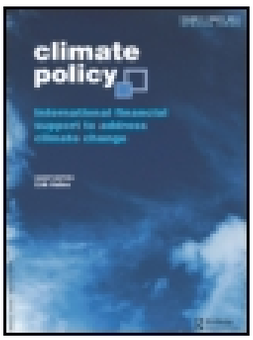
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RESEARCH ARTICLE

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Zero carbon energy system pathways for Ireland consistent with the Paris Agreement

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ABSTRACT

The Paris Agreement is the last hope to keep global temperature rise below 2°C. The consensus agrees to holding the increase in global average temperature to well below 2°C above pre-industrial levels, and to aim for 1.5°C. Each Party's successive nationally determined contribution (NDC) will represent a progression beyond the party's then current NDC, and reflect its highest possible ambition. Using Ireland as a test case, we show that increased mitigation ambition is required to meet the Paris Agreement goals in contrast to current EU policy goals of an 80–95% reduction by 2050. For the 1.5°C consistent carbon budgets, the technically feasible scenarios' abatement costs rise to greater than €8,100/tCO_2 by 2050. The greatest economic impact is in the short term. Annual GDP growth rates in the period to 2020 reduce from 4% to 2.2% in the 1.5°C scenario. While aiming for net zero emissions beyond 2050, investment decisions in the next 5–10 years are critical to prevent carbon lock-in.

Key policy insights

- Economic growth can be maintained in Ireland while rapidly decarbonizing the energy system.
- The social cost of carbon needs to be included as standard in valuation of infrastructure investment planning, both by government finance departments and private investors.
- Technological feasibility is not the limiting factor in achieving rapid deep decarbonization.
- Immediate increased decarbonization ambition over the next 3–5 years is critical to achieve the Paris Agreement goals, acknowledging the current 80–95% reduction target is not consistent with temperature goals of 'well below' 2°C and pursuing 1.5°C.
- Applying carbon budgets to the energy system results in non-linear CO_2 emissions reductions over time, which contrast with current EU policy targets, and the implied optimal climate policy and mitigation investment strategy.

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1. Introduction

Decarbonization targets need to be ambitious to stabilize temperature and equitable to enable global collective action, while acknowledging common but differentiated responsibilities and respective capabilities to mitigate and adapt (Schellnhuber, Rahmstorf, & Winkelmann, 2016; UNFCCC, 2015). The nationally determined contributions (NDCs) which built the consensus underpinning the 2015 Paris Agreement have reduced the probability of global temperature increase below the previous projections of 3.7°C to 4.8°C during the 21st century

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(Edenhofer et al., 2014), but only marginally so. On their current trajectory, the NDCs will not put global GHG emissions on a trajectory consistent with the Paris Agreement goals of limiting temperature increase well below 2°C towards 1.5°C (International Energy Agency, 2015; UNFCCC, 2016).

Cumulative emissions of anthropogenic CO_2 is the primary driver of post-industrial anthropogenic temperature increase (Allen et al., 2009; IPCC, 2013; Matthews, 2009; Millar et al., 2017; Rogelj, Reisinger, et al., 2015). van Vuuren et al. (2016) point to the simple strength of this near linear relationship in that, (1) long-term temperature does not depend on CO_2 emissions at a specific time, (2) near-term emissions are important as they also exhaust the carbon budget and (3) CO_2 emissions will need to be phased out to net zero eventually to achieve temperature stabilization (see also Rogelj, Schaeffer, et al., 2015). The remaining cumulative CO_2 emissions that would result in a 1.5°C or 2°C temperature increase with a given probability can be ascribed to a total carbon budget (Friedlingstein et al., 2014; Rogelj et al., 2016), and needs to be fairly allocated given acceptable effort sharing rules (Bows & Anderson, 2008; Kober, Van Der Zwaan, & RöSler, 2014; Raupach et al., 2014; Robiou du Pont et al., 2017).

The EU has committed to policies to mitigate the risks of climate change and to minimize the eventual adaptation costs required of EU citizens. The long-term policy perspective is that EU GHG emissions reduction should be between 80% and 95% below 1990 levels by 2050. This goal was established by an EU Parliament resolution in 2009, taking the lead from the fourth Assessment report of the Intergovernmental Panel on Climate Change (Meinshausen et al., 2007), but which was predicated upon a 2°C limit, not a 1.5°C target, where global CO_2 emissions would plateau between 2000 and 2015 at levels 16% lower than the current rate.

This article explores deep decarbonization scenarios consistent with the Paris Agreement and above current national EU mitigation targets using equitable carbon budgets.

We take Ireland as a case study, and explore the impacts of equitable carbon budgets constraints on a hybrid general equilibrium technology-rich integrated energy systems modelling method. Ireland is a particularly interesting case study for several reasons. It is unique in the EU with a large share (>30%) of GHG emissions from agriculture. The reduced scale of mitigation options in agriculture – both in terms of the production efficiencies currently available and potential future options in research and development (Chiodi et al., 2016; Kuramochi et al., 2018) – places a disproportionately high burden on the energy system to decarbonize relative to other member states. Ireland's transition from an agriculture to service-based economy in a relatively short industrialization period will be of interest to similar open service-based economies, and emerging economies aspiring to replicate this transition. Ireland is unusual in that it is one of seven member states likely to breach the EU 2020 GHG annual reduction targets, from 2016 onwards, and is one of only two member states (alongside Malta) that did not bank enough emissions allowances following the economic recession of 2008–2009 to balance the cumulative GHG reduction component of the 2020 targets (European Environment Agency, 2017). Ireland's electricity network is the smallest national synchronous power system in the EU. It has the highest share of variable renewable electricity supply on a synchronous power system and is leading globally in wind energy integration. Lastly, Ireland is a useful case study in that it is large enough to be relevant, yet small enough to enable detailed analysis.

1.1. From uncertain reduction targets to equitable carbon budgets

The remaining global carbon budgets for a 66% probability of limiting temperature rise to 2°C are estimated between 590GtCO_2 and 1240GtCO_2 (Friedlingstein et al., 2014; Rogelj et al., 2016). Carbon budget uncertainty is largely driven by the dynamics of non-CO_2 GHGs, such as methane from agricultural emissions (IPCC, 2014; Rogelj et al., 2016). The remaining carbon budget to stay below 1.5°C by 2100 with greater than 50% probability is estimated at 200GtCO_2–700GtCO_2 (IPCC, 2015; Millar et al., 2017; Rogelj et al., 2018). Given that cumulative carbon emissions are a strong linear indicator of temperature increase, historical cumulative emissions can be seen as one simple measure of proportional responsibility to anthropogenic temperature increase, both past and future. Ethically attributing responsibility and capability, however, is politically far from simple, with complex national circumstances to be accounted for and balanced during climate negotiations (Gardiner, 2010; Holz, Kartha, & Athanasiou, 2018).

The cumulative carbon budgets for Ireland utilized in this analysis range from 766 MtCO_2 to 128 MtCO_2 from 2015 to the end of the time horizon (2070). They are derived from the Irish population share of 0.064% of the

global population and the same 0.064% share of the remaining global carbon budgets. These carbon budgets relate to a 66% probability of achieving a 2°C limit, to a 50% probability of reaching a 1.5°C limit, and are chosen to span the technically feasible range of territorial mitigation. This approach can be justified by the fact that Irish population as a percentage of the global population has been remarkably stable over the last 50 years, and is projected to remain so. In addition, unlike other developed nations that industrialized earlier in the 18th and 19th centuries (Nordhaus, 2015), Ireland is not in significant carbon debt (Gignac & Matthews, 2015; Le Quéré et al., 2015); Irish historical CO_2 emissions from fossil fuel combustion and cement production from 1751 to 2015 are estimated at approximately 2.04GtCO_2 (Le Quéré et al., 2016), which is less than 0.064% of 3200GtCO_2 the Irish per capita share of the all-time 2°C global carbon budget.[1] However, Ireland has consumed more than its per capita share of a global 1.5°C carbon budget. Irish per capita territorial CO_2 emissions are now at 8.4tCO_2 per person – nearly twice the global average – and are growing. Relatively high per capita income implies Ireland has significant mitigation capacity.

The results of this analysis show the technology pathway options that meet these carbon budget constraints, and outline the costs, technology sensitivity, and the macroeconomic impacts of increased decarbonization ambition.

1.2. Demand response in energy system decarbonization

Irish climate and energy policy legislation has been informed by the Irish-TIMES energy systems model (Deane et al., 2013), investigating mitigation targets to 2020 (Chiodi, Gargiulo, Deane, et al., 2013), long-term targets to 2050 (Chiodi, Gargiulo, Rogan, et al., 2013), questions of bioenergy import dependency (Chiodi, Deane, Gargiulo, & Ó Gallachóir, 2015), technical realism of the electricity sector soft-linked to power systems model (Deane, Chiodi, Gargiulo, & Ó Gallachóir, 2012), energy security (Glynn et al., 2014; Glynn, Chiodi, & Ó Gallachóir, 2017), and agriculture sector feedback to energy system emissions targets (Chiodi et al., 2016). These previous studies outline the energy system evolution under differing technical and environmental scenario constraints and solve a partial equilibrium least cost optimization, i.e. equilibrium within the energy market but not the overall economy. The methodological innovation in this article is in introducing a hybrid general equilibrium with feedback between the energy system and the macro-economy which outlines how the overall economy may react to a decarbonizing energy system. The induced changes in economic growth, sectoral energy service demands, consumption and investments are brought about by substitution of investment capital and human capital with productive energy services. The method applied in this article is the first national application of this decomposition general equilibrium method (MSA – MACRO-stand-alone) to calculate first order macro-economic impacts of decarbonizing the energy system to the Irish economy. Similar methods have been used in UK, China and global analyses (Chen, 2005; Kypreos & Lehtila, 2015; Strachan & Kannan, 2008). The article estimates GDP losses, changes in consumption and investment for a range of deep decarbonization scenarios, starting with the target of an 80% reduction in energy system CO_2 emissions by 2050, and then increasing ambition with equitable per capita shares of the remaining global carbon budgets with sensitivity to grid inertial limits, energy service demand reduction, bioenergy carbon capture and storage (BECCS), carbon capture and storage (CCS) and bioenergy imports in the Irish context.

2. Methods

Please see the Supplementary Material for a detailed description of the Irish-TIMES energy system model and implementation of the MACRO-stand-alone (MSA) extension.

2.1. Scenario definitions

The 38 scenarios considered are chosen to outline the range of potential energy system changes under differing effort-sharing carbon budgets based on equitable per capita shares of the remaining global carbon budgets. This article does not explore emissions inertia grandfathering type constraints where current national per capita emissions converge to a global average at a point in the future, increasing what could be perceived as

an equitable carbon budget (Nordhaus, 2015; Peters, Andrew, Solomon, & Friedlingstein, 2017; Pye, Li, Price, & Fais, 2017; Raupach et al., 2014). Scenario variants are used to account for uncertainty in climate mitigation policy choices, their implied constraints, immediate action vs delayed action, technology availability, and energy service demand responses to macroeconomic feedback.

- REF – Reference Energy System Scenario. This scenario shows the least cost optimal energy system evolution to 2070 in the absence of emissions constraints.
- CO_2-80. This scenario achieves at least an 80% reduction in CO_2 emissions relative to 1990 by 2050 in line with the interim targets of the EU 2020 climate energy package (EU, 2009b, 2009a).
- 766 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 766 $MtCO_2$ between 2015 and 2070 without interim CO_2-80 annual emissions pathway targets. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 1200 $GtCO_2$ consistent with a 66% probability of meeting a 2°C target with immediate action. This scenario has its solution fixed to the reference solution to 2015 and evolves thereafter, showing what a post Paris Agreement mitigation pathway with immediate action from 2015 might have looked like.
- 638 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 638 $MtCO_2$ between 2020 and 2070 without interim emissions pathway targets, with the results fixed to the reference case before 2020. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 1000 $GtCO_2$ consistent with a 66% probability of meeting a 2°C target with mitigation action commencing in 2020, and where exogenous non-CO2 emissions are at the low end of the feasible global range.
- 376 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 376 $MtCO_2$ between 2020 and 2070 without interim emissions pathway targets, with the results fixed to the reference case before 2020. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 590 $GtCO_2$ consistent with a 66% probability of meeting a 2°C target with mitigation action commencing in 2020, and where exogenous non-CO2 emissions are at the high end of the feasible global range. Note that Ireland has high non-CO_2 agricultural emissions.
- 223 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 223 $MtCO_2$ between 2015 and 2070 without interim emissions pathway targets. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 350 $GtCO_2$ consistent with a 50% probability of meeting a 1.5°C target in 2100 with immediate action in 2015.
- 128 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 128 $MtCO_2$ between 2015 and 2070 without interim emissions pathway targets. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 200 $GtCO_2$ consistent with a 66% probability of meeting a 1.5°C target in 2100 with immediate action in 2015. (Note that none of the 128 $MtCO_2$ scenarios proved technically feasible.)

2.1.1. Scenario sensitivity variant definitions

- MSA. This scenario variant incorporates the MSA algorithm to calculate demand responses and macroeconomic feedback in a general equilibrium.
- DA25. This scenario variant delays mitigation action further to 2025 by fixing the scenario to continue along the reference path to 2025.
- NoSNSPLim. This scenario variant removes the default limit on system non-synchronous penetration of variable renewable generation, which represents the inertial limits of the Irish electricity grid. This constraint controls for the non-synchronous nature of generators with low inertial mass such as wind turbines and the potential frequency fluctuations these generators can induce upon an island grid.
- NoBECCS. This scenario variant does not allow BECCS in the power generation sector of the energy system model.
- NoCCS. This scenario variant does not allow CCS in the power generation sector of the energy system model. Note that CCS is still allowed in industry for cement production in this scenario variant.

- NoBioImp. This scenario variant only allows domestic bioenergy to be utilized within the energy system and does not allow bioenergy imports.

Note: Scenario variants can be run together in combination; and most scenarios in this article combine the MSA scenario variant to estimate price response and demand feedback with other constraints imposed by another scenario variant. Each carbon budget scenario is also run without MSA (macroeconomic feedback) to show the effect of inelastic demand response.

3. Results

Irish CO_2 emissions in the energy system are estimated in the official national GHG inventory projections to rise from 38.5 $MtCO_2e$ in 2015 to 48.5 $MtCO_2e$ in 2035 as Irish economic activity continues to grow (EPA, 2017). Under the reference case scenario in this analysis, CO_2 emissions do not follow a recovery path as with economic recovery *per se*, but find an optimally efficient energy system under reference macroeconomic conditions and show a flat projection to 42.2 $MtCO_2e$ in 2050. The three largest CO_2 emitting sectors in the reference scenario in 2050 are transport at 14.8 $MtCO_2$, electricity generation at 9.4 $MtCO_2$ and industry at 6.6 $MtCO_2$. The CO_2-80 scenarios follow EU decline rates of 2.2%/yr to final emissions of 6.8 $MtCO_2$ in 2050. The cumulative carbon budget constraint scenario of 766 $MtCO_2$, consistent with the 2°C target with 66% probability with immediate action, results in an 81–99% emissions reduction by 2050 from 1990 levels depending on available technology options and demand reduction options within the economy. The cumulative carbon budget constraint scenarios of 638 $MtCO_2$–376 $MtCO_2$, consistent with the 2°C target with >66% probability with delayed action until 2020 result in an 81–105% emissions reduction by 2050 again on 1990 levels. Faster emissions reduction rates are required in the medium term as a result of delayed action, with economic feedback enabling some optimization of discounted welfare and gross domestic product (GDP) losses while balancing medium-term emissions reductions and long-term abatement costs. Delayed action between 2015 and 2020 has considerable impacts on the rates of decarbonization required for a 2°C consistent mitigation pathway. Immediate decarbonization allows slower emissions reductions of 1.6–2 $MtCO_2$/year for a 2°C target, as opposed to the delayed action case whereby CO_2 emissions need to be reduced by 1.6–3 $MtCO_2$/year by 2030 if energy system emissions do not peak until 2020. For a 1.5°C target, emissions reductions need to be immediate and in the range of 3.5–3.9 $MtCO_2$/year. Annual emissions are reduced by at least half to 18.3 $MtCO_2$ in 2020 for a 1.5°C consistent scenario using the 223 $MtCO_2$ budget scenario, and slowing to near net zero by 2050. Further details are in Figure 1.

The electricity generation sector covered by the EU emissions trading scheme (ETS) and the transport sector are the energy system sectors that most require aggressive decarbonizing. Deep decarbonization using a cumulative carbon budget of 128 $MtCO_2$ without macroeconomic demand reductions or bioenergy imports are infeasible in this model version.

The range of marginal abatement costs of CO_2 are logarithmic in scale across the 2°C set of scenarios. CO_2 abatement costs begin in 2020 at €75/tCO_2 and by 2025 range from €96/tCO_2 to €640/tCO_2 with a median value of €132/tCO_2 rising to €362/tCO_2 to €3308/tCO_2 in 2050 in real terms. For the 1.5°C consistent carbon budgets, the technically feasible scenarios' abatement costs range from €965/tCO_2 to €3080/tCO_2 in 2020 and rise to greater than €8,100/tCO_2 by 2050.

3.1. Overall energy system outlook

The overall makeup of the energy system changes radically across the set of scenarios considered and across individual scenario variants. There is relatively little difference in the 2050 energy systems for 2°C or 1.5°C, contrasting with the significant variation in 2030 between 2°C and 1.5°C scenarios, highlighting immediate action is critical for achieving a 1.5°C scenario. It is clear from Figure 2, given the variability of fuels, technology choices and carbon intensity across scenarios, and the resultant energy system by 2030, that the public and private energy investment decisions made before the UNFCCC global stocktake (GST) in 2023, are critical

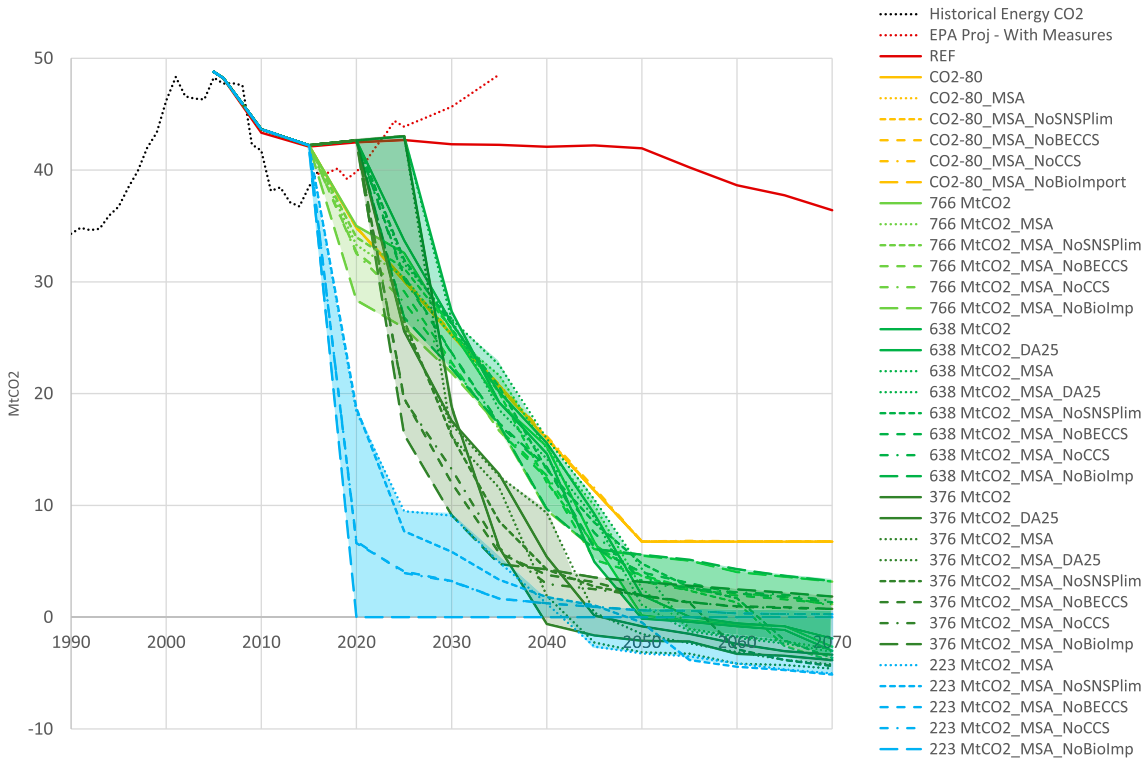


Figure 1. Energy system CO_2 emissions pathways per scenario variant run.

in starting a likely pathway towards remaining well below a 2°C threshold, while aiming for 1.5°C. The REF case is proportionally a continuation of the current energy system. Oil and gas dominate the fuel mix at 7.5 Mtoe and 5.2 Mtoe, respectively and account for 80% of the reference primary energy requirement (TPER) in 2050.

The 2–1.5°C decarbonization scenarios lead to reductions in TPER relative to the REF of between 18% and 27% by 2030 largely as a result of demand reduction, energy efficiency and fuel switching. Natural gas is used as a bridging fuel in the medium term, being substituted by a trend towards consumption of bioenergy for energy intensive demands in transport and industry, and electrification in less energy intensive demands in lighting and low temperature heating. Natural gas is also used as an alternative to bioenergy in electricity generation for scenario variants when bioenergy imports are not allowed. Higher electrification increases installed generation capacity from 6.7 GW in the 2030 reference case, to 9.6–10.8 GW in the 2°C scenarios, and 13.5 GW in the 1.5°C scenarios where renewable electricity makes up 5.1–6.4–7.8 GW of installed capacity. Onshore wind energy and natural gas, dominate the generation mix to 2030, beyond which gas-CCS, bioenergy and BECCS become prevalent.

The sectoral proportions of Total Final Energy Consumption (TFC) remain largely as they are in 2015, with the industrial demand reduction response being larger than in other sectors due to lack of technology substitution options for some industrial energy services. The TFC in the reference case in 2030 is 12.4 Mtoe, with the 2°C scenarios ranging from 10.6 Mtoe to 9.7 Mtoe. Fossil fuels as a proportion of TFC drop from 77% in the reference case, to 62–39% for the 2°C scenario in 2030 and to less than 8% in the 1.5°C scenario. Bioenergy represents more than 16–34% of TFC by 2030 in all 2°C scenarios in variants without bioenergy limits, with electricity representing the remainder, ranging between 22% and 27% TFC. The shift to indigenous bioenergy and renewables has a positive influence on energy security by reducing import dependency to 67% in the 1.5°C scenarios, from 91% in the reference scenario in 2030.

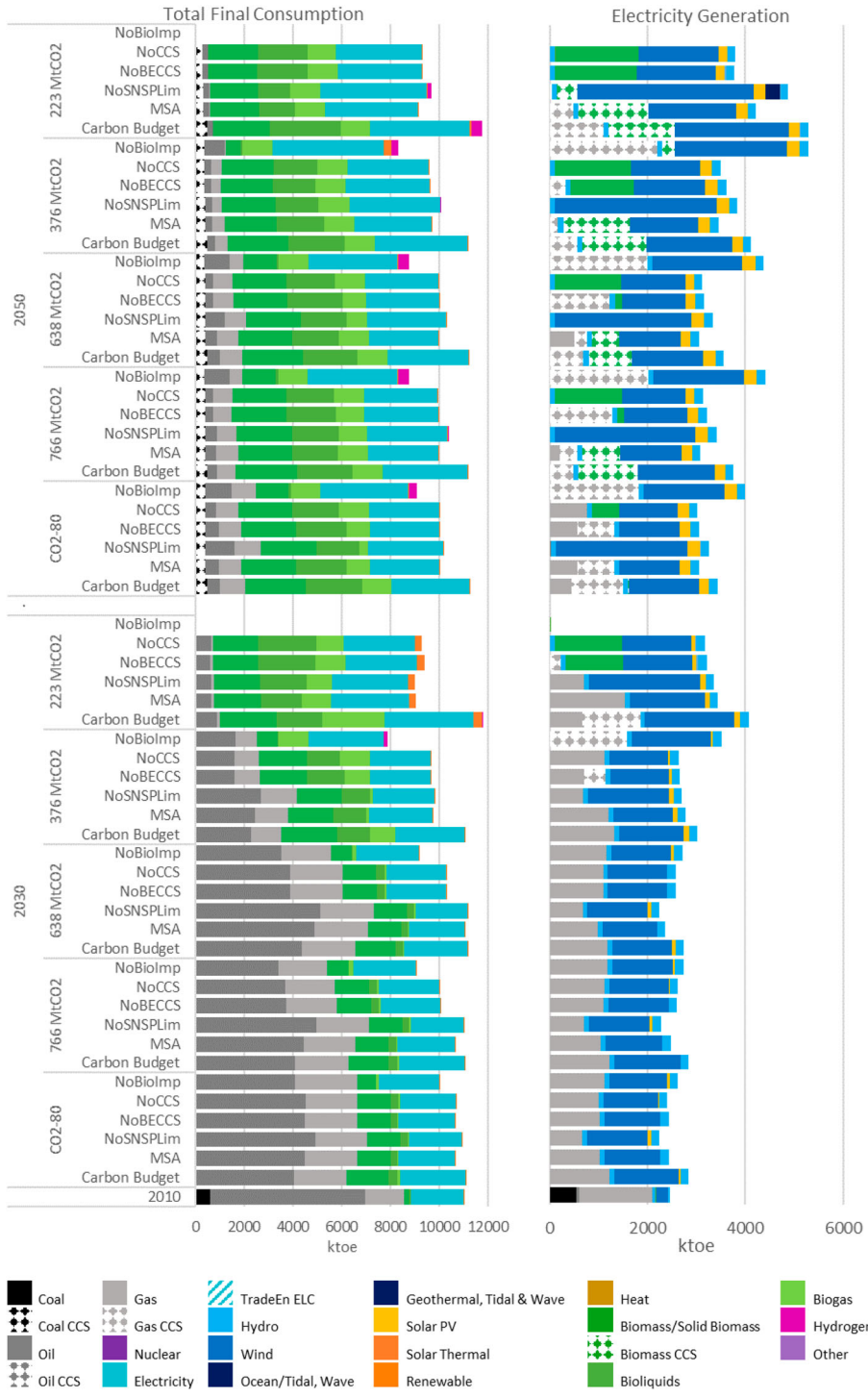


Figure 2. Total final energy consumption and electricity generation by fuel per scenario variant.

3.2. Energy service demand response and consumption

A key element of this analysis is including and quantifying the role of energy service demand reduction as an element in national mitigation strategy as it endogenously responds to price changes in a bottom up technology rich model. Energy service demand response significantly affects decarbonization trajectories and the CO_2 abatement cost. Scenarios, sectors and energy service demands with the largest abatement cost, induce the largest overall energy system costs and incur the largest energy service demand adjustment (see Figure 2, supplementary material). Energy service demand reductions, relative to the reference case in the decarbonization scenarios, range from 5 to 19% by 2030 in the residential sector, and further up to 50% demand reduction in some energy and carbon insensitive industry sectors such as lime and cement production. This demand reduction is brought about through the elasticity of demand with price. The abatement cost of CO_2 is exacerbated for energy service demands in sectors with limited alternative low carbon technology options, creating the need for innovation in construction materials manufacturing and fossil fuel dependent rail transport in Ireland. In terms of passenger transport options, private car energy service demand drops by 5–10% for the 2°C decarbonization scenarios by 2030. Intercity diesel trains show the largest transport demand reductions of 3–13% by 2030, all relative to the reference scenario. Road freight sees a similar reduction in demand of 5–17% by 2030. The energy service demand reductions are plotted in Table 1 in the Supplementary Material. These demand reductions are induced by the cost of the technology choices and the carbon intensity of these technologies driving fuel switching and efficiency in the system.

The energy system costs, consumption losses, and sectoral CO_2 emissions are plotted in Figure 2 in the Supplementary Material and show that reductions in consumption play a significant role in achieving deeper decarbonization goals both in the medium term to 2030 and increasingly to 2050. The 'carbon budget' scenarios without macroeconomic feedback in contrast to the same scenario with macroeconomic feedback, 'MSA', highlight the considerable role of reductions in energy service demand response and the consequent changes in material consumption towards cost reductions in achieving a 2°C target, and even more so for a 1.5°C consistent scenario.

3.3. Economic impacts of mitigation

Energy systems models do not produce forecasts, but instead can provide insights as the decision-making process of a benevolent system planner, minimizing the cost of the energy system in line with the social good. Enforcing a national carbon budget shifts the portfolio of energy system costs toward increased investment in new low carbon infrastructure and generation capacity, reducing the fuel bill of incumbent carbon-intensive technologies, while minimizing other variable costs. Figure 2 in the Supplementary Material shows the cost breakdown for the years 2030 and 2050 for the reference scenario, alongside the 2°C and 1.5°C decarbonization scenarios as a percentage of projected GDP. The reference energy system discounted cost is €24.5bn in 2030, 9.2% of a projected €267bn GDP in 2015 Euro prices. The gross cost of the energy system consistent with the 2°C scenarios increases in the order of 0.6% GDP in 2030 relative to the reference case. The structure of the costs changes, as there is an increase in investment costs of up to 18% from the reference case, with a reduction in fuel costs of 13–20%. The trend changes somewhat by 2050, with increases in real terms and as a proportion of GDP for energy system costs. Consumption reductions and energy service demand reductions become a larger component of the energy system costs in meeting the more ambitious 2–1.5°C scenarios. Investment costs continue to increase for the 2°C scenarios up 23–26% from the reference case. Fuel costs in the 2050 2°C cases generally remain smaller than the reference case.

3.4. Maintaining economic growth in deep decarbonization scenarios

The annualized GDP growth for the reference calibration scenario is projected at 4% between 2015 and 2020, slowing to 2.2% in 2020, and 1.2% beyond 2030 growing to €338bn by 2050 in 2015 Euro prices. The projected actual GDP, for each scenario for each period year, reflects the increasing energy costs when including the external cost of carbon and resultant relative loss in projected GDP. The 2°C decarbonization scenarios GDP losses

range from 0.1 to 0.3% by 2020, highlighting the low-hanging fruit, and relatively negligible losses in GDP in the short term to 2020. By 2030 GDP losses range from 0.5 to 3.2% GDP, increasing with the level of ambition for decarbonization and delays in action. Final GDP losses in 2050 range from 1.3 to 3.3% in the 2°C scenarios (see Figure 3 Supplementary Material). The 1.5–°C scenarios show GDP losses in the medium term to 2030 of 3.6–5.2% relaxing then to 2.7–3.9% by 2050. The annualized effect of these GDP losses in the 2°C scenarios dampens GDP growth slightly, slowing relative to the reference case by up to 0.4% per year with a median value of 0.05% per year in the short term, and by 0.13% in the medium term to 2030. While the economic recession of −3.9% real GDP in 2008 and −4.6% in 2009 and the resultant austerity imposed is still present in the memory of Irish policy and investment planners, this analysis shows the Irish economy could continue to grow considerably, at rates above the projected EU average, with more than 2.2% growth in the 1.5°C cases and more than 3.9% growth in the 2°C cases.

4. Discussion

Compared to national EU mitigation targets set before the Paris Agreement, short-term national mitigation ambition needs to increase to play an equitable role in meeting the Paris Agreement goals. Equitable carbon budgets induce awareness of long-term net-zero emissions requirements to stabilize temperature, meaning that national EU targets need to look beyond 2050 to achieve a least cost trajectory, as ambitious early action reduces long-term costs and risks beyond the current planning horizon. The current EU climate and energy package targets of an 80−95% reduction of GHG from 1990 levels by 2050 are likely to underestimate the short-term and long-term mitigation ambition required at a national level to equitably meet the Paris Agreement. EU policy did not envision a global 1.5°C target temperature limit, and thus currently underestimates the action required to meet this goal. A collective review and ratcheting of EU-28 and national mitigation targets is therefore required to test consistency with pathways to stay well below 2°C and long-term net zero emissions requirements by 2070. While equity principles are generally concerned with inter-regional equity, inter-generational equity and life style and welfare constraints imposed by delayed action and carbon budgets should also be considered.

Reductions in consumption play a significant role in achieving deeper decarbonization goals both in the medium term to 2030 and increasingly so beyond to 2050. Maximizing the social good by minimizing the carbon intensity of consumption is a potential systematic policy target to efficiently minimize sectoral carbon emissions. This overarching objective could be balanced with sectoral objectives of maximizing the production of low carbon intensity per value added goods and services. In an efficient carbon market framework, the economy could aim to maximize value added production with the lowest carbon intensity, which, with competition, should converge over time to an average carbon intensity per value added across all sectors; without this efficiency some sectors will be required to inefficiently and expensively mitigate above the optimum abatement levels and costs per sector, resulting in higher than necessary carbon abatement costs to the economy as a whole. A national social cost of carbon fee on goods and services, which rises annually (see Figure 1 in the Supplementary Material for scale) until net-CO_2 neutrality is achieved, is one such policy instrument to induce investment in decarbonizing the energy system. There is no implicit assumption that this fee is collected by government in this model, but the implementation method could have macroeconomic consequences and should be designed carefully. This carbon fee could be balanced by revenue recycling to ensure net-neutral tax revenue to government, no increased tax burden on individuals, while incentivizing institutional and behavioural decarbonization. Other revenue recycling options could include accelerated payment of government debt, or economic stimulus in co-benefits of low carbon mitigation, climate adaptation measures and energy poverty alleviation.

It is clear that energy system investments made before the Paris Agreement GST in 2023, and the resultant energy system by 2030 are critical in determining the likelihood of remaining below a 2°C threshold, while aiming for 1.5°C. While the energy system cost requirements for 2°C and 1.5°C pathways slow economic growth, the transition to a net-zero carbon energy system is not envisaged to be a considerable concern to growth. As the structure of the economy changes in a decarbonized energy system and the relative energy service demand costs of carbon intensive sectors becomes expensive, there is a greater incentive

for technical innovation and entrepreneurial opportunities. The myopic political option value of delayed action should be assessed against the increased economic opportunity costs, mitigation costs and climate damage risks.

It should be noted that this model does not include an economic damage function or ecosystem service losses as a result of production changes due to climate change, nor does it include the induced competition effect due to unequal international effort sharing over time (Millar et al., 2007; Stern, 2006; The Global Commission on the Economy and Climate, 2014). An economic climate damages function may have a positive effect on relative economic growth compared to the reference case, as mitigation will reduce climate damages to the economy and capitalize on opportunities in developing new industries and services around emergent low carbon technologies and innovation, increased ecosystem services and natural capital accumulation. Competition effects may depend on the impact on production costs from the relative rate of decarbonization between trade partners and competitors. Inclusion of an ecological economic feedback mechanism to a structural economy model including an ecosystem service damage function will give greater insight into the economic costs and benefits of decarbonizing the energy system.

Limits on System Non Synchronous Penetration (SNSP) of variable renewable generation becomes a binding constraint on the power system in deep decarbonization scenarios for Ireland. If the Irish electricity grid can increase the stable levels of acceptable variable renewable generation, this affects the generation mix, the level of electrification, and reduces the marginal abatement cost of CO_2. Imported bioenergy availability is the most considerable model sensitivity in terms of feasible rates of decarbonization and macroeconomic impact.

5. Conclusion

The modelling results suggest that a cumulative carbon budget induces a different optimum decarbonization trajectory shape than a linear trajectory to an 80% GHG reduction as in the current EU policy, and thus differing annual emission reduction targets and investment portfolios are optimal. The removal of each marginal tonne of CO_2 is more difficult, therefore considering carbon budgets instead of annual emission targets, rates of decarbonization are faster in the near term removing low-hanging fruit, than the medium and longer term, and is dependent on discounting and inter-generational equity. The cumulative carbon budget constraint scenarios of 638 $MtCO_2$–376 $MtCO_2$, consistent with a 2°C target with >66% probability with delayed action until 2020 results in an 81−105% emissions reduction by 2050.

Delayed action considerably increases CO_2 abatement costs in both the medium and long term. Delayed action between 2015 and 2020 has considerable impacts on the rates of decarbonization required for a 2°C consistent mitigation pathway. Immediate decarbonization allows slower emissions reductions of 1.6–2 $MtCO_2$/year for a 2°C target, as opposed to the delayed action case whereby CO_2 emissions need to be reduced by 1.6–3 $MtCO_2$/year by 2030 if energy system emissions do not peak until 2020.

This hybrid model approach shows that using equitable carbon budgets creating ambitious decarbonization of the Irish energy system is not excessively expensive as a proportion of GDP, nor is the reduction in production significant enough to pose concern for annual economic growth. Even in the case of deep decarbonization pathways based on equity principles, with more ambitious emission reductions than EU 2050 targets, this analysis shows the economic impact is not significant, in that the economic growth is projected to continue across each scenario. Rapid and highly ambitious decarbonization for the 1.5°C target does incur a considerable slowing of GDP growth in the short term. A social cost of carbon scheme requires assessment in greater detail with a structural computable general equilibrium model of the economy for more policy prescriptive insights to the distributional effects, impacts of revenue recycling, and biases to competitiveness from unequal international rates and costs of decarbonization.

Note

1. The 3200$GtCO_2$ figure is based on the historical emissions range of 2200$GtCO_2$ (±257$GtCO_2$) from the global carbon project (Le Quéré et al., 2016) added to the remaining central 2°C budget of 1000$GtCO_2$ from Friedlingstein et al. (2014).

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