A multi-model framework to assess the role of R&D towards a decarbonized energy system

Supplementary Information

The supplementary information provides extra and complementary information regarding the methodology and results of our study. Section A describes and compares the main models taking part in the study (WITCH, MERGE-ETL, GEM-E3 and TIAM-ECN), while section B reports the main quantitative parameters adopted by the models with ITC. Section C shows assumptions regarding technologies and policies and section D shows additional figures detailing the results obtained with TIAM-ECN that complement the discussion carried out in our paper.

A. Additional Information to the Methodological Approach

Figure S.1 illustrated the soft-link and the harmonization among the four models considered in this study, as explained in section 2.1 of the paper:

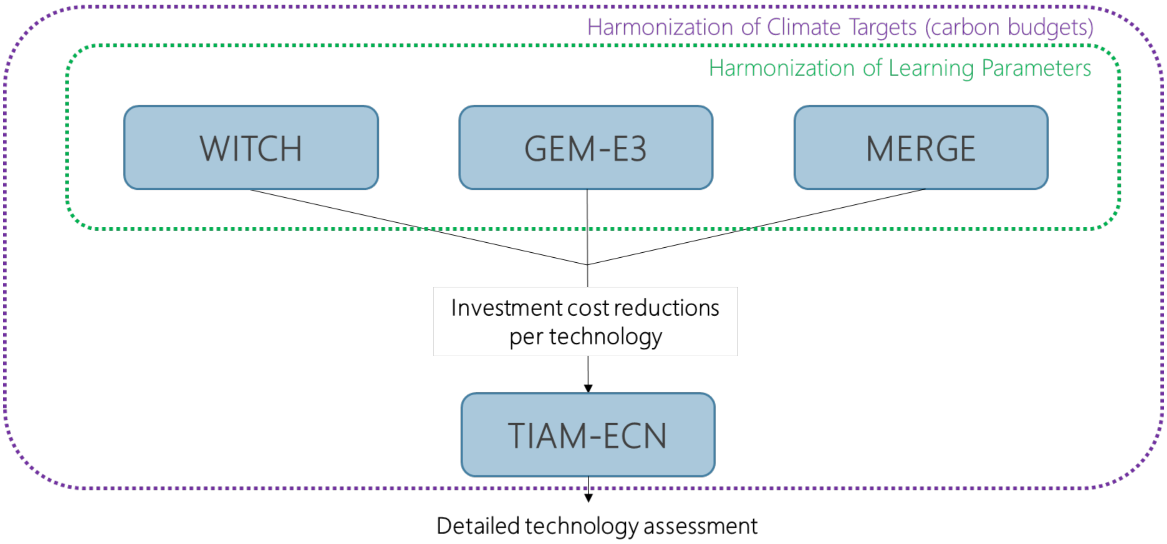

Figure S.1 - Harmonization scheme and soft-link adopted in this study.

A.1. WITCH, MERGE and GEM-E3: IAMs and Endogenous R&D

The three IAMs with ITC employed in this study differ in a number of aspects, such as the regional disaggregation, the temporal resolution, the level of detail in the representation of the different energy and economic sectors, and the technology portfolio (see Table 1). GEM-E3 is a computable general equilibrium (CGE) model with a detailed representation of economy, while MERGE-ETL and WITCH are hybrid models with a single-sector economy description combined with a detailed representation of the energy system. Still, MERGE-ETL and WITCH differ with respect to the representation of energy sectors, especially in the demand side. A commonality between the three IAMs is that they have perfect foresight in their decisions.

All three IAMs endogenously account for ITC based on two-factor learning curves, thus incorporating a set of parameters related to learning effects from experience (or learning-by-doing, LBD) and from R&D (or learning-by-researching, LBR). The two-factor learning curve is a common approach to assess technology learning leading to cost reductions in the energy sector (Rubin et al., 2015; Emmerling et al. 2016, Paroussos et al. 2019, Fragkiadakis 2020, Verdolini et al. 2018). It is based on the cumulative installed capacity (or production) and on the cumulative R&D expenditure, which are reflected on the LBD and LBR rates, respectively (Rubin et al., 2015; Söderholm and Sundqvist, 2007; Kouvaritakis et al.

2000, van der Zwaan and Seebregts, 2004). Some IAMs also include other parameters related to R&D: WITCH and GEM-E3 integrate regional specific knowledge spill-over assumptions to depict the dependence of a region to innovate based on knowledge created elsewhere (Emmerling et al. 2016, Fragkiadakis et al 2019 and 2020). GEM-E3 is also able to include the capacity of a region to absorb knowledge depending on its human capital (Fragkiadakis et al., 2019). In MERGE-ETL and GEM-E3, R&D in one technology may benefit other technologies through direct improvements in common components and methods or through technological spill-overs (see Fragkiadakis et al., 2019; Marcucci, 2014). Because of the ITC feature in these IAMs, the effect of R&D assumptions can be observed in the resulting capital costs of energy technologies. Therefore, we make this the main link between these three models and TIAM-ECN. Because of their intrinsic differences, the three IAMs with ITC will respond differently to the R&D and climate policy assumptions that define our scenarios, thus producing distinct trajectories for the evolution of capital costs of the technologies assessed in this paper.

For further details on the three IAMs with ITC used in this study, we refer the reader to the model documentation of WITCH (Emmerling et al., 2016), MERGE-ETL (Marcucci and Turton, 2015; Marcucci, 2014) and GEM-E3 (Capros et al., 2017).

A.2. TIAM-ECN: Bottom-up IAM and Technology Diffusion

TIAM-ECN (operated by the Energy Transition Unit of TNO) is based on the ETSAP-TIAM, a global energy system cost-optimization model built upon the TIMES model generator (see Loulou and Labriet, 2008; Loulou, 2008; Syri et al., 2008). It minimizes discounted global energy system's cost based on a partial equilibrium in order to meet end-use service demands subject to a diverse set of constraints. Energy flows and energy conversion technologies are linked from resource level to final use, hence encompassing all main economic sectors, namely: fossil fuels extraction, power and heat supply, industry, transport, built environment and agriculture. Direct links between energy, economy and environment are thus explicitly represented in the model.

One remarkable feature of TIAM-ECN is its technology richness and high regional disaggregation – it spans more than a thousand technologies across 36 geographical regions. This has allowed us answering a diverse set of research questions related to the energy transition at regional and national levels (see, for instance, [references removed]). Technology cost assumptions are usually exogenously defined and, in this study, it is the key variable we use to investigate how combining R&D policies with CO_2 mitigation targets can affect the long-term technology mix.

TIAM-ECN includes exogenous demand projections for different energy end-uses in all economic sectors and regions. These energy service demand projections are fully aligned with SSP2 socio-economic assumptions (Riahi et al., 2017), which are also adopted as reference by the other three models. Moreover, TIAM-ECN accounts for price elasticity of demand, which partially incorporates the impacts of policies on end-use energy consumption.

The table below provides a structured comparison of all models used in this study in order to summarize their main differences and similarities:

Table S.1 – Basic characteristics of the models used in this study.

Model Characteristics	TIAM-ECN	WITCH	MERGE	GEM-E3

Model Framework	Energy System (Bottom-Up)	Top-down, bottom up (Hybrid)	Top-down, bottom-up (Hybrid)	Hybrid CGE
Number of Technologies	1200	28	30	51
Number of Regions	36	18	10	19* (46 if EU28 is disaggregated)
Time Horizon (years)	120	150	120	45
Time-Step (years)	10	5	10	5
Technological Learning	Exogenous	Endogenous	Endogenous	Endogenous

*In this study, EU28 is considered one single region. The number of regions can reach 46 if EI28 is disaggregated.

B. R&D Parameters

Table S.2 - Learning parameters harmonized in WITCH, MERGE-ETL and GEM-E3

Sector	**Learning by doing**			**learning by research rates**			**Time from investment to cost reduction**	**Knowledge depreciation rate**
	2015-2030	**2030-2050**	**2050-2100**	**2015-2030**	**2030-2050**	**2050-2100**		
Advanced biofuels	0.08	0.04	0.02	0.13	0.13	0.13	5	0.05
CCS	0.05	0.05	0.05	0.03	0.03	0.03	5	0.05
DACC	0.15	0.15	0.08				5	0.05
Wind onshore	0.059	0.059	0.03	0.17	0.17	0.17	5	0.05
Wind offshore	0.103	0.05	0.03	0.17	0.17	0.17	5	0.05
Solar PV	0.18	0.18	0.09	0.12	0.12	0.12	5	0.05
Battery	0.20	0.15	0.08	0.27	0.27	0.27	5	0.05

Table S.3 - Floor costs harmonized in WITCH, MERGE-ETL and GEM-E3. Regionalization based on WITCH model. (Note: bra – Brazil; can – Canada; chi – China; eu – Europe; ind – India; indn – Indonesia; jpnkor – Japan and South Korea; laca - Latin America and Caribbean; mena – Middle East and North Africa; mex – Mexico; oce – oceania; sasia – South Asia; seasia – Southeast Asia ; sa – South Africa; ssa – Subsaharan Africa; te - Non-EU Eastern European countries, including Russia; usa – United States of America)

Floor costs [T$2005/TW]	**bra**	**can**	**chi**	**eu**	**ind**	**indn**	**jpnkor**	**laca**	**mena**	**mex**	**oce**	**sasia**	**seasia**	**sa**	**ssa**	**te**	**usa**
Advanced biofuels																	
Power plant | Coal | CCS | Standard	1.51	2.07	0.97	1.46	1.00	0.98	1.95	1.51	2.07	1.51	1.26	1.00	0.98	1.16	2.07	1.44	1.44
Power plant | Coal | CCS | Oxy-fuel	1.51	2.07	0.97	1.46	1.00	0.98	1.95	1.51	2.07	1.51	1.26	1.00	0.98	1.16	2.07	1.44	1.44
Power plant | Coal | CCS | Integrated gasification combined cycle	1.51	2.07	0.97	1.46	1.00	0.98	1.95	1.51	2.07	1.51	1.26	1.00	0.98	1.16	2.07	1.44	1.44
Power plant | Gas | CCS	0.98	1.05	0.74	0.75	0.74	0.74	0.99	0.98	1.05	0.98	0.68	0.74	0.74	0.63	1.05	0.73	0.66
Power plant | Biomass | CCS | Integrated gasification combined cycle	2.00	2.50	1.60	2.00	1.60	1.60	2.43	2.00	2.50	2.00	2.05	1.60	1.60	2.00	2.50	2.00	2.00
Wind onshore	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Wind offshore	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Solar PV	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Solar CSP	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Battery																	
Energy efficiency																	
Direct Air capture	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06

Table S.4 – Initial Knowledge Stock harmonized in WITCH, MERGE-ETL and GEM-E3. Regionalization based on WITCH model. (Note: bra – Brazil; can – Canada; chi – China; eu – Europe; ind – India; indn – Indonesia; jpnkor – Japan and South Korea; laca - Latin America and Caribbean; mena – Middle East and North Africa; mex – Mexico; oce – oceania; sasia – South Asia; seasia – Southeast Asia ; sa – South Africa; ssa – Subsaharan Africa; te - Non-EU Eastern European countries, including Russia; usa – United States of America)

Initial knowledge stock [G$2005]	**bra**	**can**	**chi**	**eu**	**ind**	**indn**	**jpnkor**	**laca**	**mena**	**mex**	**oce**	**sasia**	**seasia**	**sa**	**ssa**	**te**	**usa**
Advanced biofuels	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
Power plant | Coal | CCS | Standard	0	0,8	0	0,9	0	0	0,4	0	0	0	0,3	0	0	0	0	0	1
Power plant | Coal | CCS | Oxy-fuel	0	0,8	0	0,9	0	0	0,4	0	0	0	0,3	0	0	0	0	0	1
Power plant | Coal | CCS | Integrated gasification combined cycle	0	0,8	0	0,9	0	0	0,4	0	0	0	0,3	0	0	0	0	0	1
Power plant | Gas | CCS	0	0,8	0	0,9	0	0	0,4	0	0	0	0,3	0	0	0	0	0	1
Power plant | Biomass | CCS | Integrated gasification combined cycle	0	0,8	0	0,9	0	0	0,4	0	0	0	0,3	0	0	0	0	0	1
Wind onshore																	
Wind offshore																	
Solar PV																	
Solar CSP																	
Battery	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Energy efficiency	0,8	6,0	2,2	35,2	0,8	0,3	24,2	0,8	1,0	0,4	2,6	0,0	0,3	0,7	0,0	1,3	41,5
Direct Air capture																	

C. Technology and Policy Assumptions

Table S.5 - Technology portfolio to which investment cost reductions were applied

Technology description	**WITCH**	**MERGE-ETL**	**GEM-E3**	**TIAM-ECN**
Hydrogen from gas steam reforming	Advanced Biofuels	gas-H2	-	HNGA105
Hydrogen from gas steam reforming	Advanced Biofuels	gas-H2	-	HNGAD105 (decentralized)
Hydrogen from gas steam reforming with CCS	Advanced Biofuels	gas-a-H2	CCSequipmn	HZNGA120
Coal Fischer Tropsch	Advanced Biofuels	coal-FT	-	UFTSYNCOA
Coal Fischer Tropsch with CCS	Advanced Biofuels	coal-a-FT	CCSequipmn	UFTSYNCOACCS
Hydrogen from coal gasification	Advanced Biofuels	coal-H2	-	HHCO105
Hydrogen from coal gasification	Advanced Biofuels	coal-H2	-	HBCO105
Hydrogen from coal gasification with CCS	Advanced Biofuels	coal-a-H2	CCSequipmn	HZHCO120 (hard coal)
Hydrogen from coal gasification with CCS	Advanced Biofuels	coal-a-H2	CCSequipmn	HZBCO120 (brown coal)
Biomass Fischer Tropsch	Advanced Biofuels	bio-FT	AdvBiofuels	UFTDBIOSLD110
Biomass Fischer Tropsch with CCS	Advanced Biofuels	bio-a-FT	AdvBiofuels	UZFTDBIOSLD110
Hydrogen from biomass gasification	Advanced Biofuels	bio-H2	AdvBiofuels	HBIO105
Hydrogen from biomass gasification with CCS	Advanced Biofuels	bio-a-H2	AdvBiofuels	HZBIO120
Hydrogen from solar thermal	Advanced Biofuels	sth-H2	-	HLYS120
High pressure electrolysis	Advanced Biofuels	hpe-H2	-	HLYSI05
High pressure electrolysis	Advanced Biofuels	hpe-H2	-	HLYSDI05 (decentralized)

Electric car	Battery	-	EVehiclesEq	TRCELC010
Gasoline plug-in hybrid car	Electric Vehicles	-	EVehiclesEq	TRCGASPHY010
Diesel plug-in hybrid car	Electric Vehicles	-	EVehiclesEq	TRCDSTPHY010
Electric truck for freight transport	Electric Vehicles Freight	-	EVehiclesEq	TRTELC005
Biomass thermal with CCS	Power plant | Biomass | CCS | Integrated gasification combined cycle	bio-a	CCSequipmn	EZBIOSLD120
Biomass thermal with CCS	Power plant | Biomass | CCS | Integrated gasification combined cycle	bio-a	CCSequipmn	EZBIOSLD130 (efficiency improvement)
Biomass thermal with CCS	Power plant | Biomass | CCS | Integrated gasification combined cycle	bio-a	CCSequipmn	EZBIOSLD150 (efficiency improvement)
Integrated coal gasification with CCS	Power plant | Coal | CCS | Integrated gasification combined cycle	igcc-a	CCSequipmn	EZIGC1110
Integrated coal gasification with CCS	Power plant | Coal | CCS | Integrated gasification combined cycle	igcc-a	CCSequipmn	EZIGC1120 (efficiency improvement)
Integrated coal gasification with CCS	Power plant | Coal | CCS | Integrated gasification combined cycle	igcc-a	CCSequipmn	EZIGC1130 (efficiency improvement)
Integrated coal gasification with CCS	Power plant | Coal | CCS | Integrated gasification combined cycle	igcc-a	CCSequipmn	EZIGC925 (for synfuel production)
concentrated solar power	Solar CSP	-	-	ESOTH105
concentrated solar power	Solar CSP	-	-	ESOTHS205 (1h storage)
concentrated solar power	Solar CSP	-	-	ESOTHS305 (7.5h storage)

concentrated solar power	Solar CSP	-	-	ESOTHS305 (15h storage)
Gas turbine combined cycle with CCS	Power plant | Gas | CCS	ngcc-a	CCSequipmn	EZCCGT110 (post-combustion)
Gas turbine combined cycle with CCS	Power plant | Gas | CCS	ngcc-a	CCSequipmn	EZCCGT120 (post-combustion with efficiency improvement)
Gas turbine combined cycle with CCS	Power plant | Gas | CCS	ngcc-a	CCSequipmn	EZCCGT130 (post-combustion with efficiency improvement)
Gas turbine combined cycle with CCS	Power plant | Gas | CCS	ngcc-a	CCSequipmn	EZCCGO110 (oxyfuel)
Gas turbine combined cycle with CCS	Power plant | Gas | CCS	ngcc-a	CCSequipmn	EZCCGO120 (oxyfuel with efficiency improvement)
Gas turbine combined cycle with CCS	Power plant | Gas | CCS	ngcc-a	CCSequipmn	EZCCGO130 (oxyfuel with efficiency improvement)
Gas turbine combined cycle with CCS	Power plant | Gas | CCS	ngcc-a	CCSequipmn	EZSOFGAS35 (solid oxyfuel)
Coal supercritical with CCS	Power plant | Coal | CCS | Standard	pc-a	CCSequipmn	EZPCOA110 (post-combustion)
Coal supercritical with CCS	Power plant | Coal | CCS | Standard	pc-a	CCSequipmn	EZPCOA120 (post-combustion with efficiency improvement)

Coal supercritical with CCS	Power plant | Coal | CCS | Standard	pc-a	CCSequipmn	EZPCOA130 (post-combustion with efficiency improvement)
Coal supercritical with CCS	Power plant | Coal | CCS | Standard	pc-a	CCSequipmn	EZSOFCOA35 (solid oxyfuel)
Coal supercritical with CCS	Power plant | Coal | CCS | Oxy-fuel	pc-a	CCSequipmn	EZOCOA110(oxyfuel)
Coal supercritical with CCS	Power plant | Coal | CCS | Oxy-fuel	pc-a	CCSequipmn	EZOCOA120 (oxyfuel with efficiency improvement)
Coal supercritical with CCS	Power plant | Coal | CCS | Oxy-fuel	pc-a	CCSequipmn	EZOCOA130 (oxyfuel with efficiency improvement)
Solar PV	Solar PV	spv	PVpanels	ESOPV0105
Solar PV	Solar PV	spv	PVpanels	ESOPV105 (cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPV1105 (cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPV2105 (cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPV3105 (cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPV4105 (cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPV5105 (cost reduction)

Solar PV	Solar PV	spv	PVpanels	ESOPVD0105 (decentralized)
Solar PV	Solar PV	spv	PVpanels	ESOPVD105 (decentralized with cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPVD1105 (decentralized with cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPVD2105 (decentralized with cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPVD3105 (decentralized with cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPVD4105 (decentralized with cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPVD5105 (decentralized with cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPVDMG105 (decentralized with cost reduction)
Solar PV	Solar PV	spv	PVpanels	ESOPVDSA105 (decentralized with cost reduction)
Wind turbine	Wind offshore	wnd	WindTurb	EWIND205

Wind turbine	Wind onshore	wnd	WindTurb	EWIND105
Wind turbine	Wind onshore	wnd	WindTurb	EWIND305 (cost reduction)
Wind turbine	Wind onshore	wnd	WindTurb	EWINDDMG105 (decentralized)
Wind turbine	Wind onshore	wnd	WindTurb	EWINDDMG105 (decentralized with cost reduction)
Ethanol production from bio solids	Advanced Biofuels	-	AdvBiofuels	UETHBIOSLD110
Electric bus	Electric Vehicles	-	EVehiclesEq	TRBELC005
Electric small vehicle	Electric Vehicles	-	EVehiclesEq	TRSVELC010

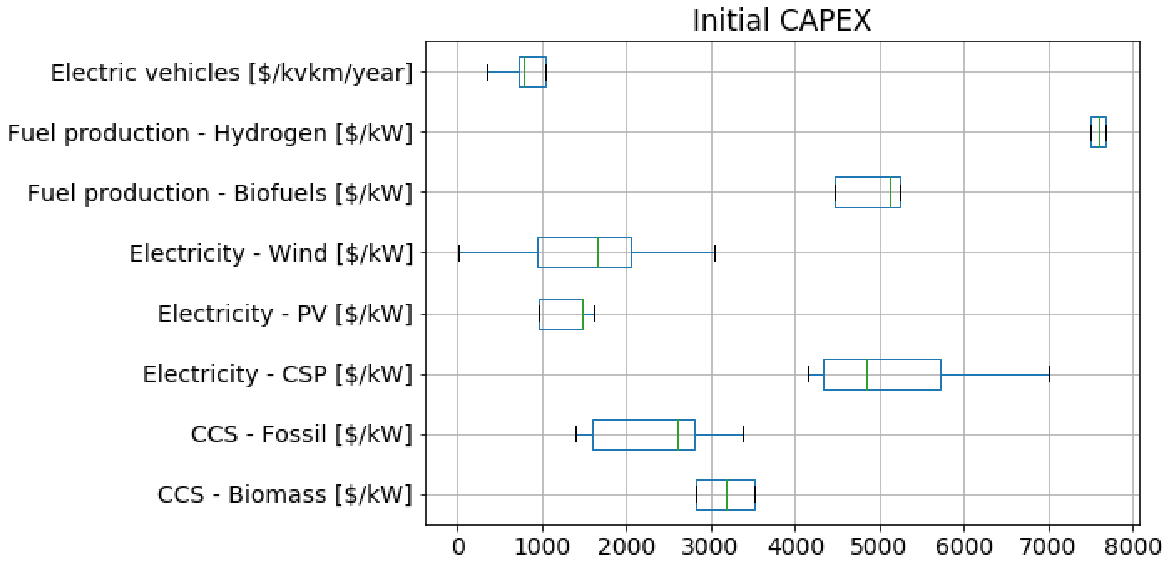

Figure S.2 – Initial Investment Cost (reference year: 2020) range in TIAM-ECN technologies per technology group.

Table S.6 – Prices applied to non-CO_2 greenhouse gases per scenario in TIAM-ECN, in US$/t$CO_{2eq}$

Year	REF	CB1460	CB710
2020	0	0	0
2030	0	0	200
2040	0	27	200
2050	0	55	200
2060	0	200	200
2070	0	200	200
2080	0	200	200
2090	0	200	200
2100	0	200	200

D. Results

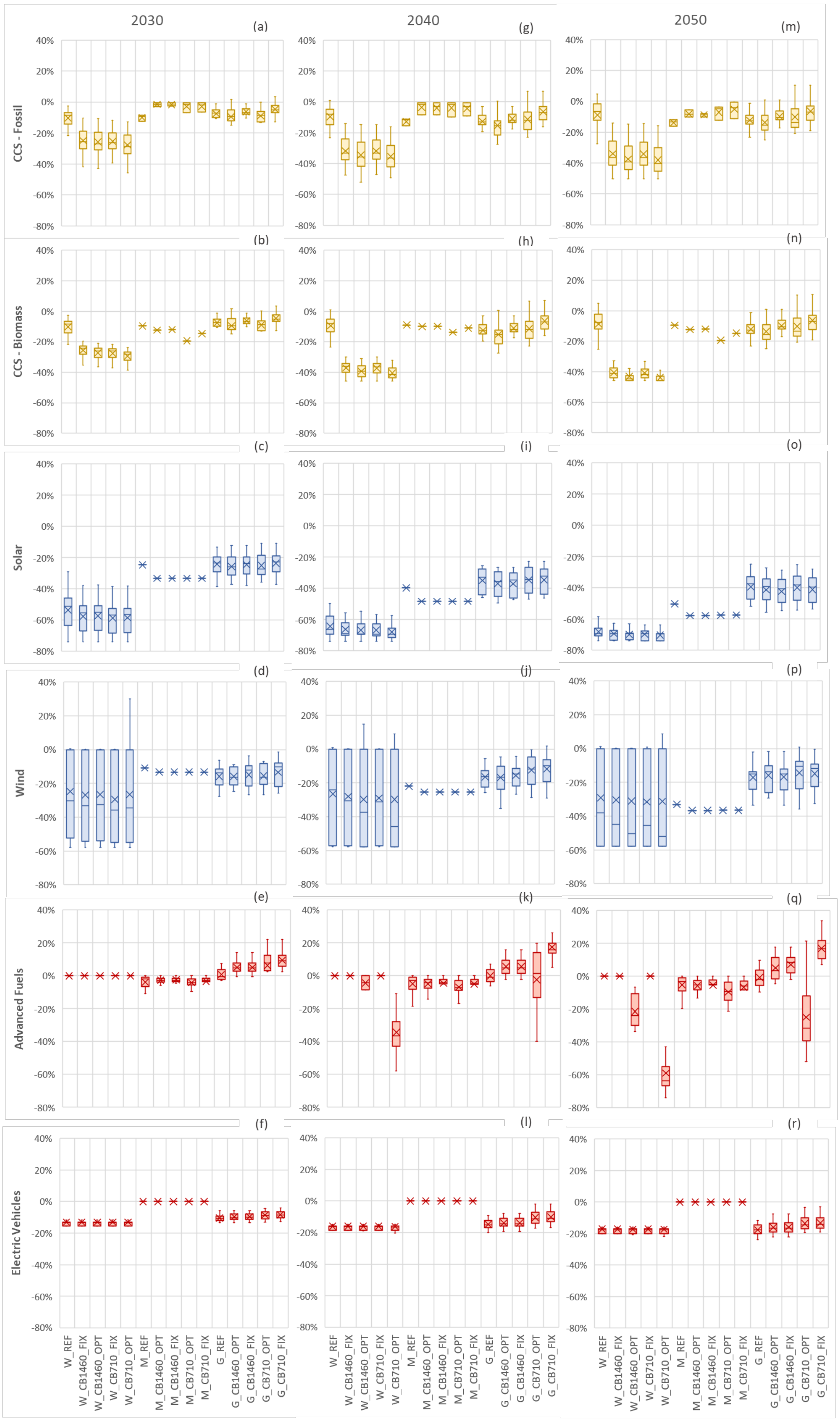

Figure S.3 – Relative Capital cost reductions w.r.t. 2020 for all scenarios

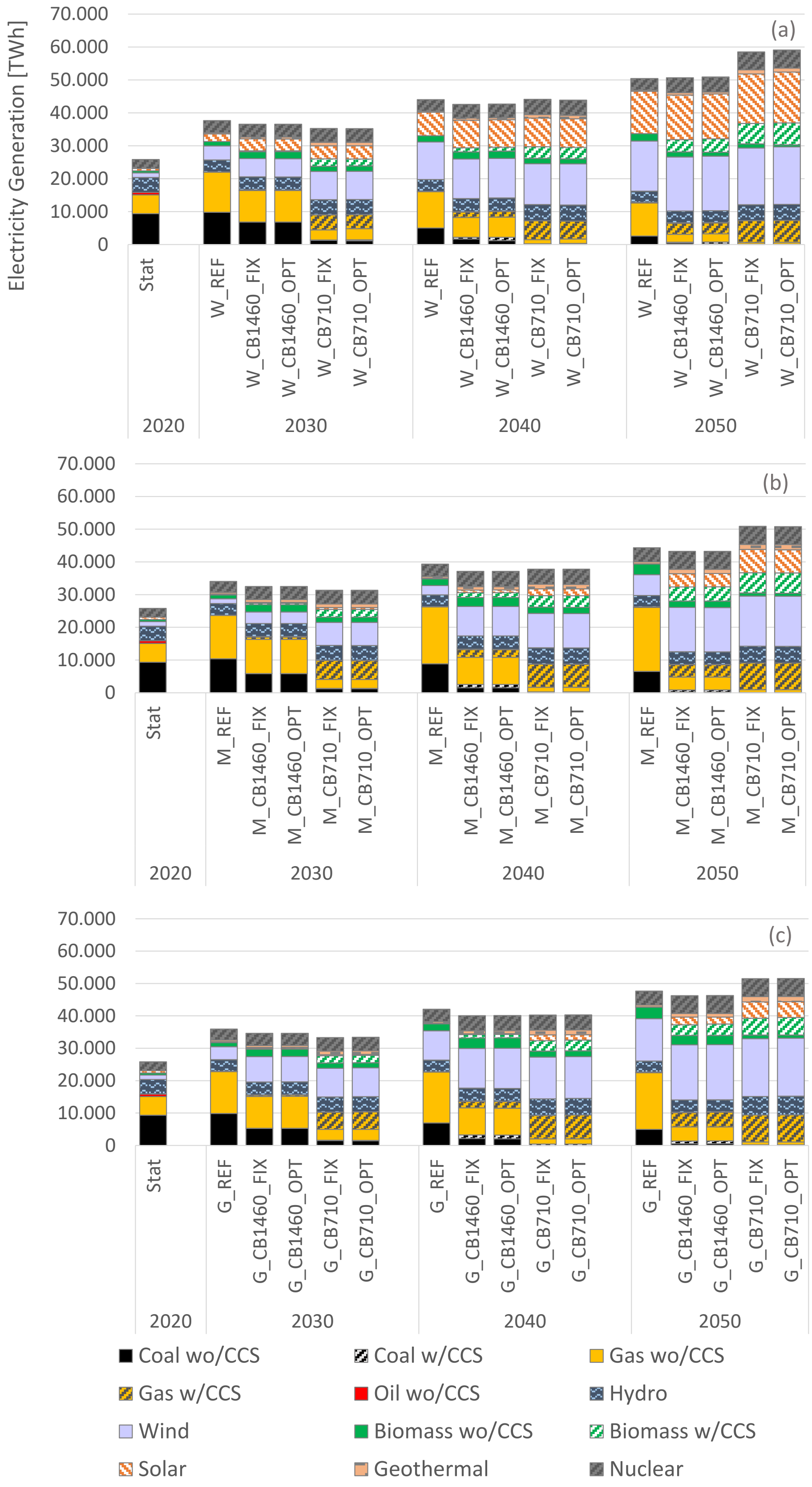

Figure S.4 – TIAM-ECN projections for electricity generation in TWh. R&D-driven technology investment cost reductions derived from WITCH (a), MERGE-ETL (b) and GEM-E3 (c).

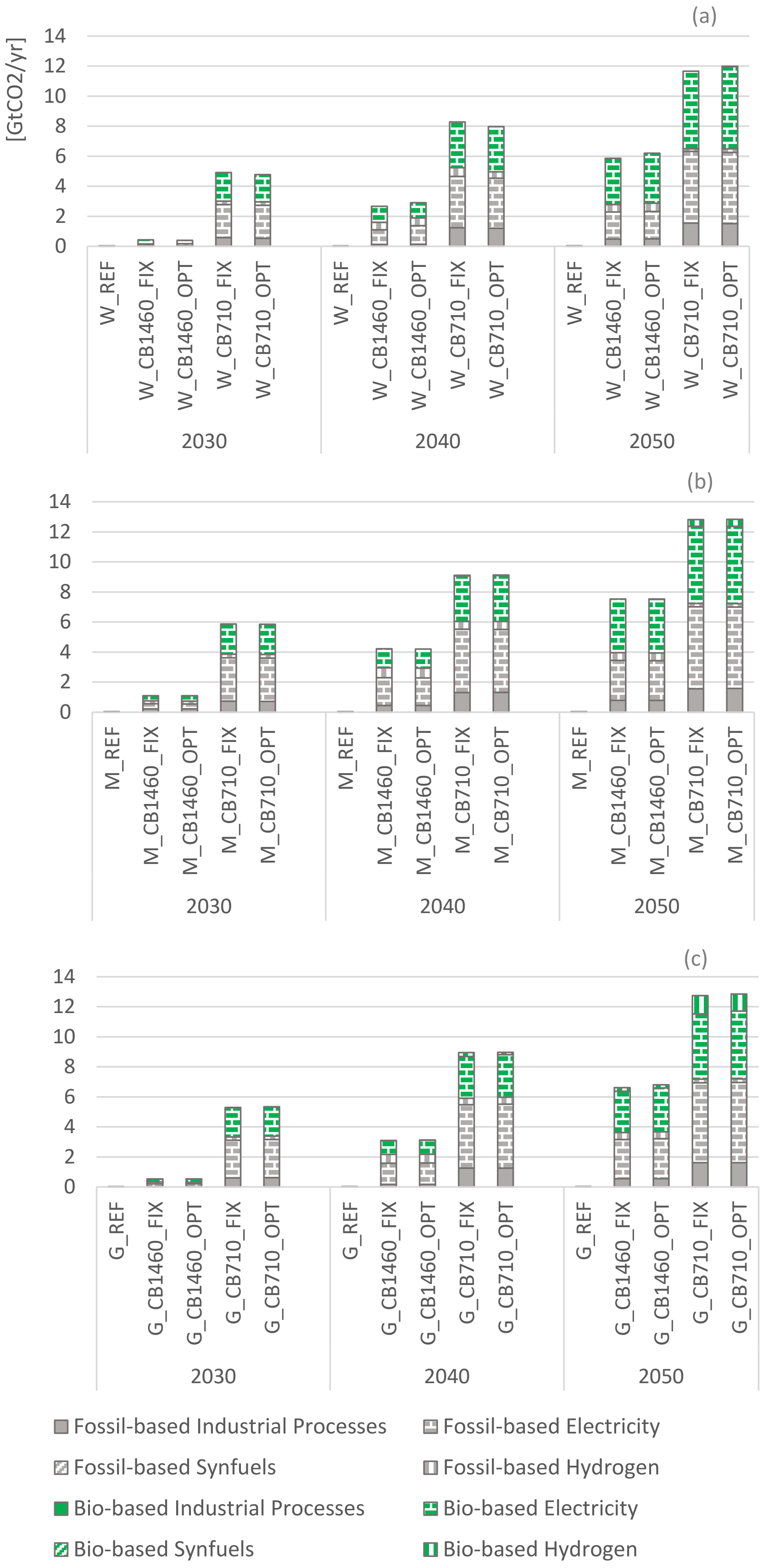

Figure S.5 – Uptake of CCS technologies, GtCO$_2$/yr.

Supplementary Material References

Capros P., Van Regemorter D., Paroussos L., Karkatsoulis P., 2017. GEM-E3 Model Manual. E3M Lab, Institute of Communications and Computers Systems, National Technical University of Athens. Available at: http://www.e3mlab.eu/e3mlab/GEM%20-%20E3%20Manual/GEM-E3_manual_2017.pdf. (Accessed: 11 March 2022).

Dalla Longa, F., van der Zwaan, B., 2021. Heart of light: an assessment of enhanced electricity access in Africa. *Renewable and Sustainable Energy Reviews* (136), 110399, doi: https://doi.org/10.1016/j.rser.2020.110399

Emmerling, J., Drouet, L., Reis, L.A., Bevione, M., Berger, L., Bosetti, V., Carrara, S., Cian, E.D., D'Aertrycke, G.D.M., Longden, T., Malpede, M., Marangoni, G., Sferra, F., Tavoni, M., Witajewski-Baltvilks, J., Havlik, P.: The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways. *Working Paper 2016.42, Fondazione Eni Enrico Mattei (2016),* https://ideas.repec.org/p/fem/femwpa/2016.42.html

Fragkiadakis, K., Paroussos, L., Capros, P. (2019). D4.3.2: Technical description of the R&D module of GEM-E3-RD model, *Public deliverable of MONROE H2020 project*.

Fragkiadakis, Kostas, Panagiotis Fragkos, and Leonidas Paroussos. 2020. "Low-Carbon R&D Can Boost EU Growth and Competitiveness" Energies 13, no. 19: 5236. https://doi.org/10.3390/en13195236

Kober, T., Falzon, J., van der Zwaan, B., Calvin, K., Kanudia, A., Kitous, A., Labriet, M. (2016) 'A Multi-Model Study of Energy Supply Investments in Latin America under Climate Control Policy', *Energy Economics*. Elsevier B.V. doi: 10.1016/j.eneco.2016.01.005.

Kouvaritakis, N., Soria, A., Isoard, S., 2000. Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching. International Journal of Global Energy Issues, 14, 1-4. 10.1504/IJGEI.2000.004384

Loulou, R. (2008) 'ETSAP-TIAM: The TIMES integrated assessment model. Part II: Mathematical formulation', *Computational Management Science*, 5(1–2), pp. 41–66. doi: 10.1007/s10287-007-0045-0.

Loulou, R. and Labriet, M. (2008) 'ETSAP-TIAM: The TIMES integrated assessment model Part I: Model structure', *Computational Management Science*, 5(1–2), pp. 7–40. doi: 10.1007/s10287-007-0046-z.

Marcucci, A., Turton, H., 2015. Induced technological change in moderate and fragmented climate change mitigation regimes. *Technological Forecasting and Social Change*, 90(A), 230-242, doi: https://doi.org/10.1016/j.techfore.2013.10.027.

Marcucci, A., 2014. The MERGE-ETL model: 2014 Assumptions and Model Calibration. Available at: https://www.psi.ch/sites/default/files/import/eem/ModelsEN/2014MergeCalibration.pdf (Accessed: 27 January 2021)

Nogueira, L. P., Dalla Longa, F., van der Zwaan, B., 2020. A cross-sectoral integrated assessment of alternatives for climate mitigation in Madagascar. Climate Policy 20(10), 1257-1273, doi: https://doi.org/10.1080/14693062.2020.1791030

Paroussos, L., Mandel, A., Fragkiadakis, K. et al., 2019. Climate clubs and the macro-economic benefits of international cooperation on climate policy. *Nature Climate Change*, 9, 542–546. https://doi.org/10.1038/s41558-019-0501-1

Riahi, K., van Vuuren, D., Kriegler, E., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, *Global Environmental Change*, 42, 153-168, doi: https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rösler, H., van der Zwaan, B., Keppo, I., Bruggink, J. (2014) 'Electricity versus hydrogen for passenger cars under stringent climate change control', *Sustainable Energy Technologies and Assessments*. Elsevier, 5, pp. 106–118. doi: 10.1016/J.SETA.2013.11.006.

Rubin, E., S., Azevedo, I. M. L., Jaramillo, P., Yeh, S., 2015. A review of learning rates for electricity supply technologies. *Energy Policy*, 86, pp. 198-218. https://doi.org/10.1016/j.enpol.2015.06.011

Söderholm, P., Sundqvist, T., 2007. Empirical challenges in the use of learning curves for assessing the economic prospects of renewable energy technologies. Renewable Energy 32(15), pp. 2559-257. https://doi.org/10.1016/j.renene.2006.12.007

Syri, S. et al. (2008) 'Global energy and emissions scenarios for effective climate change mitigation—Deterministic and stochastic scenarios with the TIAM model', International Journal of Greenhouse Gas Control. Elsevier, 2(2), pp. 274–285. doi: 10.1016/J.IJGGC.2008.01.001.

van der Zwaan, B., Rösler, H., Kober, T., Aboumahboub, T., Calvin, K. V., Gernaat, D. E. H. J., Marangoni, G., McCollum, D. (2013) 'A Cross-Model Comparison of Global Long-Term Technology Diffusion Under a 2°C Climate Change Control Target', *Climate Change Economics*. World Scientific Publishing Company, 04(04), p. 1340013. doi: 10.1142/S2010007813400137.

van der Zwaan, B., Kober, T., Calderon, S., Clarke, L., Daenzer, K., Kitous, A., Labriet, M., de Lucena, A. F. P., Octaviano, C., Di Sbroiavacca, N. (2016) 'Energy technology roll-out for climate change mitigation: A multi-model study for Latin America', *Energy Economics*. North-Holland, 56, pp. 526–542. doi: 10.1016/J.ENECO.2015.11.019.

van der Zwaan, B., Kober, T., Dalla Longa, F., van der Laan, A., Kramer, G. J. (2018) 'An integrated assessment of pathways for low-carbon development in Africa', *Energy Policy*. Elsevier, 117, pp. 387–395. https://doi.org/10.1504/IJETP.2004.004591

van der Zwaan, B., Seebregts, A., 2004. Endogenous learning in climate-energy-economic models – an inventory of key uncertainties. *Int. J. Energy Technology and Policy*, Vol. 2, Nos. 1/2, 2004. DOI: 10.1504/IJETP.2004.004591

Verdolini, E., Anadón, L.D., Baker, E., Bosetti, V., Reis, L.A., 2018. Future prospects for energy technologies: Insights from expert elicitations. *Review of Environmental Economics and Policy* 12 (1), 133–153. https://doi.org/10.1093/reep/rex028