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Appendix A Supplementary Material

A.1 Modelling approach using the Irish TIMES model

The Irish TIMES model is built with The Integrated Markal-Efom System (TIMES) framework, written in the General Algebraic Modelling Software (GAMS) and solved with CPLEX. The framework is developed within an implementing agreement of the International Energy Agency (IEA); the Energy Technology Systems Analysis Programme (ETSAP), is distributed freely to member countries, well documented, transparent, maintained, and upgraded on an ongoing collaborative basis.

TIMES is a techno-economic bottom-up (BU) model generator for local, national, or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long term, multi-period time horizon. It is usually applied to the analysis of the entire energy system, but may also be applied to detailed studies of individual sectors (e.g. the electricity sector or transport sector). TIMES computes a time varying inter-temporal partial equilibrium on inter-regional energy markets. The objective function maximizes total surplus. This is equivalent to minimizing the discounted total energy system cost while respecting environmental, technical, and policy scenario constraints. The system cost includes investment costs, operation and maintenance costs, cost of imported fuels, less the income from exported fuels, the terminal values, and salvage value of technologies at the end of the horizon. The technical foundations of MARKAL models are outlined in Fishbone and Abilock (Fishbone & Abilock, 1981) while the full updated technical documentation of TIMES is hosted online[*] with the ETSAP group (Loulou, Remme, Kanudia, Lehtila, & Goldstein, 2005).

A.2 Model sets and assumptions

The Irish TIMES technology database contains descriptive time dependant economic and technical data for approximately 1600 supply and demand side energy technologies. The model specification has 12 annual time slices; four seasons, day, night, and peak for a time horizon of 65 years from the base year of 2005 to 2070. The model is cyclically updated with

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[*] http://www.iea-etsap.org/web/Documentation.asp

physical energy service demand projections derived from exogenous macroeconomic drivers. The model version used in this analysis is based on macroeconomic recovery scenario projections from the Economic and Social Research Institute's (ESRI) medium term review in 2013. These demand driver projections utilise the ESRI's in house HERMES model in conjunction with the GEM-E3 model of industry Autonomous Energy Efficiency Improvement (AEEI, GEM-E3) (Fitzgerald & Kearney, 2002; Hennessy & FitzGerald, 2011). Primary energy supply commodity prices are based on the 2015 IEA current policy scenario in the world energy outlook (IEA, 2015). Domestic bioenergy potentials and costs are outlined in (Chiodi, Deane, Gargiulo, & Ó Gallachóir, 2015) taken from a range of most recent national studies where available. Non-dispatchable renewable electricity generation has an instantaneous limit at 70% per time slice, and an annual average limit of 50% which is based on the power system technical limits (Eirgrid & SONI, 2010; ESB international, 2008). Detailed model assumptions and inputs are available at http://www.ucc.ie/en/energypolicy/irishtimes/. This model version does not include non-energy related agricultural emissions, as such emissions reduction targets are adjusted exogenously assuming agricultural GHG emissions maintain the same growth rate as national projections to 2020 and onwards to 2050 (EPA, 2013).

A.3   Hybrid general equilibrium approach using Macro Stand Alone

MACRO Stand Alone (MSA) as previously outlined (Glynn et al., 2015; Kypreos & Lehtila, 2015) enables a hard-linked hybrid approach to calculate a general equilibrium solution between energy service demands and the energy system costs in the TIMES-MACRO framework (Manne & Wene, 1992), similar to that used in MESSAGE-MACRO (Messner & Schrattenholzer, 2000). The method used here, an updated approach to MACRO, called MACRO Stand Alone (MSA), decomposes TIMES-MACRO (TM) into a small non-linear macroeconomic model, where the TIMES energy system is emulated by quadratic cost-supply functions (QSF) for each energy service demand (Kypreos & Lehtila, 2015). This enables the optimisation of the overall objective function for welfare maximisation, giving a general equilibrium between prices and demands, all within a reasonable computational time frame (<5min for a single region model), 100 times faster than the original MACRO algorithm.

MACRO solves an objective function which maximises an inter-temporal utility function for a single representative producer-consumer agent (Equation (1)). The key

variables and equations outlined below are the capital stock (K), labour (l), energy services (DEM), and the elasticity of substitution (ρ) between energy services (DEM) and a capital (K)-labour (l) aggregate, as the factors of production which determine the output (Y) of the economy (2). Simultaneously, Production (Y) balances with Consumption (C), Investment (INV), and the Energy system Costs (EC) equation (3). In a single region application such as this case, the production function is not weighted by the wealth distributing Negishi weights (Stanton, 2011), nor is net export trade in non-energy related numeraire good (NTX(nmr)) required to be modelled. Therefore, this model does not take into account decreased international competitiveness that could result from differing rates of decarbonisation within trade partners, differing costs of carbon, and their resulting differing production costs.

$$Max\ U = \sum_{t=1}^{T} pwt_t . dfact_t . ln(C_t) \quad (1)$$

$$Y_t = \left(akl \cdot K_t^{kpvs \cdot \rho} \cdot l_t^{(1-kpvs) \cdot \rho} + \sum_k b_k \cdot DEM_{t,k}^{\rho} \right)^{\frac{1}{\rho}} \quad (2)$$

$$Y_t = C_t + INV_t + EC_t + NTX(nmr)_t \quad (3)$$

pwt – Weight Multiplier

dfact – Utility discount factor

C - Consumption

Y – Production

INV – Investment

EC – Energy Cost

NTX(nmr) – Net exports of Numeraire good

akl – Production function constant

K – Capital

kpvs – Capital value share

l - Labour

b – Demand coefficient

ρ – Elasticity of substitution

DEM - Energy Demands

k - Technology type subscript

r - Region subscript

t - Time subscript

The labour-capital aggregate and demand multiplier coefficients akl, and b, are benchmarked in the constant elasticity of substitution (CES) production function (Equation (2)) allowing a relationship between economic activity, price of energy services, and demand for energy services to be formulated. However, this formulation cannot take into account price independent technological change, as a result of the constant elasticity of substitution. The demand decoupling factors (DDF) for each energy service demand enable the production

function to take account of structural changes in the economy, primarily increased energy efficiency and increased productivity as a result of technology progress.

Once calibrated, MACRO endogenously calculates energy service demand responses for a policy scenario as a function of economic activity and relative energy prices to the baseline calibration scenario. These factors are in turn calculated as a function of substitution between the factors of production and the energy costs as a result of policy constraints upon the energy system. An iterative process is required to balance the price dependent energy demands from the production function MACRO model with the energy service demands from the energy systems TIMES model. This forms the essence of the macroeconomic feedback between the TIMES model and the MACRO model. The TIMES model provides energy costs to MACRO, and MACRO provides revised energy demands to TIMES, iterating until the energy service demands of both models converge within an acceptable specified tolerance. The algorithm results in an estimate of the macroeconomic impacts of decarbonising the energy system given by GDP change, consumption and investment changes, as well as estimates of price dependent energy service demand changes.

A.4 Energy Service Demand responses in hybrid general equilibrium framework.

				Residential	Commercial	Industry					Transport		
						Cement	Lime	Chemicals	Metals	Other Energy Intensive	Passenger	Freight	Int.Shipping
			Unit	Ktoe	ktoe	Mt	Mt	ktoe	ktoe	ktoe	MPKm	MtKm	PJ
2030	CO2-80		MSA	-5%	-8%	-24%	-14%	-10%	-12%	-10%	-5%	-5%	-10%
			NoSNSPLim	-6%	-9%	-24%	-14%	-11%	-12%	-11%	-4%	-5%	-10%
			NoBECCS	-5%	-8%	-24%	-14%	-10%	-12%	-10%	-5%	-5%	-10%
			NoCCS	-5%	-8%	-25%	-14%	-10%	-12%	-10%	-5%	-5%	-11%
			NoBioImp	-5%	-8%	-25%	-14%	-12%	-14%	-12%	-5%	-6%	-10%
	766 MtCO2		MSA	-5%	-7%	-24%	-13%	-10%	-12%	-10%	-5%	-4%	-10%
			NoSNSPLim	-5%	-8%	-23%	-12%	-10%	-12%	-11%	-4%	-4%	-9%
			NoBECCS	-6%	-9%	-26%	-15%	-12%	-13%	-12%	-5%	-5%	-12%
			NoCCS	-7%	-9%	-27%	-16%	-12%	-13%	-12%	-5%	-5%	-12%
			NoBioImp	-10%	-14%	-32%	-23%	-20%	-23%	-20%	-7%	-10%	-17%
	638 MtCO2		MSA	-4%	-7%	-25%	-13%	-10%	-12%	-10%	-5%	-4%	-10%
			NoSNSPLim	-4%	-7%	-24%	-12%	-10%	-12%	-10%	-4%	-4%	-9%
			NoBECCS	-5%	-8%	-25%	-15%	-11%	-12%	-11%	-5%	-4%	-11%
			NoCCS	-5%	-8%	-25%	-15%	-11%	-12%	-11%	-5%	-5%	-11%
			NoBioImp	-10%	-13%	-32%	-22%	-19%	-23%	-19%	-6%	-9%	-17%
	376 MtCO2		MSA	-9%	-12%	-31%	-20%	-13%	-15%	-13%	-6%	-10%	-15%
			NoSNSPLim	-8%	-11%	-30%	-20%	-13%	-15%	-13%	-6%	-9%	-15%
			NoBECCS	-10%	-14%	-34%	-24%	-15%	-16%	-15%	-7%	-10%	-18%
			NoCCS	-11%	-15%	-35%	-25%	-15%	-16%	-16%	-7%	-10%	-19%
			NoBioImp	-18%	-24%	-46%	-37%	-31%	-35%	-31%	-10%	-17%	-30%
	223 MtCO2		MSA	-17%	-19%	-53%	-47%	-16%	-18%	-16%	-9%	-12%	-35%
			NoSNSPLim	-18%	-21%	-53%	-47%	-17%	-19%	-17%	-9%	-12%	-35%
			NoBECCS	-19%	-24%	-57%	-53%	-19%	-21%	-19%	-10%	-13%	-40%
			NoCCS	-19%	-25%	-57%	-52%	-18%	-23%	-18%	-9%	-13%	-39%

			Residential	Commercial	Cement	Lime	Chemicals	Metals	Other Energy Intensive	Passenger	Freight	Int.Shipping
		Unit	Ktoe	ktoe	Mt	Mt	ktoe	ktoe	ktoe	MPKm	MtKm	PJ
2050	CO2-80	MSA	-7%	-12%	-18%	-25%	-13%	-12%	-13%	-5%	-8%	-15%
		NoSNSPLim	-5%	-9%	-17%	-22%	-9%	-10%	-9%	-4%	-7%	-15%
		NoBECCS	-7%	-12%	-18%	-25%	-13%	-12%	-13%	-5%	-8%	-24%
		NoCCS	-8%	-13%	-18%	-27%	-14%	-13%	-14%	-5%	-8%	-15%
		NoBioImp	-11%	-18%	-20%	-32%	-25%	-27%	-24%	-6%	-12%	-23%
	766 MtCO2	MSA	-8%	-13%	-18%	-26%	-14%	-13%	-14%	-5%	-9%	-15%
		NoSNSPLim	-5%	-9%	-17%	-25%	-9%	-10%	-9%	-4%	-7%	-15%
		NoBECCS	-9%	-14%	-19%	-30%	-13%	-12%	-13%	-5%	-8%	-25%
		NoCCS	-9%	-14%	-19%	-30%	-14%	-13%	-15%	-5%	-9%	-15%
		NoBioImp	-13%	-20%	-22%	-38%	-27%	-29%	-27%	-7%	-14%	-29%
	638 MtCO2	MSA	-8%	-13%	-18%	-26%	-14%	-13%	-14%	-5%	-9%	-15%
		NoSNSPLim	-5%	-9%	-17%	-24%	-10%	-10%	-10%	-4%	-7%	-15%
		NoBECCS	-8%	-13%	-19%	-28%	-13%	-12%	-13%	-5%	-8%	-24%
		NoCCS	-8%	-13%	-19%	-29%	-15%	-13%	-15%	-5%	-9%	-15%
		NoBioImp	-13%	-20%	-22%	-37%	-27%	-29%	-27%	-7%	-13%	-29%
	376 MtCO2	MSA	-10%	-16%	-21%	-36%	-16%	-16%	-16%	-5%	-9%	-15%
		NoSNSPLim	-8%	-11%	-20%	-35%	-10%	-11%	-10%	-5%	-8%	-15%
		NoBECCS	-11%	-16%	-23%	-40%	-16%	-15%	-16%	-6%	-9%	-30%
		NoCCS	-12%	-18%	-23%	-41%	-15%	-15%	-16%	-6%	-10%	-16%
		NoBioImp	-17%	-27%	-26%	-53%	-32%	-35%	-33%	-10%	-17%	-41%
	223 MtCO2	MSA	-12%	-20%	-34%	-57%	-21%	-21%	-21%	-9%	-12%	-21%
		NoSNSPLim	-8%	-14%	-34%	-57%	-10%	-13%	-10%	-7%	-9%	-18%
		NoBECCS	-15%	-23%	-40%	-57%	-21%	-22%	-21%	-11%	-14%	-49%
		NoCCS	-14%	-23%	-40%	-57%	-20%	-20%	-20%	-10%	-14%	-23%

Table 1 Energy Service Demand responses per scenario in 2030 and 2050
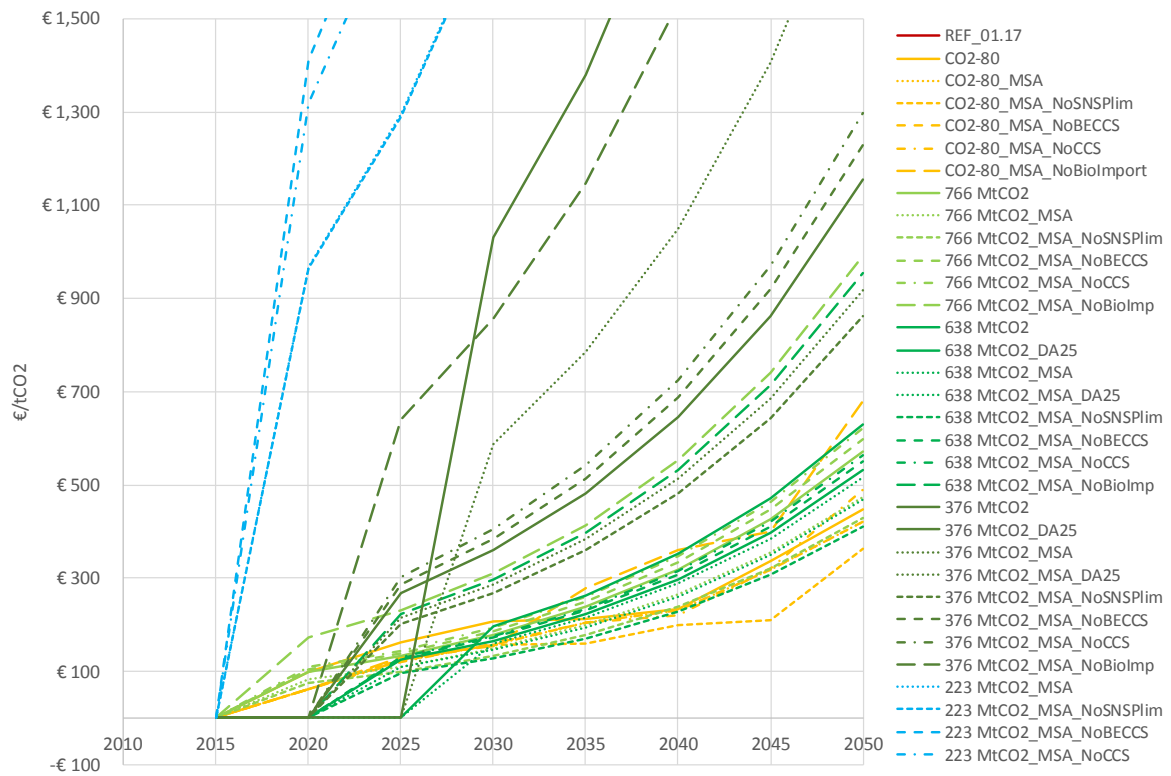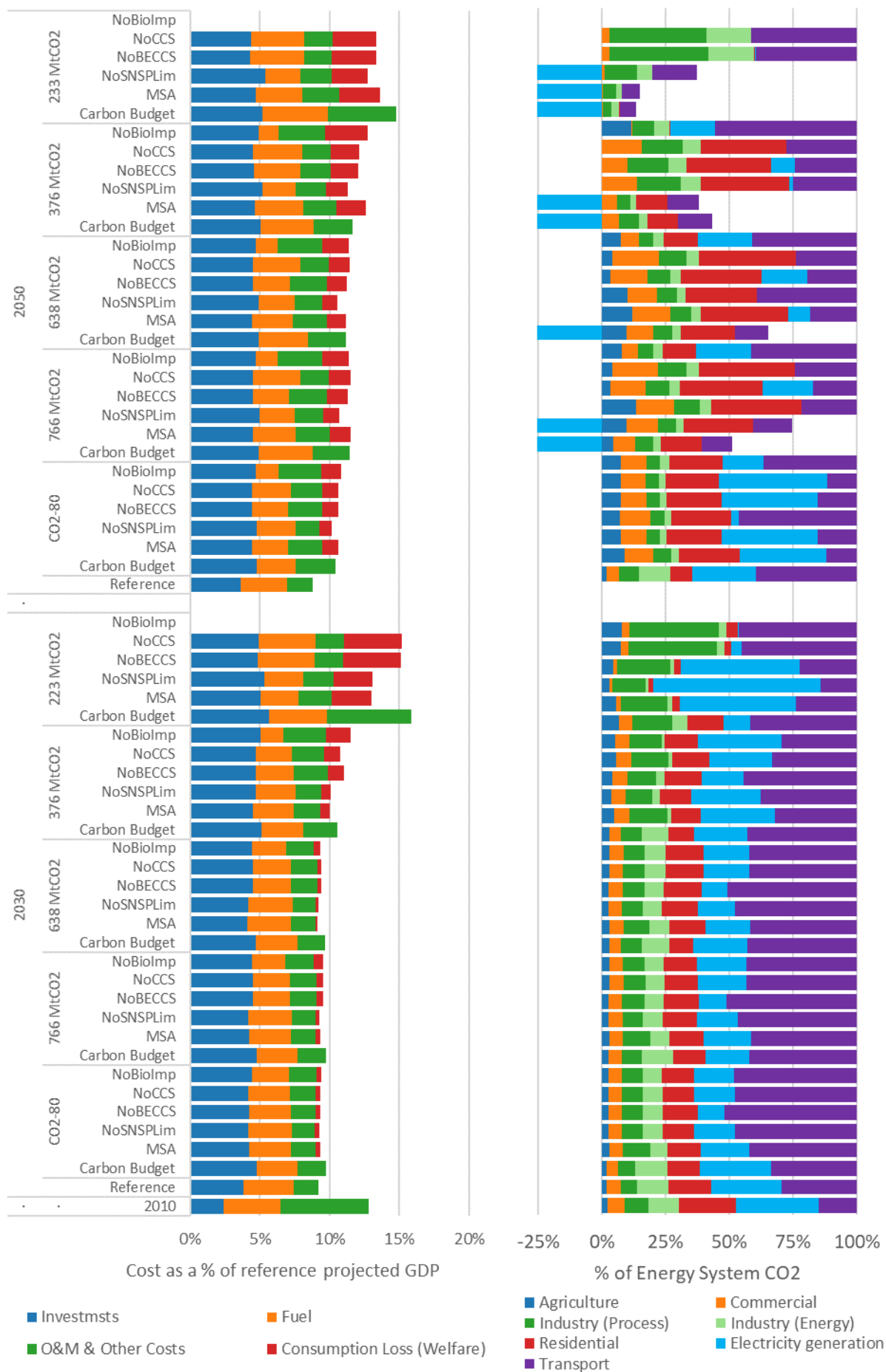
A.5 Marginal Abatement Cost of CO_2

Figure 1. Marginal abatement price of CO_2

A.6 Energy System Costs and Carbon Intensities

Figure 2 Below left) Energy system summary costs as percentage (%) reference projected GDP per scenario. Below right) Emissions percentage (%) per sector.

Left panel (x-axis): Cost as a % of reference projected GDP

Right panel (x-axis): % of Energy System CO2

Left panel legend:
- Investmsts
- Fuel
- O&M & Other Costs
- Consumption Loss (Welfare)

Right panel legend:
- Agriculture
- Commercial
- Industry (Process)
- Industry (Energy)
- Residential
- Electricity generation
- Transport

Row labels (top to bottom):

2050:
- 233 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- 376 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- 638 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- 766 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- CO2-80: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- Reference

2030:
- 223 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- 376 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- 638 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- 766 MtCO2: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- CO2-80: NoBioImp, NoCCS, NoBECCS, NoSNSPLim, MSA, Carbon Budget
- Reference
- 2010

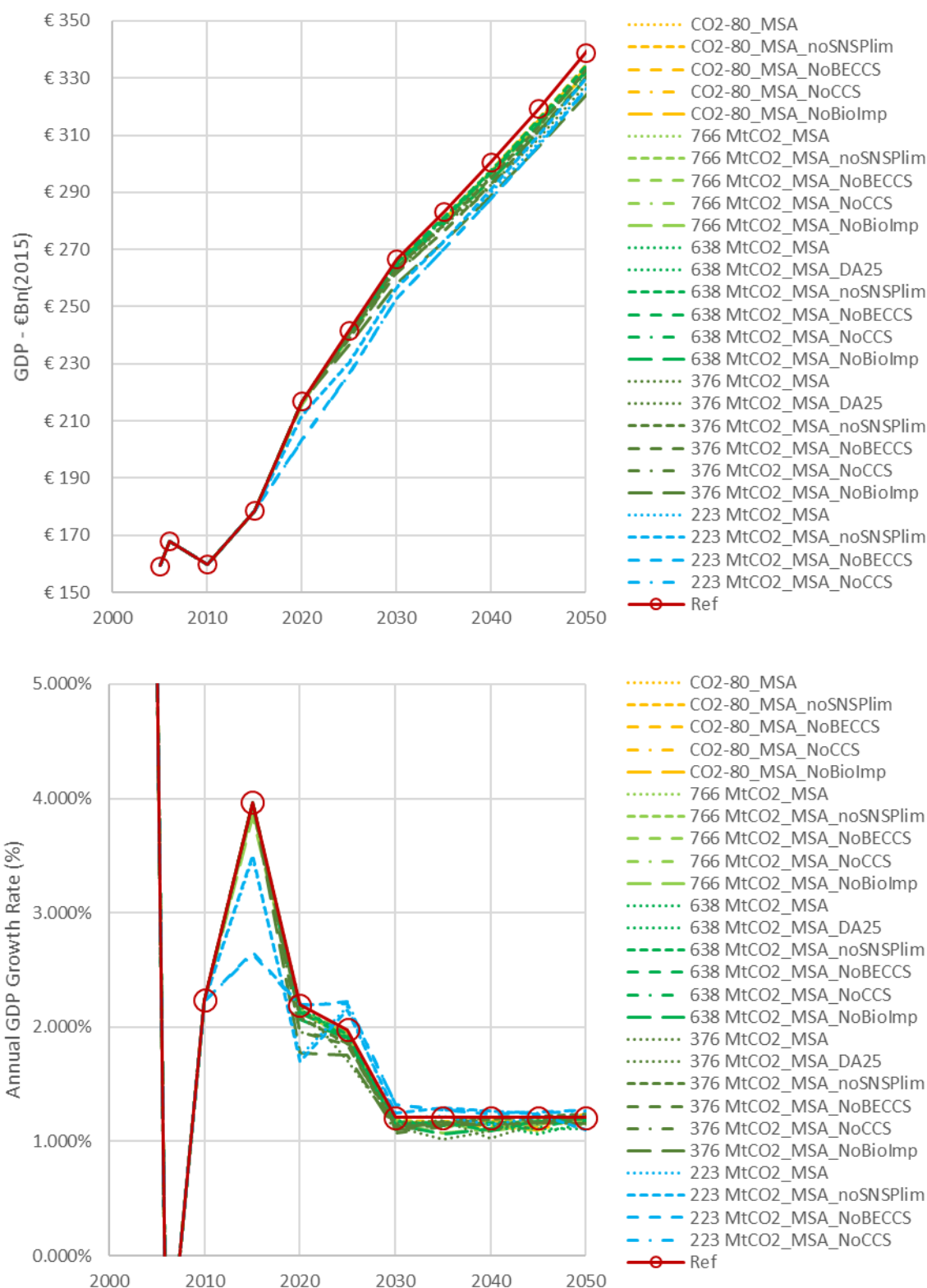## A.7 GDP Growth under deep decarbonisation Scenarios

Figure 3. Relative GDP change to the reference GDP projection.

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