reserves and resources.[a]

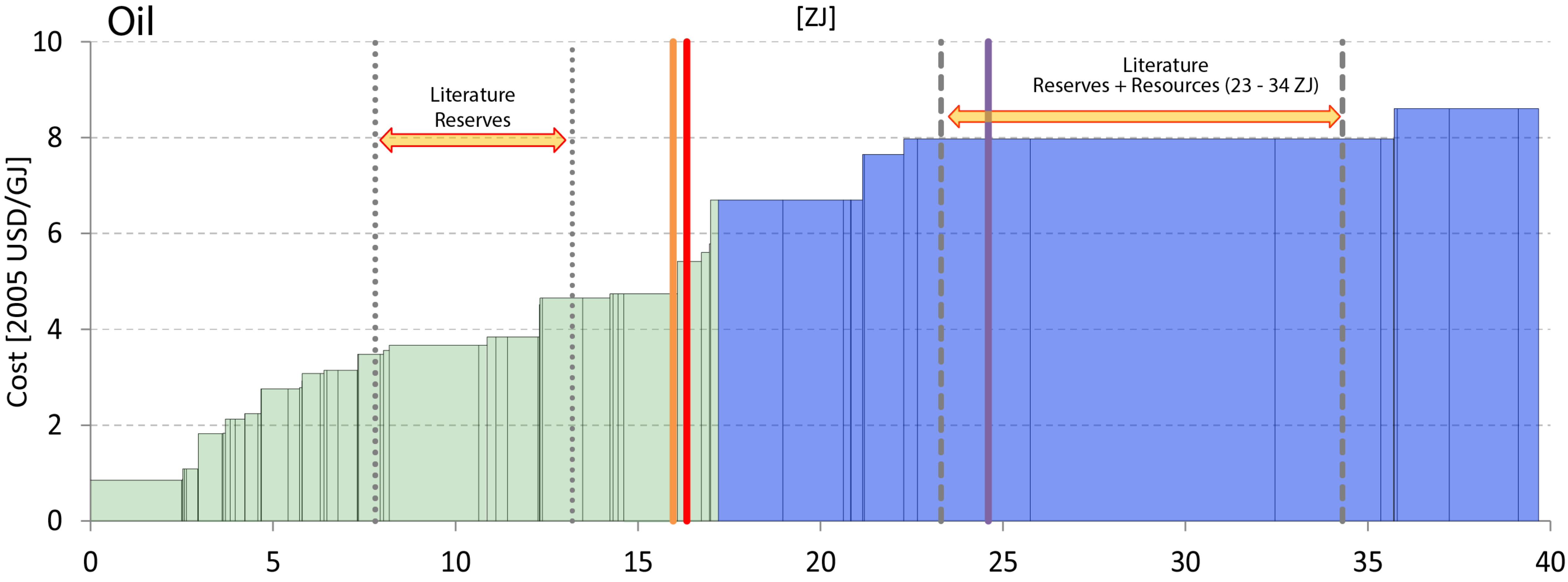
Region	Oil production 2009	Historical production till 2009	Reserves BP	Reserves BGR	Reserves USGS	Resources BGR	Resources USGS	Reserves + Resources BGR	Reserves + Resources USGS
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
USA	15.00	1246	162	162	183	420	476	582	659
CAN	6.70	200	189	28	36	101	21	129	57
WEU	8.98	329	74	88	179	186	492	275	671
EEU	0.28	47	4	6	15	13	11	19	26
FSU	27.64	1017	704	735	953	1008	952	1743	1906
NAF	10.38	336	389	388	252	184	158	573	410
EAF	0.00	0	0	4	0	13	7	17	7
WCA	6.07	214	263	254	142	302	375	556	517
SAF	3.78	48	77	77	24	150	97	227	121
MEE	50.78	1823	4308	4286	2967	889	1654	5175	4621
CHN	7.90	220	85	84	142	97	95	181	237
OEA	1.02	11	26	26	0	32	1	58	1
IND	1.57	46	33	33	40	17	18	50	58
OSA	0.14	4	4	2	3	13	11	15	13
JPN	0.01	2	0	0	0	0	0	1	0
OCN	1.20	41	25	24	94	44	108	69	202
PAS	4.90	203	68	65	22	88	63	153	86
LAC	20.30	862	1203	479	426	614	853	1093	1279
Circum-Arctic							768		768
Total	166.68	6647	7615	6742	5477	4172	6161	10914	11,638

[a] Includes natural gas liquids (NGLs). USA = United States of America; CAN - Canada; WEU = Western Europe, incl. Turkey; EEU = Central and Eastern Europe; FSU = Former Soviet Union; NAF = Northern Africa; EAF = Eastern Africa; WCA = Western and Central Africa; MEE = Middle East; CHN =China; OEA = Other East Asia; IND = India; OSA = Other South Asia; JPN =Japan; PAS = Other Pacific Asia; OCN = Australia, New Zealand, and other Oceania; LAC = Latin America and the Caribbean

Sources: author's estimate; BP, 2010; USGS, 2000; 2008; BGR, 2009; 2010.

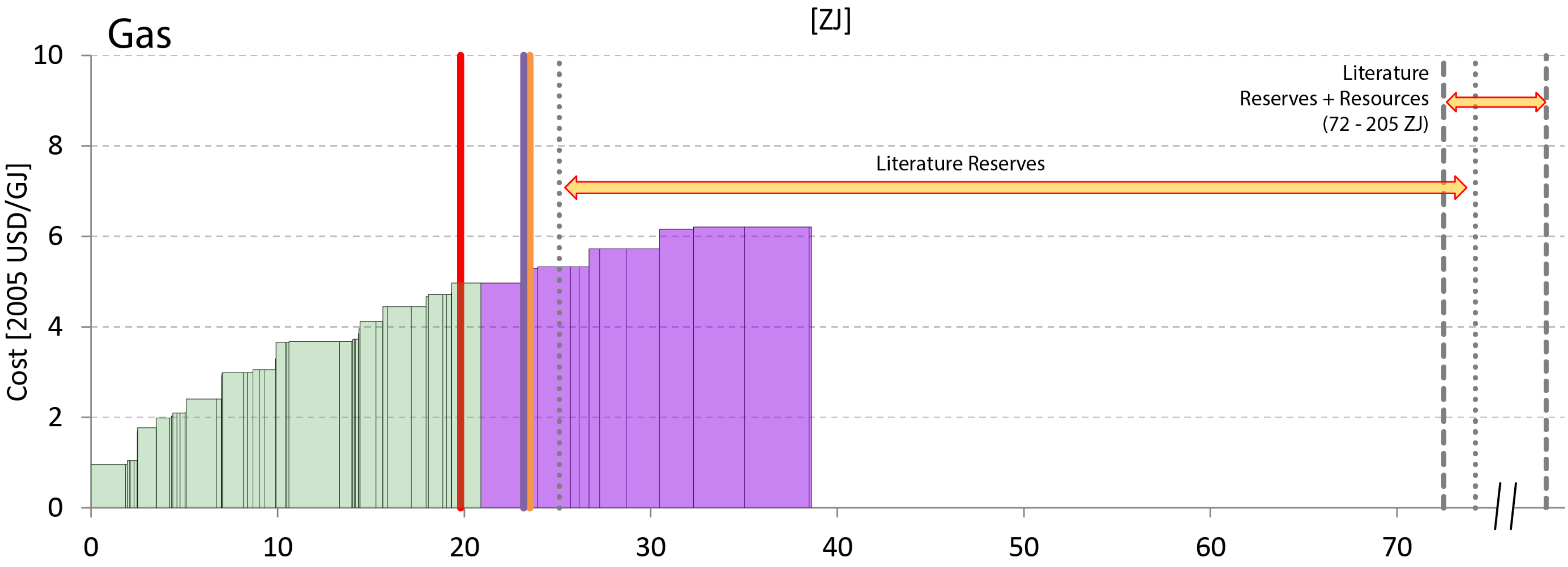
Rogner et al. (2012)

Supply Curves: Oil



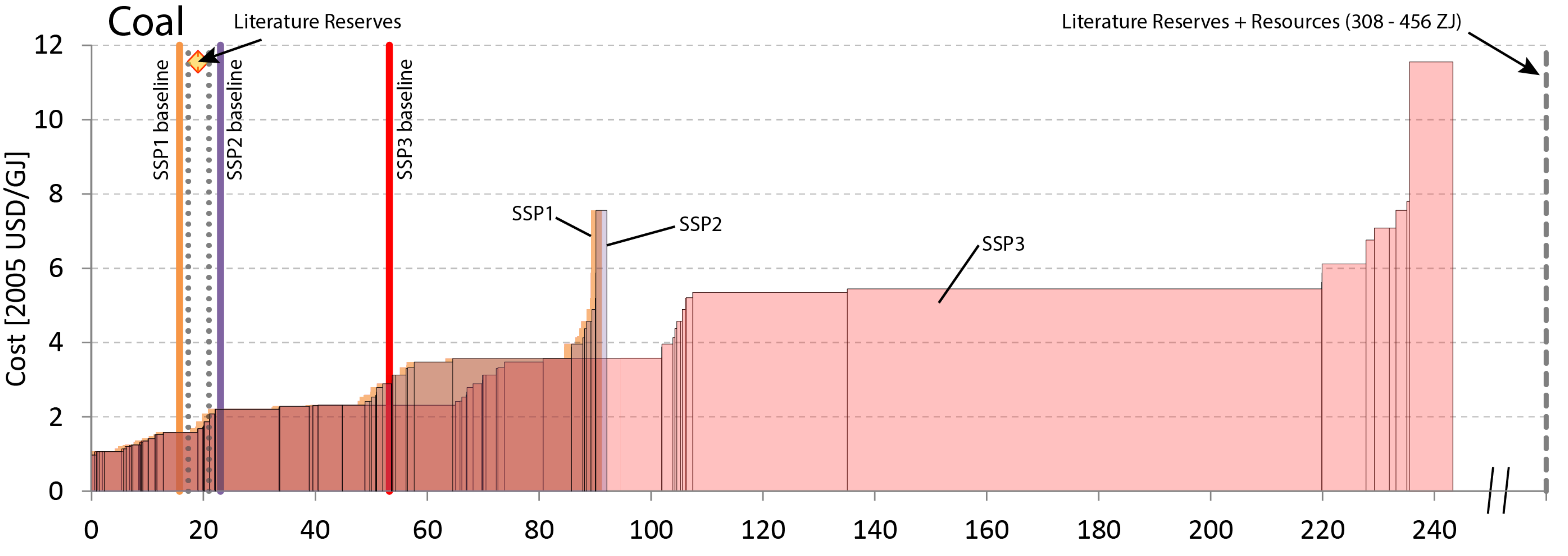
Fricko et al. (2017)

Supply Curves: Gas



Fricko et al. (2017)

Supply Curves: Coal



Fricko et al. (2017)

Renewable energy potential and flows

Table 7.2 | Renewable energy flows, potential, and utilization in EJ of energy inputs provided by nature.[a]

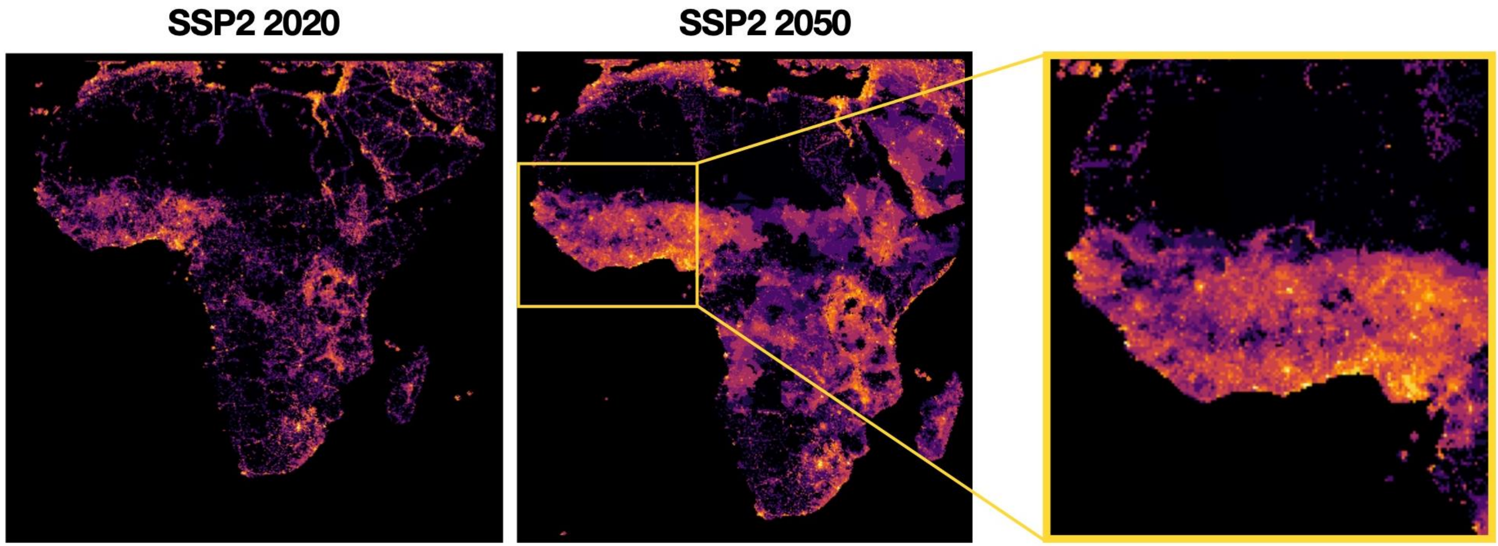
	Utilization 2005 [EJ]	Technical potential [EJ/a]	Annual flows [EJ/a]
Biomass, MSW, etc.	46.3	160–270	2200
Geothermal	2.3	810–1545	1500
Hydro	11.7	50–60	200
Solar	0.5	62,000–280,000	3,900,000
Wind	1.3	1250–2250	110,000
Ocean	–	3240–10,500	1,000,000

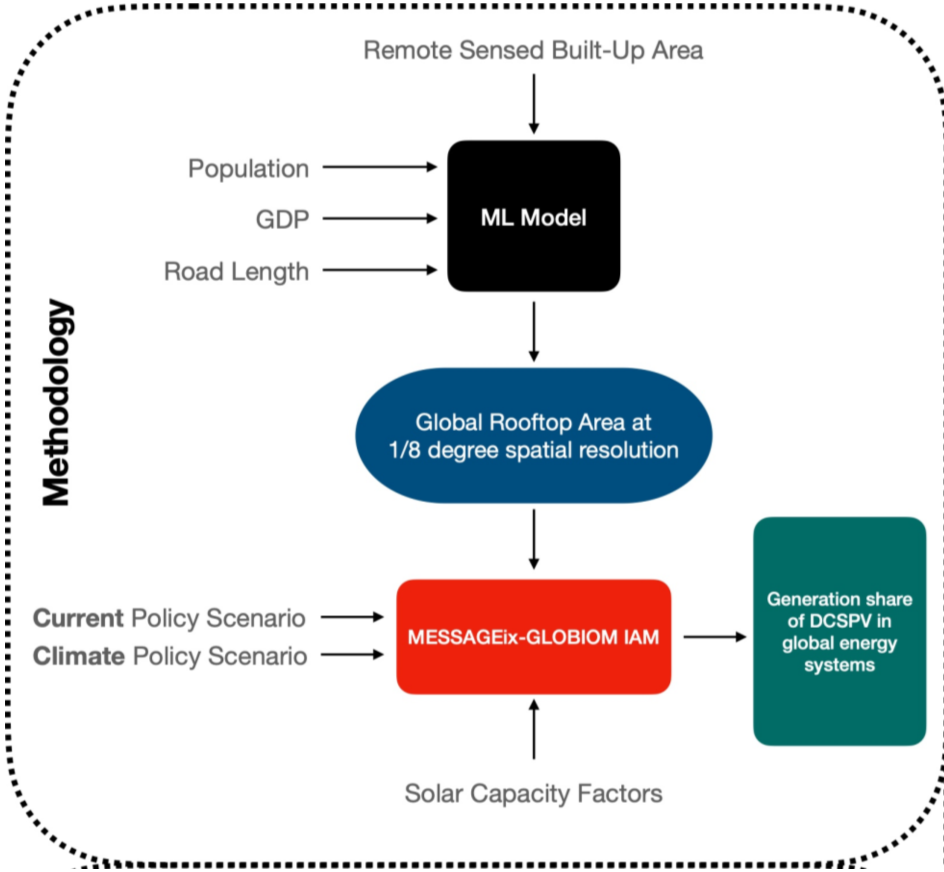
[a] The data are energy-input data, not output. Considering technology-specific conversion factors greatly reduces the output potentials. For example, the technical 3150 EJ/yr of ocean energy in ocean thermal energy conversion (OTEC) would result in an electricity output of about 100 EJ/yr.

Rogner et al. (2012)

Example: Decentralized solar PV potential

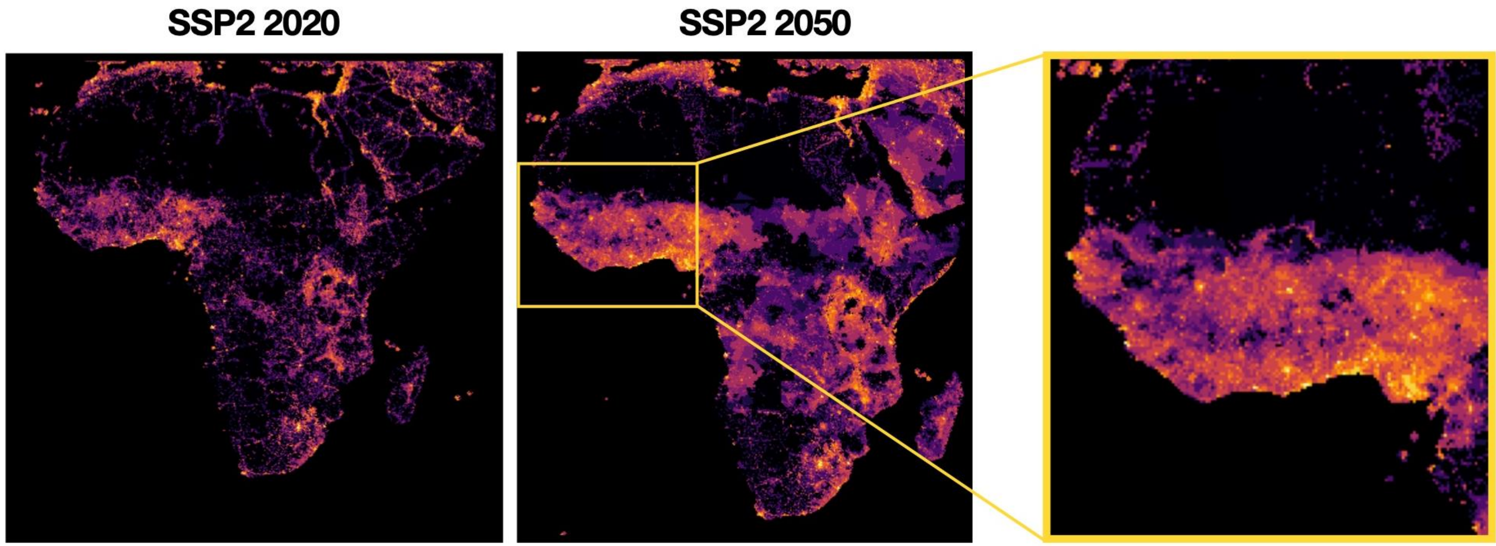
- Rooftop solar PV potential @30% rooftop coverage and 20% panel efficiency:
  - ⇒ ~21 PWh/yr (2020), 0.25 Mkm^2
  - ⇒ ~26-33 PWh/yr (2050, across SSPs)

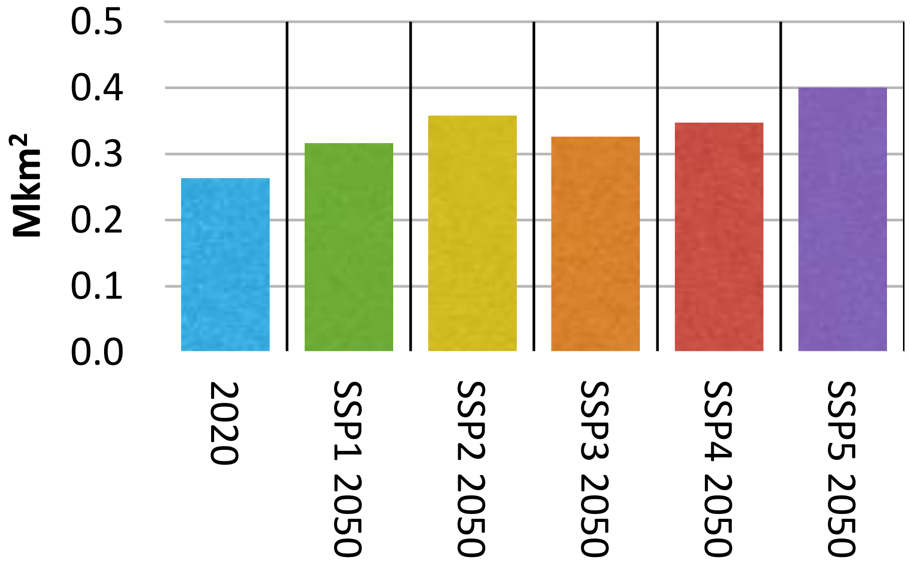


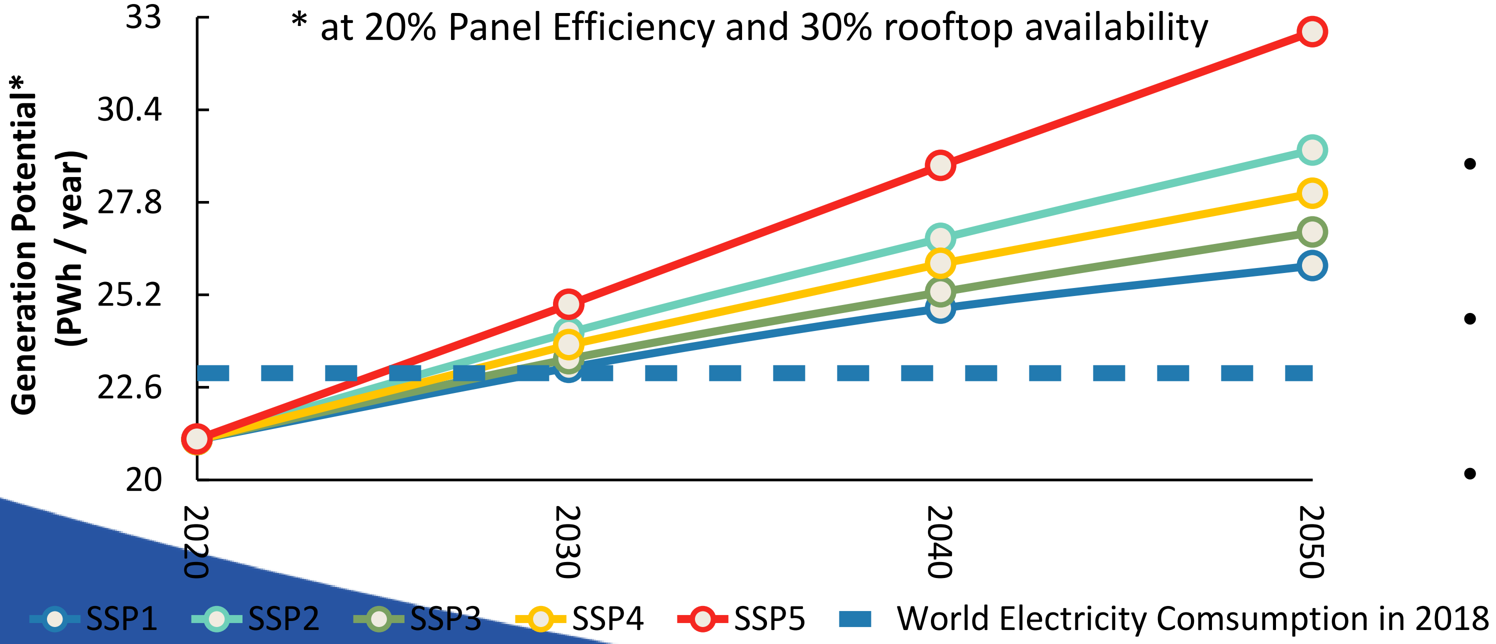


Source: Joshi et al. (2021), Joshi et al. (2024)

Example: Decentralized solar PV potential







- Machine learning approach to identify rooftop area
- Projection of build-up and rooftop area
- Translated into generation potential

Source: Joshi et al. (2021), Joshi et al. (2024)

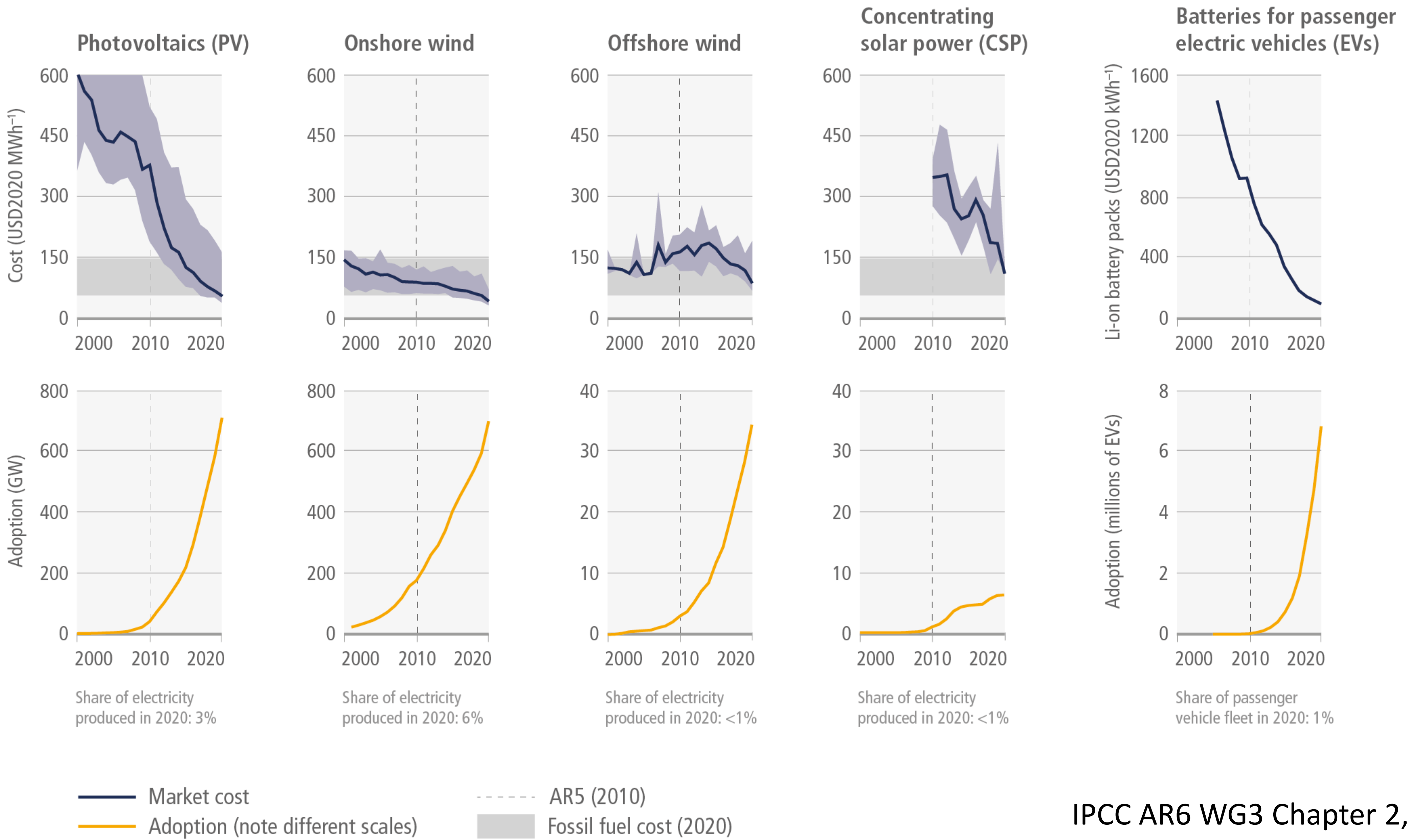
Techno-economic Parameters

- …

Techno-economic Parameters

- Cost attributes
  - ⇒ Investment Costs
  - ⇒ Fixed Operation and Maintenance Costs
  - ⇒ Variable Operation and Maintenance Costs (incl./excl. fuels)
- Capacity factor (maximum)
- Lifetime
- Operation Modes
  - ⇒ Input/Output of commodities (energy and other)
  - ⇒ Emission coefficients (CO2, others)
  - ⇒ Other services (e.g., system integration)
- Diffusion constraints (activity/capacity)

Technological Change: Granular learns faster



IPCC AR6 WG3 Chapter 2, Figure 2.22

A comparison of techno-economic assumptions

Contents lists available at ScienceDirect

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Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models

Volker Krey [a, b, *], Fei Guo [a], Peter Kolp [a], Wenji Zhou [a], Roberto Schaeffer [c], Aayushi Awasthy [d], Christoph Bertram [e], Harmen-Sytze de Boer [f, g], Panagiotis Fragkos [h], Shinichiro Fujimori [i, s], Chenmin He [j], Gokul Iyer [k], Kimon Keramidas [l], Alexandre C. Köberle [c, m], Ken Oshiro [n], Lara Aleluia Reis [o], Bianka Shoai-Tehrani [p], Saritha Vishwanathan [q], Pantelis Capros [h], Laurent Drouet [o], James E. Edmonds [k], Amit Garg [q], David E.H.J. Gernaat [f, g], Kejun Jiang [j], Maria Kannavou [h], Alban Kitous [l], Elmar Kriegler [e], Gunnar Luderer [e], Ritu Mathur [d], Matteo Muratori [r], Fuminori Sano [p], Detlef P. van Vuuren [f, g]

Research Background and Purposes

The electricity sector is robustly projected to decarbonize first under the 2°C target. However, the speed of this transition and the resulting technology mix in power generation can be very different across IAMs (Clarke et al. 2014).

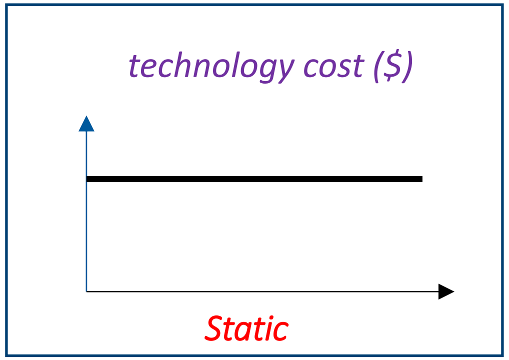
This can be attributed to three important differences across IAMs.

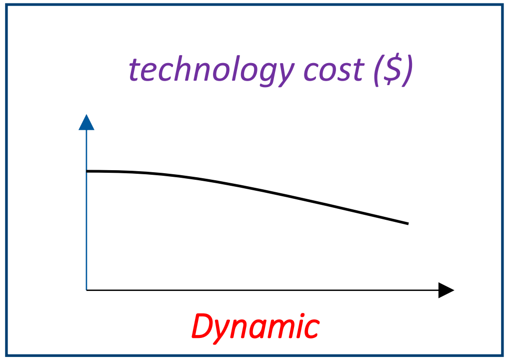
1. differences in the applied modeling methodologies;
2. the *representation* of different technology options;
3. the parameterization of technologies, typically referred to as *techno-economic assumptions*, within the power sector;

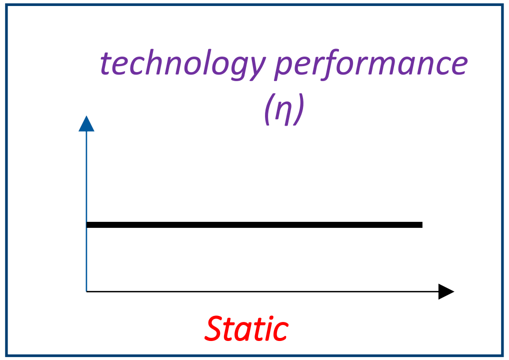
14 IAMs included in the study (7 global + national)

IAMs		Regional coverage	Time horizon	Time step	Developer
Global models	**DNE21+ V.12A**	Global (16 regions)	2050	5 years before 2030/ 10 years after 2030	**RITE, Japan**
	GCAM4.2_ADVANCE	Global (32 regions)	2100	5 years	**JGCRI/PNNL, USA**
	IMAGE 3.0	Global (26 regions)	2100	1-5 years	**PBL, Netherlands**
	MESSAGEix-GLOBIOM_1.0	Global (11 regions)	2100	10 years	**IIASA, Austria**
	POLES MILES	Global (24 regions)	2100	10 years	**EC-JRC, University of Grenoble, Enerdata, France**
	REMIND 1.6	Global (11 regions)	2100	5 years before 2060/ 10 years after 2060	**PIK, Germany**
	WITCH-GLOBIOM 4.4	Global (13 regions)	2150	5 years	**CMCC and FEEM, Italy**
National models	**BLUES**	Brazil (6 regions)	2050	5 years	**COPPE, Brazil**
	IPAC-AIM/technology_V1.0	China (1 region)	2050	10 years	**ERI, China**
	PRIMES_V1	EU (28 regions)	2050	5 years	**ICCS, Greece**
	AIM/Enduse[Japan]	Japan (10 regions)	2050	1 year	**NIES, Japan**
	DNE21+ V.MILES	Japan (1 region)	2050	5 years before 2030/ 10 years after 2030	**RITE, Japan**
	AIM/E-India [IIMA]	India (1 region)	2050	5 years	**IIMA, India**
	India MARKAL	India (1 region)	2050	5 years	**TERI, India**

Four basic strategies of techno-economic parameters in IAMs

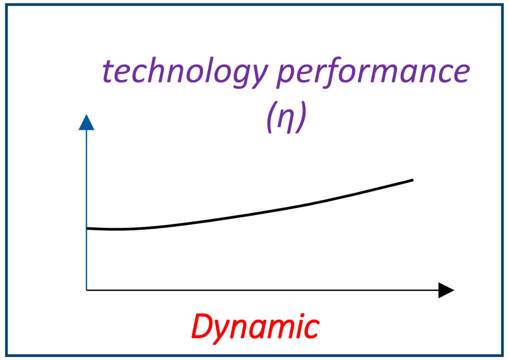






- AIM/Enduse[Japan]
- AIM/E-India [IIMA]
- India MARKAL

- BLUES
- MESSAGEix-GLOBIOM_1.0



- REMIND 1.6
- WITCH-GLOBIOM 4.4

- DNE21 +V.12A
- DNE21+ V.MILES
- GCAM 4.2_ADVANCE
- IMAGE 3.0
- POLES MILES
- IPAC-AIM/technology_V1.0
- PRIMES_V1

(using coal power plants as the example)

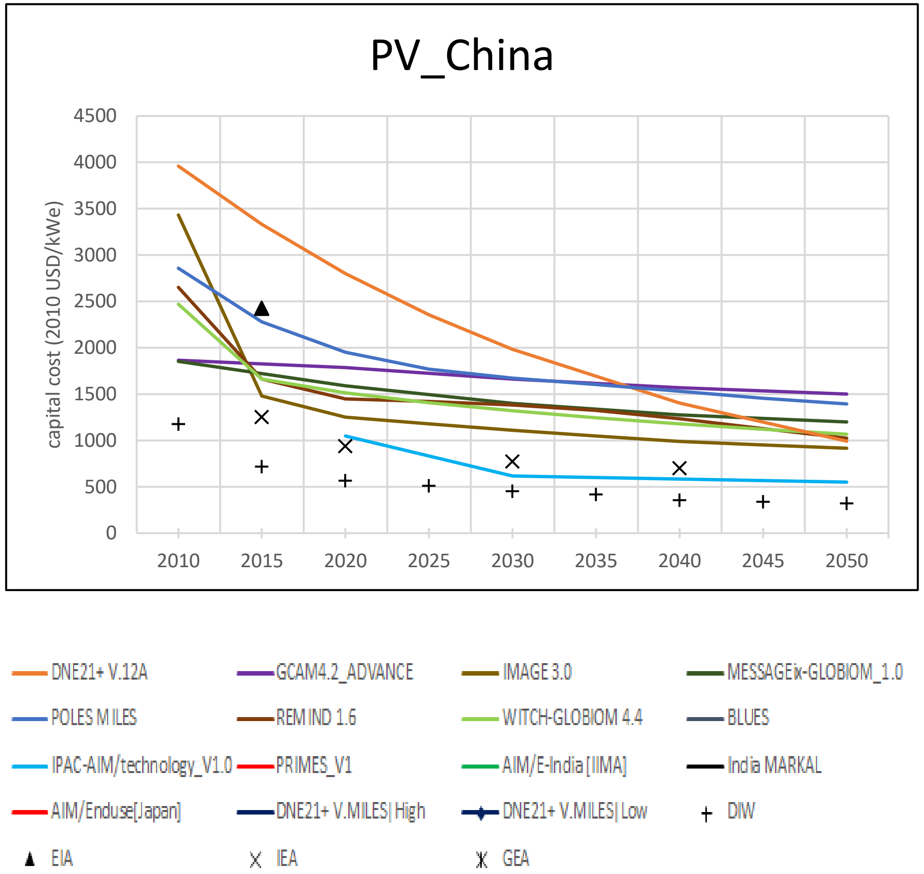
Regional technology variation in global IAMs

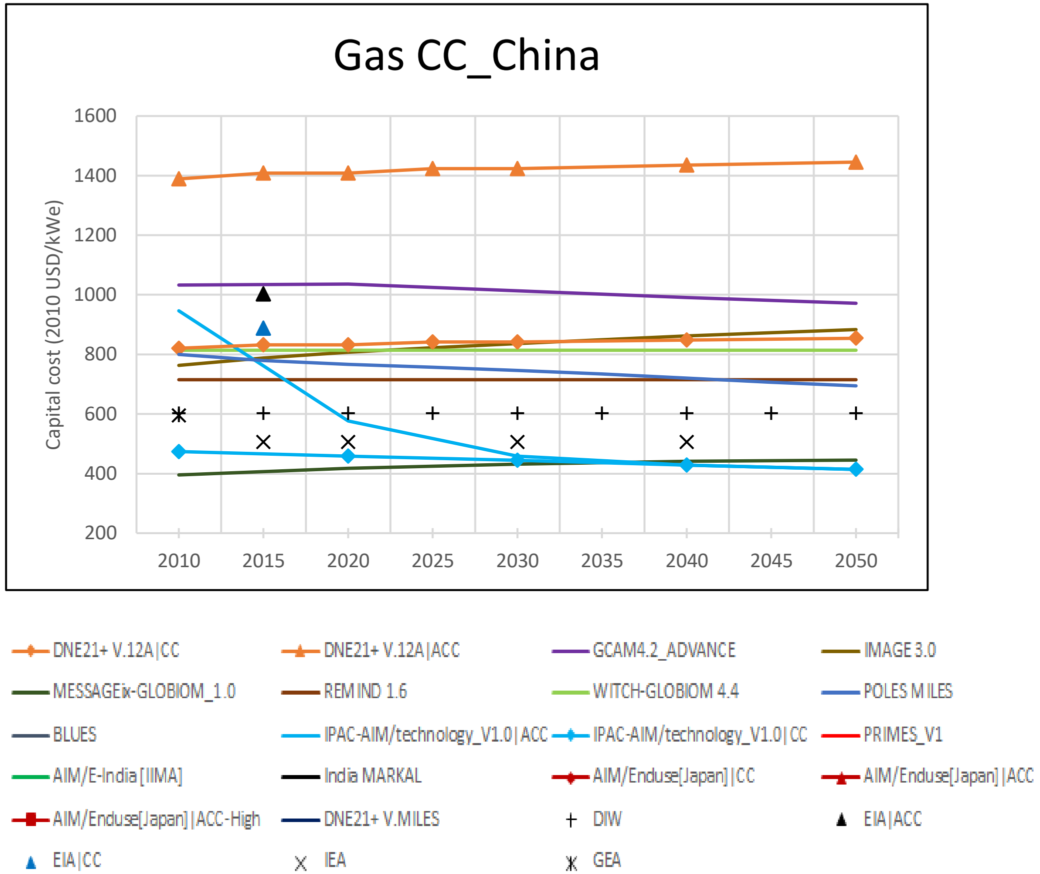
Note: Models are under different scenarios: “MESSAGEix-GLOBIOM_1.0” (NoPolicy_V3); “WITCH-GLOBIOM 4.4” and “DNE21+ V.12A” (AMPERE2-Base-FullTech-OPT); IEA Assessment (450ppm).

(using capital cost of combined cycle gas power plants as the example)

Capital cost

For the same region, capital cost of technology, assumed among different IAMs (both global and national), vary significantly.

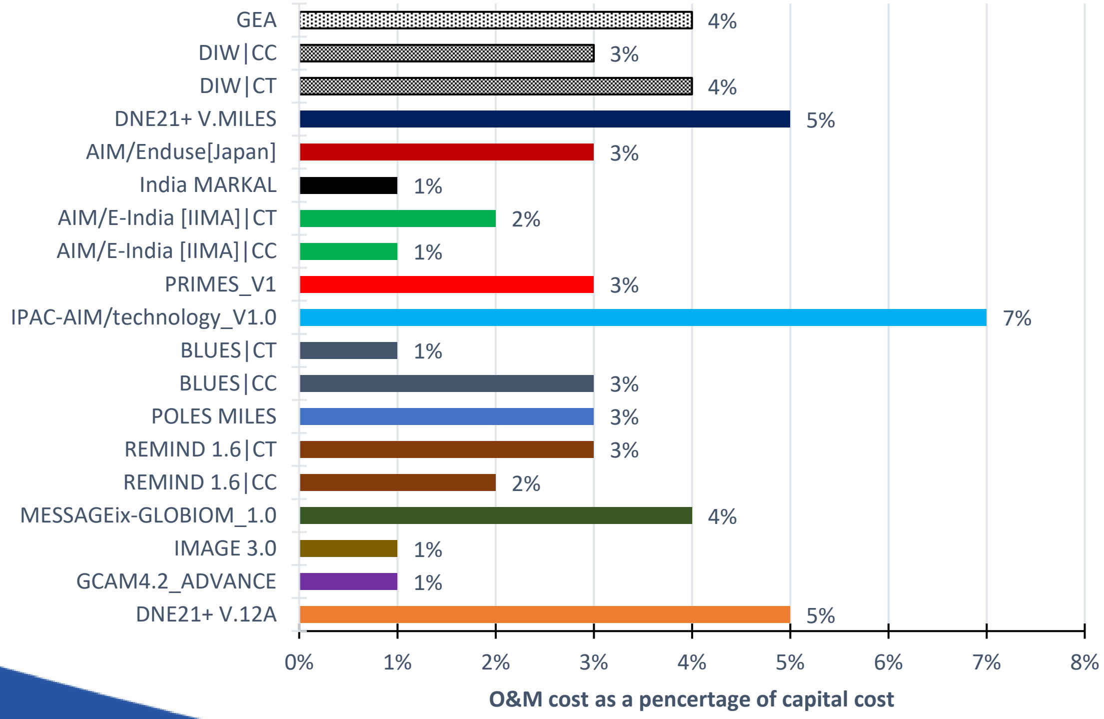


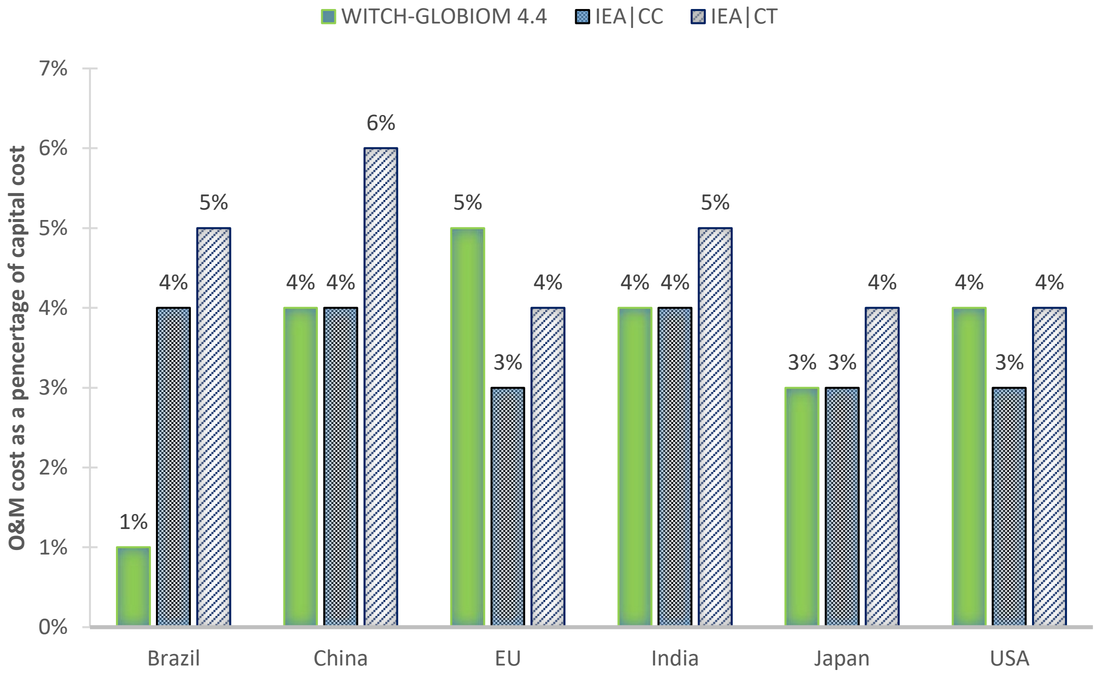


Note: for the comparison, data from a range of assessments including IEA (2016), EIA (2016a), DIW (2013) and GEA (2012) are also shown in the figures.

Fixed Operation and Maintenance cost

- O&M costs are usually assumed to be a fixed percentage of capital cost in IAMs the percentage does not change over time.
- However, in some IAMs the percentage varies across regions.

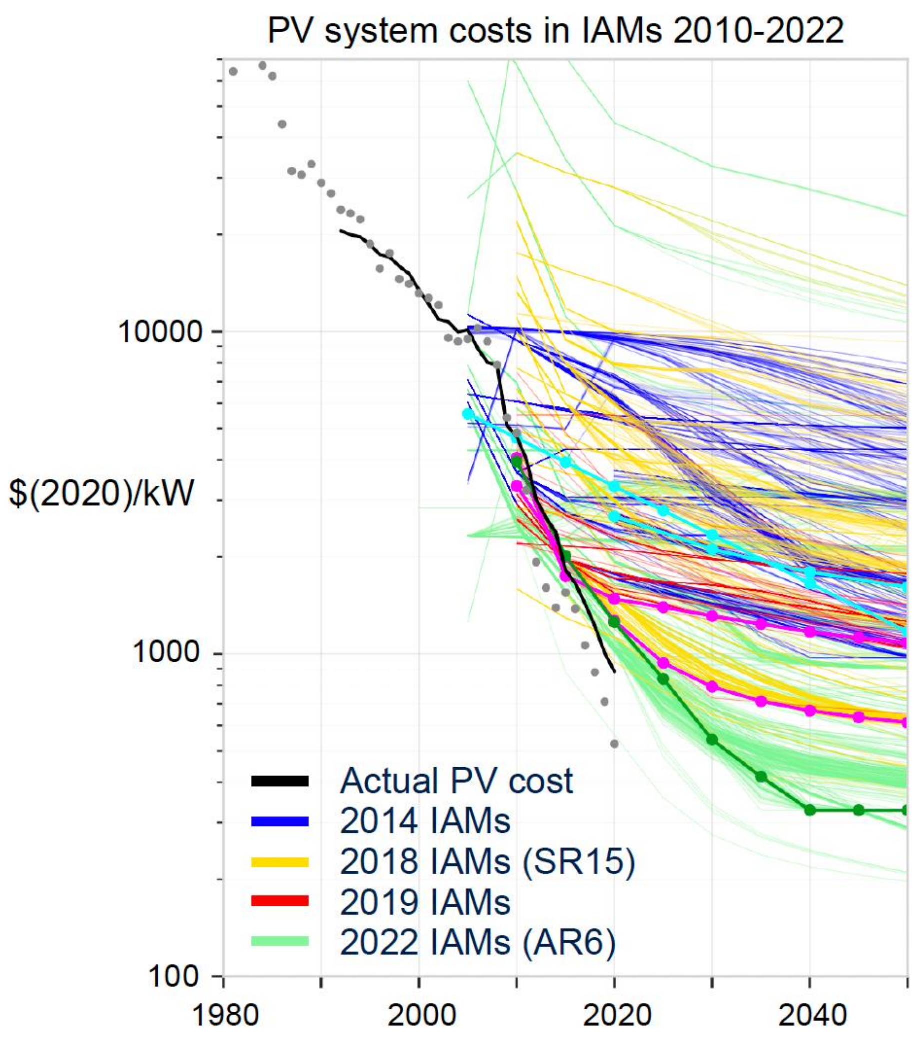




(using gas power plants as the example)

Challenge to keep up with technological change

- There are large differences in the structural representation and numerical parameterization of technologies across IAMs
- IAMs utilize a wide range of assumptions and inputs for techno-economic parameters



Source: Way et al (2022)

Input Datasets: MESSAGEix-GLOBIOM

Land-use Emulator

Resources | Primary | Secondary | Final | Useful

Extraction

Fossils: Rogner et al., 1997 and 2012.
- Federal Institute for Geosciences and Natural Resources (BGR)
- U.S. Geological Survey (USGS)

Renewables
- NREL

Heat generation

Liquid production

Electricity generation

Gas production

- *Capacity*: Platts
- *Activity*: IEA
- *Costs*: World Energy Outlook, IRENA, EIA, JRC and others

- Activity: IEA

Vehicle groupings

Industrial processes

Heating and cooking

Demands: “Scenario-Generator” using SSP-drivers

Emissions and pollutants (non-land-use):
- GAINS
- US-EPA
- RCP
- EDGAR
- McJeon
- Velders

MACRO

GLOBIOM-G4M Lookup-tables
- FAO
- EPIC

IEA Energy Balances

Spreadsheets contain more detailed information

IIASA

Austria / Autriche : 2000

Units

TJ

GWh

TJ

Million tonnes of oil equivalent / *Million de tonnes d'équivalent pétrole*

SUPPLY AND CONSUMPTION *APPROVISIONNEMENT ET DEMANDE*	Coal *Charbon*	Crude Oil *Pétrole brut*	Petroleum Products *Produits pétroliers*	Gas *Gaz*	Nuclear *Nucléaire*	Hydro *Hydro*	Geotherm. Solar etc. *Géotherm. solaire etc.*	Combust. Renew. & Waste *En. ren. combust. & déchets*	Electricity *Electricité*	Heat *Chaleur*	Total *Total*
Production	0.29	1.02	-	1.53	-	3.61	0.07	3.16 e	-	-	9.69
Imports	2.99	7.69	4.38	5.27	-	-	-	0.11	1.19	-	21.62
Exports	-0.00	-0.14	-1.34	-0.01	-	-	-	-0.16	-1.31	-	-2.96
Intl. Marine Bunkers	-	-	-	-	-	-	-	-	-	-	-
Stock Changes	0.31	0.03	0.15	-0.27	-	-	-	-	-	-	0.23
TPES	**3.59**	**8.61**	**3.20**	**6.52**	**-**	**3.61**	**0.07**	**3.11**	**-0.12**	**-**	**28.58**
Transfers	-	0.05	-0.03	-	-	-	-	-	-	-	0.02
Statistical Differences	-	-0.04	-0.04	0.00	-	-	-	-	-	-	-0.07
Electricity Plants	-0.43	-	-0.15	-0.16	-	-3.61	-0.01	-0.04	3.95	-	-0.46
CHP Plants	-1.01	-	-0.37	-1.53	-	-	-	-0.32	1.24	0.77	-1.22
Heat Plants	-0.00	-	-0.06	-0.13	-	-	-0.01	-0.26	-0.00	0.38	-0.08
Gas Works	-	-	-	-	-	-	-	-	-	-	-
Petroleum Refineries	-	-8.62	9.05	-	-	-	-	-	-	-	0.42
Coal Transformation	-0.87 e	-	-	-	-	-	-	-	-	-	-0.87
Liquefaction Plants	-	-	-	-	-	-	-	-	-	-	-
Other Transformation	-	-	-	-	-	-	-	-	-	-	-
Own Use	-0.11	-	-0.56	-0.24	-	-	-	-	-0.22	-	-1.12
Distribution Losses	-	-	-	-	-	-	-	-	-0.35	-0.10	-0.45
TFC	**1.16**	**-**	**11.05**	**4.46**	**-**	**-**	**0.05**	**2.48**	**4.50**	**1.05**	**24.75**
Electricity Generated - GWh	***6693***	***-***	***1991***	***7857***	***-***	***41995***	***70***	***1715***	***-***	***-***	***60321***
Electricity Plants	*2118*	*-*	*769*	*857*	*-*	*41995*	*70*	*141*	*-*	*-*	*45950*
CHP plants	*4575*	*-*	*1222*	*7000*	*-*	*-*	*-*	*1574*	*-*	*-*	*14371*
Heat Generated - TJ	***2884***	***-***	***8886***	***24310***	***-***	***-***	***378***	***11595***	***39***	***-***	***48092***
CHP plants	*2844*	*-*	*7152*	*19348*	*-*	*-*	*-*	*2779*	*-*	*-*	*32123*
Heat Plants	*40*	*-*	*1734*	*4962*	*-*	*-*	*378*	*8816*	*39*	*-*	*15969*

Source: IEA Energy Balances 2008

Thank you very much for your attention!