PATHWAYS FOR IRELAND'S ENERGY SYSTEM TO 2050

Modelling analysis to support the Climate Change Advisory Council on the Second Carbon Budget Programme

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EXECUTIVE SUMMARY

Ireland's energy system must achieve net-zero emissions well before 2050 to meet carbon budgets consistent with the Paris Agreement commitment, requiring accelerated cuts in greenhouse gas emissions in power, buildings, industry and transport. Delays in implementing mitigation measures will increase costs and make it harder to meet carbon budgets, highlighting the urgency of immediate action to avoid locking in fossil fuel use and relying on uncertain carbon removals.

Global demand for fossil fuels has not yet peaked, putting the world on track to significantly breaching the temperature goals set out in the Paris Agreement. Temperatures will continue to rise until greenhouse gas emissions reach net-zero. Ireland, which contributes disproportionately to global heating, has established a legal framework and detailed implementation plan to reduce greenhouse gas emissions significantly by 2030. Although the energy transition is gathering pace, current mitigation measures are not on track to meet legally-binding carbon budgets. This projected overshoot poses a major risk and represents a lost opportunity. The urgency of limiting cumulative emissions—and hence global warming—calls for the development of long-term strategies that extend beyond 2030.

This report outlines multiple scenarios for Ireland's energy system from now until 2050, under varying levels of climate ambition. It focuses primarily on the decade after 2030 to inform the Climate Change Advisory Council's (CCAC) assessment of third and fourth carbon budgets. Developed iteratively by the Energy Policy and Modelling Group in UCC in 2023-24 as part of the Carbon Budgets Working Group (appointed by the CCAC), the scenarios present the necessary investments, mitigation measures, and choices across energy supply, electricity, transport, heating, and industry under carbon budgets of different stringency, with varying assumptions about near-term decarbonisation and future energy demands.

Key findings are as follows:

- **Net-zero is critical, but cumulative CO_2 emissions determine total global warming.** Ireland's climate ambition should be framed around cumulative carbon budgets, as the pathway and timing to net-zero are crucial to limit dangerous temperature rise. Emissions from Ireland's energy system need to reach net-zero, or close to zero, well before 2050 and turn negative thereafter. For example, the most ambitious scenarios show a need for Ireland to reach net-zero by around 2035 and also deliver significant reductions in non-CO_2 emissions. If emissions overshoot the committed carbon budgets to 2030 (as projected), the remaining budget post-2030 will be negligible, even under moderate ambition.
- **All scenarios require deeper emissions cuts in the period to 2030 and 2040 than currently planned.** An immediate acceleration of mitigation measures is necessary. Delayed action will increase costs, lead to negative trade-offs (e.g., land use), and make long-term targets less feasible.
- **Costs and Benefits:**
    - The most ambitious carbon budget modelled (*250Mt*) can be achieved with a modest increase in total annualised expenditure relative to a "*No Mitigation*" scenario—only 0.3% of GDP in 2020. This is due to long-term savings from reduced fossil fuel imports.
    - Current policy scenarios ("With Additional" and "With Existing Measures") are more costly than several of the modelled carbon budget scenarios because they do not phase out fossil fuels in favour of cheaper, low-emitting alternatives.
- **A near-complete phase-out of fossil fuels is required by 2040 for power, buildings, and transport.** The phase-out of peat, coal, and oil is particularly urgent. There is nearly no remaining carbon budget for new investments in fossil fuels, including internal combustion engine vehicles, and natural gas demand declines significantly, requiring a plan to decommission its infrastructure.

- **Electrification of transport, heat, and industry is a key mitigation lever,** alongside decarbonising electricity supply. While this transition requires substantial upfront investment, it is cost-effective in the long run due to falling costs of renewables and batteries and the broader societal, health, and economic benefits.
- **Delivering the scenarios relies on strong political, societal, and institutional capacity.** Most of the required technologies are mature and affordable: time, not technology, is the primary constraint. Significant operational and market innovations, such as in energy storage and grid management, will be needed.
- **Final energy demand reduction is essential for meeting ambitious carbon budgets.** Reducing energy demand through compact urban development, modal shift in transport, and shifting support to less carbon-intensive economic activities are an important complement to technology transitions. These changes will require substantial state investment and policy support.
- **Buildings and transport need to be almost fully decarbonized by the mid-2030s.** This requires a rapid phase-out of oil- and gas-based heating systems and internal combustion engine vehicles by 2025, which is not aligned with current market trends.
- **Carbon dioxide removals (CDR) will be necessary for most scenarios,** especially under ambitious mitigation targets or if early carbon budgets are overshot. CDR technologies such as Biomass with Carbon Capture and Storage (BECCS) bring risks, including high costs, technology uncertainties, and conflicts with land use and biodiversity. Pursuing strategies that minimise reliance on CDR through strong early mitigation is essential.
- **Ireland may need to adopt negative carbon budgets** due to potential overshoot of its current carbon budgets and the likelihood that the 1.5°C threshold will be exceeded soon. Any overshoot must be compensated in future budget periods, leaving limited flexibility and necessitating net-negative targets.
- **Comparison with EU Targets:** The European Commission has recommended that the EU cut greenhouse gases by 90% by 2040 relative to 1990 levels. While Ireland's exact target is yet to be defined, the scenarios in this report provide a benchmark against a range of potential 2040 targets.
- **Availability of results:** The scenarios were developed using the peer-reviewed, open-source TIMES-Ireland Model. Detailed results for all scenarios can be explored and downloaded on a web portal: https://epmg.netlify.app/TIM-Carbon-Budget-August_2024

ACKNOWLEDGEMENTS

We acknowledge and are grateful for the contributions of past and current members of UCC's Energy Policy and Modelling Group, particularly those who contributed to the development of TIM and its predecessor, the TIMES-Ireland Model. We are also thankful to the CCAC and members of the CBWG, particularly SEAI's energy modelling team and Prof. John FitzGerald, for constructive feedback on previous iterations of this research, and others who provided comments on the draft report. This research was part-funded by the Department of Environment, Climate and Communications through the CAPACITY project - Climate and Energy Modelling Services to the Climate Action Modelling Group (CAMG) (grant no. RFT2022/S 164-466018).

1 INTRODUCTION

1.1 TERMS OF REFERENCE

UCC's Energy Policy and Modelling Group (EPMG) is supporting the Climate Change Advisory Council (CCAC) through the Carbon Budgets Working Group (CBWG) in the Council's statutory role of proposing finalised carbon budgets 3 (2031-35) and 4 (2034-40) by the end of 2024. The CBWG is tasked with developing an evidence base for the Council's carbon budget proposals by providing modelling and analytical support.

As part of this process, the EPMG modelled future potential pathways for Ireland's energy system consistent with different levels of decarbonisation ambition, covering energy supply, electricity, transport, buildings and industry. The purpose of these scenarios is to indicate the pace and depth of change across the energy system necessary to meet different levels of mitigation ambition, including the timing of introducing new technologies, indicating the reliance on speculative technologies, and the role of energy demand reduction. While TIM does not explicitly model several important aspects of climate action, including the just transition, biodiversity impacts, climate justice, and consequences for investment, the macroeconomy, energy bills and energy security, these modelled scenarios provide a quantitative basis for developing analyses on these aspects of climate action.

This report is the final outcome of this process, describing the results from the third round of three modelling iterations during 2023 and 2024. The report also contains an accompanying descriptive narrative for each of the modelled scenarios, outlines the rates of deployment and costs by technology, describes the role of carbon dioxide removal (CDR), and includes a commentary on potential pitfalls and practical implications. The report also discusses the implications of overshooting existing carbon budgets in the period to 2030 on the basis of current policies.

This set of scenarios have been developed following feedback and review from the Council and other members of the CBWG. While our approach has been endorsed by the Council, it should not be seen in any way as an indication of the Council's position on the second carbon budget programme.

This report contains three appendices. Appendix 1 contains an in-review academic paper, which examines the implications of early carbon budget overshoot. This study is based on the first iteration of modelled scenarios for the CBWG but insights remain applicable to this report. Appendix 2 describes our approach to developing carbon budgets (2021-2050) for Ireland. And Appendix 3 contains more detailed model assumptions and data sources, as well as limitations and caveats.

2 METHODOLOGY AND KEY ASSUMPTIONS

Model description: The TIMES-Ireland Model (TIM) produces detailed technology-explicit pathways on the future evolution of Ireland's energy system – which encompasses the import and extraction, processing, transformation and consumption of all energy carriers (electricity, heat, and liquid, gaseous and solid fuels, whether fossil or non-fossil) in each sector (transportation, buildings and industry), as well as the investment and operation of all technologies that generate, transform or consume energy, and resultant greenhouse gas emissions arising from the combustion of fossil fuels and industrial processes. Rather than predicting or forecasting the future, this model works backwards from a given carbon budget, set of possible future energy demands and assumptions around available technologies, to develop "least cost" pathways. User-defined constraints are typically imposed to reflect the speed at which new technologies can be practically deployed. In this way, energy systems models like TIM can inform the necessary milestones for the energy transition, which can be used to develop policy, prepare infrastructure and examine trade-offs between certain objectives. Energy systems models are often used in conjunction with other detailed sectoral models.

Carbon budgets: The scenarios developed for this study are centred around five different Carbon Budgets (CBs) ranging from 250 million tonnes of CO_2e (Mt) to 450Mt (Figure 1). These CBs are imposed as a constraint on total GHG emissions from the sectors covered in TIM - fossil fuel combustion across Ireland's energy system (covering power, buildings, transport) plus industrial process emissions, and excluding international aviation and shipping. Additionally, in the core scenarios, an additional CB constraint of 275Mt is imposed on the period 2021-2030 to reflect the mandated SECs in the first two carbon budgets[1]. Emissions embodied in the SECs already overshoot the most ambitious climate mitigation scenario, and if fully utilised would leave 25Mt of carbon removals in the period after 2030. At the other end of the spectrum, fully utilising the SEC carbon budgets would allow 175Mt of GHG emissions post-2030 in the least ambitious 450Mt scenario.

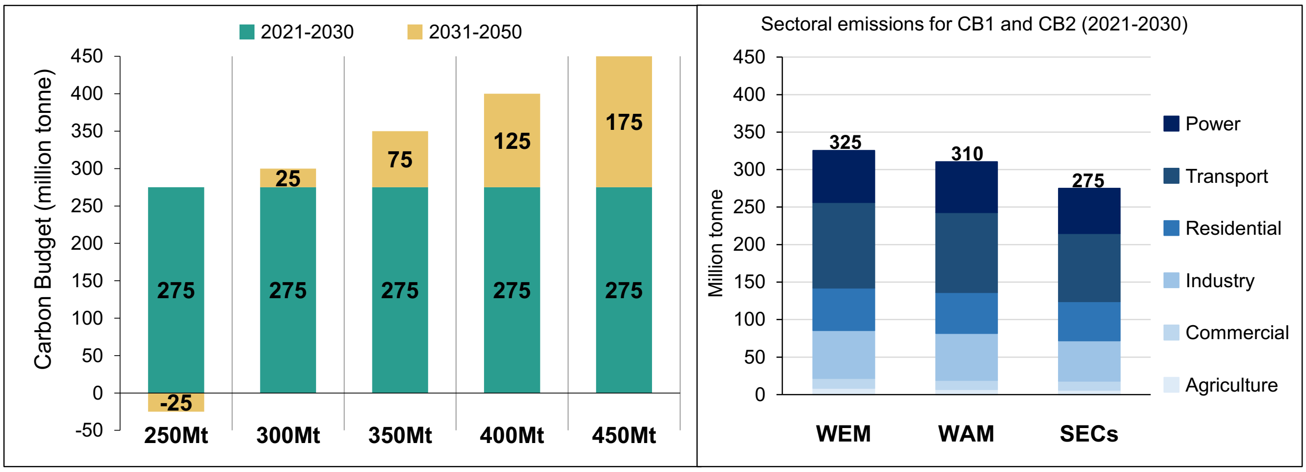

FIGURE 1: MODELLED CARBON BUDGET SCENARIOS FOR THE ENERGY SYSTEM, COMPARED TO CARBON BUDGETS COMMITTED DURING CARBON BUDGETS 1 & 2, AND THE REMAINING CARBON BUDGET FROM 2031-50 (LEFT PANEL), AND ENERGY SYSTEM SECTORAL EMISSIONS FOR CARBON BUDGETS 1 & 2 (RIGHT PANEL)

The implications of overshooting early carbon budgets are explored in detail in a paper which is under review for publication in an academic journal, and contained in Appendix 1.

Current policy scenarios: Despite the development and implementation of mitigation policies as part of the annual Climate Action Plans[2], greenhouse gas emissions are on track to exceed the legislated sectoral budgets in the period to 2030, according to projections by the Environmental Protection Agency (EPA)[3]. The EPA's "With Existing Measures" (WEM) scenario is a projection of future emissions based on the measures currently implemented and actions committed to by Government, while the "With Additional Measures" (WAM) scenario includes all policies and measures included in the WEM scenario, plus those included in Government plans but not yet implemented.

According to Ireland's climate law, any exceedance of GHG emissions in one CB period must be made up for with additional mitigation in the subsequent CB period (in other words, an overshoot in one CB is subtracted from the subsequent one). Therefore failure to deliver on CBs will lead to even smaller CBs in the 2030-2040 period, which is a major threat to their feasibility. To assess the threat to future carbon budgets of a failure to deliver on carbon budgets this decade, this report includes scenarios for each CB case which imposes CBs aligned with WEM and WAM in the period to 2030. These scenarios are named "*300Mt-WAM*", "*450Mt-WEM*" etc.

Moreover, this analysis also includes three additional scenarios which do not impose carbon budgets:

- *BaU-WEM2050* – aligns each sector's GHG emissions with the EPA WEM scenario from 2024-2050
- *BaU-WAM2050* - aligns each sector's GHG emissions with the EPA WAM scenario from 2024-2050
- *NoMitigation* - no carbon budget or GHG target is imposed in this scenario.

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[1] https://www.gov.ie/en/publication/76864-sectoral-emissions-ceilings/

[2] https://www.gov.ie/en/publication/79659-climate-action-plan-2024/

[3] https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/irelands-greenhouse-gas-emissions-projections-2023-2050.php

Final energy demand: Two distinct demand projection scenarios, Business as Usual (BAU) and Low Energy Demand (LED), are considered (see in detail in Appendix 3). Additional details of the distinction between the two scenarios can be found in Gaur et. al. (2022)[1]. We model all five CBs with the BAU and LED demand projections. Combining the CB and demand projection pathways, we analyse mitigation pathways across 30 scenarios (Figure 2).

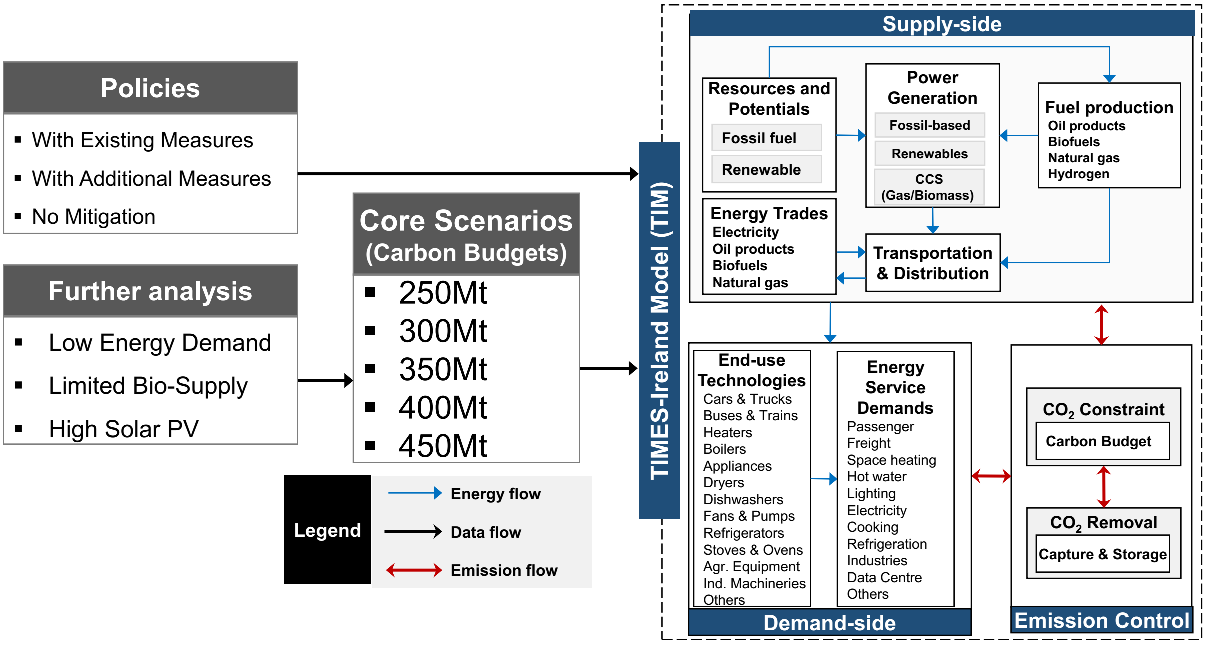

FIGURE 2: SCENARIO DEFINITIONS AND MODEL SCHEMATIC

Key assumptions and detailed methodology: Details on TIM's core methodology can be found in the model documentation paper[2]. The model itself is open-source and peer reviewed, and its files and input data and results archives used for this study can be downloaded from EPMG's GitHub repository[3]. The software tools necessary to solve and interact with the model are available, but require advanced training[4].

Generally speaking, these scenarios do not model the impact of technology targets or measures, such as the number of electric vehicles or production of biomethane in 2030. Rather, these are key outputs of the model, which choses the "optimal" level of technology deployment in a given year to meet carbon budgets and energy demands in each scenario. However, in some cases, technology deployment rates are influenced by user constraints, which are often used to limit the speed at which new energy sources and technologies can be deployed. Otherwise, the model could choose pathways that could be considered "infeasible", or so unlikely so as to be incredible – such as installing 5 GW of offshore wind capacity in 2025. Choosing user constraints to reflect "feasible" rates of technology deployment requires subjective judgment. Key assumptions are detailed in Appendix 3.

Detailed results: Detailed results for all scenarios can be explored and downloaded on a web portal: https://epmg.netlify.app/TIM-Carbon-Budget-August_2024

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[1] Gaur, A., Balyk, O., Glynn, J., Curtis, J. & Daly, H. Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland. *Renewable and Sustainable Energy Transition* **2**, 100024 (2022) https://doi.org/10.1016/j.rset.2022.100024

[2] Balyk, O. et. al. (2022): TIM: Modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1.0), *Geoscientific Model Development*, https://doi.org/10.5194/gmd-2021-359

[3] Model files: https://github.com/MaREI-EPMG/times-ireland-model
Archive of model results: https://zenodo.org/records/13497444

[4] IEA-ETSAP, Antti-L, & G. Giannakidis. (2021). ETSAP-TIMES/TIMES_model: TIMES Version 4.5.3 (v4.5.3). Zenodo. https://doi.org/10.5281/zenodo.4660551

3 CARBON BUDGET PATHWAYS

3.1 CARBON BUDGETS WITH BAU ENERGY DEMAND

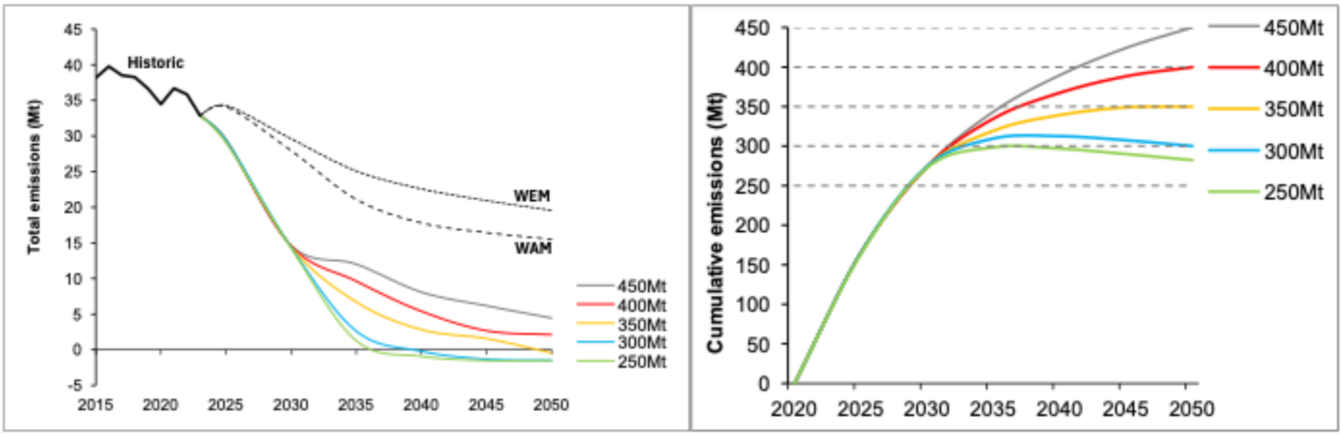


Figure 3 describes the annual and cumulative GHG pathways. Higher carbon budgets allow for greater emissions in later periods: the *400Mt* and *450Mt* cases do not achieve net-zero by 2050, while the *250Mt* and *300Mt* cases each reach that milestone before 2040 and thereafter go negative.

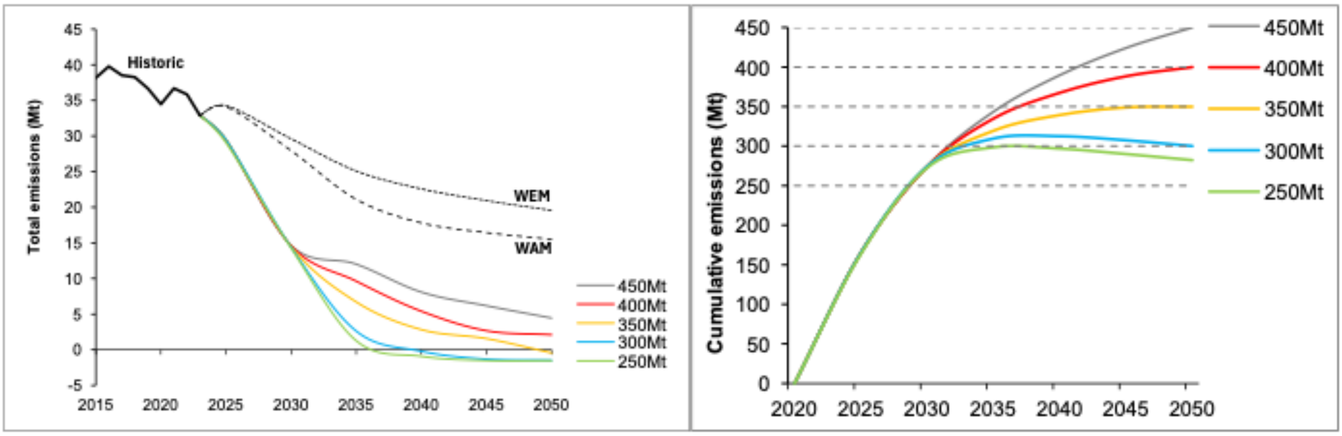
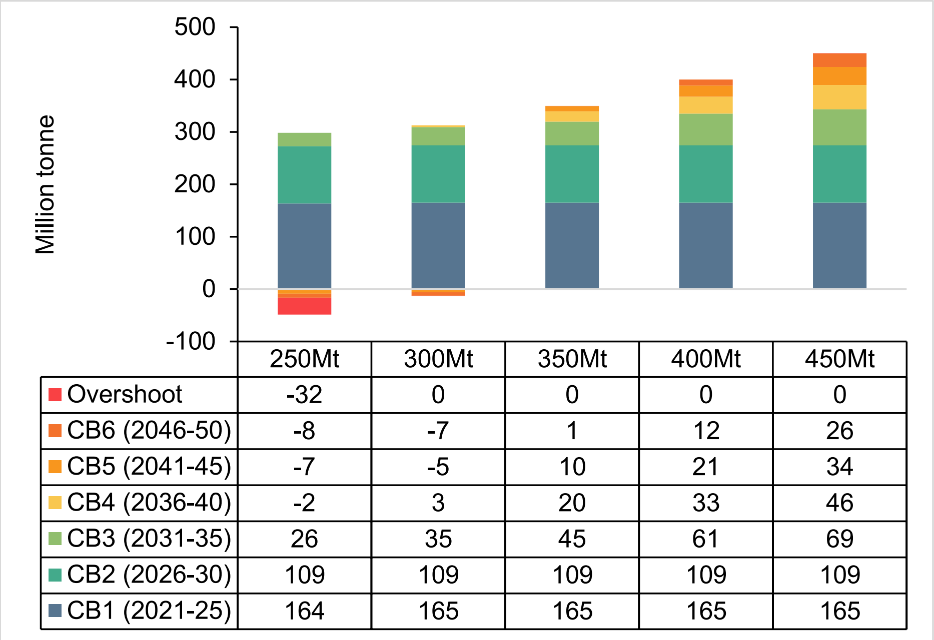


FIGURE 3: EMISSIONS PATHWAYS IN EACH CARBON BUDGET SCENARIO WITH BAU DEMANDS, COMPARED TO THE EPA "WITH EXISTING MEASURES" (WEM) AND "WITH ADDITIONAL MEASURES" (WAM) SCENARIOS (LEFT) WITH CUMULATIVE PATHWAYS (RIGHT).

Figure 4 shows the 5-year distribution of carbon budgets in each scenario. It shows that each carbon budget is fully delivered in each, apart from *250Mt*, where there is an "overshoot" of 32Mt. "Overshoot", or "unmitigated emissions" in this context refers to greenhouse gas emissions from the energy system which the model could not find a viable solution to mitigate (at a cost of <€2000/t), within the given scenario framework - the modelled set of carbon budgets, demands and technology assumptions.

As shown later in this report, in section 3.3, this overshoot is eliminated with LED assumptions. It is also reduced with more ambitious assumptions on solar PV deployment.



	250Mt	300Mt	350Mt	400Mt	450Mt
🟥 Overshoot	-32	0	0	0	0
■ CB6 (2046-50)	-8	-7	1	12	26
■ CB5 (2041-45)	-7	-5	10	21	34
■ CB4 (2036-40)	-2	3	20	33	46
🟩 CB3 (2031-35)	26	35	45	61	69
🟩 CB2 (2026-30)	109	109	109	109	109
■ CB1 (2021-25)	164	165	165	165	165

FIGURE 4: 5-YEAR BREAKDOWN OF CARBON BUDGET FOR EACH BAU SCENARIO, INCLUDING "OVERSHOOT" (UNMITIGATED EMISSIONS)

Figure 5 shows the average marginal abatement cost (MAC)[1] in each decade across each core scenario. Smaller carbon budgets lead to larger MACs. Specifically, the abatement cost more than doubles in the *250Mt* case compared to the *300Mt* scenario – this is because in the former case, the model is unable to fully deliver the carbon budget without "overshoot" with GHG mitigation measures, and is required instead to invest in a backstop carbon removal technology. which cost €2000/tCO_2.

The average MAC from 2021-2030 in each scenario between *300Mt* and *450Mt* – around €750/tCO_2 – is higher than in subsequent decades because a core assumption is that legally-binding SECs are imposed in this decade.

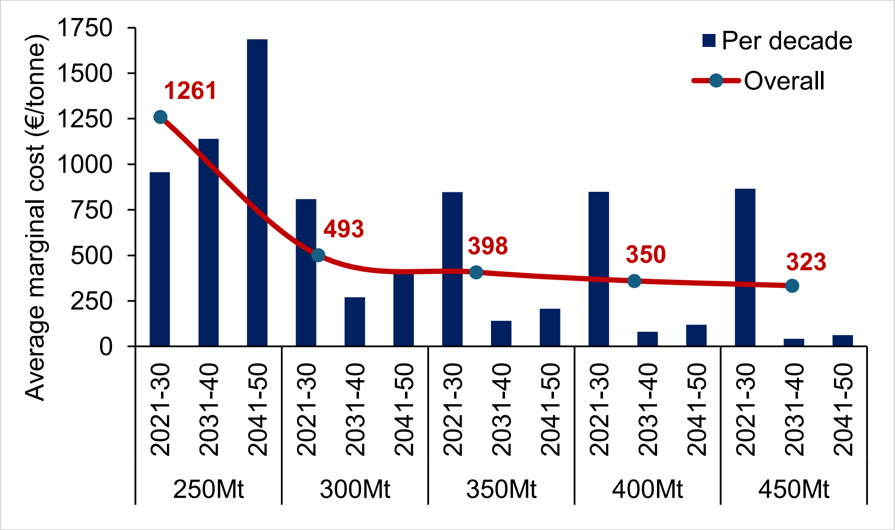


FIGURE 5: MARGINAL ABATEMENT COST IN CORE SCENARIOS

Figure 6 illustrates the financial implications of each carbon budget scenario compared to a "No Mitigation" scenario, where no climate policy is imposed. The total cumulative energy system cost in the most stringent carbon budget case, *250Mt*, is €42 billion over the period 2021-2050, which translates to a cost of €21 per person per month over the 30

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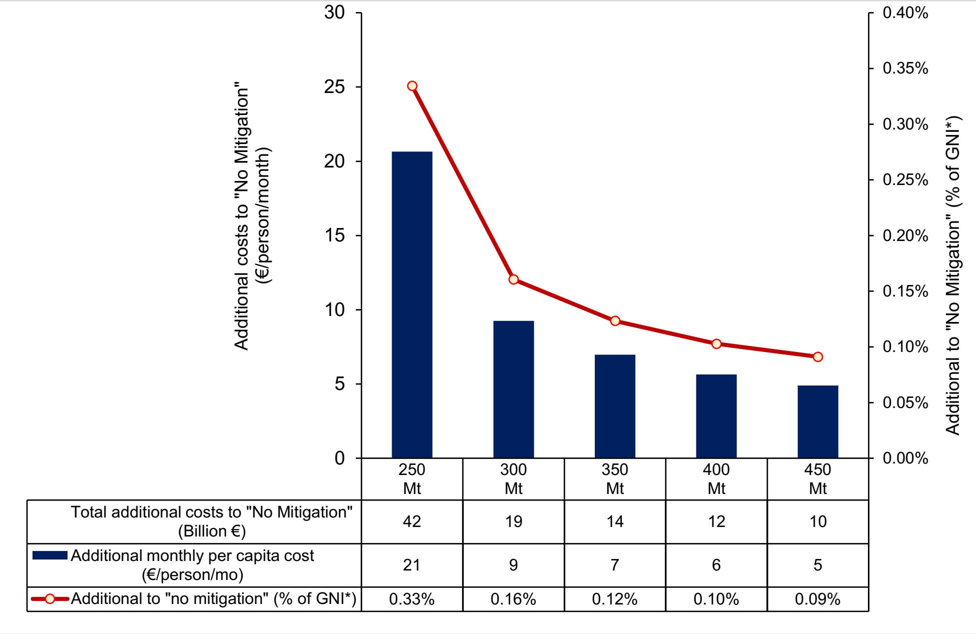
[1] The marginal abatement cost is the (discounted) cost to the model of removing the most expensive tonne of GHG emissions from the energy system – it is a measure of the most expensive mitigation measure in a given scenario, rather than the average cost.

years. This additional cost is equivalent to 0.33% of the average modified Gross National Income (GNI*) over the period. The additional costs in other scenarios are significantly lower.



	250 Mt	300 Mt	350 Mt	400 Mt	450 Mt
Total additional costs to "No Mitigation" (Billion €)	42	19	14	12	10
■ Additional monthly per capita cost (€/person/mo)	21	9	7	6	5
—○— Additional to "no mitigation" (% of GNI*)	0.33%	0.16%	0.12%	0.10%	0.09%

FIGURE 6: ADDITIONAL COSTS IN CORE SCENARIOS COMPARED TO THE NO MITIGATION SCENARIO

While these scenarios bring a modest additional cost relative to a scenario where no carbon budget is imposed, they actually bring cost savings relative to the WEM and WAM scenarios

Figure 7 shows the additional costs of WEM and WAM compared to the core *300Mt* scenario. An important finding is that both WEM and WAM lead to higher total and per capita costs than the *300Mt* scenario, with WEM being significantly more expensive—an extra €9 billion in total cumulative costs over 2021-2050 compared to WAM, and €23 billion relative to the *300Mt* scenario. While WAM represents more ambitious mitigation than WEM, it is still less cost-effective than the core *300Mt* scenario, because of the prolonged reliance on fossil fuels in later decades. The analysis highlights the economic advantage of taking stronger mitigation actions now rather than delaying decarbonisation, as delayed action imposes a greater financial burden on society in the long run from fossil fuel dependence.

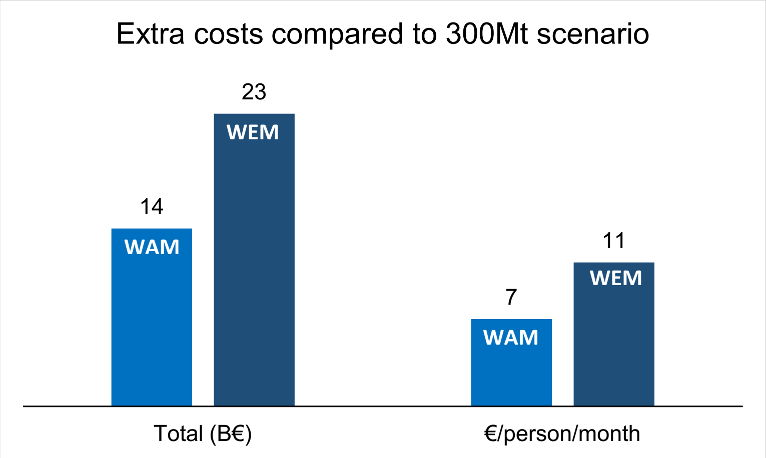


FIGURE 7: ADDITIONAL COSTS (CUMULATIVE DISCOUNTED ENERGY SYSTEM COSTS, 2021-50) ASSOCIATED WITH WEM AND WAM RELATIVE TO *300MT* SCENARIO.

3.2 IMPACT OF WEM AND WAM

This section describes the implications for different carbon budget cases of following a "current policy" trajectory in the period to 2030. It finds that following mitigation trends implied by existing and additional policies (as depicted in the WEM and WAM scenarios) significantly increases the infeasibility of delivering overall carbon budgets.

In WEM and WAM, 324 $MtCO_2$ and 311 $MtCO_2$ are emitted cumulatively from 2021-30 respectively, significantly overshooting the Sectoral Emissions Ceiling for the energy system in that period (275 $MtCO_2$), and overshooting the total 2021-50 target carbon budget in the *250Mt* and *300Mt* cases already by 2030. Because the Climate Act requires that any overshoot in one carbon budget period must be subtracted from subsequent periods (to maintain a total overall carbon budget), following a WEM or WAM pathway leaves vanishingly small carbon budgets after 2030, and would require both infeasibly steep mitigation in the 2030s and significant CDR.

Figure 8 illustrates the implications of the WEM and WAM scenarios on emissions reduction in the *250Mt* case - near-vertical emissions reduction post-2030 – the scenarios need to achieve annual GHG reductions of 27% and 26% respectively each year between 2030 and 2033. The feasibility of this trajectory has not been examined in detail, and should not be considered a plausible scenario.

WEM and WAM significantly increase the scale of emissions the model cannot find a mitigation solution for (right panel in Figure). These grow from 32 $MtCO_2$ in the core case to 73-89 $MtCO_2$ under WAM and WEM.

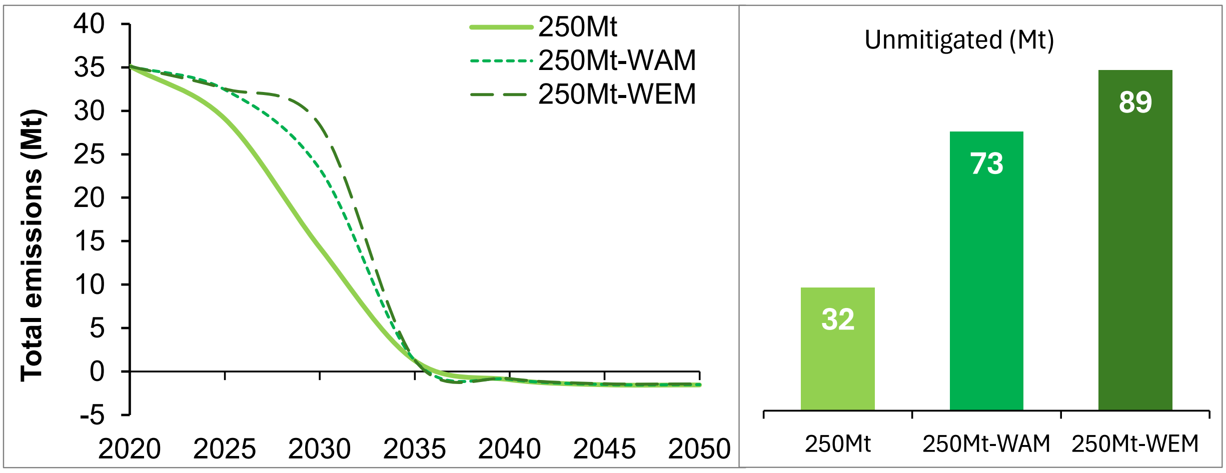


FIGURE 8: IMPACT OF WEM AND WAM ON EMISSION MITIGATION (RIGHT) AND UNMITIGATED EMISSIONS (RIGHT) UNDER 250MT SCENARIO

In other carbon budget cases, following WEM and WAM pathways to 2030 creates similar dynamics and issues: limited emissions reductions pre-2030 requires a radical decline post-2030, and greater levels of unmitigated emissions.

For example, while the model can deliver mitigation options to fully meet the carbon budget in the core *300Mt* case, following WAM and WEM in the period to 2030 leaves 23 Mt and 39 $MtCO_2$ of unmitigated emissions in these cases.

Following WEM and WAM to 2030 brings forward the timeline for achieving net-zero emissions by 5 to 8 years. This suggests that failure to accelerate emissions cuts during the current decade and to meet or exceed SECs will necessitate unprecedented emissions reductions after 2030, pushing forward net-zero targets, and substantially increasing unmitigated emissions.

It is crucial to emphasise that TIM overestimates the feasibility of achieving these rapid GHG reductions between 2030 and 2035. This raises concerns about the realistic ability to meet such steep emissions reductions within this timeframe, emphasising the critical need for rapid climate action in the near term to avoid over-reliance on infeasible post-2030 reductions and reliance on risky and costly CDR measures.

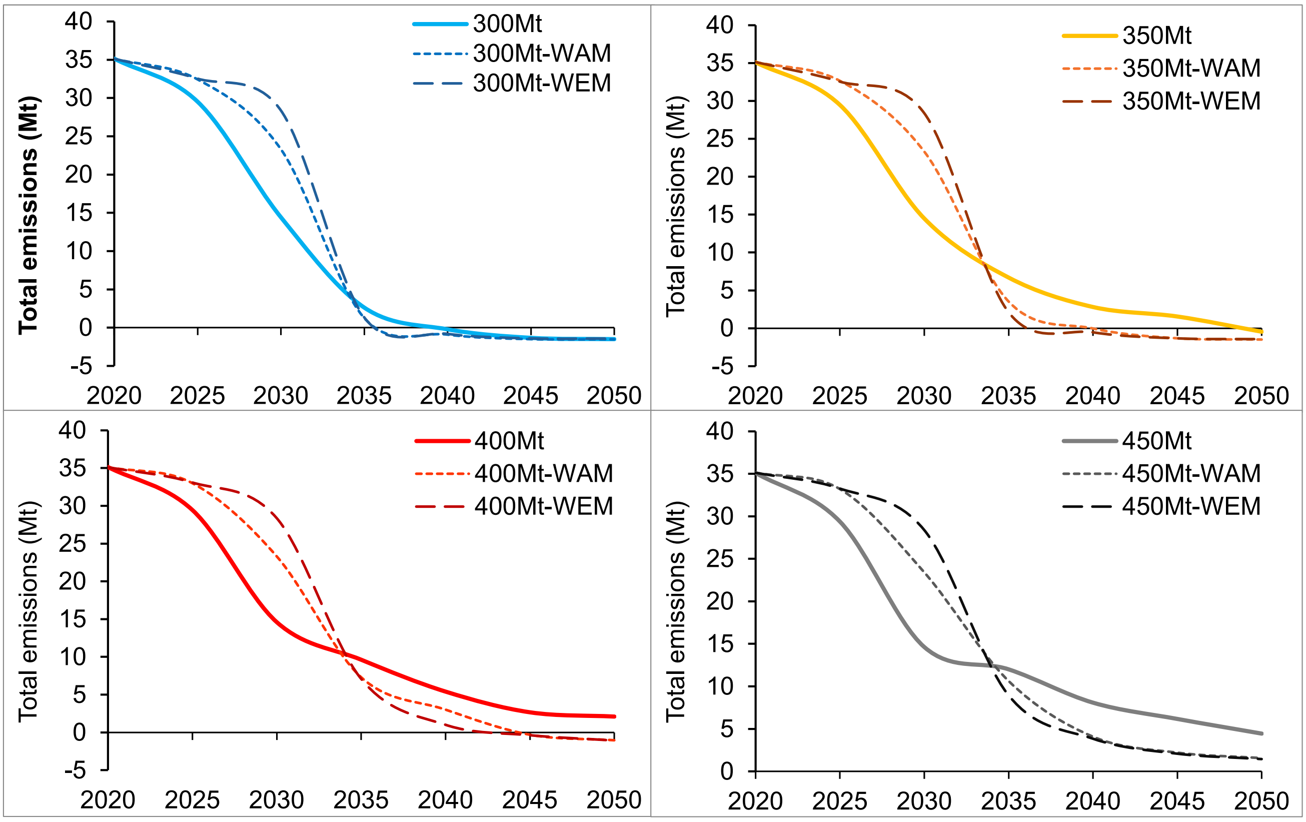


FIGURE 9: IMPACT OF WEM AND WAM ON EMISSION MITIGATION FOR OTHER CORE SCENARIOS

3.3 IMPACT OF LOW ENERGY DEMAND (LED)

The Low Energy Demand (LED) case allows the most ambitious carbon budget – *250Mt* – to be fully delivered with no unmitigated emissions. It enables this by increasing the feasibility of faster emissions reductions particularly in the first and second carbon budget periods (2021-30). Figure 10 shows cumulative emissions in *250Mt-BAU* – which overshoots the total carbon budget by 2028 and is unable to recover from this overshoot with CDR by 2050. The *250Mt-LED* case overshoots the carbon budget later, after 2030, and by a lower amount, and is able to return to the total budget with CDR (via BECCS) by 2050.

LED measures allow more ambitious carbon budgets to be met, and allows mitigation to be met with less rapid deployment of mitigation measures, and with lower reliance on more speculative measures or those which have a higher risks of negative trade-offs, such as BECCS and hydrogen.

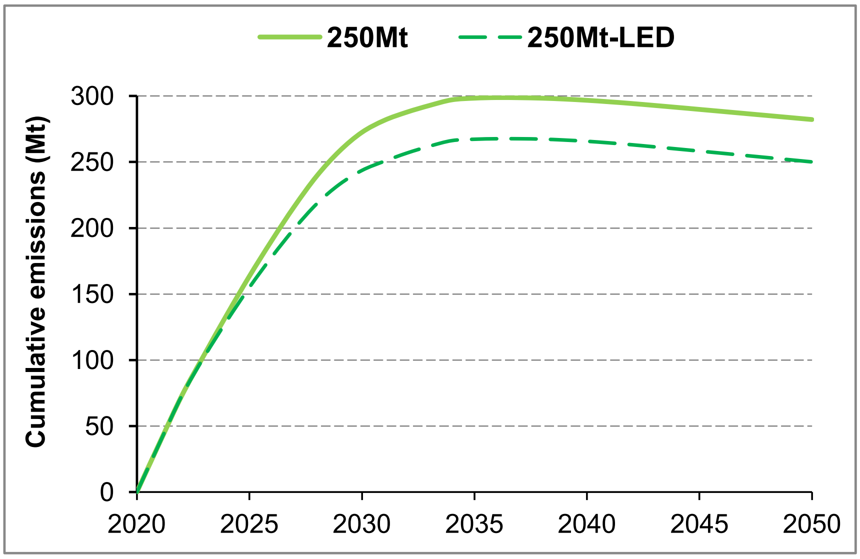


FIGURE 10: CUMULATIVE EMISSIONS IN *250MT-BAU* AND *250MT-LED*

Figure 11 shows total CO_2 reductions relative to 2018 in each scenario. Total emissions in 2030 fall by 62-72%, which is significantly higher than currently policy is planning to deliver. By 2040, emissions in six out of the eight carbon budget scenarios fall by more than 90%, and in three already reach net-negative.

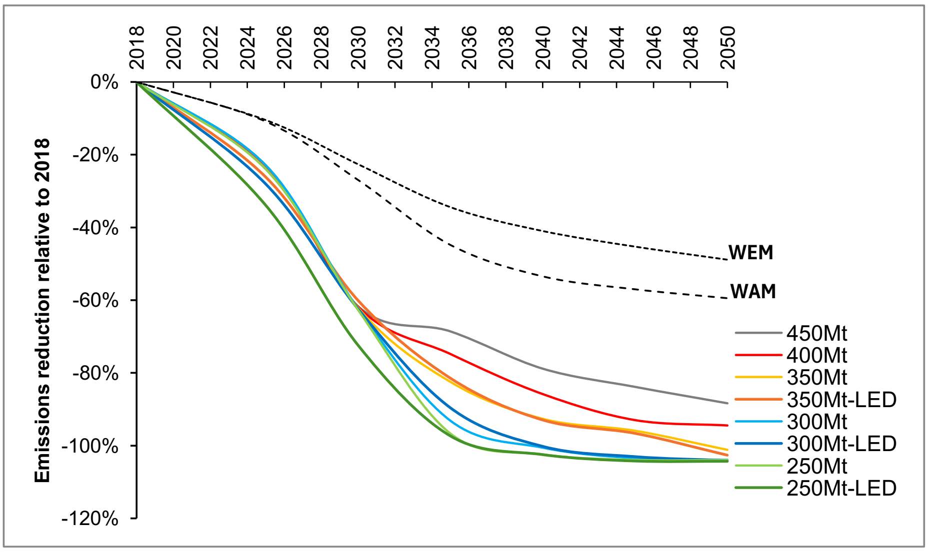


FIGURE 11: TOTAL CO2 EMISSIONS REDUCTIONS RELATIVE TO 2018 BY SCENARIO

3.4 KEY INDICATORS IN 2040

Table 1 details key indicators in 2040, including annualised and cumulative cost, gross and net CO_2 emissions and reductions in energy-related CO2 emissions relative to 2020.

	250Mt-BAU	250Mt-LED	300Mt-BAU	300Mt-LED	350Mt-BAU	350Mt-LED	400Mt-BAU	450Mt-BAU	WAM	No Mitigation
2040 Annualised System Costs (B€ 2018)	25.9	19.8	25.3	19.1	24.5	18.3	24	23.9	23.9	23.2
Cost as % of 2020 GDP	2.3%	1.7%	2.2%	1.7%	2.2%	1.6%	2.1%	2.1%	2.1%	2.0%
2031-2040 Cumulative System Cost (B€)	235	190	229	180	224	174	221	219	217	212
Gross Domestic CO_2 Energy Emissions (Mt)	0.9	0.9	1.6	1.7	2.8	2.7	5.4	8.1	14.6	13.0
Carbon Dioxide Removal from Energy Sector (Mt)	-1.8	-1.8	-1.8	-1.8	0	0	0	0	0	0
Net Domestic CO_2 Energy Emissions (Mt)	-0.9	-0.9	-0.2	-0.1	2.8	2.7	5.4	8.1	14.6	13.0
Energy CO_2 Reduction Relative to 1990	103%	103%	101%	100%	91%	92%	83%	75%	55%	60%

TABLE 1: KEY INDICATORS ACROSS SCENARIOS IN 2040

4 MITIGATION MEASURES

Figure 12 compares the average sectoral allocation of the carbon budget during the study period in core scenarios with actual emissions in 2018. The transport and economic sectors require a larger share of the budget than their share in 2018, because of the longer turnover of fossil fuel equipment in those sectors and a delay in deploying mitigation measures due to greater cost. This suggests that hard-to-abate sectors need more focused efforts to achieve significant emissions reductions. Moreover, significant reductions in power sector emissions will be required by fundamental transformations and significant development of renewable energy sources. A lower level of emissions in the residential sector highlights significant potential for further reductions through energy efficiency measures and electrification.

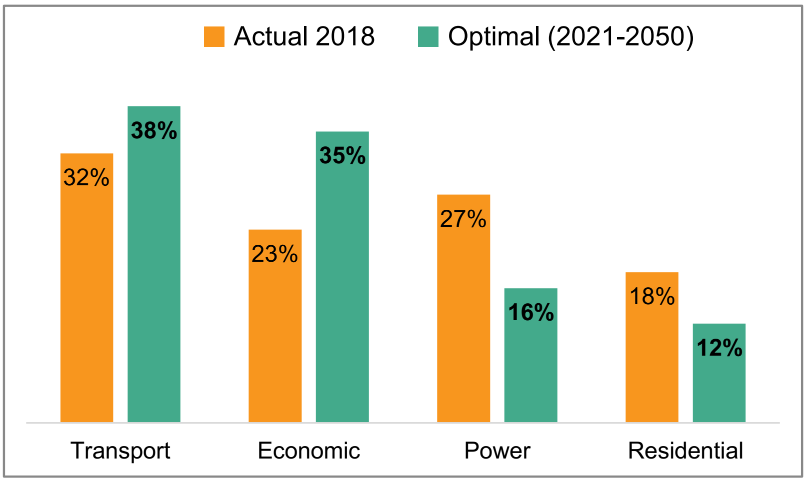


FIGURE 12: OPTIMAL SECTORAL ALLOCATION DURING THE STUDY PERIOD VERSUS ACTUAL EMISSIONS DISTRIBUTION IN 2018. ECONOMIC INCLUDES INDUSTRY (BOTH COMBUSTIONS AND PROCESSES), AGRICULTURE (FUEL COMBUSTION), AND PUBLIC SERVICES

4.1 POWER SECTOR

Electrification, along with decarbonisation of power generation, is the main decarbonisation lever in all scenarios. GHG emissions in the power sector fall below 2 $MtCO_2$ in 2030 in all cases and thereafter either turn negative before 2030 (in the *250Mt* and *300Mt* cases) (Figure 13).

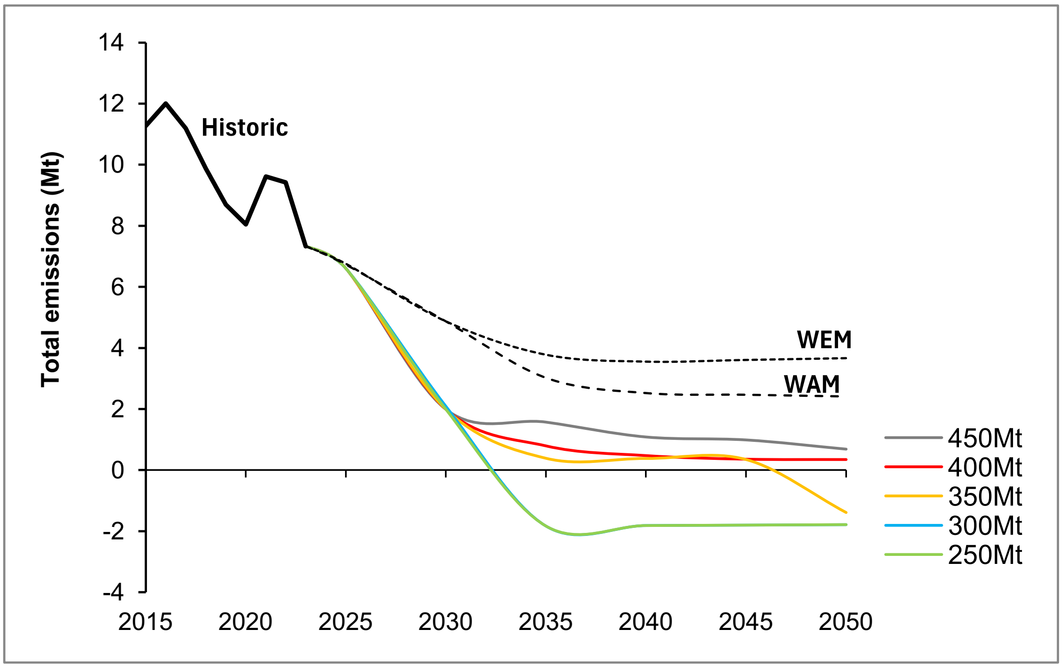


FIGURE 13: POWER SECTOR EMISSIONS IN CORE SCENARIOS

Electricity demand as a share of total final energy consumption (excluding jet kerosene) grows from 22% in 2020, to 41% in 2030, and 69% in 2040. Because electricity end uses are far more efficient than applications based on combustion, such as biofuels, electricity demand represents an even greater share of useful energy demand for transport, buildings and industry. By 2040, electricity represents 86% and 72%[1] of energy demand in domestic transport and residential buildings respectively, and 62% of industrial energy. This is driven by a transformation in power generation capacity, towards renewables and some limited biomass, and in vehicle and home heating technologies.

4.1.1 POWER GENERATION MIX

The power generation mix in each scenario can be viewed on the results portal (link). Power generation from variable renewable energy sources (wind and solar PV) strongly grows in all scenarios – by more than a factor of 4 between 2020 and 2030 in many cases. Even higher shares of renewable electricity in the generation mix are featured in 2030 – above 90% - than the level targeted in the Climate Action Plan (80%). This allows for the both the decarbonisation of the power sector and also the expansion of power generation.

The composition and scale of renewable installations varies significantly between cases: For example, 39 GW of total power generation capacity is installed in the *300Mt-BAU* scenario versus 30 GW in *300Mt-LED* in 2050. The difference is driven by 6 GW more offshore wind capacity, 2 GW of natural gas generation capacity, and 1 GW of additional hydrogen capacity in the BAU demand case.

The LED cases require lower power generation capacity. For example, *350Mt-BAU* requires 1.4 GW of hydrogen-based capacity and about 3 GW of other technologies (mostly gas-fired power generation and BECCS), significantly more than the *LED* scenario. However, additional analysis is necessary to fully explore the role of these (and other) technologies in the power system, as TIM is not designed to model in detail its operation, including investment in grids, storage and flexibility. Moreover, only energy demand for domestic demand is factored in: no exported energy is assumed, beyond that exported in currently planned interconnectors, and the potential power demand for Direct Air Capture (DAC) and e-kerosene is not assessed.

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[1] Excluding ambient heat

Emissions turn negative in the power sector in some cases due to the installation of a 500 MW Biomass with Carbon Capture and Storage (BECCS) power plant, which is in operation by 2035. This generates around 2-3% of total electricity and is responsible for 1.8 $MtCO_2$ of carbon removals annually in these cases. Biomass feedstock is discussed in section 4.2.

The results portal also includes a "*HighSolarPV*" sensitivity case which enables greater levels of solar PV capacity than is assumed in core scenarios. In these cases, solar PV capacity grows to 16.8 GW in 2030 and 18 GW in 2040, while in core cases it is capped at 8 GW in 2030 and 10 GW in 2040. This *HighSolarPV* case enables greater electrification of end-use sectors, more rapid phase-out of natural gas and lower unmitigated emissions in the *250Mt* case (link).

4.1.2 ELECTRICITY DEMAND

Figure 14 and Figure 15 display the total electricity generation by source and consumption by sector in *250Mt-LED* and *450Mt-BAU* scenarios. Both *BAU* and *LED* scenarios require very significant demand growth, as electrification is the main decarbonisation lever in end-use sectors. Growth in electricity demand from data centres is a strong driver of electricity demand in all cases.

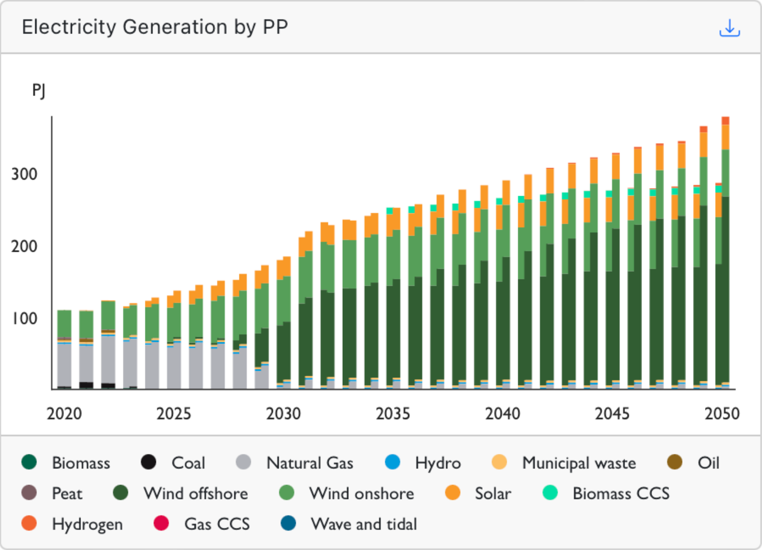

FIGURE 14: TOTAL ELECTRICITY GENERATION BY SOURCE, *250MT-LED* AND *450MT-BAU* SCENARIOS (LINK)

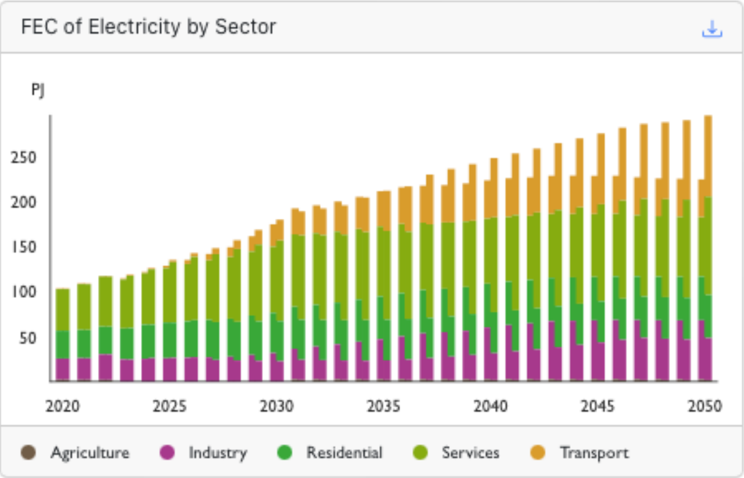

FIGURE 15: FINAL ENERGY CONSUMPTION OF ELECTRICITY BY SECTOR, *250MT-LED* AND *450MT-BAU* SCENARIOS (LINK)

4.2 BIOENERGY

Bioenergy primary energy demand grows to around 20 TWh in 2030 in the *350Mt-BAU* scenario, more than doubling the level from 2020[1]. Of this demand, 3.2 TWh is for biogas, which is all used in the industry sector, 7.5 TWh is for biodiesel and ethanol, which is used in the transport sector in the period to 2030, and then to a limited extent also in the residential sector, 3.7 TWh is for solid biomass, mainly in the industrial sector. LED scenarios and less stringent carbon budget scenarios require lower bioenergy across the energy system.

Detailed assumptions underpinning this sector are described in Appendix 3. Bioenergy and biomass supply limits and costs are derived from the SEAI Heat Study Bioenergy for Heat report for domestic bioenergy sources[2]. While bioenergy is treated in TIM as a zero carbon fuel (following the GHG inventory), there is a greater risk of causing indirect GHG emissions and other negative impacts from biofuels than other mitigation options. Low risk biomass resources include those coming from domestic waste, such as food waste and animal manure. Higher sustainability risks arise from dedicating land to grow crops to produce bioenergy, including grass for the production of biogas. Importing wood pellets from outside Europe, growing grass with current cultivation practices, and relying on imported vegetable oils for bioenergy present particularly high sustainability risks. To limit the potential negative consequences of using bioenergy for GHG mitigation, this report has taken a precautionary approach and limited the potential import of biomass, and limited the total capacity for Biomass with Carbon Capture and Storage (BECCS) to 500 MW.

A sensitivity case, *LowBio*, is also included, where there is no increase in bioenergy demand relative to 2020, in order to explore the implications across the energy system of limiting bioenergy imports. Unabated emissions rise by 11 $MtCO_2$ – this could be offset by greater speed in deploying renewables, such as solar PV, or end-use electrification measures.

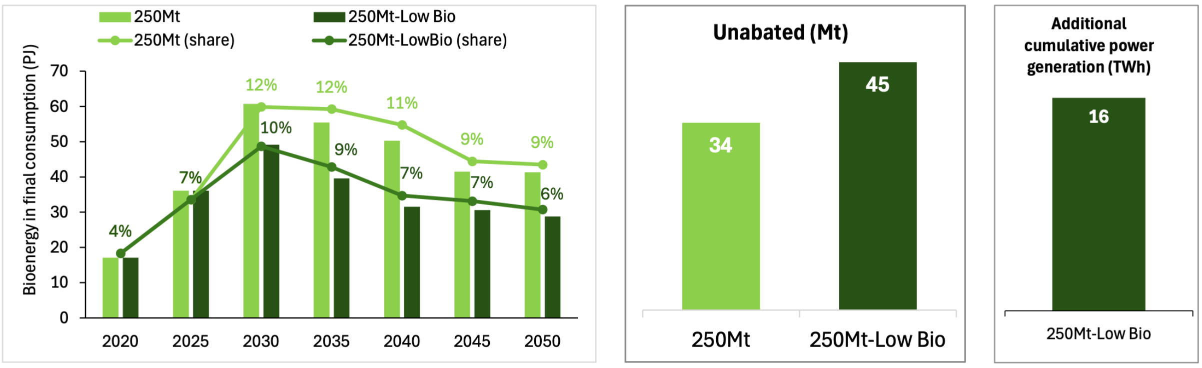

FIGURE 16: IMPLICATIONS OF *LOWBIO* CASE IN 250MT CARBON BUDGET: LOWER BIOENERGY SUPPLY INCREASES UNABATED EMISSIONS AND REQUIRES GREATER ELECTRIFICATION.

4.3 TRANSPORT

The transport sector decarbonises rapidly in all carbon budget scenarios, and reaches close to zero by 2040 (Figure 17). This is achieved through near full electrification of all vehicles by 2040, which requires an end to the sale of new internal combustion engine (ICE) vehicles by 2025 for private vehicles and 2027 for freight vehicles. Even in the absence of any climate policy, TIM finds that full vehicle electrification is the lowest cost energy system - no new private ICE vehicles are sold from 2027 or light goods vehicles by 2028 in the *“NoMitigation”* scenario, because EVs already cost less on a total cost of ownership basis than ICE vehicles in many cases. More stringent carbon budgets bring forward the full electrification date for goods vehicles. *LED* scenarios, which

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[1] Results relating to bioenergy can be found in the results portal at the following links:
Primary energy demand: Link; Final energy consumption by fuel and sector: Link; Bioenergy supply: Link.

[2] https://www.seai.ie/renewable-energy/bioenergy/biomass-in-ireland/

lower the dependence on private cars and reduces freight vehicle movements, allow a later phase out of new fossil-fuelled vehicle sales.

Full results on new vehicle sales and stock can be explored at the following link.

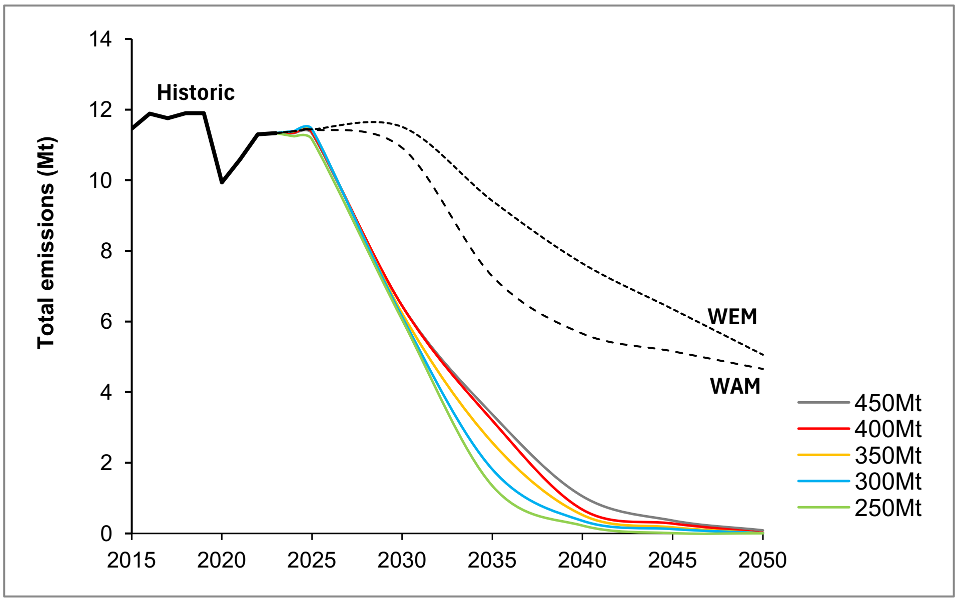

FIGURE 17: CO2 EMISSIONS IN THE TRANSPORT SECTOR

4.4 BUILDINGS

Electrification through heat pumps (facilitated by reducing the heat loss of building fabric) is the main mitigation pathway across all scenarios (link). Figure 18 shows mitigation pathways for carbon budgets in this sector, which diverge strongly from the WEM and WAM scenarios. Such rapid mitigation is delivered in the model because the most carbon-intensive buildings, especially detached buildings, are targeted with retrofitting measures first – the use of coal and peat end immediately, and the use of kerosene for heating is mostly phased out by 2030. Heat networks play an increasingly important role after 2030, in apartments and in attached homes. In scenarios with a higher carbon budget, some natural gas remains until 2040, but in more ambitious scenarios it is phased out in the early 2030s along with other fossil fuels. The model indicates a possible role for biogas in some scenarios after 2035 – for example, it provides 7% of energy for heating in 2050 in the *300Mt* case - however this requires careful analysis on the cost and feasibility of maintaining supply infrastructure, which is not within TIM's scope. New research using TIM indicates that lowering the threshold for heat loss before supporting heat pumps can facilitate more rapid energy transition at lower cost[1]

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[1] https://www.sciencedirect.com/science/article/pii/S0378778824004997?ssrnid=4644106&dgcid=SSRN_redirect_SD

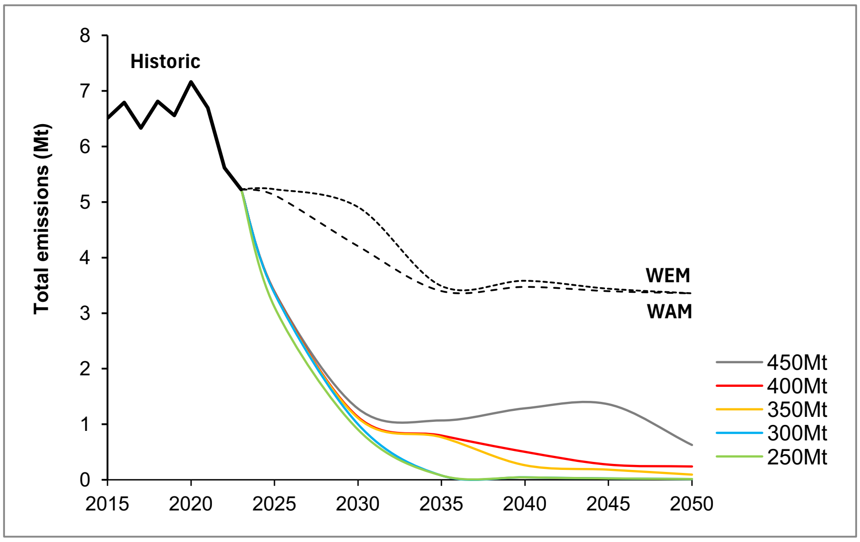

FIGURE 18: CO2 EMISSIONS IN BUILDINGS

4.5 INDUSTRY

The main mitigation levers in in industrial sector are direct electrification of most heat levels, apart from high-temperature process heat, which relies on biomass and wastes. Fuel switching from natural gas to biogas and from solid fuels to solid biomass are transitional measures in the short- and mid-term. Additionally, carbon capture and storage (CCS) installation in cement manufacturing, is deployed to decarbonise the process emissions from this process. With smaller carbon budgets, CCS technology is deployed earlier. For example, in the *450Mt* scenario, this CCS technology is not deployed while in the *400Mt* scenario it is deployed from 2045 and in other carbon budget scenarios it is used from 2030.

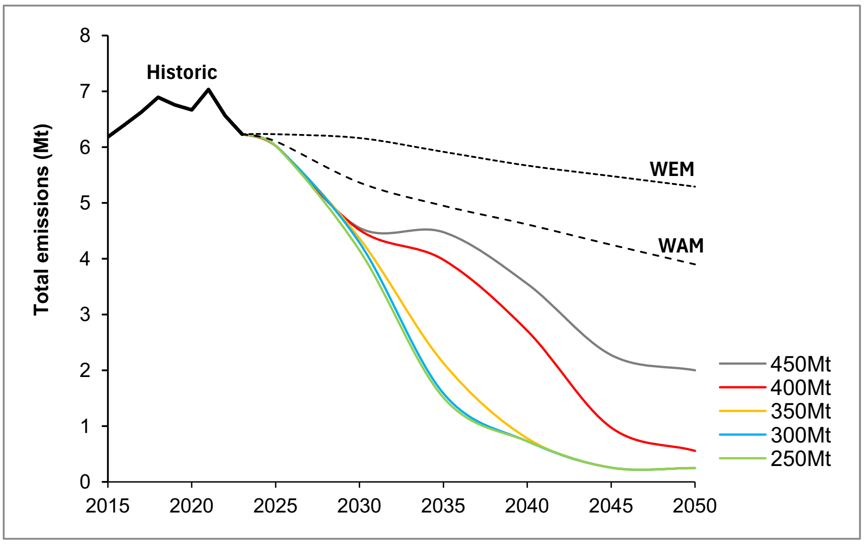

FIGURE 19: MITIGATION PATHWAYS IN THE INDUSTRIAL SECTOR

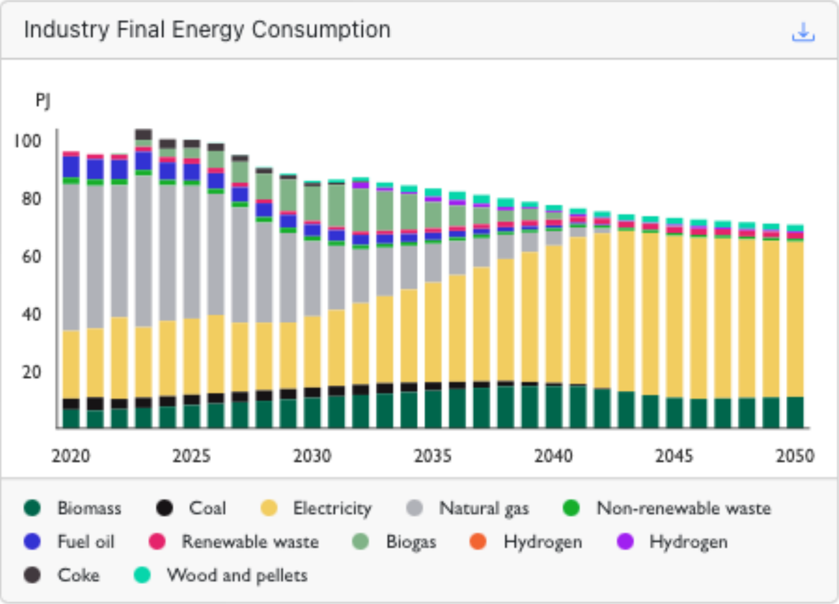

FIGURE 20: FINAL ENERGY CONSUMPTION IN THE INDUSTRIAL SECTOR, 2050MT-BAU (LINK)

4.6 RELIANCE ON CARBON DIOXIDE REMOVAL (CDR)

Many scenarios rely to some extent on carbon removals[1], either through Biomass with Carbon Capture and Storage (BECCS), which is modelled explicitly, or other forms of carbon dioxide removal (CDR), which are not explicitly modelled. Greater levels of carbon removals are required in scenarios with greater mitigation ambition (i.e., lower carbon budgets), and in scenarios with higher early overshoot of carbon budgets to 2030 (WEM and WAM cases), and with higher final energy demands. Reliance on removals brings significant risks and trade-offs, including the risk of failure for the technology to be developed or be deployed, the permanence of removals, financial cost and conflicts with biodiversity and land use. Pursuing mitigation strategies that lower dependence on CDR is important to manage these risks, through strong early mitigation efforts in the period to 2030, lowering energy demands. CDR can be thought of as a risky and costly fall-back option if present mitigation efforts fail, not as an alternative to mitigation now. A careful assessment of the sustainability and opportunity cost of BECCS feedstock is necessary. Importing biomass to deliver CDR in Ireland risks driving GHG emissions elsewhere in the world. Despite these caveats, this analysis indicates that some amount of CDR must be explored to limit and reverse the overshoot of global temperature rise above the Paris Agreement commitments on an equitable basis.

Ireland is likely to need to develop negative carbon budgets, for two reasons. Firstly, it is likely that the Paris Agreement's 1.5C temperature threshold will shortly be passed, or has already passed. Greater peak warming risks triggering irreversible feedbacks and tipping points in critical planetary systems. Secondly, unless there is an urgent course-correction, current policies and trends deviate significantly from carbon budgets 1 and 2, and any overshoot in those budgets must be compensated for in subsequent budget periods. The scale of the projected overshoot is greater than the diminishingly small carbon budgets in later carbon budget periods,

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[1] "Carbon removals" refers to technologies, practices and approaches that remove and durably store carbon dioxide from the atmosphere. Such Carbon Dioxide Removal (CDR) or Negative Emissions Technologies (NETs) can entail measures in LULUCF, such as afforestation and peatland rewetting, or the deployment of novel technologies such as Direct Air Capture (DAC). Biomass with Carbon Capture and Storage is the only CDR technology that is explicitly modelled in TIM – others are represented using a generic "backstop" carbon removal technology costing €2000/tCO_2.

leaving a negative budget. Several countries have set net-negative targets, and researchers have proposed "carbon removal budgets"[1].

5 BENCHMARKING AGAINST EU 2040 TARGET

The EU has set a target to reduce net GHG emissions by at least 55% relative to 1990 levels for 2030. Recently, the European Commission recommended a 2040 climate target, proposing a 90% reduction in net GHG emissions by 2040 relative to 1990 levels. The EU has not formally adopted this target, nor has it indicated how Member States will be allocated different targets, or whether sectors will be treated differently. In this section, we benchmark carbon budget scenarios for this report against illustrative targets which may be applied to Ireland's energy system in 2040.

Emissions from the Irish energy system were 32 $MtCO_2$ in 1990. If a 90% reduction target was applied to energy system CO_2 only, this would require emissions to fall to 3.2 $MtCO_2$ in 2040. Figure 21 illustrates emissions reduction pathways from the energy sector across the carbon budget scenarios modelled for this analysis compared to illustrative targets from 85% to 90% based on the energy system's CO2 emissions in 1990. The most ambitious carbon budget scenarios – *250Mt-LED* and *250Mt-BAU*– meet the 95% reduction target in 2035, while the least ambitious carbon budget scenario – *450Mt-BAU* – meets the 80% reduction target in 2044.

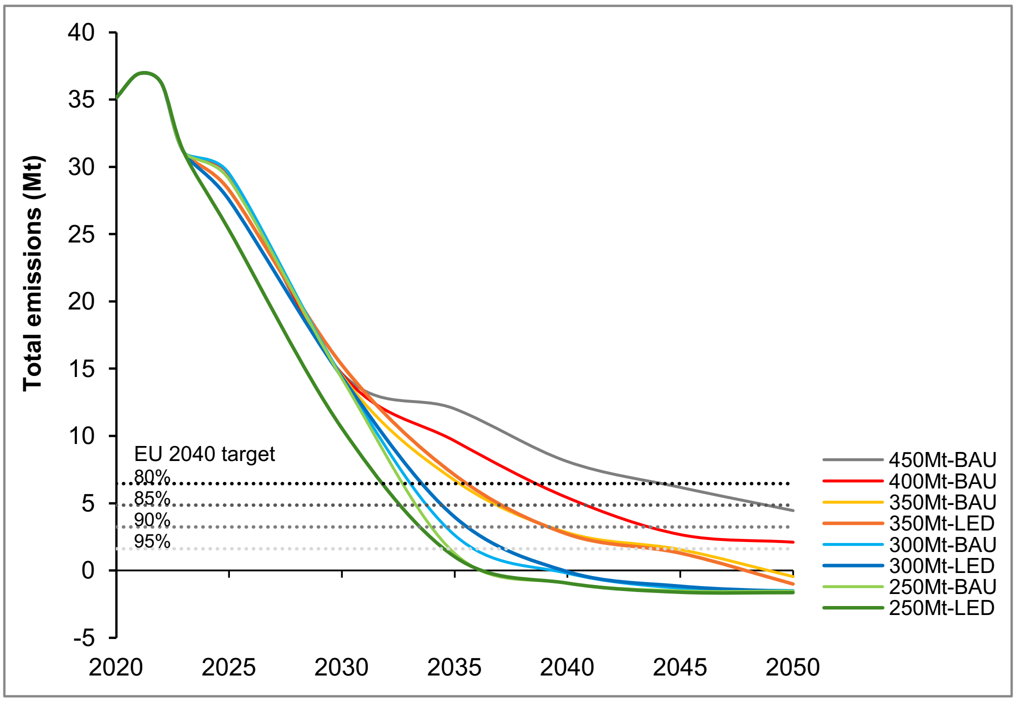

FIGURE 21: CARBON BUDGET SCENARIOS BENCHMARKED AGAINST ILLUSTRATIVE GHG REDUCTION TARGETS (RELATIVE TO GHG EMISSIONS IN THE ENERGY SECTOR IN 1990)

6 PRACTICAL IMPLICATIONS, POTENTIAL PITFALLS AND CHALLENGES

6.1 KEY FINDINGS

Key findings are as follows:

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[1] Caldecott & Johnstone, 2024. The Carbon Removal Budget: theory and practice https://doi.org/10.1080/17583004.2024.2374515

- Net-zero is a critical milestone, but cumulative CO_2 emissions determine total global warming. For this reason, Ireland's climate ambition is framed as cumulative carbon budgets. Planning the sustainable energy transition to deliver net-zero by 2050 is not sufficient: the pathway and timing of net-zero in each sector, and delays in delivering mitigation will instead determine success. Understanding this difference is critical for appreciating the scale of Ireland's mitigation challenge. Consequently, it is likely that emissions from Ireland's energy system must fall to net-zero, or close to zero, well before 2050, and thereafter turn negative. For example, this report shows that carbon budgets aligned with the most ambitious contribution to climate action globally would require existing carbon budgets in the period to 2030 to be reduced, and for Ireland's energy system to achieve net-zero by around 2035, as well as delivering significant cuts in non-CO_2 emissions. Moreover, if emissions overshoot committed and legislated carbon budgets in the period to 2030 (as indicated by projections based on current and planned policies) , this overshoot must be compensated for by reducing carbon budgets in subsequent periods. The scale of projected carbon budget overshoot would leave little-to-no carbon budget left following 2030, even under moderate ambition.
- All scenarios detail significantly greater greenhouse gas emissions cuts in the period to 2030 and 2040 than planned under current policies. An immediate acceleration in implementing mitigation measures is necessary to close this gap. Making up for this overshoot in the long-term may not be feasible, and would lead to an increase in overall costs and negative trade-offs for land use.
- The most ambitious carbon budget modelled for this study (*250Mt*) can be delivered with a very modest increase in total annualised expenditure relative to a "NoMitigation" scenario – only 0.3% of GDP in 2020 – because mitigation solutions cut the demand for expensive fossil fuels. Significant upfront investment is required, but this is largely cost effective and paid back through a reduction in fossil fuel imports. Significantly, the "With Additional" and "With Existing Measures" cases are more costly than "NoMitigation" cases, and are more costly than several carbon budget scenarios, because they do not phase out fossil fuels in favour of less costly (and lower emitting) fuels.
- A near-complete phase-out of all fossil fuels required is required in the period to 2030 to 2040 for power, buildings and transport in the majority of scenarios. The phase-out of coal and oil is urgent. From now, there is nearly no remaining carbon budget for additional investments in fossil fuels, such as internal combustion engine vehicles. This also has implications for natural gas infrastructure, for which a decommissioning plan is required.
- Electrification of transport, heat and industry, complemented by decarbonising electricity supply, are the main mitigation levers. While this energy transition requires significant upfront investment, and brings new risks and challenges, the falling cost of renewables and batteries, and the social, health, energy security and economic benefits, makes it cost effective. Greater climate ambition lowers the damage caused by greenhouse gas emissions and reduces exposure to fossil fuel supply disruptions. While this report quantifies the cost of greater climate ambition, the benefits of earlier fossil fuel phase-out for energy security, economic sectors, air pollution and household energy bills are not quantified, but are likely to be substantial.
- The feasibility of delivering the scenarios described in this report relies on political, societal and institutional capacity. With some exceptions, the technologies and measures necessary to cut emissions are available, mature, cost-effective and well tested. Time, not technology, is the main challenge. The following are some of the main technical challenges associated with delivering these pathways:
    - Operation of the power system with very little natural gas (and other fossil fuels) by the early 2030s: Moreover, total electricity demand grows at an unprecedented rate in all scenarios to meet the need to electrify transport, heating and industry.
    - This will require significant innovations and investment in the power system, including in developing short- and long-duration energy storage, strategic annual storage, flexibility and interconnection, and investment in electricity transmission and distribution. Technologies that are currently nascent and an evolution of electricity markets are necessary to realise this level and pace of decarbonisation.

- Lowering final energy demands makes the most ambitious climate scenarios more feasible than a strategy that relies on technology transitions alone, and can bring additional co-benefits. This can be achieved by reducing dependence on private cars, promoting greater housing density, wasting less energy in buildings and industries, and lowering reliance on carbon-intensive materials such as cement. While these changes will require individuals to change some of their daily practices, this "behaviour change" requires significant state investment and regulation, and the provision of information, to change the choice architecture – such improving public transport provision - to facilitate lifestyles that require lower final energy.
- Many scenarios rely to some extent on carbon removals, either through Biomass with Carbon Capture and Storage (BECCS), which is modelled explicitly, or another form of carbon dioxide removal (CDR), which is not modelled. More carbon removals are required in scenarios with greater mitigation ambition, with higher early overshoot of carbon budgets to 2030, and with higher final energy demands. Reliance on removals brings significant risks and trade-offs: technologies are not proven at scale, and if implemented at scale are likely to come with either significant land-use change implications (in the case of BECCS) or energy demands (in the case of Direct Air Capture), as well as uncertain costs. These risks can be limited through strong early mitigation and lowering demands. Careful assessment of the sustainability and opportunity cost of BECCS feedstock is necessary. Meanwhile, this report indicates that carbon dioxide removal options must be explored to limit global temperature rise to the Paris Agreement commitments.
- These scenarios indicate that buildings and transport should be close to fully decarbonised by the early-to-mid 2030s. This can be achieved through accelerating the pace and scale of decarbonisation measures outlined in the Climate Action Plan: efficiency, retrofitting, district heating and electrification. More ambitious climate scenarios require a more rapid phase-out of natural gas heating systems and of freight vehicles and vans using oil. All scenarios require a very rapid transition away from oil-based central heating systems and heating with coal and peat.
- Moreover, all scenarios see the end of sales of new internal combustion engine private cars sales by 2025, which is significantly misaligned with current trends. This highlights how new investments in technologies dependent on fossil fuels from now have a significant bearing on delivering on carbon budgets, even beyond 2035: New investments either lock in greenhouse gas emissions, or else will become stranded assets as they are retired early. Either the State or private individuals will have to bare this cost.

6.2 FEASIBILITY & PRACTICAL IMPLICATIONS

The energy transition depicted in these scenarios requires more rapid deployment of measures and new technologies than Ireland has achieved in history. However, this does not imply these scenarios are infeasible. Feasibility is a function of the technical readiness of technologies – whether they are available on the market, including supply chain constraints – as well as societal readiness, political commitment, institutional capacity and the readiness of infrastructure. Broadly speaking, the majority of the mitigation measures and technologies depicted in these scenarios are already available, and are currently undergoing exponential growth globally. There are many examples of rapid energy transitions throughout history. Overcoming the barriers to a rapid energy transition is necessary to enable the scenarios depicted in this report. This transformation can be catalysed by political leadership, social movements and disruptive events (such as the war in Ukraine). At the same time, societal forces can also work against the delivery of these climate mitigation pathways.

The following summarises the main practical implications of delivering rapid energy transitions:

- Physical infrastructure: Expanding and upgrading the power grid and investing in flexibility, storage across timescales and interconnection; building district heating networks, public transport networks
- Planning: The speed at which the planning system can approve
- Human resources and skills: Upskilling workers to deliver the energy transition while providing retraining and support for workers transitioning from roles; human resource throughout public system, including planning, civil service, local authorities and education.
- Market design: Redesigning the power market to reward flexibility and storage
- Equity and building public support: Explaining the "how and why" of the energy transition to the public; avoiding backlash by designing the energy transition to deliver multiple benefits and communicating this clearly to the public. Designing energy transition measures in an equitable way, as an end in itself and to increase public acceptance of the necessary changes.
- Finance: The overall cost of the energy transition is manageable, and in many cases will come with net savings, but significant upfront cost is necessary across all sectors to transform the energy system, which must be financed, while capital is redirected from harmful activities.
- Environmental management: Mitigating potential environmental impacts of renewable energy.
- Innovation in industry: Developing cleaner production methods and processes in energy-intensive industries like cement.

APPENDIX 1: ACADEMIC PAPER IN REVIEW

Implications of Accelerated and Delayed Climate Action for Ireland’s Energy Transition under Carbon Budgets

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Abstract

Limiting global warming requires effective implementation of energy mitigation measures by individual countries. However, the consequences of the timing of these efforts on the technical feasibility of adhering to cumulative carbon budgets – which determines future global warming – are underexplored. Moreover, existing national studies on carbon budgets either overlook integrated sectoral interactions, path dependencies, or comprehensive demand-side strategies. To address this, we analyse Ireland’s mitigation pathways under equal per-capita carbon budgets using an energy systems optimisation model. Our findings reveal that delayed mitigation brings forward the need for a net-zero target by five years, risks carbon lock-in and stranded assets, increases reliance on carbon dioxide removal technologies, and leads to higher long-term mitigation costs. To keep the Paris Agreement targets, countries must set and meet accelerated mid-term mitigation goals and address energy demand.

Introduction

To mitigate climate change, constraining cumulative net carbon dioxide (CO_2) emissions is imperative, and discussions increasingly focus on the Remaining Carbon Budget (RCB)[1,2]. The RCB represents the maximum allowable cumulative CO_2 emissions to limit global warming to a specific temperature rise with a given probability[1]. RCBs have been used for analysing the potential implications of a carbon-constrained future at the global level[3–5].

Meeting global climate commitments requires an unprecedented transformation in energy systems[6–9]. Limiting global warming to well-below 2°C above pre-industrial levels by the end of this century and pursuing efforts to cap warming at 1.5°C – the aspirational goal of the Paris Agreement (PA) – will require countries to intensify their near-term ambitions for mitigation by 2030[10–13].

However, countries typically frame climate targets around endpoint targets (e.g., achieving net-zero by 2050) without a clearly defined carbon budget, or regard to how this aligns with the RCB, risking a deviation from temperature and equity goals outlined in the PA[14]. Therefore, aligning national mitigation efforts with RCBs, and translating RCBs into detailed country- and sector-specific mitigation pathways, is crucial.

Global Integrated Assessment Models (IAMs), form the backbone of IPCC assessments, and have been highly valuable tools for climate policymaking and exploring global emissions pathways consistent with PA commitments[15], but they lack the granularity needed for informing national mitigation strategies. Moreover, existing modelling approaches insufficiently incorporate demand-side options and systems analysis[16]. Thus, national-scale energy systems modelling with explicit demand mitigation levers offers a solution by reflecting countries' unique circumstances, including their starting points, energy resources, spatial development patterns[17], economic conditions, existing technology stock, population and economic growth, and aligning with national policy objectives[18].

An emerging trend in this direction is the utilisation of downscaled global RCBs to investigate national decarbonisation pathways. Earlier studies have explored the transition of the Australian electricity sector toward renewables[19], decarbonisation scenarios for the iron and steel industry in Germany[20] and India[21], major industrial sectors in Sweden[22], and the operational and embodied carbon of buildings in Switzerland[23]. However, these studies concentrate on specific sectors. While some notable studies have analysed the broader transition under carbon budgets, envisioning energy system decarbonisation in the US[24], the UK[25], Brazil[26], and Japan[27], the timing of mitigation under RCB scenarios remains insufficiently explored.

The timing of mitigation measures - whether accelerated or delayed - determines compliance with RCBs. For a given temperature outcome, delayed action rapidly depletes the carbon budget, necessitating sharp reductions or greater reliance on carbon dioxide removal (CDR) later on. A few previous studies examining power and energy system transformations in China[28] and India[29] illustrate these dynamics within limited scenarios. They show that late action requires a higher reliance on CDR, while early action is characterised by the rapid deployment of advanced technologies. Analysing the timing of Paris-aligned mitigation actions identifies optimal moments for interventions, avoiding lock-in effects and facilitating a smoother transition. Additionally, it provides insights into the cost-effectiveness of immediate versus delayed efforts[30] and helps investors with capital allocation decisions[10].

However, despite the benefits of early action, multiple sources of inertia, driven by physical, economic, and social constraints, lead to carbon lock-in[31] and act as a barrier to rapid, widescale mitigation. Firstly, the energy system is capital-intensive, and assets are long-lived[32]. Operating existing energy infrastructure risks surpassing PA-aligned carbon budgets[33]. Thus, a trade-off emerges between the urgency of climate change mitigation efforts and maximising the utilisation of existing assets. Moreover, continued investment in fossil-based infrastructures increase the risk of stranded assets, necessitating early retirement or underutilisation[34]. Secondly, while rapid changes in energy consumption behaviours and cultural norms can occur during rare and specific circumstances (e.g., the COVID-19 pandemic period[35]), these changes typically take decades to become sustained. In light of these constraints, demand-side mitigation efforts become crucial, playing a pivotal role in operating energy systems under carbon budget constraints[36,37] and are particularly important for driving the pace and direction of deep decarbonisation pathways[38]. Some studies have examined demand-side strategies. These include the implementation of energy-efficient technologies and smart meters in India[39], the transition from fossil fuels to low-carbon energy carriers in buildings and transportation sectors in major economies[40].

Additionally, efforts in Russia have focused on electrifying end-use sectors and achieving large-scale energy efficiency improvements and productivity enhancements[41]. However, achieving climate goals requires comprehensive demand-side strategies ranging from improvements in energy efficiency and adoption of zero-emission fuels and technologies, to profound lifestyle changes[42].

In summary, existing national mitigation pathways consistent with a carbon budget either (1) are sector-specific, (2) explore the timing of actions in limited scenarios, (3) neglect path dependency and near- to mid-term targets, or (4) focus on technological transformation alone, and partially address demand-side strategies. We extend the existing literature by using a whole energy systems modelling framework that integrates sectoral interactions, considers path dependency, analyses the timing of actions across more than 50 scenarios, and comprehensively incorporates demand-side strategies, all within the context of two distinct carbon budgets.

We employ an energy systems optimisation modelling to construct detailed technology-, fuel- and demand-specific mitigation scenarios for the entire energy system. These scenarios align with carbon budgets aimed at limiting global temperature increases to up to 2°C. The national carbon budget is estimated using an equal per-capita approach. The framework includes explicit sub-sectoral demand projections, under both current trends and low-demand pathways, and quantifies trajectories for capital assets and fuel flows across the energy system, indicating the speed of technology deployment and reliance on CDR technologies necessary. Exploring the impact of accelerated or delayed mitigation action on the energy system under temperature outcomes aligned with global commitments allows the examination of the risk that delayed climate mitigation brings for carbon lock-in and reliance on unproven CDR. Furthermore, this approach can identify climate measures and targets that demonstrate resilience in the face of uncertain futures, while considering the long-lived nature of energy infrastructure and societal dynamics.

The framework is applied to Ireland, which has adopted legally-binding carbon budgets whose basis in legislation is consistent with, among other factors, the principle of climate justice and Articles 2 and 4 of the PA[43]. While Ireland's GHG emissions are relatively small on the global scale, the insights from this study are applicable in other high-emitting, fossil fuel-dependant countries, and the framework can be adopted and applied elsewhere.

Results

Mid-century mitigation pathways

With a larger 400Mt carbon budget (aligned with a 67% likelihood of limiting global warming to 2.0°C) and energy demands growing along with historical (BAU) trends (the *400Mt-BAU* scenario), net emissions fall by 89% in 2040 relative to 2018, and turn negative by 2050, facilitated by Bioenergy with Carbon Capture and Storage (BECCS) (Figure 1). With lower energy demands (LED), the *400Mt-LED* scenario requires no BECCS. With greater climate ambition and smaller 315Mt carbon budget (aligned with a 50% of likelihood of limiting global warming to 1.7°C), negative emissions are required by 2040, intensifying over subsequent years reaching to about 5 Mt in 2050, cumulatively captured 43 Mt during the decade.

Because the model faces constraints in deploying low-carbon technologies and therefore decommissioning existing fossil-based infrastructure, LED scenarios facilitate more rapid emissions decreases in the 2020s, particularly with a lower carbon budget. However, with increased availability of low carbon technologies, and driven by a lower remaining carbon budget, emissions in BAU scenarios fall faster in the 2030s. In the *400Mt-BAU* scenario, cumulative emissions breach the carbon budget in 2042 (right panel of Figure 1), because of earlier overshoot. In the 2040s, therefore, BAU scenarios rely on BECCS to achieve substantial negative emissions. In contrast, *400Mt-LED* scenario remains within the carbon budget over the entire time horizon and therefore do not rely on BECCS.

In the more stringent *315Mt-BAU* scenario, cumulative emissions exceed the budget limit by 2030. Even with some compensating effect from negative emissions with BECCS in the 2040s, this scenario overshoots the budget by 67 $MtCO_2$. In the *315Mt-LED* case, the budget breach occurs 6 years later, with a considerably lower excess of 26 $MtCO_2$.

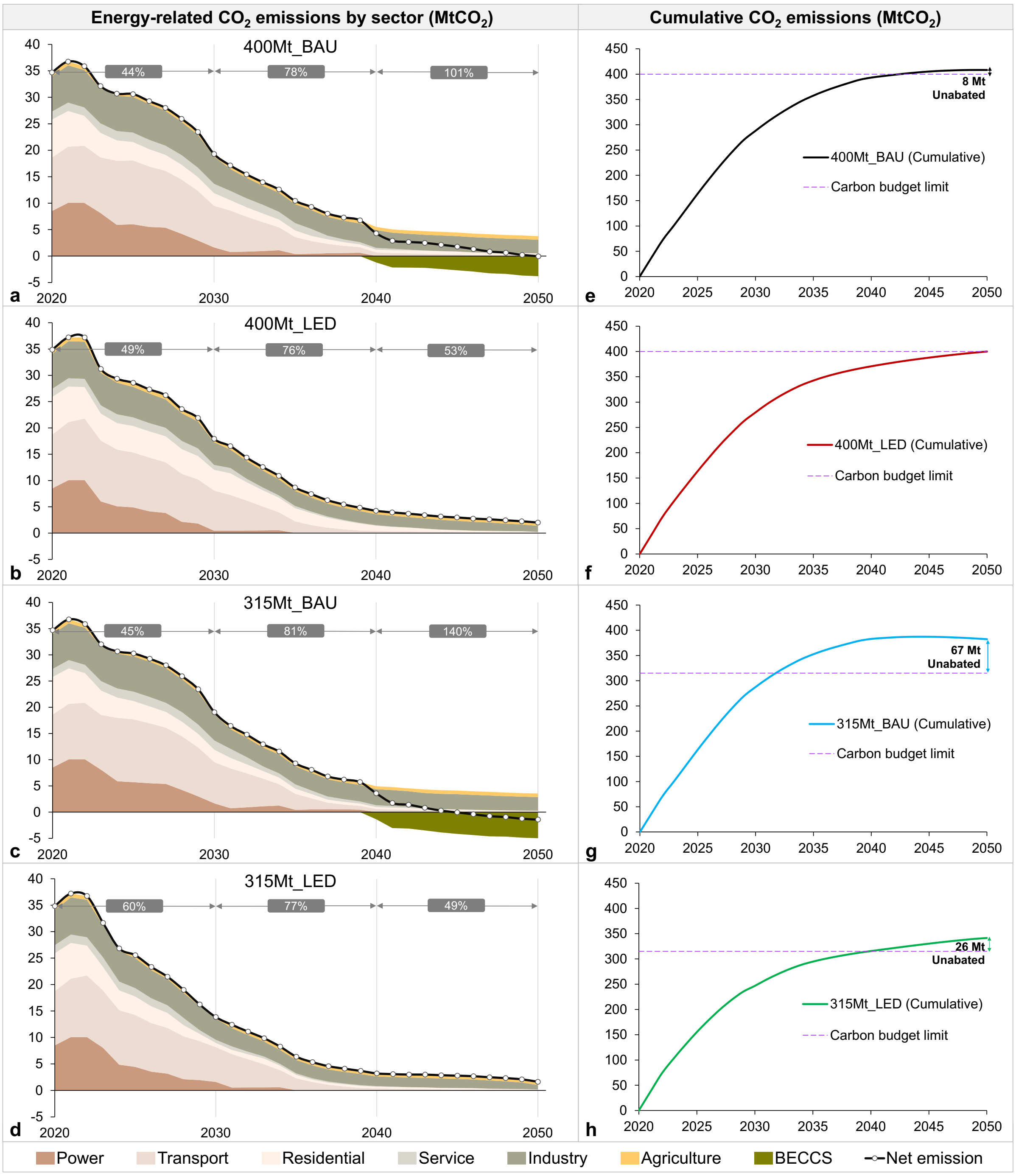

Figure 1. CO_2 emissions from the energy system across different scenarios.
The left panel shows sectoral emissions, removals, and total net CO_2 for (a) 400Mt-BAU, (b) 400Mt-LED (c) 315Mt-BAU, and (d) 315Mt-LED, measured in $MtCO_2$. The right panel displays cumulative emissions for the corresponding scenarios (e) to (h), also measured in $MtCO_2$. The percentage values within the boxes on the left panel denote the total net CO_2 reduction for each decade. “Unabated” in the right panel refers to cumulative overshoot of the carbon budget limit by 2050.

Energy system transformation

By 2050, total final energy consumption (TFEC) increases by 14% in BAU cases relative to 2020, and declines by 39% in LED cases (Figure 2). The share of fossil fuels in TFEC falls from around 75% in 2020 to below 15% in 2050 in BAU scenarios, an 80% decline in absolute consumption, and as low as 9% in LED scenarios. The share of electricity in TFEC rises from 23% to 56-60%. Fossil fuel consumption is not completely eliminated in any pathway due to lack of alternatives in the industrial sector. This transformation from an energy system based on fossil fuels to one based mainly on renewable electricity largely occurs by 2040: in all cases, the share of electricity in TFEC exceeds fossil fuels before 2035, and occurs earlier with smaller carbon budgets.

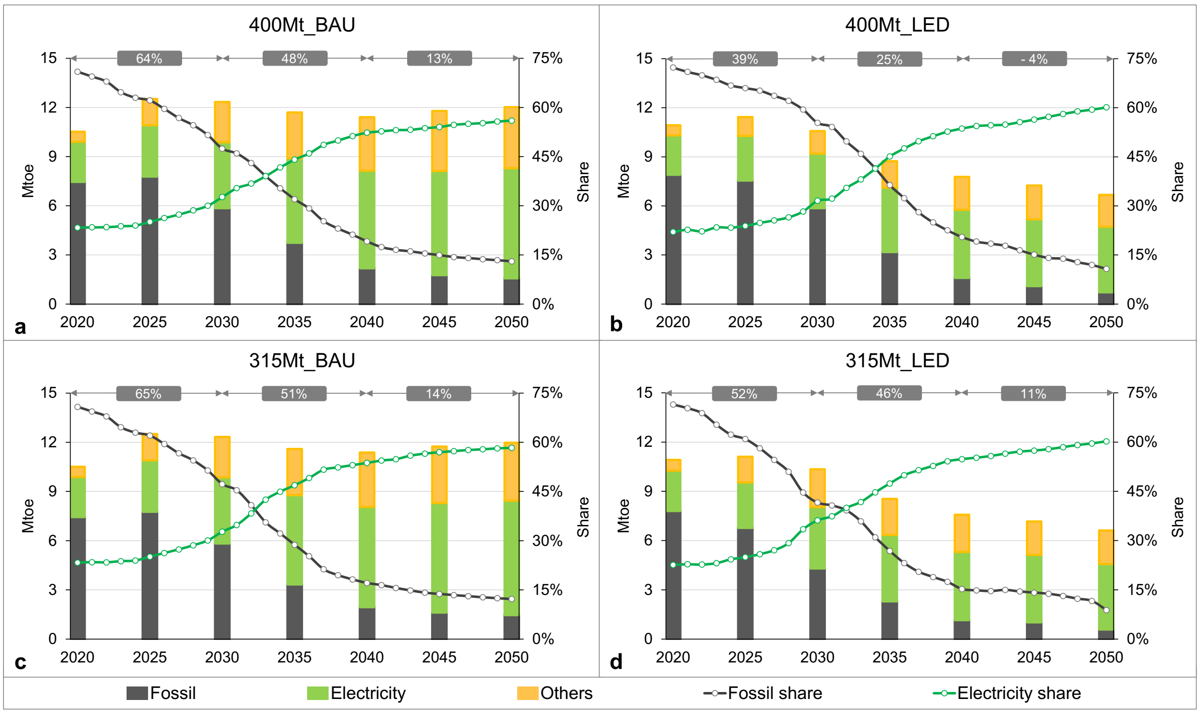

Figure 2. Final energy consumption by fuel in mitigation scenarios.
Fuel consumption is shown for (a) 400Mt-BAU, (b) 400Mt-LED (c) 315Mt-BAU, and (d) 315Mt-LED scenarios. Fuels are disaggregated into electricity, fossil (excluding jet fuel for international flights), and other sources (bioenergy, hydrogen, ambient heat, district heat, and solar heat). The percentage values within the boxes indicate the increase or decrease in total electricity consumption for each decade.

Accelerated versus delayed climate action: Detailed sectoral emissions pathways

Figure 3 presents emissions pathways for each scenario and sector, in both *accelerated* and *delayed action* cases. In *delayed action* cases, up to 30% additional of the total carbon budget is allocated before 2030, reallocated from a corresponding amount between 2030 and 2050. As a result, emissions reductions in these cases are shallower before 2030, requiring deeper cuts post-2030.

The **power sector** is fully decarbonised by 2030 to 2038. This milestone occurs around five years sooner in LED cases, as BAU cases require an additional 20% electricity in 2035, which requires an additional 4 GW of renewable capacity, equivalent to the entire renewable capacity of Ireland in 2022. This difference grows to 10 GW in 2050. Power generation across 2020-50 grows rapidly in all cases, from an average annual rate of 1.5% between 2010-20, to a minimum of 2.9% in LED cases, and at least 4.0% in BAU cases. *Delayed action* in BAU cases require a 4.5% average annual growth rate.

In the **residential sector**, *delayed action* scenarios require full decarbonisation before 2040, whereas *accelerated action* scenarios require achieving near-zero emissions (equivalent to about a 90% reduction compared to 2020) by the same year. In *Accelerated action* cases, emissions fall by on average 11% annually in the 2020s, and by 14% in the 2030s. In contrast, emissions fall annually by 8% in *delayed action* cases in the first decade, followed by an unprecedented rate of over 50% in the 2030s.

In all cases, emissions cuts in the **transport sector** converge on 55% by 2033, relative to 2020. In all cases, the sector is fully – or nearly fully – decarbonised by 2040. *Delayed action* expedites the year of near-zero by around 5 years in BAU cases. *Accelerated* cases require more rapid vehicle fleet electrification. In the *400Mt-BAU* scenario, internal combustion engine (ICE) sales cease by 2025 and 35% of the passenger vehicle fleet is fully electrified by 2030. With an intermediate delay, 19% of the passenger fleet is electrified by 2030, requiring less rapid electric vehicle (EV) adoption, but promoting carbon lock-in and stranded assets as ICE vehicles continue to be sold.

Economic sectors, including industrial, services, and agricultural sectors, do not fully decarbonise, mainly due to limited decarbonisation options for industrial process emissions and agricultural machinery.

Delayed action cases bring forward the date of net-zero by 7-10 years and in nearly all cases, increases reliance on negative emissions technologies in the 2040s (Figure. 3, bottom panels).

The range of cumulative emissions in each decade and sector is relatively limited apart from power generation in the 2040s (Figure 3, right panels), due to the sensitivity of BECCS deployment to the speed of action: wider panels indicate more flexibility. In the more stringent *315Mt* cases, the range of trajectories before 2030 is narrow, indicating that the model is deploying mitigation options to the maximum feasible extent.

In all cases, the majority of the total carbon budget - averaging 82% - is expended in the current decade by existing fossil fuel infrastructures. The breakdown includes 29% from transportation, 24% from economic sectors, 16% from power, and 13% from residential sectors. Over the entire study period, economic sectors account for an average of 41% of the carbon budget, followed by transportation at 37%, residential at 16%, and power at 6%.

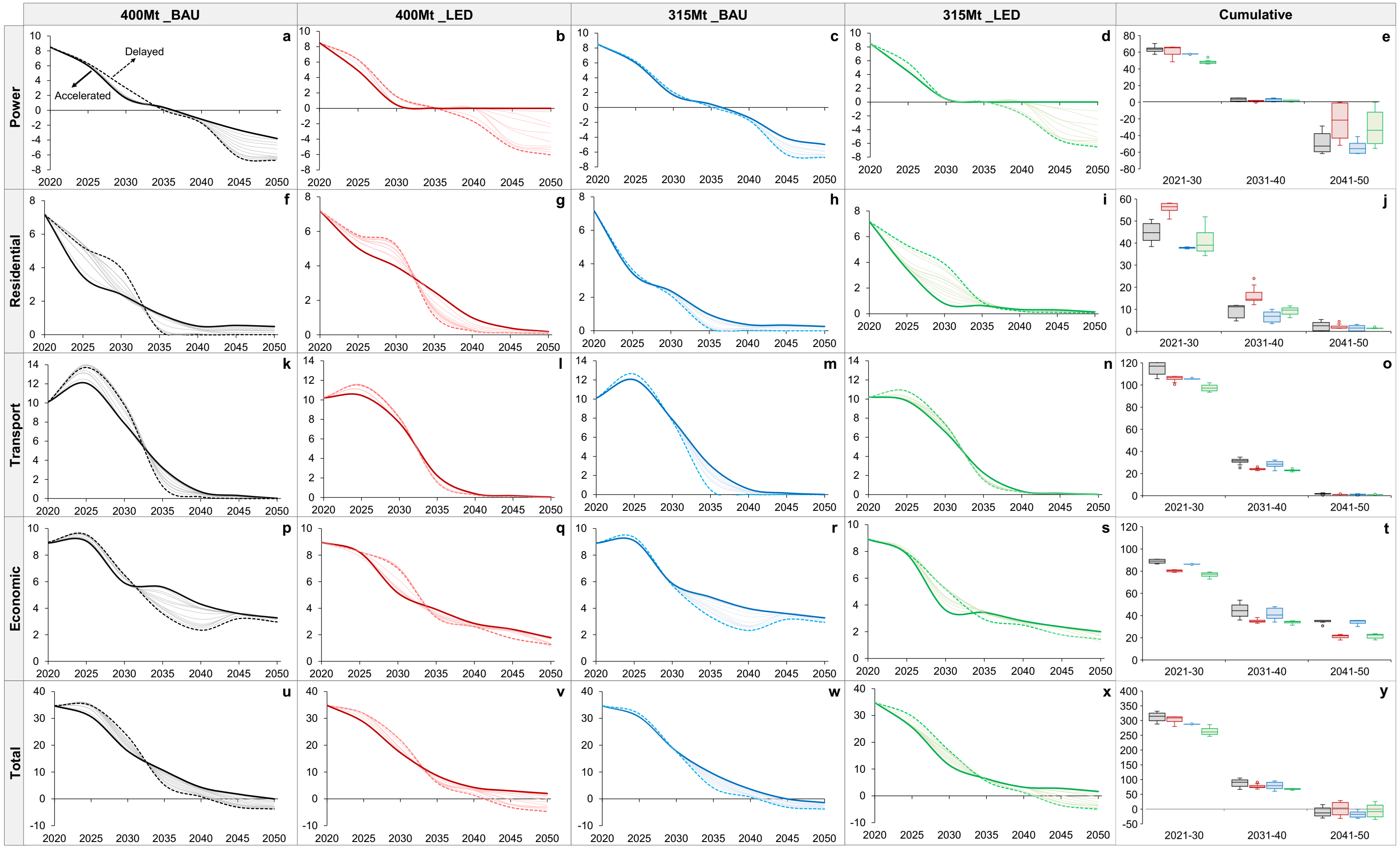

Figure 3. Emissions pathways for accelerated versus delayed climate action.

Sectoral and cumulative emissions are shown for (a)-(e) power sector, (f)-(j) residential sector, (k)-(o) transport sector, (p)-(t) economic sectors, and (u)-(y) total emissions, under different carbon budget in Mt CO_2. The boxes in the right panel indicate the range from the 25th to the 75th percentiles. The upper/lower whiskers illustrate the maximum/minimum values in the absence of outliers, extending up to ±1.5 times the interquartile range. Outliers, represented by dots, show individual data points beyond the whiskers. The lines within the boxes represent the medians, matching the colour of the scenarios. The economic sector includes the integration of the industrial, commercial, and agricultural sectors.

Carbon removal and unabated emissions

Only three out of 52 pathways achieve the carbon budget without relying on any removal technologies (Figure 4). These three pathways operate under low energy demand projections and a higher carbon budget (*400Mt-LED*), with a maximum overshoot of up to 5%. All other pathways have either unabated emissions, particularly in *accelerated* cases, where the carbon budget in the 2020s is smaller, or rely more on carbon removals (BECCS), in *delayed* cases. The highest level of unabated emissions and carbon removals combined are in *accelerated 315Mt-BAU* cases, because of a stringent budget pre-2030 and the model's limitations in immediately replacing existing fossil-based technologies with cleaner alternatives.

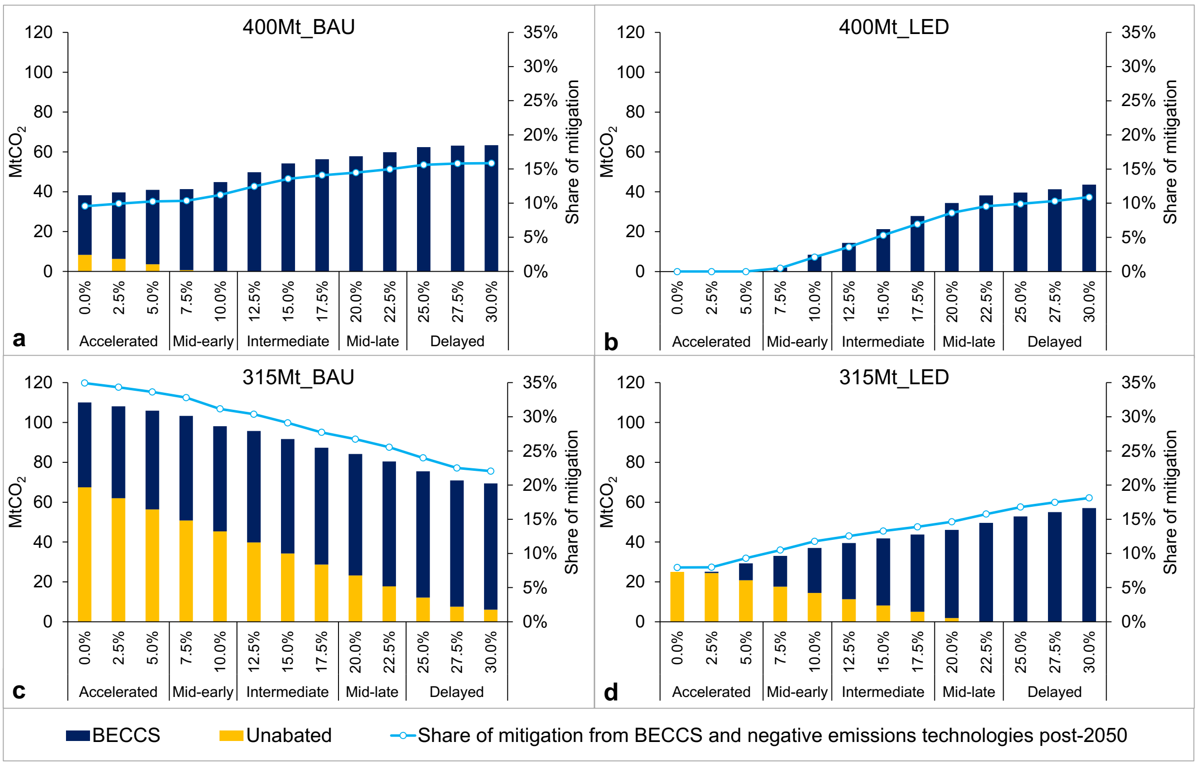

Figure 4. Cumulative activities of carbon removal technologies and unabated emissions. Cumulative activities are shown for (a) 400Mt-BAU, (b) 400Mt-LED (c) 315Mt-BAU, and (d) 315Mt-LED scenarios. The 0% represents the core scenarios, and the others representing overshoots from 2.5% to 30% in each core scenario. "Unabated" refers to emissions with no mitigation options before 2030, assumed to be addressed by negative emissions technologies after 2050.

Economic implications

Figure 5 compares system costs and marginal abatement costs per decade across different scenarios. Accelerated action incurs higher initial costs but delivers substantial long-term cost reductions. While intermediate action reduces marginal abatement costs in the first decade, it does not achieve the significant cost reductions seen under accelerated action. It is worth noting that the high marginal abatement cost does not reflect a carbon tax policy but highlights deployment constraints under the BAU demand projection. The model struggles to deploy clean energy technologies quickly enough to meet the constraints of the accelerated scenario. Consequently, this necessitates a greater reliance on expensive removal technologies, costing €2,000/tonne of captured CO_2, to avoid emissions overshoot before 2030. Delayed action offers short-term savings but results in significantly higher long-term costs across all metrics. This analysis suggests that although delaying action may offer short-term economic benefits, they are ultimately offset by higher long-term costs.

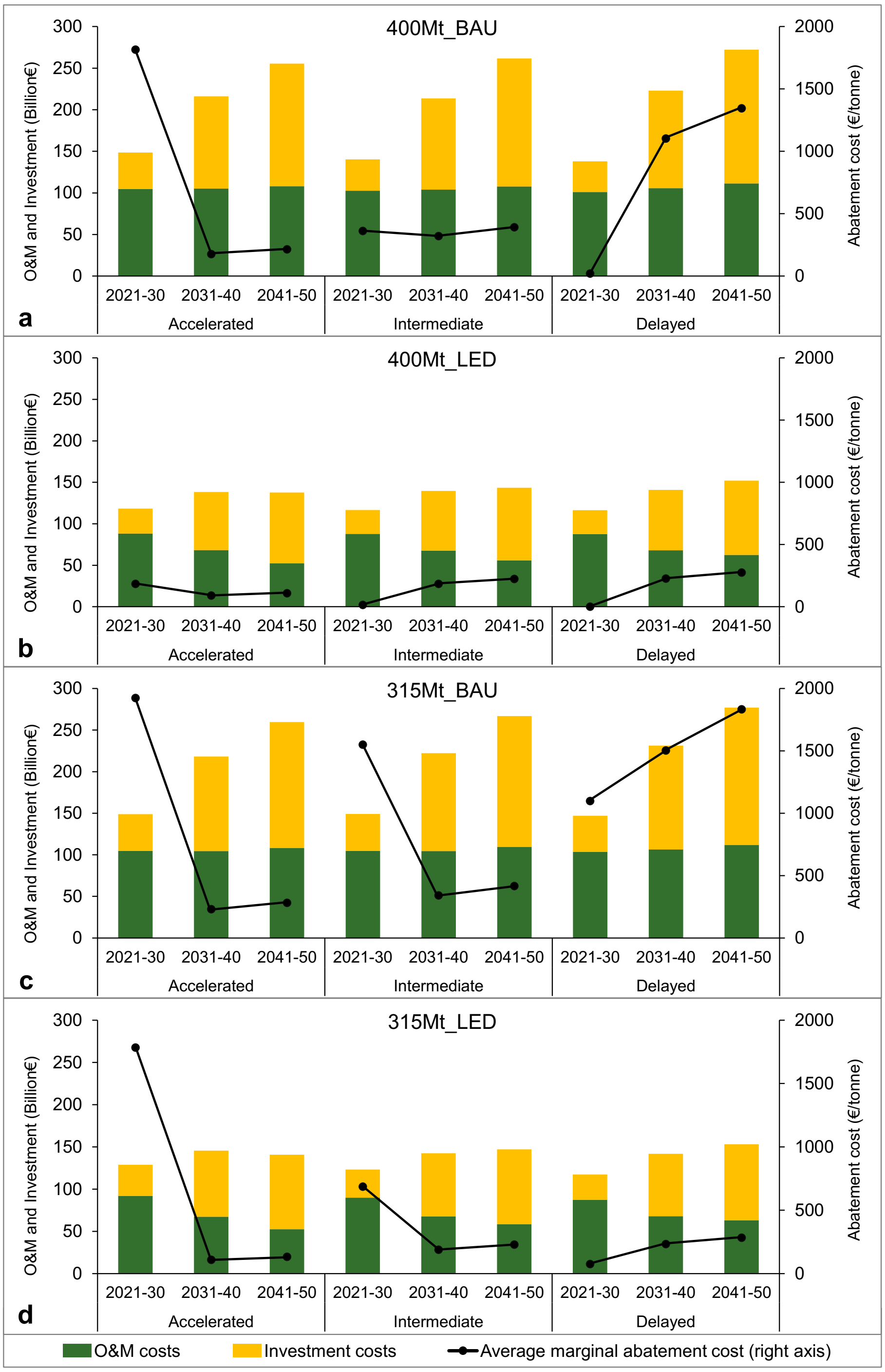

Figure 5. Total O&M costs, investment costs and average marginal abatement costs.
Costs are presented per decade for (a) 400Mt-BAU, (b) 400Mt-LED (c) 315Mt-BAU, and (d) 315Mt-LED scenarios. O&M costs include fuel costs, fixed and variable operation and maintenance costs. Accelerated, intermediate and delayed action correspond to the 0%, 15% and 30% overshoot cases, respectively. The difference in O&M and investment costs between the accelerated and delayed cases in each scenario is less than 10%. However, the absolute difference, ranging from 5 to 15 billion Euros per decade, is significant. This difference arises solely from the timing of actions, as all other factors—such as demand, carbon budget, planning horizon, net-zero year, and techno-economic parameters and constraints—remain consistent across each scenario.

Discussion

This research introduces a systematic and flexible framework for developing national energy system transition scenarios consistent with an explicit effort-sharing framework under the PA, using downscaled global carbon budgets to the country level. These energy transition scenarios consistent with downscaled carbon budgets, give important insights on the impacts of accelerated or delayed action, and on the impact of BAU and lower energy demands. The key findings are as follows.

Firstly, an acceleration in the energy transition is necessary to maintain a plausible pathway to the PA goals, a finding aligned with international[44–46] and national-level research[47,48]. Our analysis confirms conclusions from study in 2018 which found it is highly challenging to limit GHG emissions within a carbon budget compatible with 1.5°C[49]. Each year that rapid mitigation is delayed will compound this challenge, putting the PA goals increasingly out of reach. Our study confirms the finding that fossil-based infrastructures and technologies are a major barrier to achieving climate targets [33,50–52], and thus, explicit policy focus on phasing out fossil fuels is required to complement policies to stimulate zero carbon energy.

CDR becomes increasingly necessary with higher energy demands, more delayed mitigation action and more ambitious climate goals. Excessive reliance on CDR entails significant environmental, economic and legal risks [53,54] and may act as a deterrent to mitigation[55]. For example, growing crops for BECCS demands a considerable land area: the removal of 6 MtCO2/year could require around 10% of Irish agricultural land (based on the lowest land use intensity of BECCS from purpose-grown energy crops[56]), raising land use conflicts with nature, agriculture, fibre production, and natural carbon sinks. At the EU level, similar concerns are echoed in studies that indicate achieving the same magnitude of net-negative emissions by 2050 (200 MtCO$_2$/year, considering the current total emissions of about 2400 MtCO$_2$/year in the EU) would pose considerable challenges[57,58].

Furthermore, while delaying mitigation action eases the pace of change required in the short-term, it would require deeper and even more rapid changes after 2030 to meet the same carbon budget, even with increased CDR. Delayed action also requires up to 20% more power generation post-2030, for example, because of the need for deeper electrification of the residential and transport sectors. Within the residential sector, delayed action requires achieving absolute zero emissions before 2040, requiring emissions to fall by over 50% each year during the period from 2030 to 2040. Conversely, accelerated action demands near-zero emissions by 2040, a reduction of around 90%. In the transport sector, scenarios converge on a common point of a 55% reduction by 2033, but overshooting carbon budgets before that deplete the remaining budget, and expedite the need to achieve near-zero emissions by around five years.

Moreover, delayed action cases postpone the phase-out of fossil fuel technologies, leading to carbon lock-in and stranded assets. For example, delaying the phase-out of ICE vehicles could lead to a carbon lock-in, requiring underutilisation or early retirement as the remaining carbon budget dwindles.

Secondly, mitigation measures focussed on lowering energy demand are required for achieving ambitious climate targets with limited reliance on CDR, a conclusion supported by global integrated assessment modelling[59,60]. In BAU demand cases, a population-weighted downscaled carbon budget corresponding to an 83% chance of limiting global temperature rise to 2°C is breached by the early 2040s, necessitating heavy reliance on CDR – over 30% of mitigation is delivered from CDR in some cases. Conversely, the low energy demand scenario successfully stays within the carbon budget limits without relying on removal technologies. In the scenario aligned with 1.7°C, the energy system exceeds the budget in the early 2030s with BAU demands, but adopting a low energy demand approach can postpone this breach to the late 2030s, and the share of mitigation delivered from CDR falls below 10% with accelerated action.

Accelerating mitigation and lowering energy demand are robust climate strategies that offer greater flexibility, mitigate against the risk of insufficient progress in new technologies and allow for more ambitious decarbonisation aligned with the PA. Importantly, reliance on unproven at scale, or as-of-yet unavailable carbon removal technologies is reduced[61,62]. Additionally, accelerated action allows for the flexibility to adjust RCBs in response to emerging scientific findings[63], including the potential impact of carbon cycle feedback on anthropogenic emissions[64,65], and mitigates against the risk of a lack of action in other sectors, such as agriculture and land use. Finally, accelerated action helps overcome inertia in economic systems[63], enabling learning and scale effects to unfold. This, in turn, contributes to a reduction in technology costs[66] and diminishes the risk of investing in stranded assets[67].

Finally, a profound and rapid transformation in the energy system away from fossil fuels, largely towards electrification based on renewable energy sources, is required in all cases. The timeframe from 2025 to 2030 is particularly critical, to avoid carbon budget overshoot. In our scenarios, the electricity share of final energy demand exceeds fossil fuels by 2035. The share of energy services met by electricity is higher than this, given its efficiency. As of 2022, fossil fuels and electricity contribute 73% and 22% of final energy demand in Ireland[68]. This emphasises the urgency of implementing policies and initiatives that accelerate the shift towards electrification and insist on achieving a balanced fuel mix before 2035. This urgency is globally relevant, considering that fossil fuels and electricity contribute to 66% and 20% of world demand. The identified critical timeframe and the goal of achieving 40% parity provide a straightforward and measurable reference for setting global targets and timelines. It can facilitate coordinated efforts on an international scale to attain a more balanced and sustainable global energy landscape by 2035.

A focus on mitigation in later decades is also necessary – in several scenarios, emissions become net-negative by 2045, indicating the insufficiency of the goal of “net-zero by 2050”.

Many uncertainties and limitations remain. The vast majority of near-term mitigation is delivered by technologies and measures that are already available and largely cost effective. The barriers to accelerating mitigation and lowering energy demand are not technical in nature, but lie in supply chains, workforce and institutional capacity, planning and permitting, social acceptance and the need for greater policy focus[69,70] on changing energy demand behaviour and adopting new technologies which may disrupt incumbents[71]. These constraints cannot be resolved within an energy systems model. Moreover, national mitigation pathways aligned with limiting global warming to 1.5°C are limited; achieving this would require significant reliance on CDR. Therefore, detailed modelling of CDR technologies and extending the model horizon beyond 2050 will provide a better understanding of their potential impact and scalability. Finally, other downscaling approaches can substantially change the size of national carbon budgets. Further research should analyse the implications of various approaches.

Methods

Analytical framework and scenario construction

Figure 5 illustrates the methodological framework employed in this study, including three levels: global, national, and subnational.

At the global level, the analysis focuses on the RCBs aiming to align with below 2°C of global warming with high confidence. Utilising the best estimates, the RCBs stand at 1150 $GtCO_2$ for an 67% likelihood of limiting global warming to 2°C and 900 GtCO2 for a about 50% likelihood of limiting warming to 1.7°C since the start of 2020. This study uses a transparent and straightforward method to downscale global carbon budgets on a per-capita basis to estimate Ireland’s equitable share. This allocation considers population as a key factor. Two distinct energy-related carbon budgets are estimated for Ireland, each rounded to approximately 315 and 400 million tonnes for the period of 2021-2050.

The third level involves a granular examination of future energy demand projections using detailed sector-specific analysis. Accordingly, two demand projection scenarios, Business as Usual (BAU) and Low Energy Demand (LED), are considered. The LED scenario includes demand reduction and restructuring as a mitigation option. The LED scenario represents the energy sector meeting the Climate Action Bill 2021 decarbonisation objectives through structural changes in energy service demands and de-materialising the economy along with low-carbon technology. The energy service demands are decoupled from economic growth by shifting travel, increasing end-use efficiency, densifying urban settlement, focusing on low-energy intensive economic activities and changing social infrastructure. The main assumptions underlying the LED scenario are as follows (see the full details in[72]):

- Per capita passenger kilometres are expected to reach the European average of 12000km/person by 2050 through compact development of Irish cities as outlined in the National Planning Framework. A mode shift towards active and public transport is also assumed.
- The freight activities will return to the 1995 levels, achievable by reviving local economies, better logistics and reductions in consumer demand.
- New dwellings constructed henceforth will consist of apartments and attached housing types, which have lower energy service demands than detached dwellings. Further, behavioural and efficiency improvements will reduce other energy demands within households such as cloth or dish washing.
- The energy intensity (energy/GDP) of the industrial sector is assumed to decline by 45% by 2050 by increasing production efficiency and better material usage.

- The space required for commercial and public service activities will be reduced due to dense development and the promotion of practices like telecommuting.

Combining the CO_2 budgets and demand projection pathways generates four following scenarios:

- **400Mt_BAU:** This scenario involves a generous 400 Mt carbon budget aligned with the 2°C target and represents a demand projection in line with BAU projections.
- **400Mt_LED:** It involves a 400 Mt carbon budget and represents a demand projection in line with LED projections.
- **315Mt_BAU:** This scenario involves a more stringent 315 Mt carbon budget aligned with a 1.7°C target, reflecting demand projections associated with BAU practices.
- **315Mt_LED:** With a 315 Mt carbon budget, it reflects LED scenario.

The TIMES-Ireland Model (TIM), an optimisation model of the Irish energy system, is employed to assess decarbonisation pathways under these scenarios. TIM calculates the cost-optimal fuel and technology mix to meet future energy service demands while ensuring decarbonisation under carbon budget limitations. It has three major components. The supply-side module covers various energy resources, fuel production, conversion technologies, and transmission infrastructure. The demand-side focuses on energy service demands in different end-use sectors. The emission control module tracks CO_2 emissions, ensuring compliance with carbon constraints and enabling carbon-neutrality through direct CO_2 removal technology utilisation. Starting in 2030, TIM will include carbon capture and storage (CCS) technologies, with options for retrofitting existing coal, peat, and gas power plants. BECCS will also be available and provide net-negative CO_2 capture and allow negative emissions electricity generation. In our model, direct air carbon capture and storage (DACCS) will serve as a backstop technology with a fixed cost of €2,000 per tonne of CO_2. This is a very conservative assumption that sets an upper bound on the model's marginal abatement cost at a level that ensures no plausible mitigation measures are excluded. Based on the analysis by Young et al.[73], this high abatement cost reflects the sensitivity of carbon prices to the scale of carbon capture deployment. Their findings show that for EU countries like the UK and Germany, the cost of DACCS ranges from $400 to $3,000 per tonne of CO_2 for installations with a capacity of one million tonnes per year which aligns with the required capture capacity in our case study. The carbon constraints do not encompass the decarbonisation efforts related to international aviation and shipping. The detailed TIM structure and assumptions are outlined in[74] and have been utilised for decarbonisation analysis in the residential sector[75,76], light-duty [77], and heavy-duty vehicles[78].

It is worth noting that the allocation of national carbon budgets can be based on various approaches, with extensive literature using equity principles as the foundation for effort-sharing[79]. These principles include allocations of carbon budgets based on current emission shares (grandfathering), an equal cumulative per-capita distribution of emissions, considering a country's cumulative historical emissions, and ability to pay based on GDP per-capita[80–82]. Grandfathering disproportionately benefits countries with a larger share of current emissions. But the other approaches generally result in significantly smaller[81] or even negative carbon budgets[80] for developed countries or make the calculation of national carbon budgets highly sensitive to the degree of global connectivity[83].

In addition to equity-based approaches, cost-optimal allocation of carbon budgets is used for regional distribution of mitigation actions, focusing on achieving the lowest possible costs globally[84]. Yet, national distribution is highly dependent on the assumed marginal abatement cost curves and investment requirements[85,86]. Moreover, the United Nations Framework Convention on Climate Change (UNFCCC) emphasises the importance of equity principles in selecting a national allocation approach. According to the UNFCCC, all nations agreed to the principle of “common but differentiated responsibilities and respective capabilities.”[87]. Building on these principles, resource-sharing methods that account for population and current emissions –reflecting equity and inertia, respectively[88]– suggest Ireland’s carbon budget ranging from 290 Mt to 390 Mt (Extended Smooth Pathway Model) and 435 Mt to 580 Mt (Contraction and Convergence Model). The carbon budget estimations in the current research, based on equal per-capita distribution, align more closely with the lower range suggested by the former resource-sharing method.

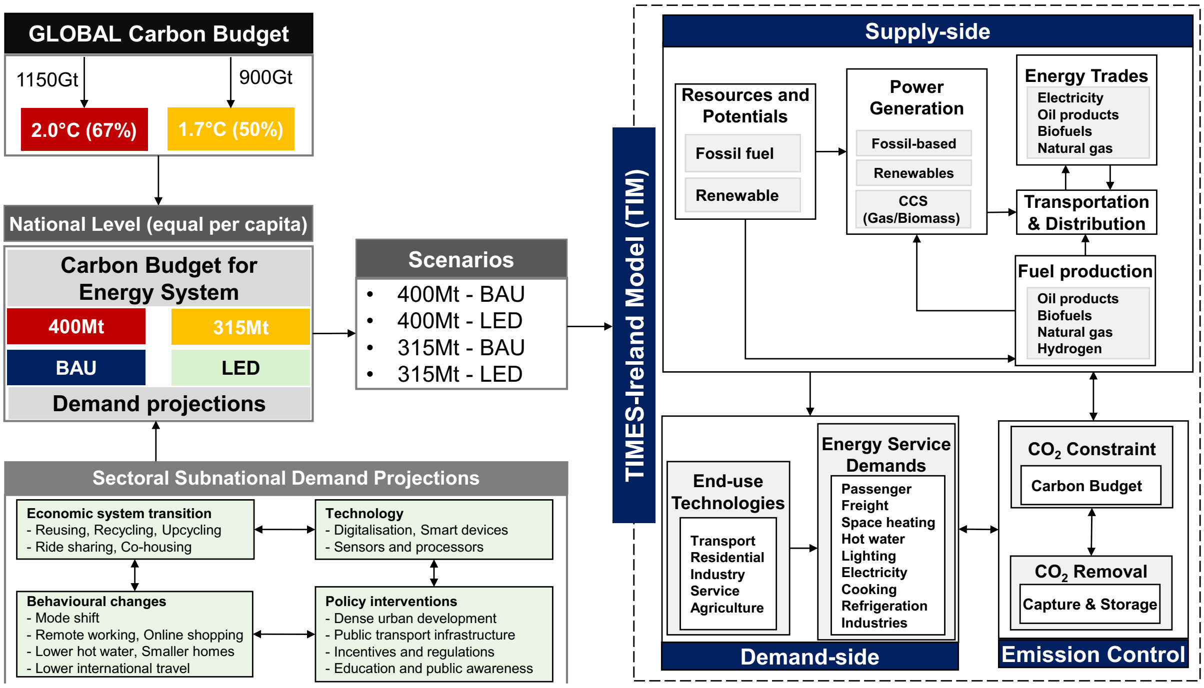

Figure 6. Methodological framework

Carbon Budgets: Accelerated versus Delayed Action

Currently, the carbon budgets are the cornerstone of Ireland’s climate action[89]. This legally-binding emission programme operates within 5-year budget periods. The allocation period is more comparable to the 400Mt CO_2 budget in this study.

To examine the impact of accelerated versus delayed action, 12 additional cases for each core scenario are defined. These cases involve overshooting the carbon budget within the first two periods of 2021-2025 and 2026-2030, with increments of 2.5%. These cases investigate overshoot scenarios ranging from 2.5% to 30% during these periods. Consequently, the study investigates four core scenarios, including two carbon budgets and two demand projections. For each of these scenarios, 12 sensitivity cases are also conducted, resulting in a total of 52 pathways. Figure 7 illustrates the distribution of two carbon budgets across various time periods. For instance, in the 400Mt scenarios with a 15% overshoot, there is a 15% higher carbon budget until 2030, followed by a reduction in the post-2030 period. Conversely, the base 400Mt scenario represents a more constrained budget in pre-2030 periods, offering an accelerated action pathway. As the permissible overshoot increases in the sensitivity cases, expanding the budget for the pre-2030 period, the model allows for more emissions in the initial periods, suggesting a delayed action pathway. The magnitude of the overshoot correlates with the timing of the action pathway, with higher overshoots indicating later action. The total emissions in all original CO_2 budgets and the sensitivity cases remain constant at 315Mt and 400Mt, and overshoots refer to exceeding the budget in the pre-2030 periods. It is worth noting that, in line with the guidelines set forth in the PA, emissions are envisioned to reach net-zero beyond 2050[90] in this study.

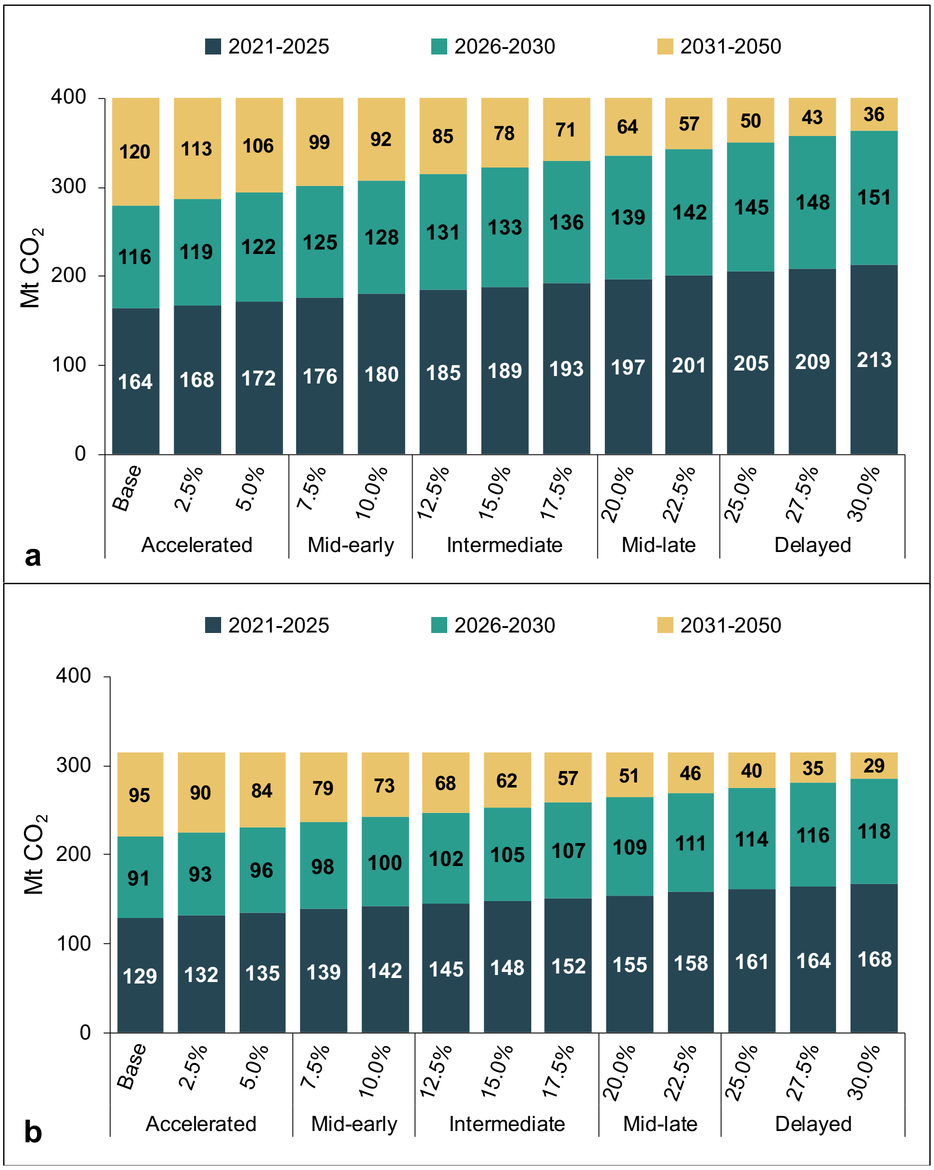

Figure 7. Carbon budget allocation in various accelerated and delayed cases
The figure represents two carbon budgets with CO_2 emission limits of (a) 400Mt and (b) 315Mt

Data availability

The data used in this research are all available on GitHub: https://github.com/MaREI-EPMG/times-ireland-model and archived on Zenodo[91]. Detailed results on investments and fuel flows across the energy system across all scenarios are available on an online portal: https://epmg.netlify.app/TIM-Carbon-Budget-2023.

Code availability

TIMES code is open source and has been archived on Zenodo[92].

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Author contributions

Conceptualisation: V.A., H.D.; Formal analysis and visualisation: V.A.; Writing - original draft preparation: V.A., H.D.; Supervision: H.D.; Investigation and Validation: V.A., O.B, J.G, A.G, J.G, H.D.; All authors contributed to reviewing and editing of the manuscript and approved the final version.

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APPENDIX 2: CARBON BUDGET CALCULATIONS

In this report, we do not attempt to take a view on what contribution Ireland should make to the global goals set out in the Paris Agreement, or the Climate Act: we do not attempt to interpret national or European law or international agreements to determine an appropriate carbon budget for Ireland. Instead, five different carbon budgets form the basis of the scenarios we model. These carbon budgets cover cumulative emissions of greenhouse gases (GHGs) between 2021 and 2050 – the vast majority of these emissions are carbon dioxide (CO_2) - from the energy system, fossil fuel combustion and industrial process emissions, excluding international aviation and shipping, and range from 250Mt to 450Mt.

To accurately model the implications of energy system pathways on the climate, it is essential to model cumulative carbon budgets, rather than targets for specific points in time: while the Climate Act sets forth a target of "climate neutrality" by 2050, it is cumulative emissions of long-lived GHGs (CO_2 and N_20), as well as the rate of CH_4 emission, which determine the overall contribution to global warming, rather than emissions at a given point in time.

There are many different approaches to determining equitable efforts under the Paris Agreement[15], which require normative judgements as well as an understanding of the physical science of climate change. Ireland has particularly high emissions of non-CO_2 greenhouse gases, with significant emissions of methane and N_2O from an agriculture which is specialised in beef and dairy production. Weighing the relative impact of mitigation across different gases, and the equitable contribution of countries to global decarbonisation efforts is complex and contested[16].

Notwithstanding this caveat, we have developed these five carbon budget scenarios by downscaling the global Remaining Carbon Budget (RCB) as determined by the IPCC AR6 WG1 to Ireland on a per-capita basis. We do not claim that this is an equitable or fair approach to take: we leave this for others to analyse. Recent estimates indicate that GCB is continuing to rapidly reduce – from the beginning of 2023, the RCB for a 50% probability of limiting warming to 1.5°C is estimated to be 250 $GtCO_2$[17]. Inadequate non-CO_2 mitigation exhausts this budget already[18]. The following describes our approach to downscaling the RCB from IPCC for this study.

Table A1 shows the RCB from the beginning of 2020. The values in this table reflect RCBs aligned with 1.5°C to 2°C of global warming, with different likelihoods from 2020. Ireland's RCB is estimated by downscaling global RCBs on a per-capita basis to estimate Ireland's equitable share. This allocation considers population as a key factor. Therefore, Ireland's population share (0.0625% of the global population) is used to generate Ireland's RCBs in Table A2. Since we used carbon budget constraints from 2021, the total actual CO_2eq emissions in 2020 (66 million tonnes) are deducted, and Table A3 shows Ireland's RCBs from the beginning of 2021.

Another factor allocates 70% of the carbon budget to Ireland's energy system, to account for CO_2 emissions not captured in our model from land use, land use change and forestry, and international aviation and shipping. The final values in Table A4 show Ireland's energy system RCBs for different temperature rises and with different probabilities. For this study, a range of RCBs rounded to 250Mt to 450Mt is used, as highlighted in blue. For instance, the lowest RCB is approximately 250Mt, which (under this interpretation) aligns with at least a 33%

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[15] Smith (2021) Rapid literature review of the setting of national carbon budgets, framed within the Irish context, with recommendations for Ireland's first and second carbon budgets. https://www.climatecouncil.ie/media/climatechangeadvisorycouncil/Andrew%20Smith%20Carbon%20Budgets%20Literature%20Review.pdf

[16] See, for example, Dooley et. al. (2021) Ethical choices behind quantifications of fair contributions under the Paris Agreement. Nature Climate Change volume 11, pages 300–305 (2021)

[17] https://www.nature.com/articles/s41558-023-01848-5

[18] https://www.nature.com/articles/s43247-023-01168-8

likelihood of limiting global warming to 1.5°C or about a 67% likelihood of limiting global warming to 1.7°C (IPCC AR6 650-700Gt CO2 RCB).

Table (A1) Global carbon budget from the beginning of 2020 (billion tonne) (Source: IPCC AR6 Table SPM.2)

	Probability of meeting temperature target				
Temperature rise	17% Certainty	33% Certainty	50% Certainty	67% Certainty	83% Certainty
1.5 Degrees C	900	650	500	400	300
1.7 Degrees C	1450	1050	850	700	550
2 Degrees C	2300	1700	1350	1150	900

Table (A2) Ireland carbon budget from the beginning of 2020 (million tonne)

	Probability of meeting temperature target				
Temperature rise	17% Certainty	33% Certainty	50% Certainty	67% Certainty	83% Certainty
1.5 Degrees C	563	406	313	250	188
1.7 Degrees C	906	656	531	438	344
2 Degrees C	1438	1063	844	719	563

Table (A3) Ireland carbon budget from the beginning of 2021 (million tonne)

	Probability of meeting temperature target				
Temperature rise	17% Certainty	33% Certainty	50% Certainty	67% Certainty	83% Certainty
1.5 Degrees C	497	340	247	184	122
1.7 Degrees C	840	590	465	372	278
2 Degrees C	1372	997	778	653	497

Table (A4) Ireland's energy system carbon budget from the beginning of 2021 (million tonne)

	Probability of meeting temperature target				
Temperature rise	17% Certainty	33% Certainty	50% Certainty	67% Certainty	83% Certainty
1.5 Degrees C	**348**	**238**	173	129	85
1.7 Degrees C	588	**413**	**326**	**260**	194
2 Degrees C	960	698	544	**457**	**348**

To reiterate, this analysis is not intended to represent an assessment of a fair and adequate mitigation pathway for Ireland. A transparent, rigorous and careful analysis is required which takes into account all greenhouse gases, Ireland's position as a developed and wealthy country.

In parallel to this report, a paper on the implications of the CCAC's Paris Test from a justice or moral philosophical point of view was undertaken[19], and points to the risks (from an ethical perspective) of choosing assumptions that are favourable to Ireland when assessing adequacy. The approach taken above, including a late starting year and downscaling the global RCB on a per-capita are likely to be considered favourable to Ireland from this perspective, and therefore should be viewed as upper bounds. Moreover, some assessments are suggesting that

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[19] Mintz-Woo, 2024. *Irish Carbon Budgets: Some Moral Considerations.*

the 1.5C temperature threshold has already been breached – not temporarily[20]. If this is the case, then the remaining GCB is zero.

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[20] Hansen J, Sato M, Simons L et al. Global warming in the pipeline. Oxford Open Clim Chan 3(1), doi.org/10.1093/oxfclm/kgad008, 2023

APPENDIX 3: DETAILED MODEL ASSUMPTIONS AND CAVEATS

KEY PARAMETERS AND MODEL-WIDE ASSUMPTIONS

- Detailed model description described in model documentation paper and model files[21]
- Energy flows are calibrated to 2022 SEAI Energy Balances
- Social discount rate: 2%
- Planning horizon: 2023-50
- The power system modelling follows CAP 2023 targets and capacity outlook from EirGrid for renewable energy sources and for other fuel supply sectors, we use data from SEAI and IEA.
- "Unmitigated emissions": mitigation backstop technology €2000/tonne CO2
- Costs include fuel imports, energy technology investments; exclude infrastructure (including public transport and electricity network investment cost).
- Near-term power generation capacity development limited to those outlined in EirGrid's 2024 Generation Capacity Statement[22]
- Heat pump deployment for existing buildings is only possible after retrofitting the building to a B energy rating

ENERGY SERVICE DEMAND PROJECTIONS

Energy service demand projections	BAU	LED
Cement production	0.9%	-1.7%
Chemicals production	1.2%	-0.8%
Food and products production	2.2%	-0.2%
Lime production	0.9%	-1.7%
Basic metals production	0.2%	-1.3%
Other manufacturing and industries	0.9%	-0.9%
Other non-metallic minerals	0.9%	-1.7%
Other non-metallic mineral products	0.9%	-1.7%
Wood and wood products production	0.3%	-1.2%
Electricity use in industry	0.9%	2.1%
Transport Demand: Short-range passenger travels	1.1%	0.9%
Transport Demand: Medium-range passenger travels	1.4%	-0.1%
Transport Demand: Long-range passenger travels	1.1%	-0.2%
Transport Demand: Goods vehicle for freight	4.2%	-0.4%
Transport Demand: Fuel tourism	-3.1%	-3.1%
Transport Demand: Navigation fuel	5.8%	0.0%
Transport Demand: Unspecified fuel	-3.1%	-3.1%
Transport Demand: Aviation domestic	0.0%	0.0%
Transport Demand: Aviation international	1.1%	0.0%
Residential Apartment	6.2%	7.0%

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[21] Balyk, O. et. al. (2022): TIM: Modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1.0), *Geoscientific Model Development*, https://doi.org/10.5194/gmd-2021-359 https://github.com/MaREI-EPMG/times-ireland-model

[22] Ten-Year Generation Capacity Statement 2023–2032, EirGrid

Residential Attached	1.1%	1.3%
Residential Detached	0.7%	0.1%
Services - Commercial Services	2.0%	0.4%
Services - Public Services	2.0%	0.4%
Services-Commercial Services: Data centers	23.0%	19.2%
Services-Public Services: Public lighting	0.6%	0.4%
Residential Refrigeration	1.5%	1.2%
Residential Cooking	1.5%	1.3%
Residential Cloth Washing	1.5%	0.7%
Residential Cloth Drying	1.5%	2.6%
Residential Dish Washing	1.5%	2.6%
Residential ELC Appliances	1.5%	0.7%

TABLE 2 ENERGY SERVICE DEMAND PROJECTIONS 2018-2050 AVERAGE ANNUAL CHANGE RATE, %[23]

BIOENERGY DATA ASSUMPTIONS

The import price of the available wood pellets was taken from the SEAI Heat Study, but the total potential amount available for importing was calculated as Ireland's energy-weighted share of Europe's sustainable bioenergy resource, reported in a European study on bioenergy resources used for the EU 2040 Impact Assessment report[24].

Feedstock	**Price**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	€/MWh	**GWh**	**GWh**	**GWh**	**GWh**	**GWh**	**GWh**	**GWh**
Forestry thinnings	29	59	62	43	22	11	11	11
Forestry thinnings	18	0	3	14	22	34	34	34
Forestry thinnings	17	1,088	1,340	1,549	1,512	1,415	1,163	723
Sawmill residues	16	1,544	1,989	2,451	3,001	3,648	3,648	3,648
Straw	25	7	0	10	10	10	10	10
Straw	15	26	0	37	37	37	37	37
Straw	10	14	0	20	20	20	20	20
Pig slurry	0	500	506	521	521	521	521	521
Residual waste	-47	1,846	1,262	1,018	680	712	732	737
Waste wood	4	75	85	96	107	115	120	122
Waste wood	0	0	0	54	120	130	136	137
Waste wood	-3	170	192	163	120	130	136	137
Industrial food waste	0	36	77	97	97	97	97	97

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[23] LED scenario described in Gaur, A., et. al., (2022) Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland. *Renewable and Sustainable Energy Transition* https://doi.org/10.1016/j.rset.2022.100024

[24] Avitabile, V., Baldoni, E., Baruth, B., Bausano, G., Boysen-Urban, K., Caldeira, C., Camia, A., Cazzaniga, N., Ceccherini, G., De Laurentiis, V., Doerner, H., Giuntoli, J., Gras, M., Guillen Garcia, J., Gurria, P., Hassegawa, M., Jasinevičius, G., Jonsson, R., Konrad, C., Kupschus, S., La Notte, A., M`barek, R., Mannini, A., Migliavacca, M., Mubareka, S., Patani, S., Pilli, R., Rebours, C., Ronchetti, G., Ronzon, T., Rougieux, P., Sala, S., Sanchez Lopez, J., Sanye Mengual, E., Sinkko, T., Sturm, V., Van Leeuwen, M., Vasilakopoulos, P., Verkerk, P.J., Virtanen, J., Winker, H. and Zulian, G., Biomass production, supply, uses and flows in the European Union, Mubareka, S., Migliavacca, M. and Sanchez Lopez, J. editor(s), Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/811744, JRC132358

Food waste	-9	44	69	92	118	127	132	134
Food waste	-36	44	69	92	118	127	132	134
Food waste	-63	87	138	184	235	253	264	268
Used cooking oil	56	49	52	54	55	57	59	60
Used cooking oil	81	49	52	54	55	57	59	60
Tallow	40	323	328	328	328	328	328	328
Tallow	37	175	178	177	177	177	177	177
Tallow	31	350	356	355	355	355	355	355

TABLE 3: SUSTAINABLE DOMESTIC BIOENERGY RESOURCES WITH ASSUMED COSTS[25]

	Cost (€/GJ)	2020	2025	2030	2040	2050
Import of Wood Pellets - Step 1	9.6	1.8	1.8	1.8	3.6	7.2
Import of Wood Pellets - Step 2	9.6	0	3.6	18	54	61.2

TABLE 4: WOOD PELLET IMPORT LIMITATIONS, PJ

INDUSTRY SECTOR

For this analysis, the industry sector in TIM has undergone a substantial update, which is not documented in the peer-reviewed paper. This section details the assumptions and updates in that model.

The new industry sector is developed according to the SEAI National Heat Study and consists of 9 subsectors/end-uses. And the sector is calibrated accordingly with 4 heat temperature levels and ETS/non-ETS share division according to the SEAI data (details shown in the table below). Electricity use reported as a separate end-use (subsector) as the SEAI data do not split it by industry subsectors and it is assumed to stay the same until the end of the model time horizon. But other sectors/end-uses have different decarbonisation options including direct electrification, biomass and biofuel/biogas combustion and hydrogen. Additionally, there is carbon capture and storage option for process emissions in the cement sector from the use of clinker, and no other options to substitute clinker production are considered at the current stage.

No high temperature heat pumps are included as a decarbonisation option as it needs careful assessment of available waste heat as an input to the heat pump.

Subsectors/end-uses	2019, PJ	ETS share, %
Cement production	11.6	100%
Chemicals production	7.4	51%
Food and products production	17.9	83%
Lime production	1.5	100%
Basic metals production	24.4	90%
Other manufacturing and industries	4.7	34%
Other non-metallic minerals	2.7	18%
Wood and wood products production	5.1	100%
Electricity use	23.4	

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[25] Sustainable Bioenergy for Heat: Spatial Assessment of Resources and Evaluation of Costs and Greenhouse Gas Impacts, Report 7 of the National Heat Study, SEAI

CAVEATS AND MODEL LIMITATIONS

- GHG emissions in the LED case are calibrated until 2023 – the cases already display carbo budget savings early in the CB1 period, which has already passed. This slightly over-estimates the GHG reductions in the LED cases, by around 3 $MtCO_2$.
- The costs and constraints of infrastructure (electricity grids, charging stations, gas/biogas networks, etc.) and of the operation of the power system, including storage and flexibility, which play an important role in the energy transition, are not fully captured in the model. Additional analysis is necessary to fully explore the role of these (and other) technologies in the power system, as TIM is not designed to model in detail its operation. Moreover, only energy demand for domestic demand is factored in: no exported energy is assumed, beyond that exported in currently planned interconnectors, and the potential power demand for Direct Air Capture (DAC) and e-kerosene is not assessed.
- The "timeslice" structure of the model does not fully capture the operational constraints of the power system.