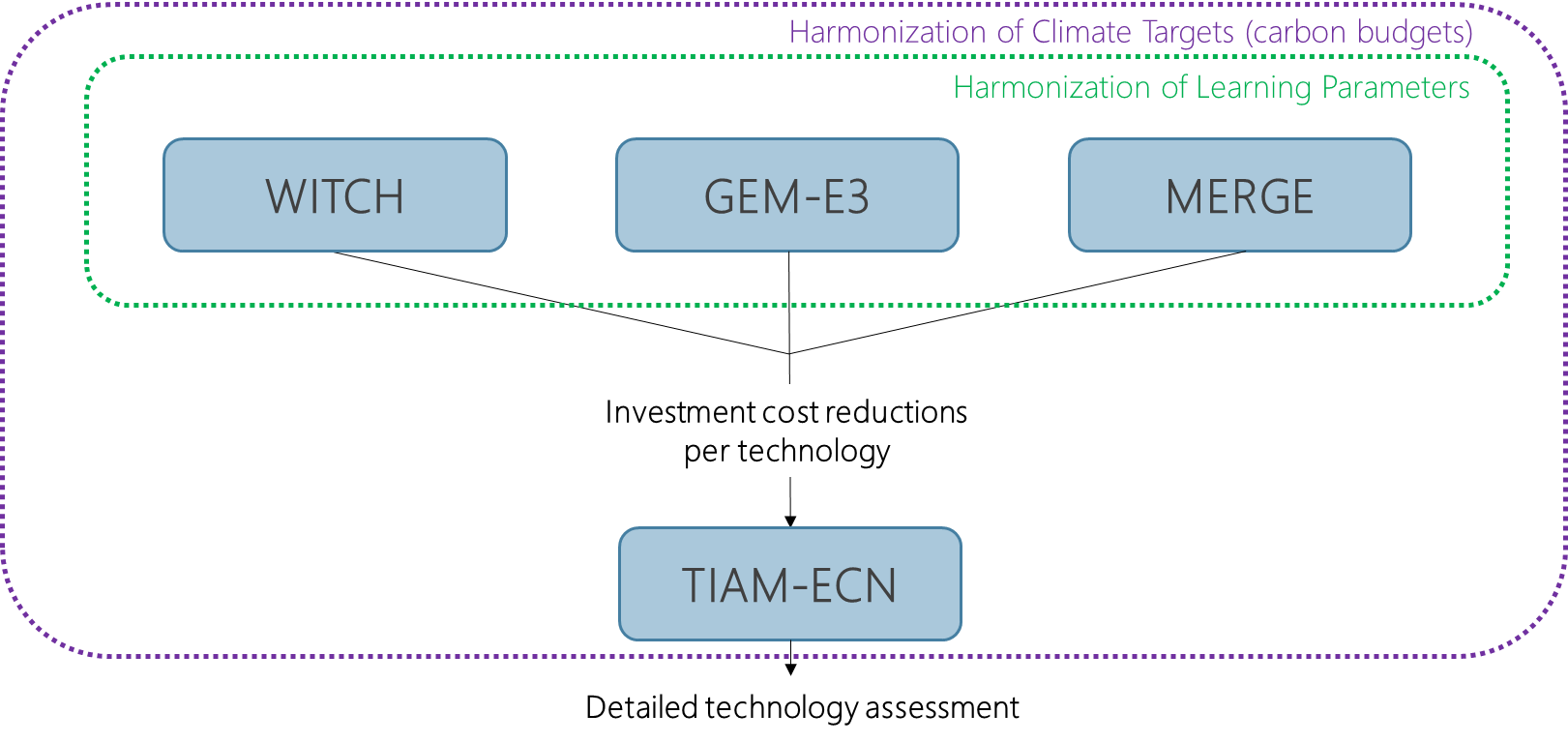
**A multi-model framework to assess the role of R&D towards a decarbonized energy system**

**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.

1. **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 CO2 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.

1. **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** | **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 | 0.05 |
| CCS | 0.05 | 0.05 | 0.05 | 0.03 | 0.03 | 0.03 | 5 | 0.05 | 0.05 |
| DACC | 0.15 | 0.15 | 0.08 |  |  |  | 5 | 0.05 | 0.05 |
| Wind onshore | 0.059 | 0.059 | 0.03 | 0.17 | 0.17 | 0.17 | 5 | 0.05 | 0.05 |
| Wind offshore | 0.103 | 0.05 | 0.03 | 0.17 | 0.17 | 0.17 | 5 | 0.05 | 0.05 |
| Solar PV | 0.18 | 0.18 | 0.09 | 0.12 | 0.12 | 0.12 | 5 | 0.05 | 0.05 |
| Battery | 0.20 | 0.15 | 0.08 | 0.27 | 0.27 | 0.27 | 5 | 0.05 | 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 |

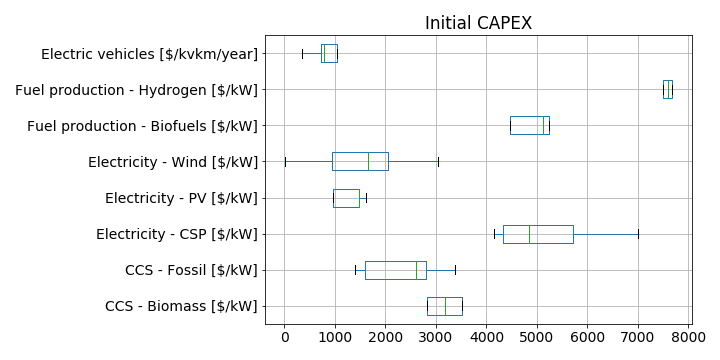
*Table S.4 – Initial Knowledge Stock harmonized in WITCH, MERGE-ETL and GEM-E3. Regionalization based on WITCH model. (Note: bra – Brazil; can – Canada; chi – China; eu – Europe; ind – India; indn – Indonesia; jpnkor – Japan and South Korea; laca - Latin America and Caribbean; mena – Middle East and 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$]** | **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 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

1. **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 |
| 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 |
| Hydrogen from coal gasification with CCS | Advanced Biofuels | coal-a-H2 | CCSequipmn | HZBCO120 |
| 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 |
| 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 |
| Biomass thermal with CCS | Power plant | Biomass | CCS | Integrated gasification combined cycle | bio-a | CCSequipmn | EZBIOSLD150 |
| 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 |
| Integrated coal gasification with CCS | Power plant | Coal | CCS | Integrated gasification combined cycle | igcc-a | CCSequipmn | EZIGC1130 |
| Integrated coal gasification with CCS | Power plant | Coal | CCS | Integrated gasification combined cycle | igcc-a | CCSequipmn | EZIGC925 |
| concentrated solar power | Solar CSP | - | - | ESOTH105 |
| concentrated solar power | Solar CSP | - | - | ESOTHS205 |
| concentrated solar power | Solar CSP | - | - | ESOTHS305 |
| concentrated solar power | Solar CSP | - | - | ESOTHS305 |
| Gas turbine combined cycle with CCS | Power plant | Gas | CCS | ngcc-a | CCSequipmn | EZCCGT110 |
| Gas turbine combined cycle with CCS | Power plant | Gas | CCS | ngcc-a | CCSequipmn | EZCCGT120 |
| Gas turbine combined cycle with CCS | Power plant | Gas | CCS | ngcc-a | CCSequipmn | EZCCGT130 |
| Gas turbine combined cycle with CCS | Power plant | Gas | CCS | ngcc-a | CCSequipmn | EZCCGO110 |
| Gas turbine combined cycle with CCS | Power plant | Gas | CCS | ngcc-a | CCSequipmn | EZCCGO120 |
| Gas turbine combined cycle with CCS | Power plant | Gas | CCS | ngcc-a | CCSequipmn | EZCCGO130 |
| Gas turbine combined cycle with CCS | Power plant | Gas | CCS | ngcc-a | CCSequipmn | EZSOFGAS35 |
| Coal supercritical with CCS | Power plant | Coal | CCS | Standard | pc-a | CCSequipmn | EZPCOA110 |
| Coal supercritical with CCS | Power plant | Coal | CCS | Standard | pc-a | CCSequipmn | EZPCOA120 |
| Coal supercritical with CCS | Power plant | Coal | CCS | Standard | pc-a | CCSequipmn | EZPCOA130 |
| Coal supercritical with CCS | Power plant | Coal | CCS | Standard | pc-a | CCSequipmn | EZSOFCOA35 |
| Coal supercritical with CCS | Power plant | Coal | CCS | Oxy-fuel | pc-a | CCSequipmn | EZOCOA110 |
| Coal supercritical with CCS | Power plant | Coal | CCS | Oxy-fuel | pc-a | CCSequipmn | EZOCOA120 |
| Coal supercritical with CCS | Power plant | Coal | CCS | Oxy-fuel | pc-a | CCSequipmn | EZOCOA130 |
| Solar PV | Solar PV | spv | PVpanels | ESOPV0105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPV105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPV1105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPV2105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPV3105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPV4105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPV5105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVD0105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVD105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVD1105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVD2105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVD3105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVD4105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVD5105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVDMG105 |
| Solar PV | Solar PV | spv | PVpanels | ESOPVDSA105 |
| Wind turbine | Wind offshore | wnd | WindTurb | EWIND205 |
| Wind turbine | Wind onshore | wnd | WindTurb | EWIND105 |
| Wind turbine | Wind onshore | wnd | WindTurb | EWIND305 |
| Wind turbine | Wind onshore | wnd | WindTurb | EWINDDMG105 |
| Wind turbine | Wind onshore | wnd | WindTurb | EWINDDMG105 |
| Ethanol production from bio solids | Advanced Biofuels | - | AdvBiofuels | UETHBIOSLD110 |
| Electric bus | Electric Vehicles | - | EVehiclesEq | TRBELC005 |
| Electric small vehicle | Electric Vehicles | - | EVehiclesEq | TRSVELC010 |

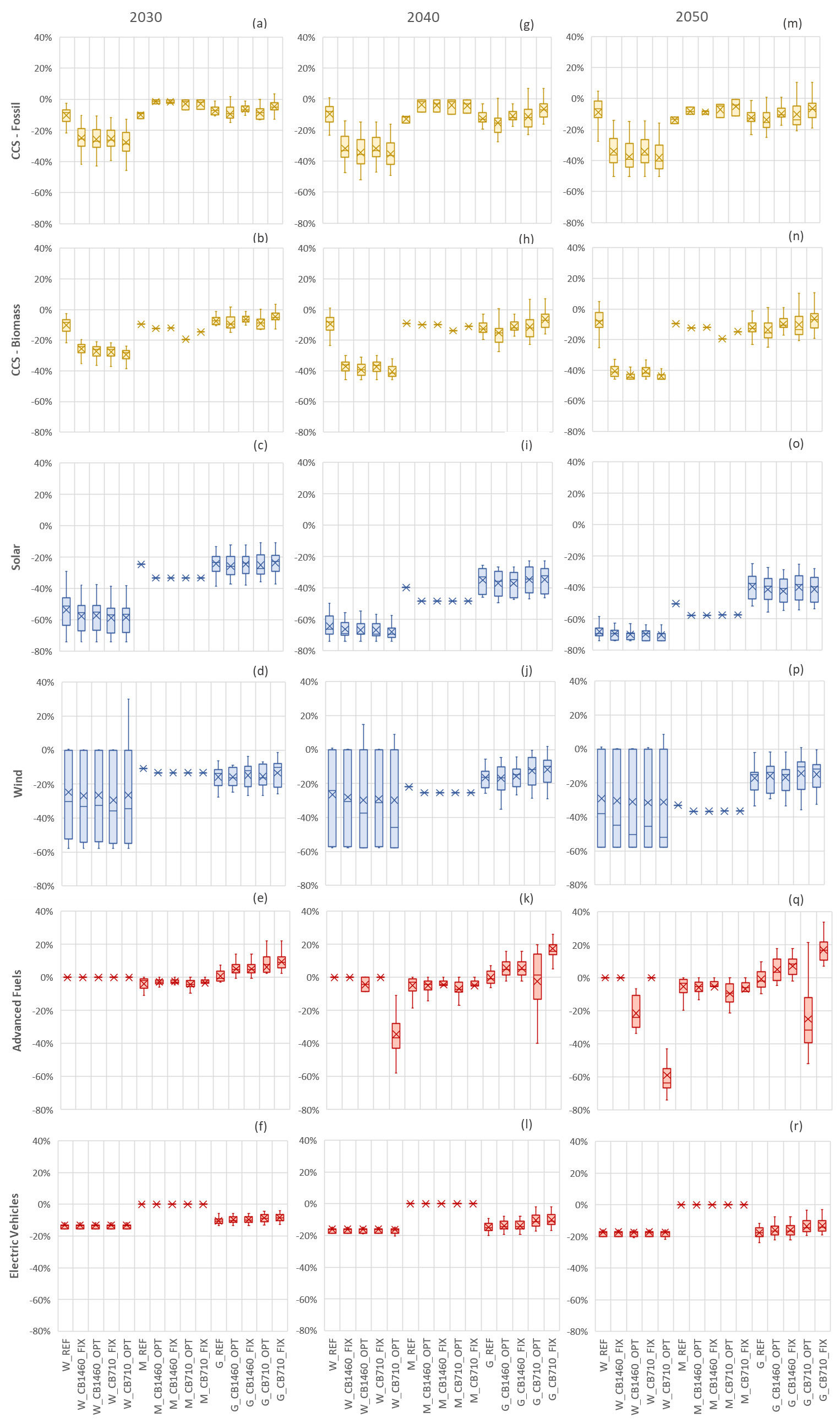


*Figure S.2 – Initial Investment Cost (reference year: 2020) range in TIAM-ECN technologies per technology group.*

*Table S.6 – Prices applied to non-CO2 greenhouse gases per scenario in TIAM-ECN, in US$/tCO2eq*

|  |  |  |  |
| --- | --- | --- | --- |
| 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 |

1. **Results**

**

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



*Figure S.4 – Initial Investment Cost (reference year: 2020) range in TIAM-ECN technologies per technology group.*



*Figure S.5 – Uptake of CCS technologies, GtCO2/yr.*

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