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Report

Emission Scenarios for Europe under the CATALYSE Project: Beyond the Green Deal

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CATALYSE

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Abstract

The pursuit of net zero emissions in the European Union can deliver significant human health co-benefits. Mitigation actions reduce emissions of air pollutants that contribute to a range of diseases. The *Climate Action To Advance HeaLthY Societies in Europe* (CATALYSE) project, funded by Horizon Europe, seeks to quantify these climate and health co-benefits within a European context. This multi-dimensional initiative spans fundamental research to identifying optimal communication channels for information dissemination.

This report documents the approach, methodology, and results of the development of gridded emission scenarios for air pollutants in Europe until 2050 within the CATALYSE project. The main scenarios include a reference baseline (REF), a scenario achieving Green Deal goals (GD), and a Beyond Green Deal scenario that envisages additional behavioral changes to curb emissions (BGD). A fourth scenario "Beyond Green Deal 90" (BGD90), is a variant that introduces further end-of-pipe air pollution control measures. The activity pathways underlying the scenarios are modeled using the PRIMES and CAPRI models, with assumptions defined collaboratively by modelling team experts in the buildings sector (UCL), active mobility (ISGlobal), and food systems (UOX). Although the projections also include energy and industry sectors, the scenario differentiation emphasizes the buildings, transport, and agriculture sectors because of their relevance for health. Air pollutant emissions are calculated using the GAINS model, which combines activity data with information on air pollution control application rates and technology-specific emission factors to determine national-level sectoral emissions. These emissions are then spatially distributed using appropriate proxies to produce gridded outputs for subsequent modelling of health co-benefits within CATALYSE.

The main scenarios indicate emission reduction pathways for CO_2 and air pollutants in the EU. Between 2020 and 2050, the REF scenario delivers an emission reduction of 53% for CO_2, 61% for $PM_{2.5}$, 58% for SO_2, 55% for NO_x, 30% for NMVOC and 9% for NH_3. Emissions are further reduced in the GD and BGD scenarios over this time period, notably with CO_2 emissions reductions of 91% for both.

Results reveal sector-specific patterns across air pollutants. Changes in residential combustion is a major contributor to reductions in $PM_{2.5}$ whose sector share of total emissions falls from about 64% in 2020 to 30% in 2050 for the REF, 27% for the GD, and 25% for the BGD. Road transport, meanwhile, drives NO_x reductions, with a sector share of total NOx emissions decreasing from about 38% in 2020 to 8% in REF and 2% in the GD and BGD in 2050. Similarly, power plants and industry contribute to reductions in SO_2 and while changes in the agricultural sector contribute to the reduction of NH_3 emissions. While the main scenarios reduce emissions significantly, the BGD90 scenario variant demonstrates significant remaining technical emissions reduction potential across air pollutants, indicating that deeper emission cuts are technically achievable.

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Emission scenarios for CATALYSE

1. Introduction

One of the aims of CATALYSE is to quantify the health co-benefits and potential trade-offs of mitigation policies designed to achieve carbon neutrality in the EU27 but also explore such impacts in scenarios that could either fail or go beyond Green Deal targets and objectives. Policies (mitigation measures) may target different levers of change including technological change, institutional and individual behavior change, or finance (e.g., taxation).

The objective of the CATALYSE scenario development (Task 2.1) is to develop mitigation policy scenarios and model the associated emissions of greenhouse gases (GHGs) and air pollutants, which will subsequently be used in the project to quantify health co-benefits through exposure to ambient air pollution. This report describes the development of policy-relevant scenarios through 2050 that include mitigation actions across various sectors of the economy.

We use a framework of interconnected models which share common assumptions. The core system models are the same which are regularly used to inform policy processes in the EU:

- PRIMES (Capros et al., 2019), an energy system model operated by E3M[1]
- CAPRI, an agriculture system model, operated by EuroCare[2]
- and GAINS (Amann et al., 2011), an integrated air pollution model, developed and operated at IIASA[3].

Emission scenarios are defined by two main elements:

- Projections of activity drivers (pathways),
- Air pollution control legislation applied.

Activity pathways are modelled with the PRIMES and CAPRI models, with assumptions defined jointly between the respective modelling team experts in the buildings sector (UCL), active mobility (Barcelona Institute for Global Health (ISGlobal)), and food (University of Oxford (UOX)). Although the projections include also energy and industry sectors, the emphasis of scenario differentiation is on the buildings, transport, and agriculture

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[1] https://e3modelling.com/modelling-tools/primes/

[2] EuroCARE is part of a European network of agencies developing and operating the CAPRI system (https://www.capri-model.org/). The system is based on an open source policy and a wiki documentation is available (https://www.capri-model.org/dokuwiki_help/doku.php).

[3] https://gains.iiasa.ac.at/models/

sectors due to their particular relevance for health. Figure 1 illustrates the workflow and involvement of different groups in the development of energy and agriculture activity scenarios that are imported into the GAINS model and combined with information on application rates of air pollution controls and their technology-specific emission factors to calculate sectoral emissions at a national level, which are then spatially distributed using appropriate proxies to produce gridded emission outputs for use in the remaining tasks of CATALYSE WP2.

This report is organized as follows. The basic framework of scenarios is outlined in Section 2 and details of assumptions are described in Section 3. Models and approaches are introduced in Section 4. Trends in activity pathways are detailed in Section 5 with resulting emissions of CO_2 and air pollutants presented in Section 6.

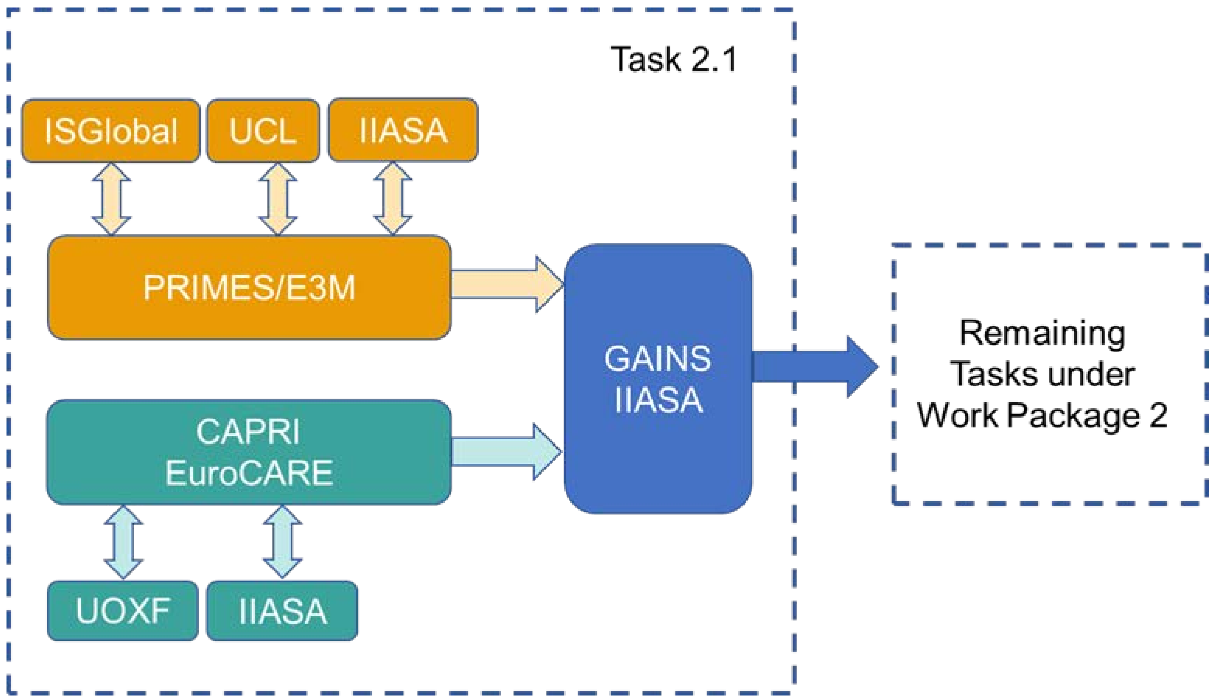


Figure 1. Schematic of interactions between the teams and models in the scenario development process within CATALYSE Task 2.1.

2. Scenario framework

In recent years, the EU has developed a comprehensive package of mitigation policies which are part of the Green Deal proposed by the Commission in 2019 and adopted in 2023, designed to make the EU carbon neutral by 2050. The original pathway proposed by the Commission to achieve carbon neutrality is shown in Figure 2. Emission reduction targets have been formulated at the EU level: -55% reduction of net GHG emissions by 2030 compared to 1990 levels with targets for 2040 proposed and in negotiations at the time of writing. A set of climate, energy, transport and taxation policies were adopted to enable the achievement of these reductions.

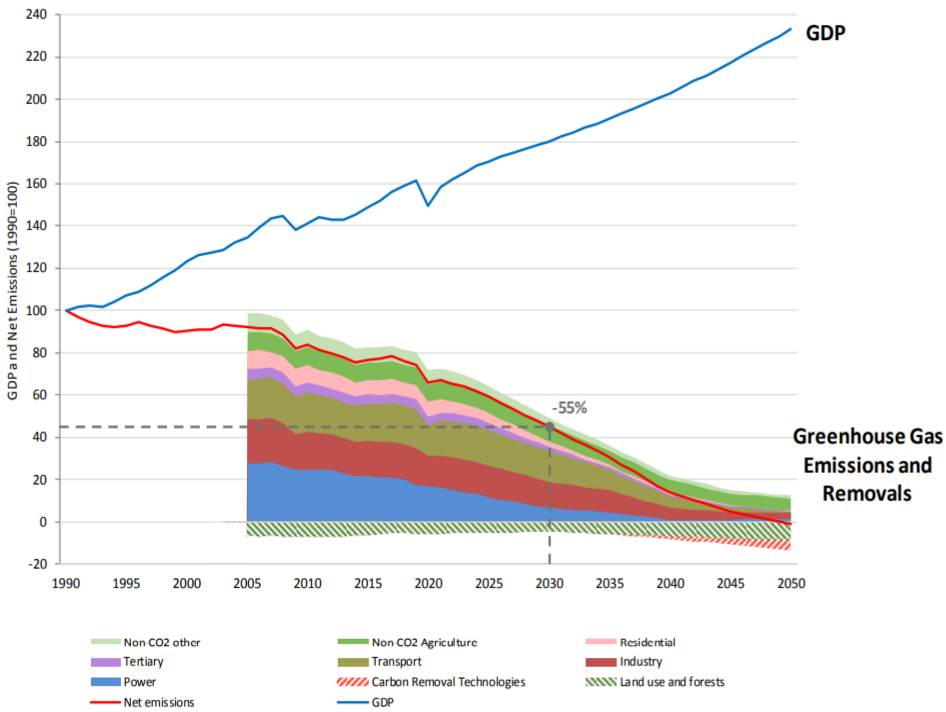


Figure 2. Pathway for achieving net-zero carbon emissions as suggested in the original Commission Proposal for the Green Deal (COM(2020) 562, 17.9.2020).

Scenarios for CATALYSE need to reflect and build upon these policy processes. Given that the model suite in CATALYSE is the same that was used to underpin the scientific inputs to the impact assessments by the Commission, the project is optimally set up for this task.

The starting point for the scenarios for CATALYSE are the emission scenarios underlying the development of the EU Green Deal including the energy and climate regulatory requirements and proposals of the Fit for 55 initiatives as published by the European Commission (European Commission, 2022c). Together with the Reference scenario representing the expected evolution of emissions before the publication of the EU Green Deal, this sets the framework for EU climate policy for the coming decades. The Fit for 55 initiatives take into account recent events that affect the evolution of emissions, activity and energy supply in Europe. The COVID-

19 pandemic and the war in Ukraine are of particular relevance as presented in the RePowerEU Communication (European Commission, 2022b).

CATALYSE investigates where opportunities exist to go beyond the Green Deal focusing on additional behavioral changes. It focuses on the buildings and transport sectors (not part of the assumptions in the Green Deal) and explores additional technical potential for air pollution emission controls. Additional air pollution emission controls would contribute to meeting, for example, air quality consistent with the 2021 WHO air quality guidelines and could further reduce greenhouse gases to improve several equity and health indicators.

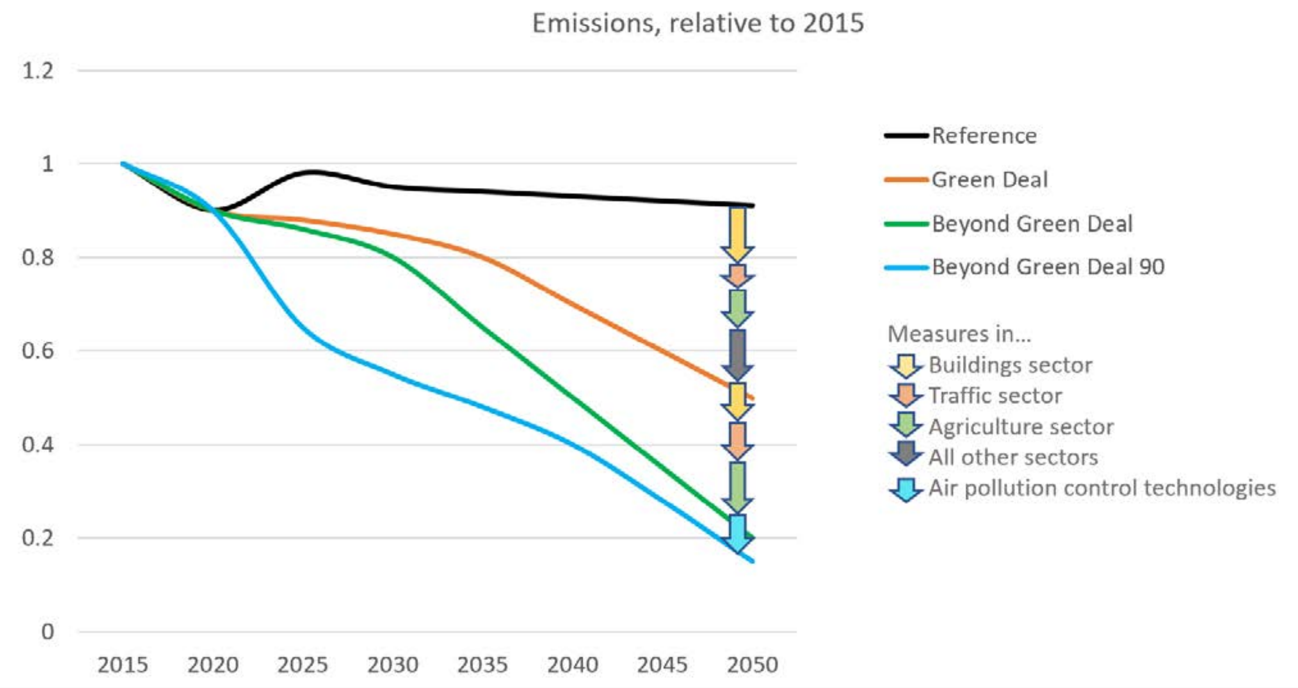


Figure 3. Conceptual illustration of scenarios at the example of emissions of a particular pollutant, showing impacts of sectoral measures / interventions / behavioral changes that lead to the differences between scenarios.

The scenario framework consists of three main scenarios and a scenario variant (Figure 3) for the EU27. The main scenarios for emissions modelling are the *Reference* (REF), *Green Deal* (GD), and *Beyond Green Deal* (BGD) scenarios - details are given below. The focus is on analysis of interventions in the whole energy and agriculture systems with a particular focus on three key sectors: *Buildings*, *Transport*, and *Agriculture.* For these sectors, several interventions (policies) have been defined affecting activity (or energy consumption) drivers, including their impacts with regards to spatial distribution aspects. These main scenarios are harmonized across all sectors and can be analyzed consistently across all exposure pathways covered in CATALYSE (air pollution, diets, active mobility). The scenario variant, *Beyond Green Deal 90* (BGD90), introduces additional technical air pollution controls across sectors of the BGD scenario to achieve 90% of maximum technically feasible emission reductions.

Gridded emissions for estimating health impacts are also available for non-EU countries. This global baseline considers currently agreed energy and air pollution policies and is based on Shared Socioeconomic Pathways (SSPs) or World Energy Outlook storylines to be consistent with the narrative of the key CATALYSE scenario categories.

In addition to these main scenarios, variants for individual sectors will be developed in specific Tasks within Work Package 2. These focus on buildings, transport, and food and agriculture. The variants are then only analyzed for exposure pathways associated with the specific sector (for example, dietary risks associated with different assumptions on dietary changes) and are not part of this report.

Socioeconomic assumptions describe the likely evolution of the European economy and are common in all models. Long-term projections on population, as well as economic activity are exogeneous variables to the models. This means they are used as inputs into the PRIMES energy system model as well as the CAPRI agriculture system model and form the macro-economic baseline for the assessment of socioeconomic impacts on the emissions mitigation scenarios. All scenarios in this study share common macro-economic drivers such as gross domestic product (GDP), population projections, international fossil fuel price projections, and technoeconomic assumptions – details are described in Section 3.1. From these macroeconomic trends, the PRIMES and CAPRI models derive demand and supply for energy services from different energy carriers as well as food and agriculture as cost-optimal solutions while meeting the constraints set by EU targets on GHG emissions, shares of renewables, energy efficiency gains, etc.

Key characteristics of the scenarios are:

REF scenario:

- The REF scenario serves as a baseline. This means that it is used for comparison to the GD and BGD scenarios where all envisaged sectoral policies, behavioral changes and technical solutions are achieved.
- It considers currently implemented policies, as described in the final integrated national energy and climate plans (NECPs) for the period from 2021 to 2030 submitted by EU countries by 31 December 2019 and assuming their successful implementation.
- It does not achieve the goals of the Green Deal, since no additional policies are envisaged apart from the ones described in the 2019 NECPs after 2030.
- The Reference 2020 scenario which was used as a starting basis for the development of the Green Deal in 2020 is documented in European Commission: Directorate-General for Climate Action et al. (2021). In comparison with the Reference 2020 scenario, the CATALYSE REF has the following differences:
    - Updated macroeconomic assumptions, as presented in Section 3.1,
    - Updated international fuel prices - taking into account the recent spike (2022-2023) as a result of the energy crisis and the Russian war of aggression against Ukraine, also presented in Section 3.1,

- Recalibrated PRIMES model to the 2021 energy balances of Eurostat[4]

- Updated techno-economic assumptions to all PRIMES sub-models[5]

- Agricultural projections are aligned with PRIMES, but also consider the November 2023 Agricultural Outlook by DG AGRI, factoring in the expected further decline in Ukraine production potential.

GD scenario:

- This scenario achieves the objectives of the EU Green Deal as implemented in the EU Climate Law, i.e. 55% reduction of GHG emissions in the EU by 2030 compared to 1990 with the goal of reaching carbon neutrality by 2050.

- The EU Green Deal goals are achieved with policies and strengthened legislative initiatives of the Fit for 55 policy proposal package that includes EU-wide and sectoral goals (see Table 1 for more details).

- The energy system follows a least-cost solution quantified with PRIMES that meets the demand for energy services while achieving the EU Green Deal targets by incorporating the Fit For 55 policy portfolio.

- The agriculture system (not part of the ETS) follows the PRIMES carbon value path, but at a moderate level.

- Supply side measures support the achievement of other environmental goals according to the Farm to Fork Strategy and a moderate shift towards more healthy diet takes place in Europe.

BGD scenario:

- This scenario is based on the GD scenario and thus considers all related policies. It achieves the overall EU Green Deal and other policy-specific targets. In addition to the GD scenario, it considers changes in three end-use sectors, namely transport, buildings, diet/agriculture driven by behavioral changes:

    - **Buildings:** The main element expressing behavioral change in the buildings sector is materialized in the reduction of the energy needs of households (i.e. useful energy or energy demand) before these are satisfied by heating and cooling equipment and electrical appliances. The modelling implementation of behavioral changes refers to lifestyle changes,

[4] https://ec.europa.eu/eurostat/cache/infographs/energy_balances/enbal.html?geo=EU27_2020&unit=KTOE&language=EN&year=2021&fuel=fuelMainFuel&siec=TOTAL&details=0&chartOptions=0&stacking=normal&chartBal=&chart=&full=1&chartBalText=&order=DESC&siecs=&dataset=nrg_bal_s&decimals=0&agregates=0&fuelList=fuelElectricity,fuelCombustible,fuelNonCombustible,fuelOtherPetroleum,fuelMainPetroleum,fuelOil,fuelOtherFossil,fuelFossil,fuelCoal,fuelMainFuel

[5] Details documented in the "Technology Assumptions used in modelling" under "Documents" here: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en#documents

such as adjustments to thermostat settings and showering time. In addition, higher renovation rates are also considered as part of behavioral changes as well as enhanced uptake of renewable heating and cooling equipment (i.e. heat pumps) resulting in increased energy efficiency and decarbonization rates.

  - **Transport:** Additional effort by adjusting levers that induce the efficiency of the transport system further by also influencing behavioral and lifestyle changes (e.g. modal shift, enhanced cycling, walking, shared mobility), particularly in urban areas. The decarbonization rate compared to the GD is also higher.

  - **Food sector:** Climate friendly mitigation in EU agricultural production is reinforced. The major difference to the GD scenario is a nearly complete shift of diets towards the EAT Lancet recommendations.

- It focuses on actions leading to any type of health co-benefits through air pollution, active travel, healthier diet.

- Not all actions included in BGD lead to reduced air pollution. Lifestyle transformations are applied where they reduce useful and final energy consumption. These do not necessarily lead to further CO_2 or air pollution emissions reductions.

- In its main scenario, the BGD assumes current legislation for air pollution controls, so that all emission differences to the REF and GD scenarios are exclusively driven by changes in activity levels.

BGD90 scenario:

- This scenario variant is based on the BGD scenario and thus considers all related policies and behavioral change in three end-use sectors. In addition, it introduces enhanced end-of-pipe air pollution controls across sectors to achieve 90% of maximum technically feasible emission reductions compared to the BGD scenario that applies current legislation. The portfolio of measures is chosen as a cost-effective solution using the GAINS cost optimization module; the target of 90% progress towards maximum technically feasible reductions has been chosen as an illustrative case for high policy ambition while avoiding the costliest measures.

3. Main assumptions in the scenarios

The following sections describe assumptions taken in the different scenarios specifically in the EU. First, the overall macroeconomic trends shared across all scenarios are introduced (Section 3.1), after which the scenarios REF, GD, BGD and BGD90 are differentiated (Sections 3.2-3.5). The three latter scenarios differ from REF only for the EU. Assumptions for the rest of the world are described in Section 3.6.

3.1 Macroeconomic trends

Population projections are based on Eurostat's long-term projections (EUROPOP2019[6]) combined with the short-term update of the projected population for the period 2022-2032[7]. Figure 4 shows the total EU27 population that is projected to remain relatively stable over the period to 2050. This accompanies an evident trend that shows the ageing of the EU27 population, with a 13% decline in the population in the age group 15 to 64 between 2020 and 2050.

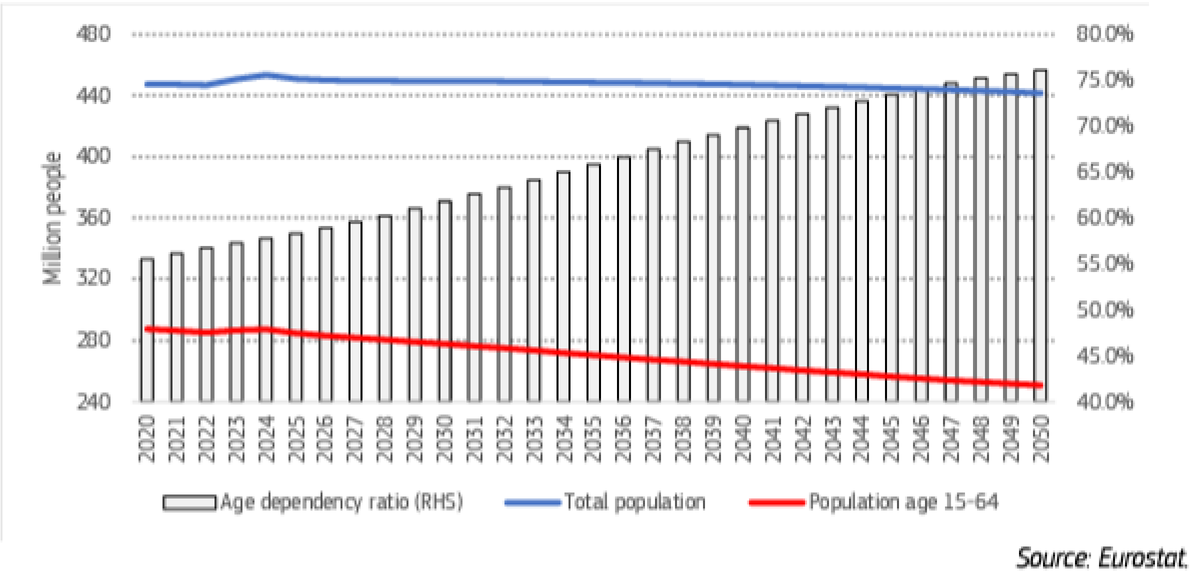


Figure 4. Population assumptions used in the modelling suite for CATALYSE (European Commission, 2024)

The past few years have been exceptionally unstable due to two major events in the EU and world economies: the COVID pandemic and Russia's war of aggression against Ukraine resulting in the sharp increase in international energy prices. In Figure 5, we show the EU27 GDP projections as used in the Climate Target Plan modelling (European Commission, 2024). GDP projections for 2022-2024 are based on the Autumn Economic

[6] https://ec.europa.eu/eurostat/web/population-demography/population-projections/database
[7] EUROPOP2019 (proj_19n) and short-term update of the projected population (2022-2032) (proj_stp22), which was the latest available projection at the time the key assumptions were adopted as a framework for all models used in the impact assessment (source: COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society - SWD/2024/63 final).

Forecast (European Commission, 2022a). From 2025 onwards, the GDP growth projections converge to those prepared by DG ECFIN for the 2021 Ageing Report (European Commission, 2020c). As a result, the real GDP assumptions introduce an update of short-term economic projections and revert to the growth rates used for the 2020 Reference Scenario and the modelling of policy scenarios in the impact assessments backing the Fit for 55 proposals. At the EU level, real GDP is projected to be 40% higher in 2040 than in 2015, and 61% higher in 2050 compared to 2015 as shown in Figure 5.

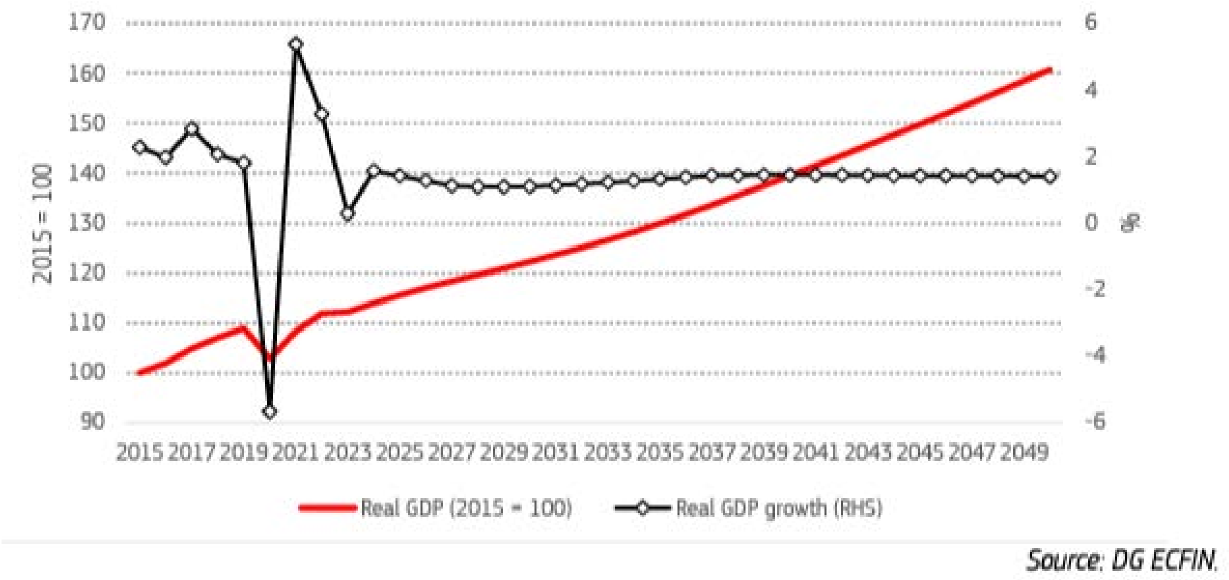


Figure 5. EU27 GDP and GDP growth (%) used in the modelling suite for CATALYSE based on European Commission (2022a; 2020b)

To reflect the recent and current energy crisis as well as the drastic reduction of Russian gas imports to the EU, international energy prices assumed in the modelling increase drastically in 2025 and to a smaller extent in 2030 and onwards. The high energy prices act on top of the scenario assumptions described, namely the enabling conditions as well as on the carbon pricing in non-ETS sectors.

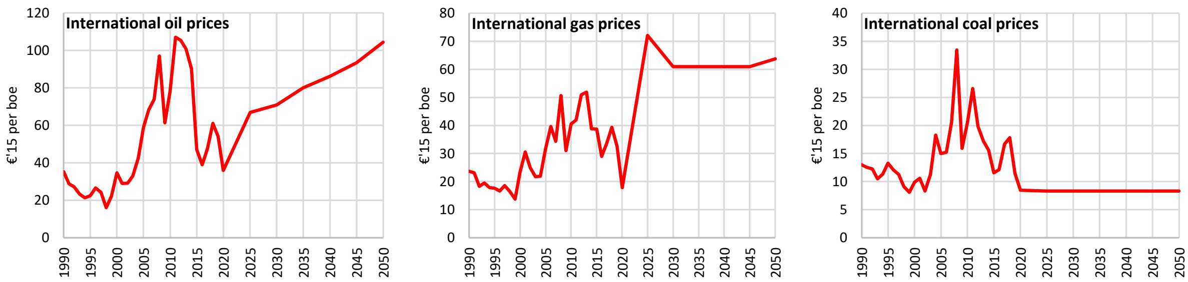


Figure 6. International Fuel prices (in €'15 per barrels of oil equivalent) used in the modeling suite for CATALYSE

Furthermore, we also assume that there is an extension of carbon pricing in non-ETS sectors (i.e., buildings sector and road transport) that acts as an explicit policy instrument and complements the bottom-up renewable and energy efficiency policies, as well as the enabling conditions of the decarbonization scenarios. The carbon price is defined exogenously and increases linearly by EUR 15 per year, reaching EUR 200 in 2040, and EUR 390 in 2050 as shown in Figure 7.

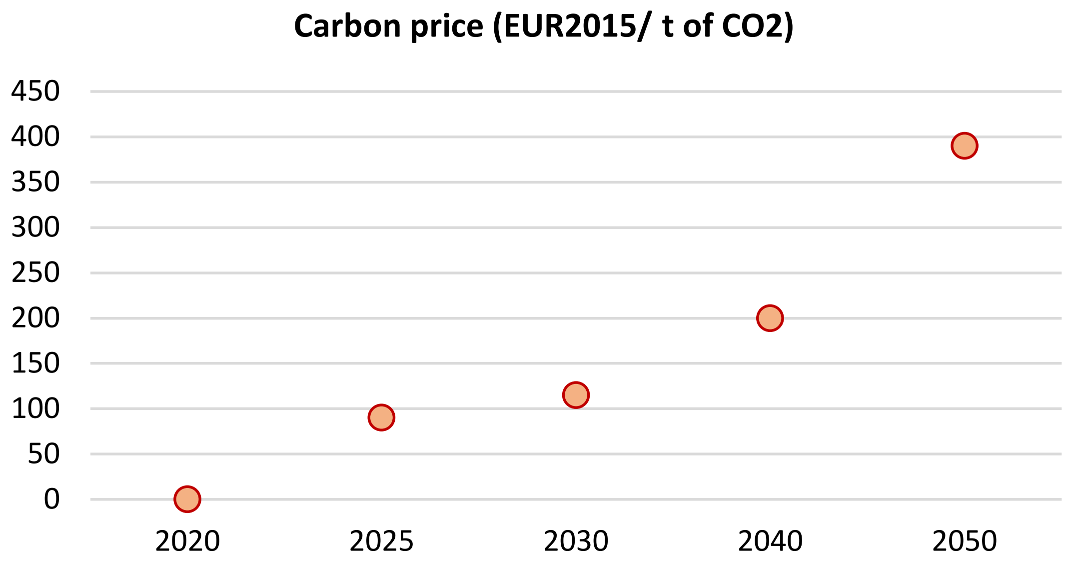


Figure 7. Carbon prices assumed for CATALYSE in €2015

3.2 Reference Scenario

The Reference 2020 Scenario which was used as a starting basis for the development of the Green Deal in 2020 is documented in European Commission: Directorate-General for Climate Action et al. (2021).

In REF policies at EU27 and Member State level, whose implementation peaks until 2030 and continues afterwards, with no additional measures envisaged between 2030 and 2050, are assumed.

EU27 level policies cover those adopted in the fields of energy, transport, and climate until December 2019 (where the latest NECPs are available). These include the directives and regulations in the “Clean Energy for All Europeans” package (Directorate-General for Energy (European Commission), 2019), the revised EU Emissions Trading Scheme Directive (Directive (EU) 2023/959, 2023), and key transport policies such as CO_2 standards for vehicles, the Directive on alternative fuels infrastructure (Regulation (EU) 2023/1804, 2023), the Clean Vehicles Directive (Directive (EU) 2019/1161, 2019), and more as described in the specific sections for each sector below.

National policies considered in the REF are the ones adopted and referred to in each Member State’s NECP and other relevant national plans (i.e. Long Terms Renovation Strategies), as well as those planned to be adopted – especially coal phase-out and nuclear specific policies.

Important national policies considered in REF are policies that Member States adopt to reach national targets, e.g., contributions to the EU energy efficiency (EE) and renewable energy (RES) targets, national transport mandates and domestic targets for ESR (Effort Sharing Regulation) emission reductions. Such policies include support schemes for renewables uptake and buildings’ deep renovation, programs for the large-scale electrification and Public-Private Partnerships for the uptake of EVs and infrastructure rollout. In addition, measures for fuel blending, incentives to boost demand response and self-consumption, and energy and transport taxation schemes (European Commission: Directorate-General for Climate Action et al., 2021).

The EU Emissions Trading Scheme (ETS) is modelled following the revision of the EU ETS Directive in 2018 (Directive (EU) 2018/410, 2018), which introduces phase IV of the EU ETS (2021-2030) and enables the EU to meet the 2030 emission reduction target. The ETS sector includes energy related combustion, process emissions of relevant industrial sectors and certain industrial non-CO_2 GHGs. While the first two are directly part of the PRIMES model, the non-CO_2 GHGs are integrated based on results of GAINS non-CO_2 modelling. In phase IV (2021-2030), the Market Stability Reserve is reinforced. The cap on EU ETS allowances is subject to an annual linear reduction factor of 2.2%. The modelling accounts for the different allowance allocation rules (auctioning, free allowances based on benchmarks) foreseen in the legislation for the different sectors, including the provisions for sectors at risk of carbon leakage.

In the REF, the EU ETS legislation is assumed to continue in its current scope (phase IV) throughout the projection period to 2050; also, the rules relating to the Market Stability Reserve, and carbon leakage are assumed to remain unchanged considering the continuation of current policies.

Buildings

In the REF, energy efficiency at large and specifically for the buildings sector is reflected via policies at EU and Member State level, including the Ecodesign Directive (Directive 2009/125/EC, 2009) and the Energy Labelling Regulation (Regulation (EU) 2017/1369, 2017) as well as the implementing measures, the revised Energy Efficiency Directive and the revised Energy Performance of Buildings Directive (Directive (EU) 2018/844, 2018). It also reflects the level of ambition of the national contributions set in the NECPs, meaning that the 32.5% energy efficiency target for the EU will not be met in 2030, due to the collective ambition gap and insufficient efforts proposed by Member States[8].

Transport

In the REF, similarly to the other sectors, transport assumptions reflect adopted energy, climate and transport policies and measures by EU Member States until December 2019. It also includes directives and regulations of the "Clean Energy for All Europeans" package (Directorate-General for Energy (European Commission), 2019). Such policies and measures drive: (a) the uptake of zero- and low-emission vehicles e.g. based on targets of CO_2 standards for light- and heavy-duty vehicles (Regulation (EU) 2019/631, 2019) and the Clean Vehicles Directive (Directive (EU) 2019/1161, 2019), (b) the roll-out of associated recharging/refueling infrastructure based on the Directive on alternative fuels infrastructure (Directive 2014/94/EU, 2014), (c) the uptake of renewable and low carbon fuels (e.g. the Renewable Energy Share in Transport share (i.e. the 14% sub-target for transport), as expressed in the NECPs, following the 2018 recast of the Renewable Energy Directive (Directive (EU) 2018/2001, 2018) and related blending obligations, the Fuel Quality Directive, etc.), (d) transport system efficiency, by making the most of digital technologies and smart pricing and further encouraging multi-modal integration and higher use of sustainable transport modes. It also includes programs for the large-scale electrification of the public fleet and Public-Private Partnerships for the uptake of EVs and infrastructure rollout, measure for fuel blending and transport taxation schemes. National blending obligations are assumed to be maintained post-2030, where these exist. Investments in efficient transport

[8] COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT Accompanying the Proposal for a Directive of the European Parliament and of the Council on energy efficiency (recast) - 14.7.2021

technologies continue beyond 2030, driven by factors including the economic competitiveness of technologies through learning by doing (e.g. battery technology for electric vehicles).

Food and agriculture

Like in the other sectors, the REF scenario for the food and agriculture sector builds on the 2020 reference run but picks up some updates. Standard updates against the reference run follow from a new database used to update historical series that are important for items without supplementary information like the fruits and vegetables sectors. A key source of supplementary information in the REF scenario is the updated DG Agri Medium Term Outlook (Directorate-General for Agriculture and Rural Development (European Commission), 2023). The CAPRI modelling had access to the detailed underlying output from the Aglink model in November 2023. This outlook helps to factor in recent developments like the reduction of agricultural production potential in Ukraine. Relevant inputs from the PRIMES model have been updated as well, which are for CAPRI mostly the production of biofuels from agricultural biomass and the agricultural area use for second generation biofuels.

The national Common Agricultural Policy (CAP) Strategic Plans[9] have not yet been reflected in the modelling for two reasons. Most important is that they should be reflecting the specific national measures taken to implement some of the Green Deal targets which should be analyzed as one of our main scenarios. Secondly, the CSP have raised the complexity and heterogeneity of CAP payments to a new level while the last Member States have only notified their national CSPs very recently. The process to adapt the CAPRI policy modules to this new complexity is still ongoing and the scenario work had to rely on the policy modules as used under the references run 2020.

3.3 Green Deal Scenario

The GD scenario is defined by more ambitious climate policies in the EU, aligning with the Fit For 55 package and the climate neutrality goal for 2050. More specifically, domestic EU GHG emission reductions in 2030 (at least 55% emission reductions from 1990 levels) are driven by:

- the EU Emission Trading System 1 (ETS1) target[10] (-62% vs. 2005 level covering electricity production and heavy industry),
- the EU Effort Sharing Regulation (ESR) target[11] (-40% vs. ESR Base Year 2005 levels), which will be partially driven by the ETS2 target (-42% compared to 2005 covering buildings, road transport and energy related CO_2 emissions from industry not covered by ETS1)

Additionally, EU Member States commit to a collective 11.7% reduction in final energy consumption by 2030 (i.e. -11.7% vs projection of the EU REF2020 scenario) corresponding to a maximum 763Mtoe final energy

[9] See https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_en
[10] See https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en
[11] See https://climate.ec.europa.eu/eu-action/effort-sharing-member-states-emission-targets/overview_en

consumption. The Renewable Energy Directive (RES) target[12] aims for a minimum share in Gross Final Energy Consumption of 42.5% by 2030 featuring sectoral targets for electricity, transport, and heating and cooling.

Dedicated to all sectors of supply and demand, specific measures are integrated, such as the Energy Performance of Buildings Directive decreeing zero-emission new buildings after 2030. Vehicle CO_2 standards evolve with significant reductions while strict regulations for Sustainable Aviation Fuels are imposed in aviation and maritime sectors. An overview of EU wide policies considered across all sectors in the GD scenario is shown in Table 1.

Table 1. EU Policies considered in the Green Deal scenario

Policy	Description
European Climate Law (adopted 2021)	Legal objective of achieving climate neutrality (net-zero) by 2050. Covers all GHG emissions and all economic sectors. Balance between emissions and removals to be achieved domestically within EU borders. Key features: ● 2030 target of at least 55% reduction of net GHG emissions compared to 1990 ● Commitment to net-zero emission by 2050 and negative emissions after 2050 ● Recognition of need to enhance EU's carbon sink through Land Use, Land Use Change, and Forestry (LULUCF) regulation
European Green Deal (proposed 2019)	Policy initiatives to set the EU on path to climate neutrality by 2050. Key initiatives*: ● EU Strategy on Adaptation to Climate Change ● EU Biodiversity Strategy for 2030 ● Farm to fork strategy with implemented elements: ○ 20% reduction in mineral fertilizer use ○ 50% reduction in nitrogen surplus ○ 25% share of organic agriculture

[12] See https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en

	○ 10% share of non-productive landscape elements ○ 30% reduction in pesticide use (watered down from the initial proposal of 50%) ○ Moderate 25% shift towards EAT Lancet recommendations on diet composition (increased in a sensitivity analysis to 50%) ● European Industrial Strategy ● Circular Economy Action Plan ● Batteries and Waste Batteries ● Just Transition Mechanism ● Clean, affordable and secure energy ● EU Chemicals Strategy for Sustainability ● Forest Strategy and Deforestation
Fit for 55 (proposed 2021, adopted 2023)	Set of legislative proposals and amendments to existing legislation to cut EU´s net GHG emissions to reach climate neutrality. Key features: ● EU Emissions Trading System, EU ETS and extension to buildings and road transport fuels ● Social Climate Fund ● Effort sharing regulation on Member States' emissions targets ● Emissions and removals from LULUCF ● Alternative Fuels Infrastructure Regulation ● Carbon Border Adjustment Mechanism, CBAM ● Reducing methane emissions in energy sector (provisional agreement in 2023) ● CO_2 emission standards for cars and vans ● CO_2 emission standards for heavy duty vehicles ● Amendment of Renewable Energy Directive > 40% renewable energy by 2030, including sectoral targets ● Reduce final energy consumption at EU level by 11.7% in 2030

	• Energy performance of buildings (provisional agreement December 2023) o all new buildings should be zero-emission by 2030 o existing buildings should be transformed to zero-emission by 2050 • ReFuelEU Aviation and FuelEU Maritime, on decarbonizing the fuel mix in aviation and shipping, respectively • Updated EU rules to decarbonize gas markets and promote hydrogen
RePowerEU Plan (2022)	Response to energy market disruptions from the Russian invasion of Ukraine. Aims to rapidly reduce dependence on Russian fossil fuels by 2027. Key features: • Increases the renewable energy target of the Fit for 55 package from 40% to 45% • Boosts industrial decarbonization • Promotes biomethane use in 2030 • Investments in energy infrastructure and interconnections • Regulatory measures to increase energy efficiency • Regulatory framework for hydrogen
Climate Target Plan 2040 (2024)	Communication to start process to establish 2040 climate target putting the EU firmly on a path towards climate neutrality by 2050. Key features: • Proposal for 90% net GHG emissions reduction compared to 1990

Buildings

In the GD scenario, the building sector is bounded by regulations, directives, and other actions in line with the Fit For 55 package that increase or set new refined targets for the buildings sector – residential and services sectors included. The regulations and initiatives are EU-wide and need to be or are already adopted by all EU Member States so that collectively the goals for GHG emissions reduction, final energy consumption reduction, and goals specific to the heating and cooling sector (of which buildings are a major part), and buildings.

A few of the sector specific policies and initiatives include the application of the Energy Efficiency Directive and minimum energy performance standards and net-zero energy buildings as described in the Energy

Performance of Buildings Directive. Moreover, the application of the Renewable Energy Directive II reflects the level of ambition when it comes to renewables uptake in the heating and cooling sector depicted in the RES Heating & Cooling target.

In addition to the preceding regulations and application of directives, a main difference of GD to REF is the Emissions Trading Scheme II (ETS II) (Directive (EU) 2023/959, 2023) application. The ETS extension applies to buildings and road transport from 2026 onwards.

Transport

In the GD scenario, the transport sector includes regulations and initiatives stemming from the Fit For 55 package that strengthen or set new targets for transport segments and their contribution to the EU Green Deal targets. The regulations and initiatives are EU-wide. The policy portfolio is described in Table 1 above.

A few key drivers that differentiate the input assumptions of GD compared to REF are:

- Strengthened CO_2 standards for both light- (cars and vans) and heavy-duty (lorries, buses and coaches) vehicles. For example, in the REF scenario the CO_2 standards called for 31% lower tailpipe CO_2 emissions from newly registered cars from 2030 onwards, while in GD they require a reduction of 50% in 2030 and 100% (i.e. banning internal combustion engines) from 2035 onwards. Similar enhancement of targets apply to all other modes (i.e. vans, lorries, coaches) while a mandate for zero-emission buses is also applied.

- Strengthened roll-out of alternative fuels infrastructure in line with distance- and capacity-based targets of the Alternative Fuels Infrastructure Regulation (Regulation (EU) 2023/1804, 2023), compared to the charging point ratio requirement as per the related Directive considered in REF (Directive 2014/94/EU, 2014).

- EURO VII/7 covering both light-duty and heavy-duty vehicles, applying enhanced emission limits to all vehicles within the same category, thus updating the EURO VI/6 standard applied in REF.

- Strengthened target of renewable energy in transport. In GD, the latest recast of the Renewable Energy Directive is applied that requires Member States to reach 29% Renewable Energy Share in Transport in 2030. This is significantly higher than the Renewable Energy Share in Transport in the Renewable Energy Directive II that is applied in the REF (i.e. 14%). In addition, specific sub-mandates on advanced fuels apply (namely RFNBOs and advanced biofuels).

- Deployment of alternative fuel in aviation and in maritime based on blending mandates and GHG emission intensity reduction targets, respectively, according to ReFuelEU Aviation (Regulation (EU) 2023/2405, 2023)and FuelEU Maritime (Regulation (EU) 2023/1805, 2023), while in REF the decarbonization policy drivers reflected inclusion in ETS and the International Maritime Organization's Energy Efficiency Design Index.

- Extension of ETS to road transport that covers fossil fuels used in the segment. In REF, ETS is not applied in road transport.

- Implementation of the Sustainable and Smart Mobility Strategy and Action Plan(European Commission, 2020a), that sets milestones to be attained for non-road transport modes (rail and water).

These policies and measures increase the uptake of clean transport technologies and fuels, and support the shift towards a more efficient transport system compared to the REF.

Food and agriculture

As the detailed representation of the national CAP Strategic Plans in the agricultural modelling is not yet possible, the implementation of Green Deal related agricultural policies has relied on the proclaimed elements expressed in EU level communications like the Farm to Fork strategy (European Commission, 2020b). The key elements are:

- 50% reduction in the per hectare nitrogen surplus in all regions is the key constraint reducing mineral fertilizer use and manure application.
- 20% reduction in mineral fertilizer use. This turned out to be an irrelevant constraint in most regions because the endogenous reduction (triggered by the surplus constraint) is more than 40% at the EU level.
- 25% increase in the organic farm area share at EU level. This has been allocated to the Member States taking into account the different potentials across the EU.
- 10% share of non-productive landscape elements. This triggers a reduction in agricultural area depending on the share that is already attained in the Member State.
- 30% reduction of pesticide use. This is a tentative estimate what might emerge in the coming years as a political compromise after the Commission had withdrawn its original proposal of a 50% reduction in May 2024[13].
- 25% move of European consumers towards the EAT Lancet recommendations for the composition of a ´flexitarian diet'. This was supplemented with a moderate 10% reduction of food waste implying a reduction of demand but without a matching decline of food intake.

These targets were phased in gradually, starting in 2025 for supply side measures and in 2030 for diet shifts with the full shifts attained in 2040[14]. At the same time an increasing carbon price had been introduced (see Section 3.1), aligned with the assumptions in PRIMES. In the PRIMES model reinforced mitigation under the following BGD scenario was implemented with a more optimistic specification for "enabling factors". As these

[13] communication C/2024/3117, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:C_202403117
[14] By mistake the waste reduction had been omitted in 2050 under the GD scenario such that a small irregularity had been introduced in the result series from 2045 to 2050.

are only implicit in the CAPRI system, the difference in mitigation efforts in agriculture between the GD and BGD scenarios has been reflected in a 20% deviation in the CAPRI carbon price from the central price path in PRIMES. This means that the carbon price was only 80% of the central path under GD, but 120% of the central path under the BGD scenario.

3.4 Beyond Green Deal Scenario

In addition to the GD scenario, the BGD assumes specific assumptions in the Buildings, Transport and Food and Agriculture sectors.

Buildings

In the PRIMES BuiMo, the BGD scenario considers all policies and measures of the GD scenario (Section 3.3). On top of that, it also assumes the implementation of several measures that could induce lifestyle and behavioral changes and affect either the energy needs of households, the increased uptake of energy renovation activities and further uptake of renewable heating and cooling solutions resulting in expanded electrification of heating compared to REF and GD.

We have examined various mechanisms in our modelling that can be summed up as follows[15] and can have different levels of adoption:

- The setpoint temperatures for heating and cooling in residential buildings shift by 1°C as a behavioral shift to limit the energy demand of households – different degrees of adoption can be modelled.
- The renovation rate in buildings increases 0.5%pt to 1%pt per year above the GD mimicking the willingness and ability to reduce energy consumption by more households.
- Flexible use of buildings, shared building spaces (e.g. co-housing and working) and policies are modelled limiting floor space in new constructions that reduce the floor space used per capita and thus the total final energy consumption of the sector compared to GD.
- Hot water conservation – limiting of shower time between 4 to 5 minutes compared to the 5.6 minutes assumed in the GD scenario.
- Choice of eco-mode for clothes and dish washing programs
- Standby electricity use – for appliances and lighting we assume that 50% of the households eliminate standby power by 2050.

Transport

In the PRIMES transport modelling, the BGD scenario considers all policies and measures of the GD scenario (see Section 3.3 Transport). In addition, it implicitly assumes the implementation of several measures that could induce lifestyle and behavioral changes, particularly in urban areas. In particular, it includes an overall reduction of the demand for private vehicle use owing to less travel, shift to public transport modes, shift to cycling and walking for short distances, and increase in vehicle occupancy. In addition, there is a reduction of road freight transport activity, and a reduction of air travel (higher reduction in shorter distance trips). Table

2 shows the assumptions used to capture the impact of additional behavioral changes in the BGD scenario, compared to the GD in 2050 (Table 2). The level of reduction is based on a synthesis from various literature sources that identify the implemented behavioral and lifestyle change trends (e.g. Akimoto et al., 2022; Berg et al., 2021; Dietz et al., 2009; Karkatsoulis et al., 2022; Koide et al., 2021; Mittal et al., 2017; Replogle & Fulton, 2014; United Nations Environment Programme, 2016; van de Ven et al., 2018; Venturini et al., 2019). With respect to the share of activity shift to active modes of transport (cycling and walking) this is based on a post-modelling assumption rationalized based on exchanges with ISGlobal using data from DG MOVE's EU-wide Passenger Mobility Survey (European Commission: Directorate-General for Mobility and Transport et al., 2022).

As part of the broader behavioral change in transport, the scenario also considers reduction of air travel demand.

Table 2. Implementation of the BGD scenario for transport (scenario change relative to the GD scenario in 2050)

Behavioral & Lifestyle changes	BGD settings
Demand for private vehicle use	10.5% reduction in passenger-kilometers for private cars
Road freight activity	5% reduction in road freight transport activity
Share of public transport	6 pp (percentage-points) share increase
Passenger aviation activity	9% reduction of aviation activity
Ride-sharing, car-sharing and car-pooling	15% increase in occupancy rate of passenger cars

Several drivers could contribute to achieve such shifts, as described below[15]:

- *Reduction in passenger travel demand:* Implement comprehensive land use changes to promote higher density and mixed-use urban planning, facilitating closer proximity of residential, commercial, and recreational spaces. Promote remote working policies and the adoption of a four-day working week to significantly reduce the necessity for daily commutes. Promote shared mobility and other schemes (e.g. access to lanes).
- *Incentives for mode shifts:* Encourage shifts towards more sustainable modes of transport such as walking, cycling, and public transit through the implementation of various policy measures:

[15] Note that these drivers are implicitly captured in the parameters used to modify the BGD scenario in PRIMES-TREMOVE and PRIMES BuiMo.

  - Low Emission Zones (LEZs) / congestion charging zones: Establish and expand LEZs to restrict access for high-emission vehicles, thereby reducing urban air pollution and encouraging the use of cleaner transportation options.

  - Parking management: Reduce the availability of parking spaces and introduce dynamic pricing mechanisms to discourage private vehicle use and promote the adoption of alternative modes of transport.

  - Pedestrianization: Increase the number of pedestrianized zones within urban centers, enhancing walkability and promoting a pedestrian-friendly environment.

  - Cycling infrastructure: Develop and expand dedicated cycling lanes and facilities to ensure safe and convenient cycling routes, encouraging a shift from car use to cycling.

  - Public transport infrastructure: Invest substantially in the enhancement and expansion of public transport networks, including the introduction of more frequent and reliable services, improved connectivity, and affordability. Focus on the electrification of public transport fleets and integration with other modes of sustainable transport.

- *Reduction in goods transport*: Encourage the consumption of locally produced goods over globally sourced products to decrease the demand for long-distance goods transport. Promote local supply chains and distribution networks to minimize the carbon footprint associated with the transportation of goods.

Food and agriculture

- The "standard" Farm to Fork elements of the Green Deal package have been maintained. This means that the nitrogen surplus shall be reduced by 50% mineral fertilizer use by 20% etc (see details in Section 3.3 Food and agriculture).

- Reinforced climate action is mimicked with a higher carbon price path (120% of the central carbon price path used in PRIMES or 120/80 = +50% against GD), reflecting either higher financial incentives, better monitoring, advisory services or education of farmers.

- A far-reaching change in consumption behavior means that the population average shifts (100%) to the EAT Lancet recommendations in terms of food composition, as far as the CAPRI resolution of products permits. Attaining 100% of the recommended composition does not mean that every household exactly follows the recommendations but that the above average reductions in meat consumption of vegan and vegetarian consumers approximately balance the remaining carnivore consumers that would reduce their meat consumption below average. Furthermore, the default version of the diet shift specification did not try to reduce the overall calorie consumption, even though European consumers also consume too much energy.

3.5 Beyond Green Deal 90 Scenario

The BGD90 scenario assumes the same activity pathway as the BGD scenario (see Section 3.4) with the introduction of additional air pollution controls. These controls achieve 90% of the maximal technical feasible reduction in population-weighted mean ambient $PM_{2..5}$ concentration levels for each Member State in the EU27.

Modelling this scenario variant exclusively with the BGD activity pathway as the most ambitious pathway for climate mitigation isolates the space for remaining action to be achieved by air pollution control. Put differently, these controls are not included for the GD scenario as this less ambitious pathway would make the remaining air pollution control space harder to identify due to overlaps with the BGD measures. These air pollution controls are modelled in GAINS using technologies available in the model as of March 2025.

It is important to emphasize that these additional technical controls reduce air pollution without altering activity levels or fuel use patterns. Therefore, they do not change GHG emissions in the GAINS model[16] and are thus less important for the quantification of co-benefits between GHG mitigation and air pollution. However, BGD90 serves a critical analytical purpose: it reveals the remaining technical potential for joined up air pollution and climate policies.

3.6 Non-EU / Rest of the world

Dedicated modelling has been done within CATALYSE only for the 27 EU Member States. However, the final gridded emission scenarios are made available globally. Outside the EU, projections rely on trends from earlier work involving the GAINS team. Only currently stated energy policies and air pollution legislation are considered.

For West Balkan, work under the EU4Green project[17] analyzed projections of energy and agriculture activities in six non-EU West Balkan countries. For these countries, energy projections from the PRIMES model were available which consider climate targets comparable to the EU.

For Ukraine, Georgia, and Moldova, energy projections from the EUCLIMIT-9East project[18] are used. These results were generated in collaboration with the PRIMES model.

For other non-EU Europe and the rest of the world, for energy sectors the scenario relies on the base year calibration from country specific energy balances from IEA World Energy Statistics (IEA, 2023a), and trends over time follow the IEA World Energy Outlook 2023 STEPS scenario (IEA, 2023b). For agriculture sectors, the calibration rely on FAO statistics (FAO, 2022) and the Baseline projections from the UN Food and Agriculture

[16] In practice, the application of additional filter technologies can in some cases decrease efficiency and increase fuel consumption slightly. This is not considered in GAINS.
[17] https://eu4green.eu/
[18] EU Commission Service Contract ENER/A3/SER/2019-563/SI2.840866 - ENER/2020/OP/0005; Extension of the EU Energy and Climate Modelling Capacity to include the Energy Community and its Nine Contracting Parties.

Organization for trends (FAO, 2018). For the waste sector, GAINS internal estimates of amount and type of waste (updated from Gomez Sanabria et al. 2021) are used in all countries.

For the food and agriculture sectors, a sensitivity version of the scenarios will be developed with non-European countries applying 50% of the EU carbon price in the agricultural and food sectors and also achieving half of the EU move towards the EAT Lancet targets. This sensitivity analysis is supposed to shed some light on the differences of impacts from unilateral EU policies as opposed to some global coordination. With widely traded agricultural commodities it may be expected that “carbon leakage” will be clearly lower in a multilateral setting, apart from the fact that the global achievements would be dominated by assumptions on non-EU changes, given the rather moderate weight of the EU in a global context.

4. Models and methods

The below sections describe the three main models used for developing the emission scenarios. All models operate in five-year timesteps from (at least) 2015 to 2050 and have a country resolution[19] covering at least the EU.

4.1 PRIMES

The PRIMES model (Figure 8) is a comprehensive, large-scale simulation model used to analyze energy systems of all EU Member States. It is designed to provide long-term energy system projections up to 2070, both in the demand and the supply sectors. The model's projections include detailed energy demand and supply balances, CO_2 emissions, investments in the energy system, technology deployment, energy prices and costs. PRIMES simulates a multi-market equilibrium, by explicitly calculating energy prices which balance demand with supply through an iterative process. The simulation of behavior of each agent is based on detailed modelling founded on micro-economics and includes engineering-oriented and policy constraints. Due to its comprehensive inclusion of policy instruments of different natures, it can be used to evaluate the impact of policy measures such as carbon pricing, subsidies, infrastructure investment, technology standards, emission and efficiency performing standards, among others. When linked with the models CAPRI (EuroCARE), GAINS (IIASA) and GLOBIOM (IIASA), the modelling suite covers the detailed simulation of all GHGs, making it a key tool for analyzing the effects of energy and climate policies on emissions reduction targets.

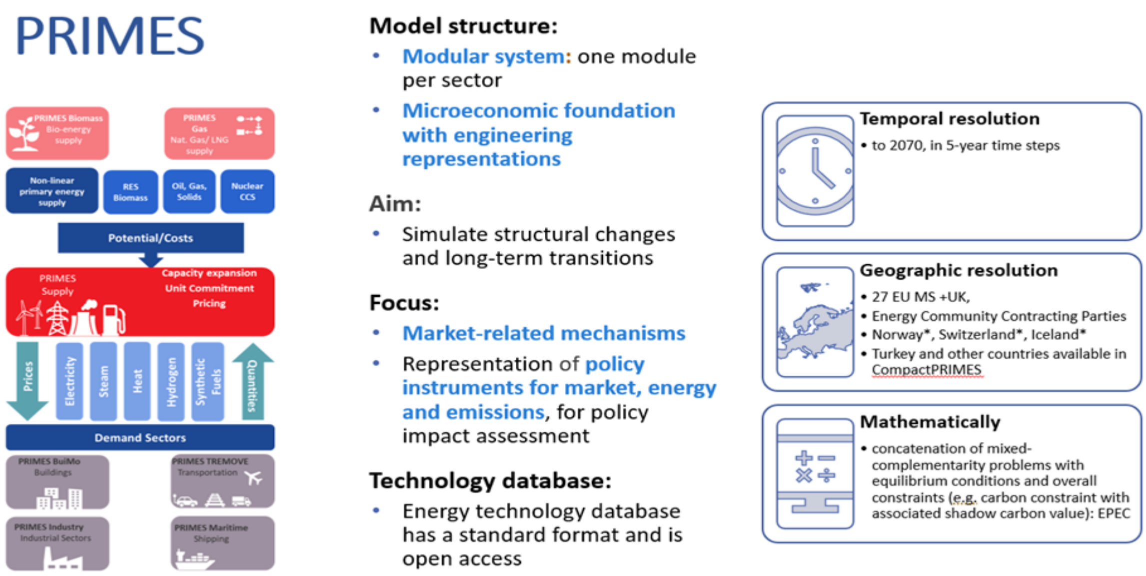


Figure 8. Schematic overview of the PRIMES model.

[19] In specific sectors, sub-national resolution is introduced through splits into urban and rural (or inter-urban) activity; however, this represents a split at national level and does not allow for the modelling of individual cities.

4.2 PRIMES-BuiMo

The PRIMES Buildings Module (BuiMo) is a component of the PRIMES modelling framework, focusing on energy demand, efficiency, and technology adoption in the buildings sector at the European level (including results of all EU member States). A schematic overview of the model elements and workflow are shown in Figure 9.

PRIMES BuiMo provides a high-resolution representation of the residential and services building stocks, embedded within an economic-engineering model that simulates multi-agent decisions regarding building renovation, heating and cooling systems, and equipment/appliances.

The model is well-suited for analyzing energy efficiency measures in buildings, such as improved envelope insulation, adoption of high efficiency and renewable heating and cooling technologies, and the renovation of the existing building stock. It is designed to offer long-term projections on future energy efficiency and fuel mix trends within the residential and services sector.

By analyzing the cost-effectiveness of a variety of policies, the module captures the influence of policies on agent's decisions, while respecting engineering constraints, specificities, and the potential for transformation within the buildings sector. To address the limitations of the representative consumer hypothesis, BuiMo generates a distribution of decisions based on each agent's features (income class, occupied building's type, age, location etc.), thus capturing the heterogeneity of the buildings sector.

Energy labelling and other policies are represented in the model and facilitate the uptake of highly efficient, yet more expensive, technology types through reducing the uncertainty and lack of information factors. In particular, PRIMES-BuiMo can represent various policy instruments including: Taxes and subsidies for energy products, Financial facilitation for renovation and the purchase of low-carbon technologies, Information campaigns, Eco-labelling of technical equipment, Eco-design standards, Building code standards and levels of compliance, Energy efficiency standards, Carbon pricing (EU and national), white certificates and targets for RES-heating and cooling.

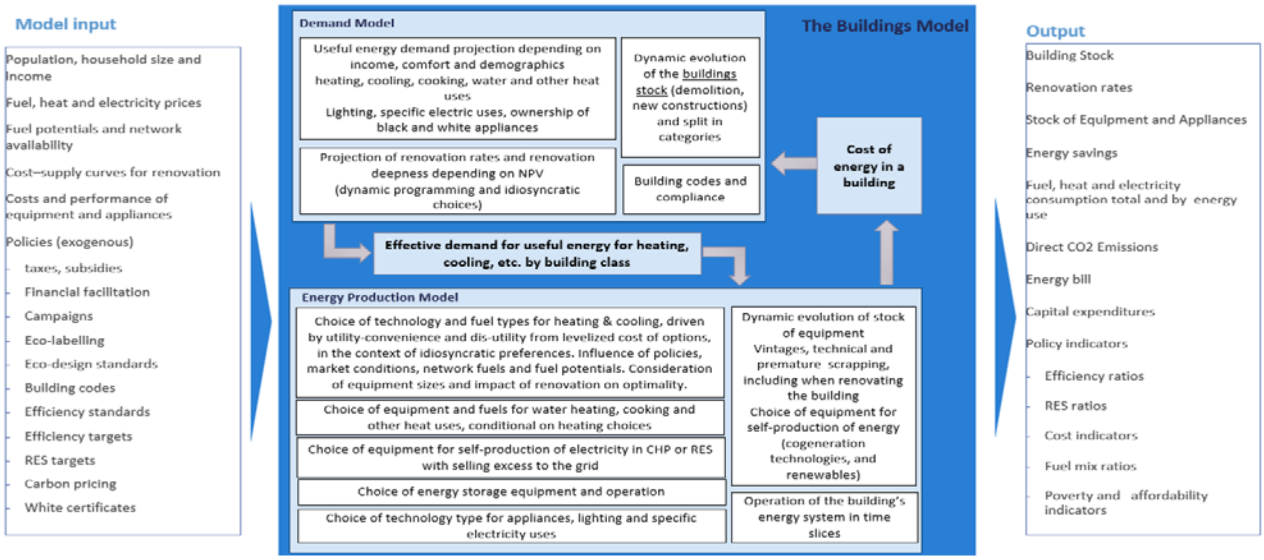


Figure 9. Schematic workflow of the PRIMES-BuiMo module.

Implementation of the BGD scenario for buildings in PRIMES BuiMo

Key developments in PRIMES-BuiMo to incorporate behavioral changes as part of the core modelling include improvements to the disaggregation of useful energy demand for thermal and electric uses, addressing space heating and cooling, water heating and electric appliances. Potential behavioral changes, like adjustments to thermostat settings and showering time, are considered in the recalibration process, enhancing the accuracy of energy savings projections. Table 2 mentions the modelling improvements in PRIMES-BuiMo and based on literature review, the changes that are imposed to PRIMES BuiMo in the BGD scenario.

Table 3. Implementation of the BGD scenario for buildings (scenario change relative to the GD scenario in 2050)

Sector	Modelled lifestyle change	Beyond Green Deal
Residential Buildings	Set-point temperature	1°C shift of thermostat setting (75% of households adopt)
	Limiting floor space	Convergence to 45 m^2/cap
	Hot water conservation	Shower time set at 5 minutes
	Eco-mode consumption	50% of households switch to eco-mode for clothes and dishwashing programs

	Standby electricity use (appliances and lighting)	50% of households eliminate standby power
	Renovation rates	0.5% p.a. increase above the base scenarios

Assumptions refer to changes from the levels of decarbonization scenarios without lifestyle changes in 2050.

The setpoint temperatures in residential buildings shift to 20 °C /19 °C (heating) and 25 °C/26 °C (cooling) by 2050, stimulated by information campaigns and policies limiting setpoints. We assume a 1°C shift in thermostat setting from the reference case (GD) to the BGD scenario. We also assume that 50% of households change their thermostat by 1°C by 2050.

The renovation rate in buildings increases by 0.5 percentage points per year above the GD levels in the BGD. More frequent and deep renovation measures are adopted progressively over time, meaning that maximum deviation from the GD is achieved in 2050.

Flexible use of buildings or shared building spaces (e.g. co-housing and working) and policies limiting floor space in new constructions reduce the floor space used per capita in the residential sector. We assume a regional cap 45 m2/cap by 2050 for residential floor space (in line with Andreou et al. 2023).

Hot water conservation leads to decreasing shower time down to 5 minutes in the BGD, similar to the low and very low demand scenarios of (Andreou et al., 2023). In PRIMES-BuiMo, this lifestyle change is simulated compared to a baseline showering time of 5.6 minutes in the GD, reported for UK households in (Shahmohammadi et al., 2019).

The choice of eco-mode for clothes and dish washing programs increases. Based on data from the European Product Registry for Energy Labelling, the average eco-mode consumption of dishwashers in the market (A to G class) is around 0.83 kWh/cycle and that of laundry machines is 0.59 kWh/cycle (Andreou et al., 2023). To derive assumptions for eco-mode consumption, only those products from the database that range between C and G energy label are considered (average eco-mode consumption at 0.85 kWh/cycle and 0.68 kWh/cycle for dishwashers and laundry machines). In this way, we isolate the effect of eco-mode without considering the best-performing products in the market (because these will be highly efficient already). In PRIMES-BuiMo, electricity demand for dishwashers and laundry machines is adjusted according to the reduction in average cycle consumption between eco-mode and standard programs, using as baseline consumption levels those of "ordinary" technologies included in the model[20]. In the BGD, 50% of households are assumed to choose eco-mode over standard programs.

[20] PRIMES-BuiMo categorises appliances based on their efficiency as ordinary, improved, advanced and future, where learning by doing factors apply on technological development.

For standby electricity use for appliances and lighting in the BGD, we assume that 50% of the households eliminate standby power by 2050. Annual energy savings from this behavioral change are estimated based on a review of standby electricity consumption statistics for different product categories (LBNL, n.d.). Standby power estimates were transformed into avoided annual electricity consumption figures based on simplistic assumptions about the daily hours of standby of electric appliances.

4.3 PRIMES-TREMOVE

The PRIMES-TREMOVE transport model models a large range of measures for transport including soft measures (e.g. eco-driving), economic measures (e.g. subsidies and taxes on fuels, vehicles and emissions and other externalities i.e. pollution, accidents and noise), infrastructure policies for alternative fuels, and regulatory measures.

The model projects the evolution of demand for passenger and freight transport demand by mode (i.e., road, rail, air, waterborne), vehicle (e.g., cars, vans, trucks and others) and fuel (e.g., oil products, biofuels, electricity, hydrogen, synthetic fuels). For this purpose, PRIMES-TREMOVE has a demand module that projects demand for transport services of passenger and freight and a supply module that meets the projected demand via an optimum technology and fuel mix[21]. The supply module interacts with the demand module through the so-called generalized prices of transportation (measured in Euro per pass/ton km). The demand module has several alternative trip possibilities that depend on the area, time and distance by transport mode, for which different generalized prices are calculated. When the generalized prices differ from the baseline scenario, the model determines the new demand (for each of the various possible trips) based on the price differential relative to the baseline scenario and the elasticities of substitution (different among the various options) while respecting the overall budget (microeconomic foundation). Figure 10 schematically presents the interaction of the modules for passenger transport of households.

PRIMES-TREMOVE represents a dynamic system of multi-agent choices (see also Figure 10) under several constraints which are not necessarily simultaneously binding. The fuel and vehicle choice of agents is endogenous in the model and is based on: (a) internal costs, (b) perceived costs, i.e. market acceptance for each technology, (c) infrastructure availability for the energy carriers. For the purchasing of new vehicles, a range of technology options is considered; the available technology portfolio for vehicle technologies includes different configurations, different technologies with an impact on fuel consumption and fuel types. The purchase choice of vehicle technologies and fuels follows the approach of discrete choice modelling. Cost elements include all costs over the lifetime of the candidate transport means: purchasing cost, annual fixed costs for maintenance, insurance and ownership/circulation taxation, variable costs for fuel consumption depending on trip type and operation conditions, other variable costs including congestion fees, parking fees and tolled roads. Energy and pollutant emissions calculations are based on the COPERT methodology. PRIMES-TREMOVE also includes a vehicle stock sub-module which calculates the stock of transport means from previous time periods in order to determine the changes needed to meet demand. It

[21] PRIMES-TREMOVE models explicitly motorized transport (i.e. active modes are not modelled explicitly).

tracks vehicle vintages and formulates the dynamics of vehicle stock turnover by combining scrapping and new registrations.

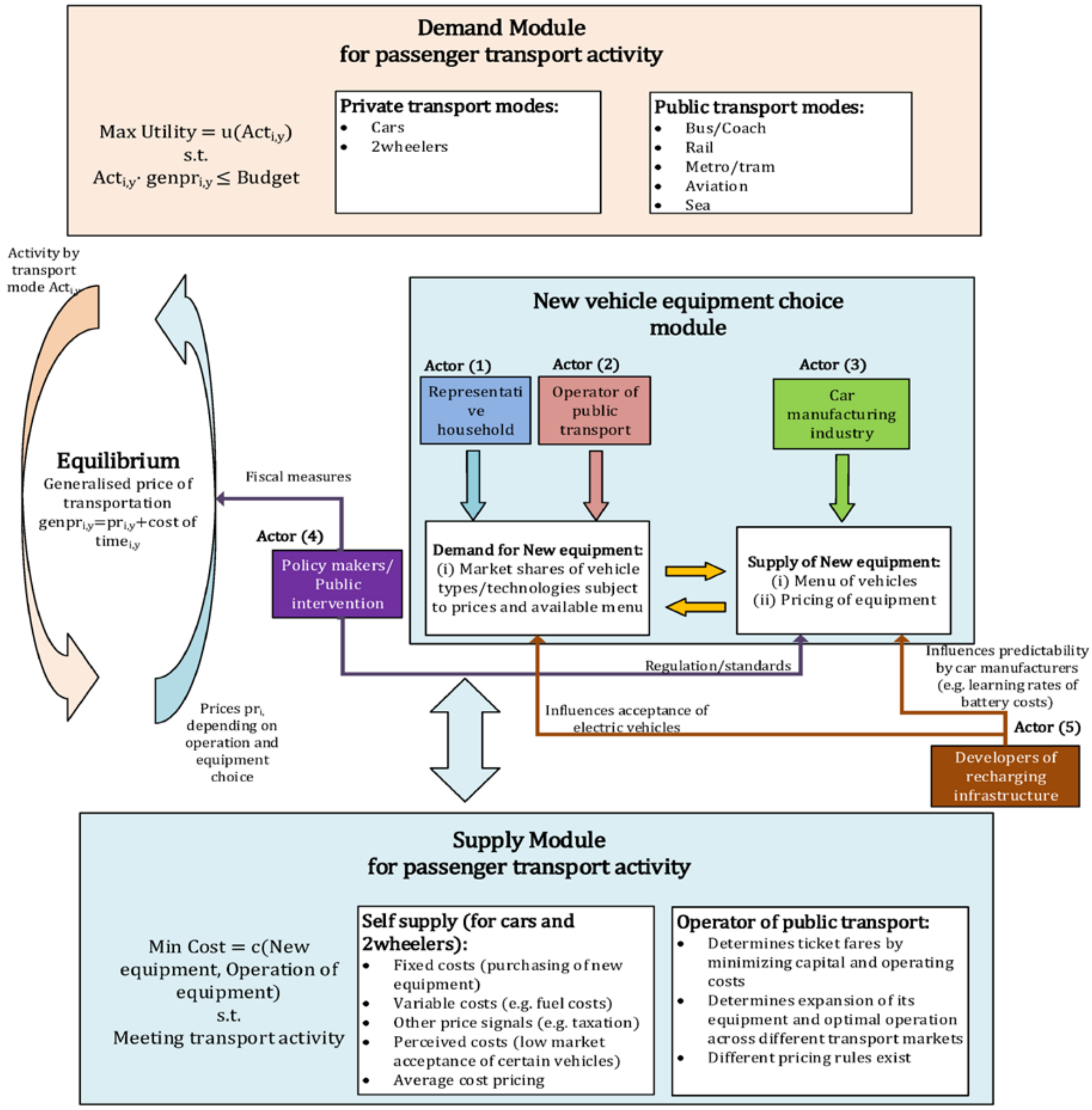


Figure 10. Interactions of the actors related to passenger transportation of households, as modelled in PRIMES-TREMOVE

4.4 CAPRI

The CAPRI (Common Agricultural Policy Regional Impact Analysis) system is a global agro-economic model used to assess impacts of agricultural, trade and environmental policies on the agricultural sector. The CAPRI economic model, comparative-static in nature, is split into two major modules: the supply module and the market module. The supply module consists of independent non-linear programming models representing farming activities at NUTS2 level in Europe. These offer a high level of detail, for example in the coverage of premiums paid under CAP, NPK balances for crops and modelling of nutrient requirements of animals, providing the link to various emissions and other environmental indicators. The supply models are solved independently at fixed prices which are delivered by an iteratively coupled global market module for about 50 primary and processed agricultural products and about 70 countries or country blocks. It is based on the Armington assumption for bilateral trade flows permitting to analyze trade policy instruments like Tariff Rate Quotas (TRQs). Inputs covered are land, fertilizers, pesticides and feed energy. The behavioral functions for supply, feed, processing and human consumption have standard micro-economic properties. Demand functions may be shifted to reflect diet shifts or waste reduction. While technical detail is higher in the programming models for EU regions, also the more aggregate representations for non-EU regions permit carbon pricing and mitigation effects.

The CAPRI database mostly relies on EUROSTAT and FAOSTAT, supplemented by other sources for special topics like land and fertilizer use. Since the end of the 1990s, the emphasis in CAPRI applications has increasingly shifted from classical agricultural and trade policy questions to environmental impacts, for example on emissions or biodiversity. The model has often been used to contribute agricultural detail to a model cluster that covers all relevant aspects concerned in an impact assessment as an ensemble, like in EUCLIMIT applications.

The CAPRI baseline relies on constrained trend projections based on the historical CAPRI database with time series starting in 1985 for man European countries. The keyword “constrained” points on the one hand to the integration of technical information (balancing equations, linkage of livestock herds to feed intake etc.). On the other hand, it also hints at the integration of projections from external sources. For the medium run the most important source is typically the Agricultural Outlook by DG-AGRI, running to 2040 in the November 2023 version. For longer run projections CAPRI usually relies on projections by GLOBIOM, in this case taken from the earlier reference run collaboration under EUCLIMIT. Inputs from PRIMES have been mentioned already as driving differences between the scenarios. In the process of the baseline preparation the parameters describing the reactions in the sector are calibrated to the baseline situation, making the model behave in accordance with the data and projected conditions. In a simulated scenario, all conditions in the baseline are maintained – except for the changes to be analyzed:

- The surplus and mineral fertilizer constraints have been introduced as explicit constraints for the programming models.
- Various other input coefficients are exogenous and have been revised in accordance with change in the organic area shares and pesticide reductions. Higher organic shares also reduce crop yields.
- Additional landscape elements act like an exogenous demand for agricultural area. These landscape elements are therefore removed from the production potential.
- Carbon prices trigger adjustment in activity levels, uptake of dedicated abatement technologies and some reduction in consumer demand.
- Demand shifts and waste reductions have been translated into shifts of demand functions.

4.5 GAINS

The GAINS model is a widely-applied policy analysis tool to identify cost-effective policy interventions to reduce health impacts of air pollution while maximizing co-benefits with other policy priorities (Hordijk & Amann, 2007; Reis et al., 2012). GAINS explores the co-control of measures on multiple air pollutant and greenhouse gas emissions, identifies trade-offs and win-win measures, and assesses their impacts on ambient air quality, population exposure, resulting health and vegetation impacts, and various climate metrics.

The GAINS model has been used in support of negotiations of several protocols of the UNECE Convention on Long-Range Transboundary Air Pollution (UNECE, 1999) and European Commission emission ceiling and air quality directives (e.g., Amann et al., 2012, 2014). In the past few years, the GAINS modeling team has been strengthening links with a number of global integrated assessment modelling (IAM) teams and applying GAINS to develop fine scale global projections of air pollutant emissions and assess the air quality impacts (Rafaj et al., 2018, 2021) as well as inputs to parameterize air pollution storylines for the Shared Socioeconomic Pathways (SSPs), used by the IPCC in the Sixth Assessment Report (Rao et al., 2017). Other studies include air quality and health impacts considering demographic developments at various scales (Dimitrova et al., 2021; Hamilton et al., 2021). The model has also been instrumental in the development of global and regional scenarios assessing future evolution, mitigation potential, and impacts of black carbon (Klimont et al., 2017; Shindell et al., 2012; UNEP, 2011, 2017; UNEP/WMO, 2011), including dedicated work for the Arctic Modelling and Assessment Program (AMAP, 2015). Finally, air quality and mitigation potential at the urban scale has been assessed recently with the help of the further developed GAINS model tools (Amann et al., 2017; Bhanarkar et al., 2018).

As a scientific tool for integrated policy assessment, the GAINS model describes the air pollution pathways from atmospheric driving forces to environmental impacts. It brings together information on economic, energy and agricultural development, emission control measures and costs, atmospheric dispersion and chemistry (Figure 11). GAINS quantifies the emissions and impacts of nine air pollutants (SO_2, NO_x, $PM_{2.5}$, PM_{10}, BC, OC, CO, NH_3, VOCs) and six greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) on human health, crop losses, acid deposition, and long-term radiative forcing in a multi-pollutant/multi-effect perspective.

GAINS relies on external projections of activities like energy production and consumption, industrial production, transport, agricultural livestock numbers, fertilizer use, etc. These are taken from other system models such as PRIMES, CAPRI, or other IAMs. Such projections are imported into GAINS, mapping the sector structure from the respective energy or agriculture model to the native GAINS structure. Where needed, sector or fuel classes are aggregated or downscaled to the GAINS level; in case of downscaling, GAINS relies on its extensive database calibrated from previous projects in order to sub-divide activity levels into its more granular structure.

Emissions are calculated at a detailed sectoral level, distinguishing more than 200 sectors and more than 70 activity categories (fuels etc.). The emissions of these air pollutants and short-lived greenhouse gases can be controlled with control technologies[22]. GAINS holds a large database of technology specific emission factors for all air pollutants and costs and combines this with information on the emission control legislation in each country. Currently the database distinguishes more than 350 different technologies. These “technologies” can be filters, scrubbers, different types of installations (for example stove types), different standards of exhaust cleaning (such as the Euro standards for vehicles) but also improved ways of handling manure, or best practice controls on process emissions etc. Some relate uniquely to one type of equipment while others represent categories of installations. In the GAINS framework, technologies influence emissions but they do not alter the activity level; the energy balance stays unchanged. Technologies can influence emissions of one or more pollutants, not every technology controls every pollutant. In some cases, the application of a control technology which is mainly designed to reduce emissions of one pollutant can lead to small increases of emissions of another pollutant (for example, selective catalytic reduction of NO_x leads to slightly increased NH_3 emissions). Such effects, both in terms of co-control of several pollutants at the same time but also trade-offs, are represented accurately in GAINS.

Emissions calculated in GAINS are determined by three main factors:

- Activity levels, in this case supplied by the other models in WP2 and described in Section 5,
- Application rates of emission control technologies (“control strategy”),
- Technology-specific emission factors.

The main equation for calculating emissions is thus (see e.g. Amann et al., 2011):

$$E_{i,p} = \sum_{k} \sum_{m} A_{i,k} ef_{i,k,m,p} x_{i,k,m,p}$$

where:

i, k, m, p - Country, activity type, abatement measure, pollutant, respectively.

$E_{i,p}$ - Emissions of pollutant p (for SO_2, NO_x, VOC, NH_3, $PM_{2.5}$, CO_2, CH_4, N_2O, F-gases) in country *i*.

$A_{i,k}$ - Activity level of type *k* (e.g., coal consumption in power plants) in country *i.*

$ef_{i,k,m,p}$ - Emission factor of pollutant *p* for activity *k* in country *i* after application of control measure *m*.

$x_{i,k,m,p}$ - Share of total activity of type *k* in country *i* to which a control measure *m* for pollutant *p* is applied.

[22] A full list of sectors, fuels and technologies considered in GAINS is available in the help center of the GAINS online model interface (http://gains.iiasa.ac.at/models/gains_models4.html, user registration required)

GAINS represents detailed economic sectors (s) and activity categories (f). Activities can be combustion of a certain fuel, kilometers driven by vehicles, animal livestock numbers, etc.

During the import of data from the PRIMES and CAPRI models, sector and activity categories in these models are matched with the resolution in GAINS and either aggregated or downscaled as appropriate.

Application levels *x* of individual emission control technologies *m* within each activity-sector combination can be freely chosen in GAINS. The complete configuration is called control strategy. It is either decided by expert judgement or derived from an optimization in GAINS. Typical configurations are:

- Current Legislation (CLE): representing the effects of all currently implemented legislation relevant to air pollution or greenhouse gas emission controls, assuming its efficient implementation.
- Maximum Technically Feasible Reduction (MTFR): The solution of the GAINS optimization for minimal emissions in a given year. Constraints are defined by available capacity (GAINS does not assume scrapping of existing stock before the end of its lifetime) but the solution is irrespective of costs.
- Cost-optimal control strategies: can be calculated with the optimization module in GAINS as a least-cost solution to reach certain emission or impact targets.

In the scenario calculation mode, GAINS follows pollutants from their sources to their impacts and thereby simulates the impacts of specific policy interventions on multiple outcomes. In its optimization mode (e.g. MTFR or cost-optimal control strategies), GAINS identifies the least-cost balance of emission control measures across pollutants, economic sectors and countries that meet user-specified air quality and climate targets (Figure 11).

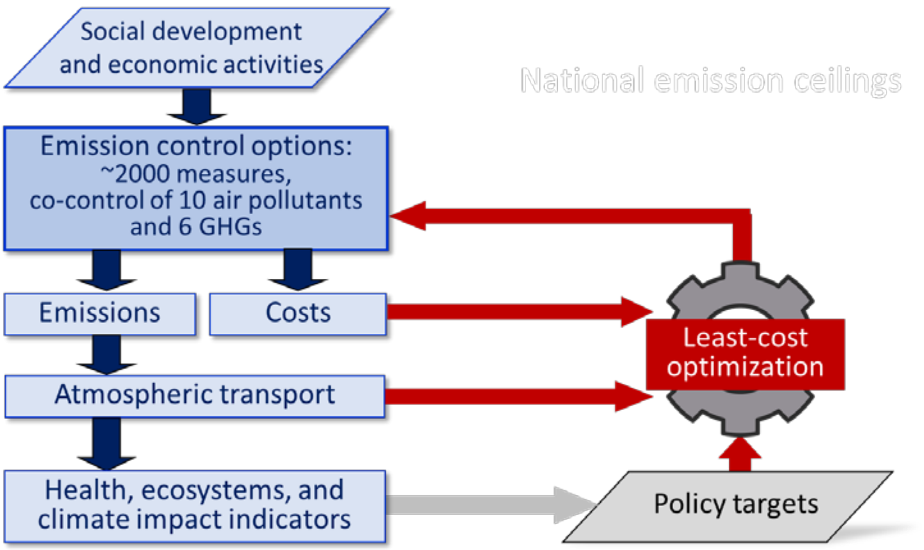


Figure 11. The flow of information in the cost-effectiveness analysis of the GAINS model.

Targets can be set on different environmental indicators. Meaningful air quality targets are often highly regional, i.e. different numerical targets are and sometimes need to be set for different countries or country groups, reflecting different socio-economic conditions, levels of industrialization and other factors in which countries differ. On the other hand, ensuring comparability and fairness across countries is also important. Therefore, it is useful to follow a certain rational narrative to set targets across a group of countries. One such narrative for setting targets is the "gap closure" approach.

This approach requires the difference (“gap”) between the CLE and the MTFR (in terms of emissions, or impacts) to be reduced by the same percentage for all countries. The CLE is the baseline scenario under analysis while the MTFR is that scenario which is technically achievable with all best available emission control technologies applied at each respective highest possible rate. The gap closure percentages therefore represent ambition levels, ranging from 0% (no ambition, equivalent to CLE) to 100% (maximum ambition, equivalent to MTFR). While emissions reductions thus differ in absolute terms, each country/region makes the same proportional progress towards the MTFR. Thus, the gap closure approach represents a burden-sharing that defines a common ambition level. The gap closure approach has been applied in a variety of policy processes, including the development of EU air quality frameworks and LRTAP Convention. It is also applied here for creating the BGD90 scenario, where a 90% gap closure on ambient $PM_{2.5}$ concentration levels estimated by GAINS is chosen to simulate an ambitious control scenario where all measures except those with the highest costs are taken.

GAINS is currently implemented for 182 countries/world regions with global coverage, including all European countries as separate entities. The GAINS model and databases are accessible over the Internet (https://gains.iiasa.ac.at/models, user registration required). The CATALYSE scenarios described in this report will be made available in the GAINS online interface in due course.

4.6 Spatial and temporal distribution of emissions

While the GAINS model calculates emissions at a national total level with fine sector/fuel granularity, the emissions are also delivered as a gridded product at 0.1°×0.1° resolution and with monthly time variation for use in atmospheric models. For this purpose, the country-level emissions are distributed spatially and in time following approaches as described here. The final product is made available publicly as NetCDF files on Zenodo (see Section 8 Data Availability).

The spatial allocation of emissions for the CATALYSE projects follows two approaches, one for the EU countries and one for the remaining regions as defined in the GAINS model. In general, GAINS has the ability to distinguish between over 40 different sectors with individual spatial patterns, for some featuring an additional pollutant specific dimension. The spatial distribution was prepared from RCP-consistent proxies with final emission sectors aggregated following RCP/CEDS standards (Feng et al., 2020) and builds on previous developments within the GAINS model. Emissions from international aviation and shipping are not included.

Sectors are aggregated from the GAINS native sector structure and include (might vary by pollutant):

- Agriculture
- Energy
- Industrial
- Transportation

- Residential (Residential, Commercial, Other)
- Solvents (production and application)
- Waste
- Agricultural Waste Burning

Outside the EU, the GAINS annual emissions for all relevant pollutants were distributed following the LRTAP_Baseline_v3 scenario developed for the review of the Gothenburg Protocol of the UNECE Air Convention and described in (Klimont et al. 2023). Over 85% of these non-EU emissions were distributed in native 0.1° resolution, with the remainder gridded at 0.5° resolution and resampled at 0.1° resolution. These form the “background” emissions and do not change between the different CATALYSE scenarios.

These data are combined with CATALYSE emissions for the 27 EU member states under three different scenarios, resulting in a harmonized, global dataset of 0.1° x 0.1° longitude-latitude grids stored in netCDF format. The temporal (monthly) disaggregation follows that of Klimont et al. (2017). The data is available from 2015 to 2050 in 5-year intervals for all scenarios and emitted emissions are provided as $kg/m^2/s$.

Emissions in EU Member States are gridded at 0.1° resolution and include the following project specific developments and adjustments.

Road transport

A major update under the CATALYSE project was developed for the spatial patterns of road traffic. The spatial distribution of emissions for vehicles in GAINS is classed into 4 categories (two-wheelers, cars and light-duty trucks, buses, heavy-duty trucks). For these sectors, the PRIMES/TREMOVE model produces a split into urban and inter-urban traffic which is incorporated in the spatial distribution. Based on the methodology described in De Ceuster et al. (2004), the geographic definition of urban and rural areas was reverse engineered as well as possible with the aim to closely match the definition used in PRIMES/TREMOVE.

Individual spatial patterns for each of the vehicle categories in the three main scenarios were produced for all timesteps. To achieve this, information on urban and rural vehicle kilometers from PRIMES/TREMOVE for a vehicle category were combined with the geographic data on urban centers as follows. For the urban traffic emissions, the spatial population pattern used in GAINS (see Buildings sector (residential combustion) below) is filtered by the geographic areas defined as urban in PRIMES/TREMOVE. Hence, solely population data is used as proxy since road networks tend to be much denser in built up areas which would make it difficult to harmonize in relation to rural areas at the grid resolution.

For the rural traffic emissions, we use the GRIP dataset from Meijer et al. (2018) and combine it with assumptions on the distribution between vehicle type and road type based on expert judgement as applied in the standard emission gridding approach in GAINS. The road length for a road type is calculated and for each grid its share of the total within a country is assigned.

To ensure that urban areas are not overrepresented, the road dataset is furthermore reduced in the grids already considered for the urban traffic emissions in proportion to the population served. These two patterns are combined by weighting according to the urban/rural share of traffic activity coming from the PRIMES/TREMOVE model.

Buildings sector (residential combustion)

The residential sector in GAINS is split into urban and rural use of different fuels for cooking and heating. Consequently, also the spatial allocation for domestic residential emissions is split between urban and rural. GAINS follows the statistics on urban and rural population based on the United Nations World Urbanization Prospects 2018 (UNDESA, 2018). This urban definition follows that of the respective national census. For the spatial allocation we combine the JRC GHSL (Pesaresi et al., 2019) data products GHS-SMOD and GHS-POP with the JRC Urban Centre Database (Florczyk et al., 2019) and scale the results to match the World Urbanization Prospects total urban and rural population. The JRC GHSL data products apply the Degree of Urbanization methodology (OECD et al., 2021) to discern between urban and rural grids.

For the urban domestic residential emissions, we first estimate the total population that can be supplied by clean fuels using fuel statistics and activity data. Through calibration against measurement stations and external data on the distribution of district heating it is assumed that 95% of this population served by clean fuels is located in the most densely populated areas first (i.e. urban centers), with the remainder being distributed across all populated urban grids. The rural domestic residential emissions are distributed across the rural population as defined in the GAINS model.

5. Activity, energy and agriculture system trends

This section describes the trends in anthropogenic activities calculated by the PRIMES and CAPRI models in response to the macroeconomic drivers and policy assumptions discussed in Section 3. It is structured by sectors: section 5.1 gives an overview of the whole energy system (PRIMES model), 5.2 and 5.3 take a detailed look at the buildings and transport sectors modelled with the PRIMES-BuiMo and PRIMES-TREMOVE submodules, and 5.4 details trends in food and agriculture systems.

5.1 Energy system

This section explores the energy system-wide impacts of the three modelled scenarios – REF, GD and BGD – in the EU27 including the power and heat sector as well as all demand sectors (buildings, industry, and transport).

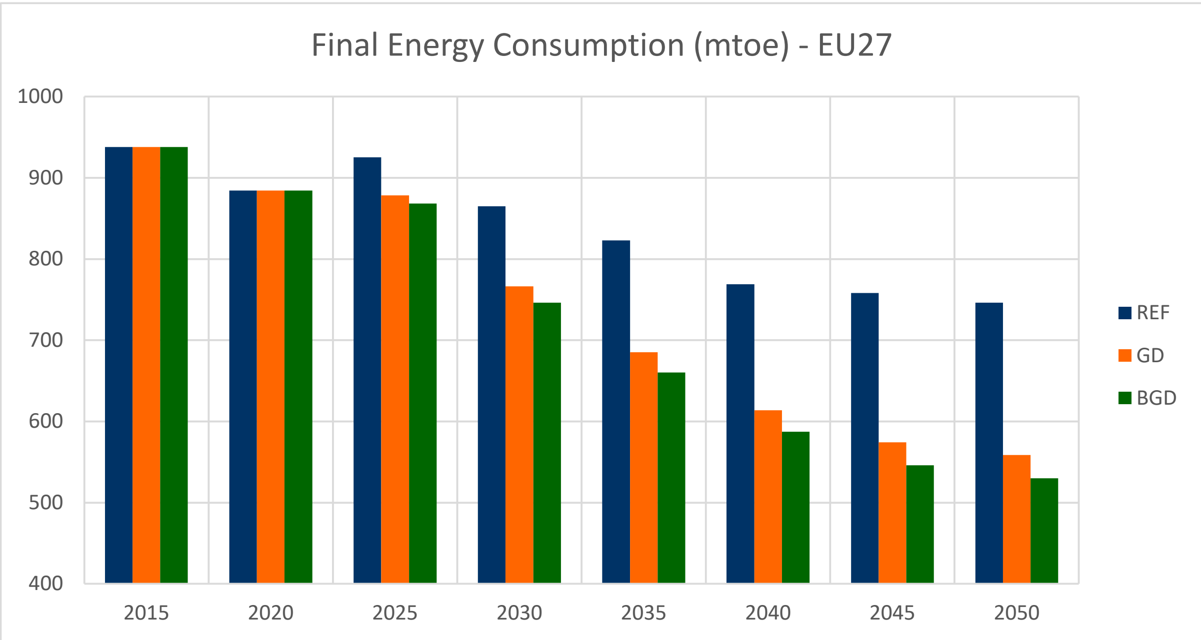


Figure 12. Final energy consumption in REF, GD and BGD for EU27

The final energy consumption of all demand sectors differs among the studied scenarios. As shown in Figure 12, the GD scenario achieves lower final energy consumption across all demand sectors compared to REF from 2025 onwards. By meeting the Green Deal's decarbonization goals, GD reduces final energy consumption by 13% in 2030 and 37% in 2050. When additional behavioral changes are implemented in the buildings and road transport sectors in the BGD, final energy consumption reduces by 16% in 2030 wrt the REF and 40% in 2050 respectively.

Figure 13 shows gross inland energy consumption for the EU27. Whereas final energy consumption is the energy consumed by end-users, gross inland energy consumption is the total quantity of energy consumed within a national territory. It is calculated as follows: primary production + recovered products + total imports + variations of stocks - total exports - bunkers.

It corresponds to the addition of final consumption, distribution losses and transformation losses. As one might expect, the picture is similar to the one of final energy consumption, with the BGD scenario exhibiting the largest reduction, compared to REF, both in 2030 and 2050. This is largely attributed to the reduced final energy consumption but also, for both the GD and the BGD, to the improvement of all energy networks and the respective reduction of distribution and transformation losses with respect to the REF.

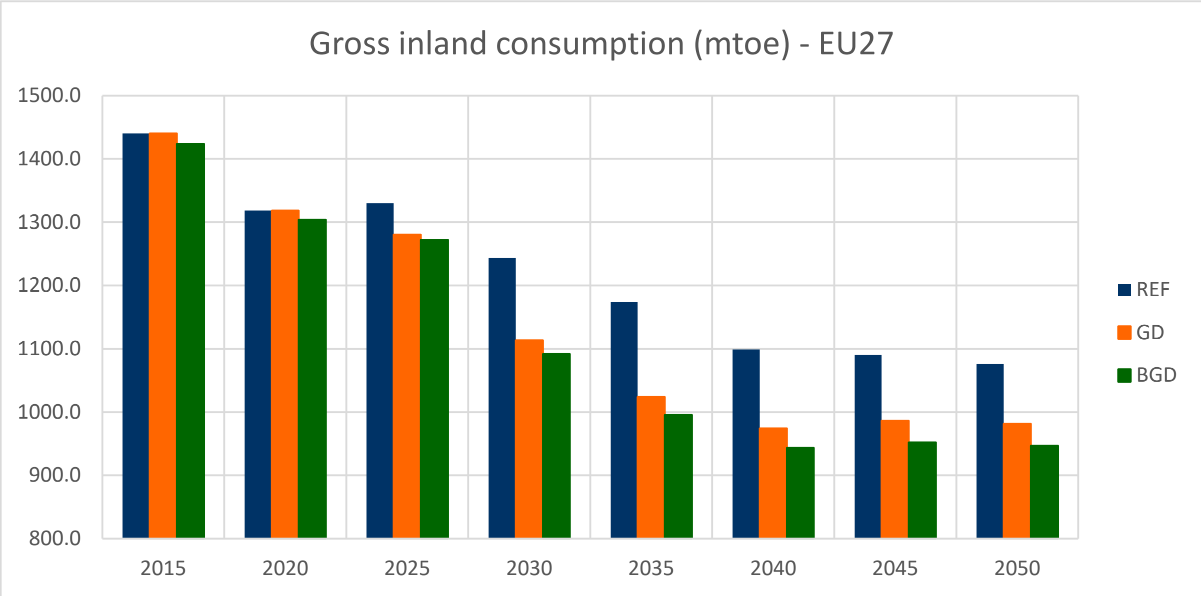


Figure 13. Gross inland consumption in REF, GD and BGD for EU27

The gradual electrification of demand-side sectors, including transport and buildings, drives up demand for electricity despite improvements in energy efficiency, resulting in increased electricity generation for the REF and decarbonization scenarios (Figure 14). The increase is stronger in a decarbonization context (GD and BGD), as ambitious climate policies push the deployment of heat pumps, accelerate the diffusion of electric vehicles in the transport sector and increase the electrification of processes in different industries.

Due to the strong electrification effort, the increase in electricity generation for the GD case is approximately 25% in 2030 and 160% in 2050 with respect to 2020 levels, while the respective changes for the REF scenario are lower at around 11% in 2030 and 32% in 2050. In the BGD, due to the lower energy needs of buildings and transport sectors, induced by behavioral changes impacting useful energy, the increase of power generation compared to 2020 levels is 25% in 2030 and 150% in 2050.

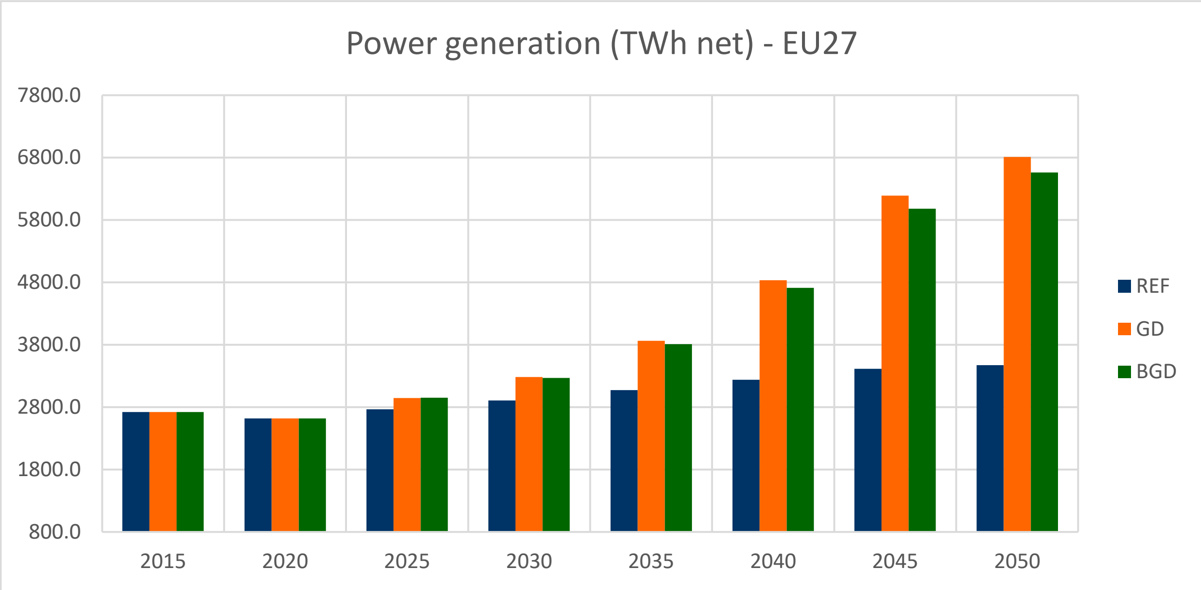


Figure 14. Power generation in REF, GD and BGD for EU27

Last, in Figure 15, we show the investment expenditure of both supply and demand sectors for the REF, GD and BGD. In REF the investment expenditure remains rather stable increasing by 34% in 2030 with respect to 2020 and by 33% in 2050. The GD scenario showcases higher investment needs to achieve the ambitious targets: an increase of 53% in 2030 compared to 2020 and 54% in 2050. The relative increase compared to REF is due to investments both in the supply and demand sectors. When it comes to the BGD, due to the lower useful energy to be satisfied, stemming from behavioral changes in buildings and road transport, the investment expenditure needed to reach the policy targets is 7% lower in 2030 with respect to GD and 9% lower in 2050 with respect to GD.

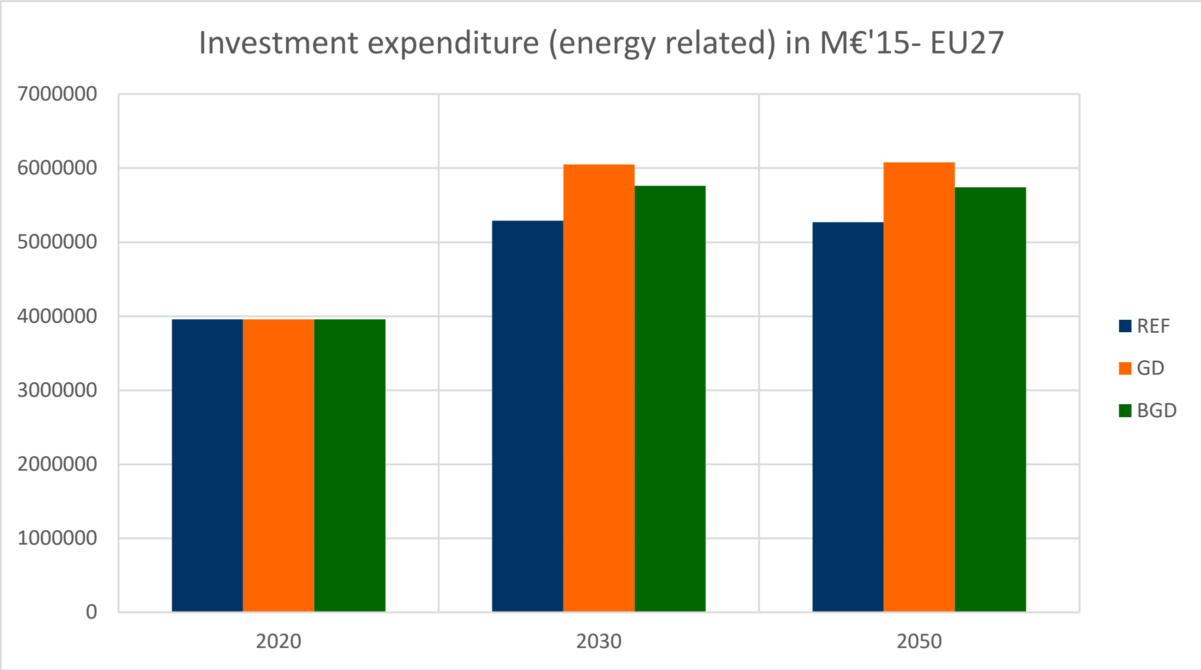


Figure 15. Energy related Investment expenditure in EU27

5.2 Buildings

This subsection presents the results of the three scenarios from PRIMES-BuiMo and explores the additional benefits, in terms of final energy use reduction and CO_2 emissions abatement, gained from shifts in consumer lifestyles at the EU-27 level. The focus here lies with the residential sector and not the commercial one as the former is the sector where behavioral changes in the BGD are applied.

Based on the scenario framework described at the beginning of this report, Figure 16 presents the useful energy demand projections in all three scenarios. The useful energy demand of the BGD is consistently the lowest across the whole period due to behavioral change. To reiterate, changes applied in the sector are focused on lowering the set-point temperature, limiting the floor space, hot water conservation, eco-mode consumption on appliances, standby electricity use (appliances and lighting) and keeping renovation rates at a 2% EU27 average.

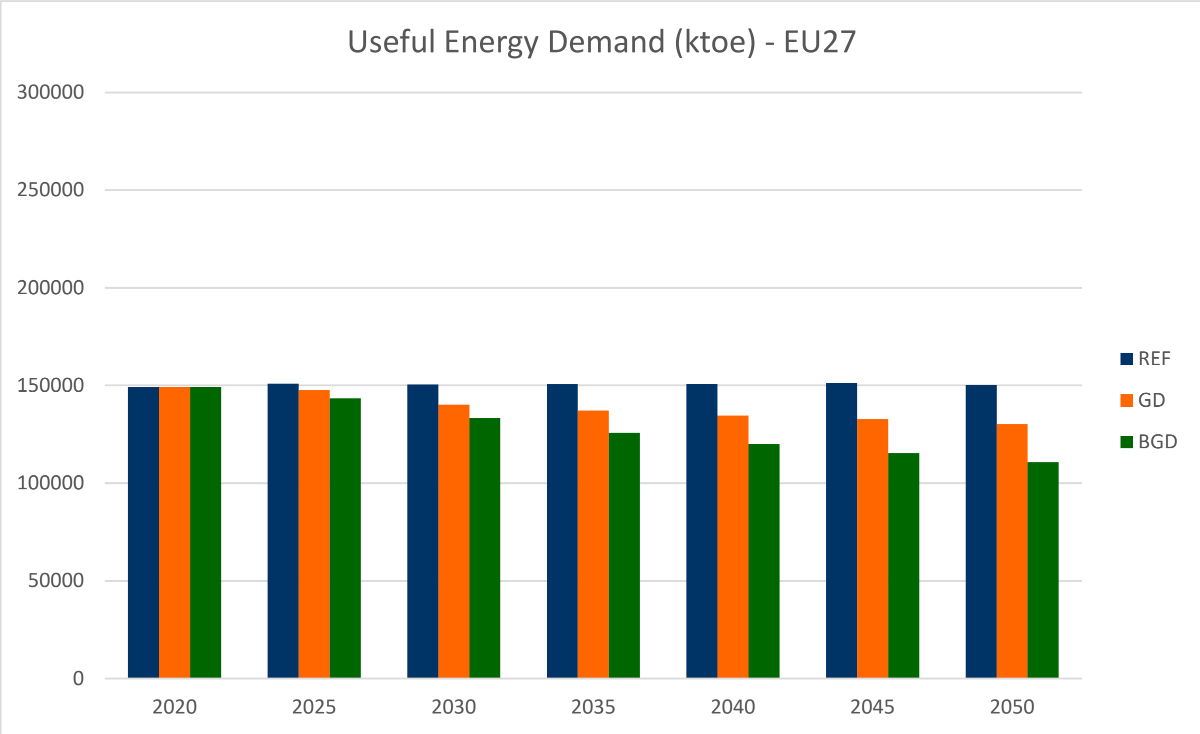


Figure 16. Useful energy demand in residential buildings for EU27

Two of the main drivers for the useful energy demand reduction in the BGD case are the floor space limitation and the increase with respect to GD of the renovation rate after 2030 (Figure 17 and Figure 18).

In the case of thermal comfort uses (space heating and cooling), which currently account for about 75% of the useful energy use in households, the energy demand is determined by the conditioned floor space (that is the area which needs to be heated/ cooled in a building). Figure 17 depicts the projections of floor space for the EU's residential sector, under the REF, GD and BGD.

In REF, PRIMES-BuiMo projects the floor space of EU27's residential buildings sector to moderately increase from 17-18 bn m^2 in 2020 to 20-21 bn m^2 in 2050 (representing a 13-23% increase from 2020 levels driven by increased income levels). The same assumption is maintained for the GD scenario. However, in the BGD, the growth in floor space is less pronounced due to scenario assumptions regarding relocation to smaller households. In terms of square meters per household this means that in the BGD achieves slightly above $90m^2$ in 2030 whereas for REF and GD this is at $97m^2$. In 2050, in the BGD the square meters per household reach $94m^2$ on average while in REF and GD this is set to reach more than $105m^2$.

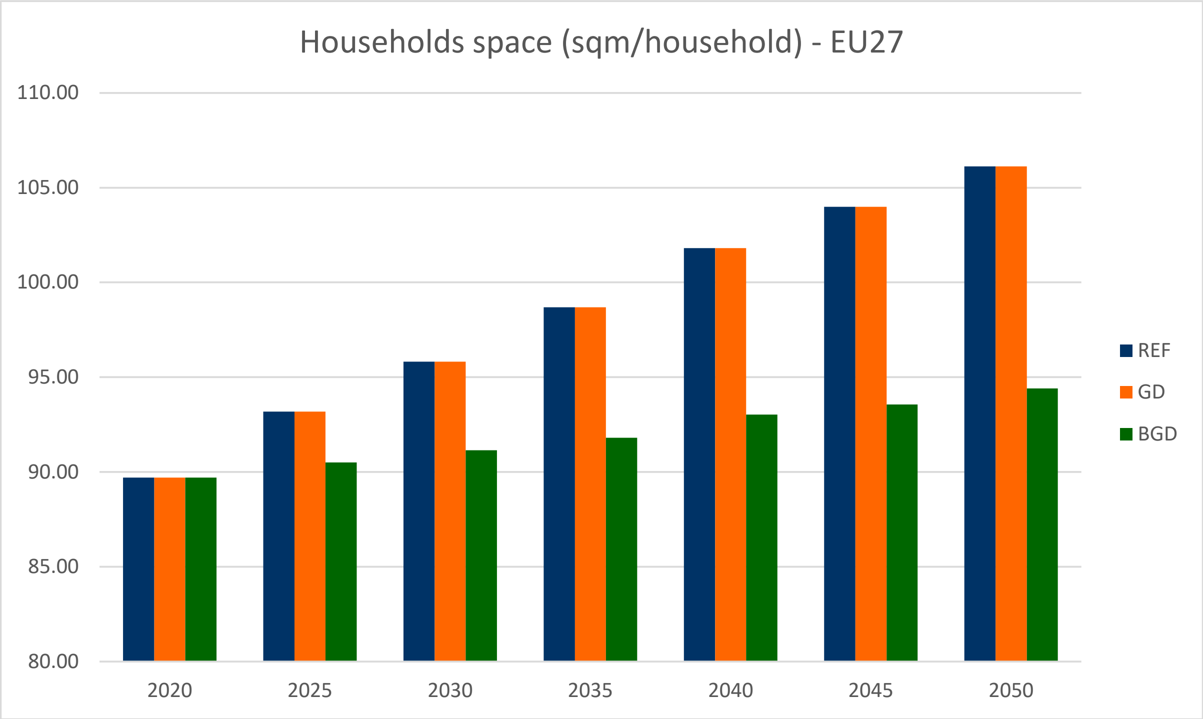


Figure 17. Projections of households' average space for EU27

Figure 18 shows the renovation rate of the residential sector projections in all three scenarios. While in REF the average renovation rate remains around 1% per year throughout the whole projection period, in GD we observe an intense effort until 2030 where the average EU27 renovation rate reaches 2.2% per year and then remains rather constant until 2050 at above 1.5% per year.

In the BGD the renovation rate remains above 2% per year for the whole projection period. However, as a metric, the renovation rate alone cannot explain in detail the changes in final energy consumption and the achievement of savings and CO_2 emissions reduction in the sector as detailed in 6.1.

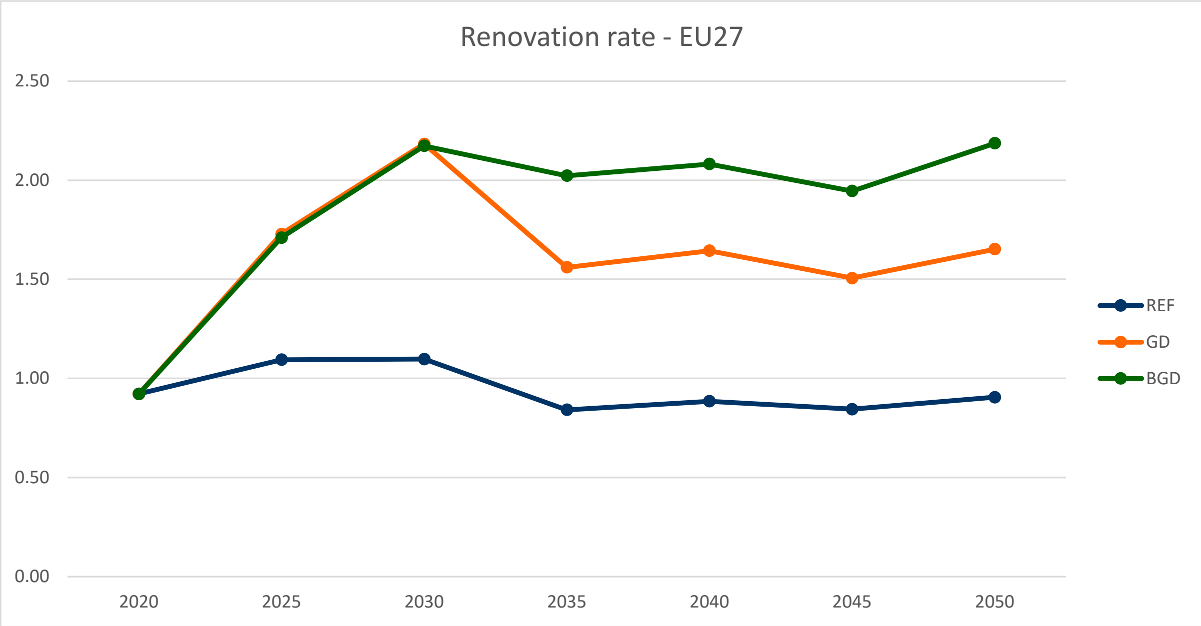


Figure 18. Renovation rate projections for the residential sector in EU27

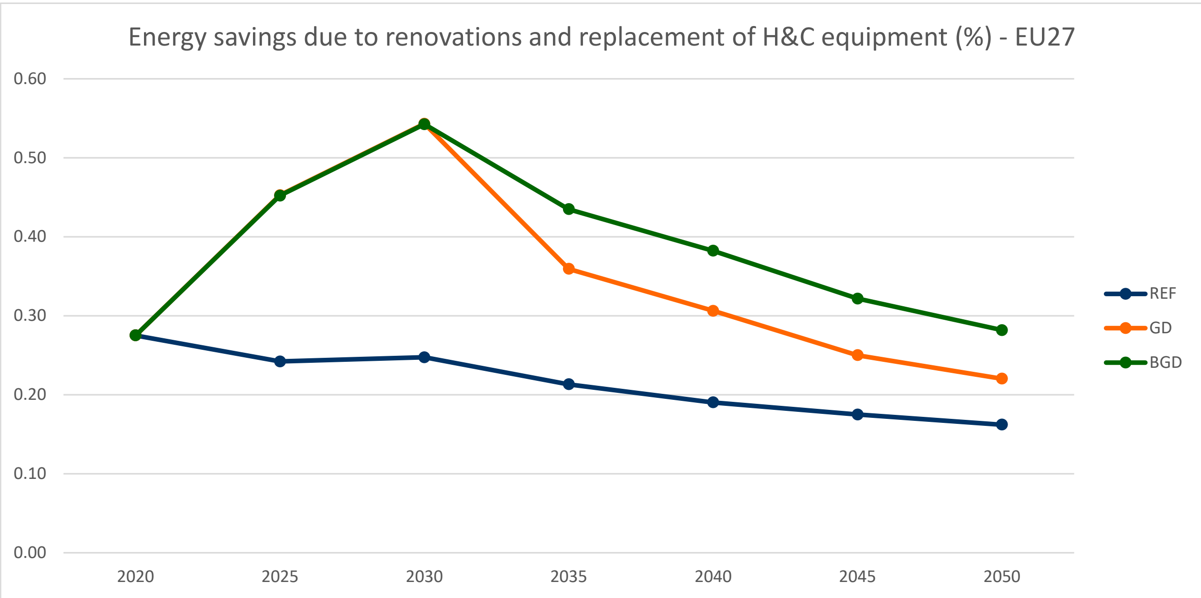


Figure 19. Energy savings due to envelope renovations and replacement of heating and cooling equipment in households in EU27

Apart from increased energy renovation rates in BGD, Figure 19 shows that the energy savings achieved in this scenario also remain higher compared to both GD and REF. This is the result of both behavioral changes and the decarbonization context in which deeper renovations take place and the uptake of heat pumps is more pronounced.

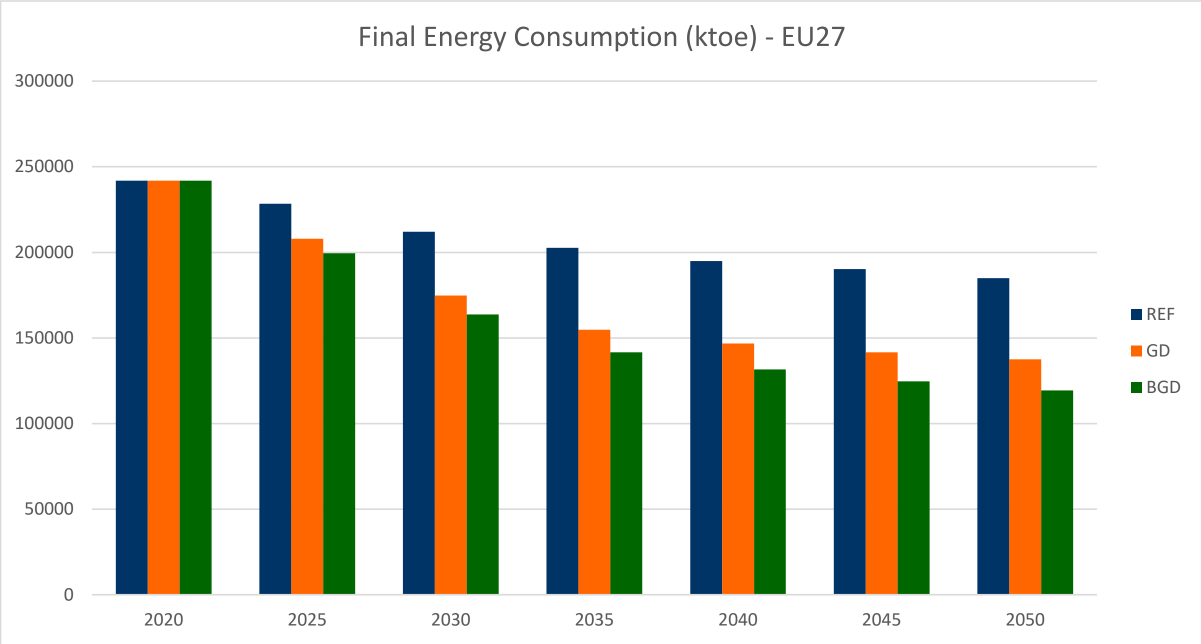
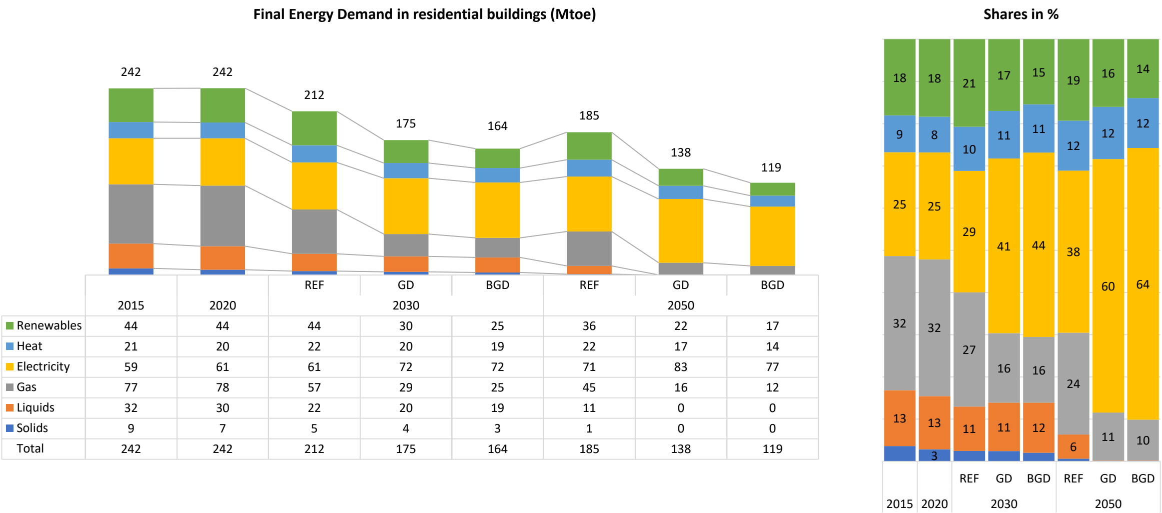


Figure 20. Final energy consumption in the residential sector for EU27

Figure 20 shows the final energy consumption of households in EU27 and Figure 21 is further depicting the fuel mix used to satisfy the useful energy demand shown in Figure 16. What is evident here is that the final energy demand follows the trends of the useful energy demand and the decrease is more evident in the BGD scenario where all behavioral measures are activated. Moreover, we see that the electrification of heat is 3% higher in 2030 in BGD compared to GD and 4% higher in 2050 compared to GD, respectively.



	2015	2020	2030 REF	2030 GD	2030 BGD	2050 REF	2050 GD	2050 BGD
Renewables	44	44	44	30	25	36	22	17
Heat	21	20	22	20	19	22	17	14
Electricity	59	61	61	72	72	71	83	77
Gas	77	78	57	29	25	45	16	12
Liquids	32	30	22	20	19	11	0	0
Solids	9	7	5	4	3	1	0	0
Total	242	242	212	175	164	185	138	119

Figure 21. Fuel mix in final energy consumption in households for EU27

5.3 Transport

Figure 22 shows projections of passenger transport activity in the EU27 in the period 2015-2050 for the three main scenarios. In all scenarios, passenger transport activity recovers fully after the notable reduction in 2020, owing to the COVID-19 pandemic. Activity grows constantly between 2030 and 2050 at an annual rate of 0.4%-0.6%, depending on the scenario. In the short-term to 2030, passenger transport activity in GD and BGD is lower than REF by about 1.5% and 3.5%, respectively. On the one hand, between the REF, GD and BGD there is somewhat lower activity owing to higher short-term decarbonization costs (e.g. higher purchasing costs of electric vehicles, higher price of flight tickets owing to ETS and fuel price). In the GD, activity is higher than the REF in 2050, mainly due to additional uptake of public transport modes enabled by infrastructure and policies that promote modal shifts. In BGD the reduction of passenger transport activity compared to the GD reaches almost 6.5% in 2050, induced by behavioral changes.

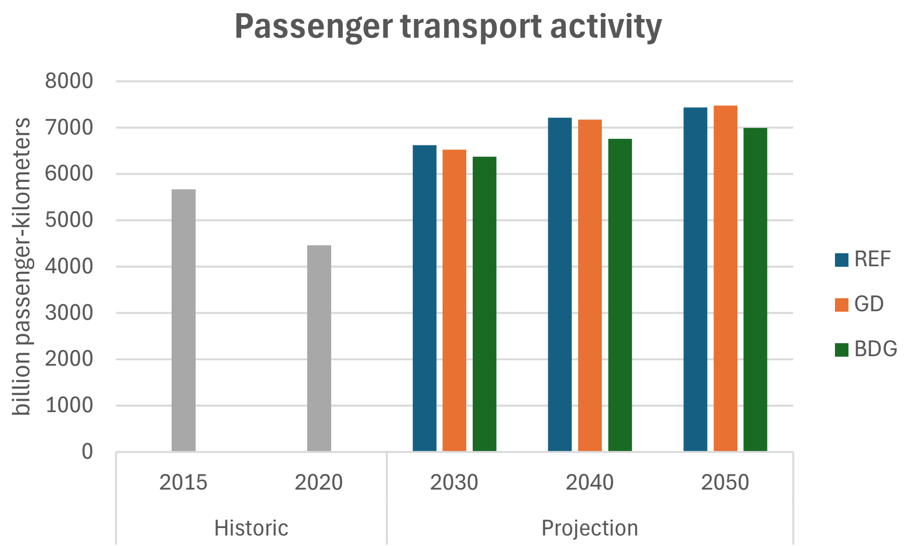


Figure 22. Passenger transport activity in the EU27 in 2015-2050. Note: Excluding international (extra-EU) aviation. Source: PRIMES-TREMOVE transport model

Similar observations can be made when looking into projections for freight transport activity but of lower intensity (Figure 23). Particularly the difference between the BGD and GD in 2050 reaches 3.5% and is lower in the BGD primarily due to a reduction in road freight transport activity by trucks and vans owing to implicit scenario assumptions on the local production of goods.

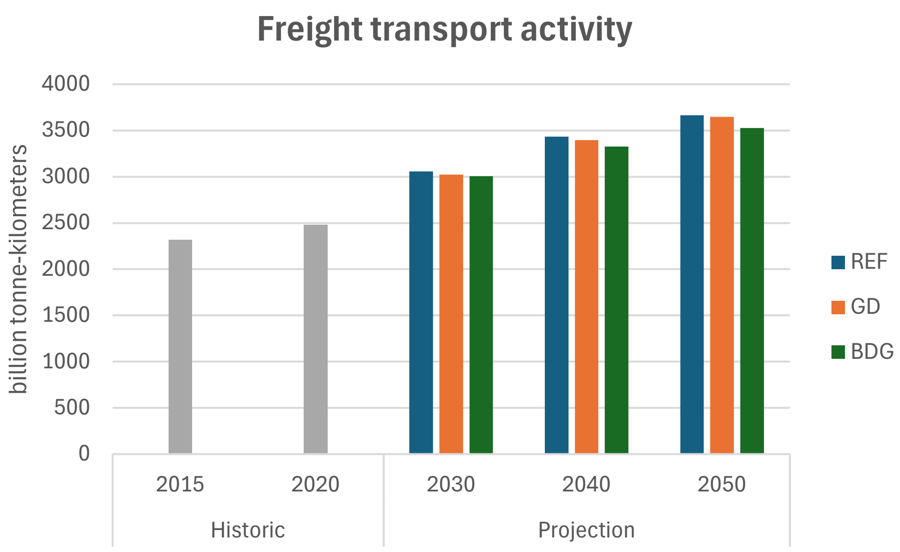


Figure 23. Freight transport activity in the EU27 in 2015-2050. Note: Excluding international maritime. Source: PRIMES-TREMOVE transport model

Due to the reduction in passenger transport activity by cars and vans as a result of modal shifts towards public transport, active modes and reduction in motorized mobility due to lifestyle changes, the modal share of passenger cars is reduced. It reduces to 71% in the REF to 70% in the GD and 69% in the BGD in 2030, and from 68% in the REF, to 67% in the GD and 64% in the BGD in 2050, with a subsequent increase of public road transport modes and rail (Figure 24). Road transport—and particularly passenger cars— take the majority share of passenger transport activity across scenarios and years.

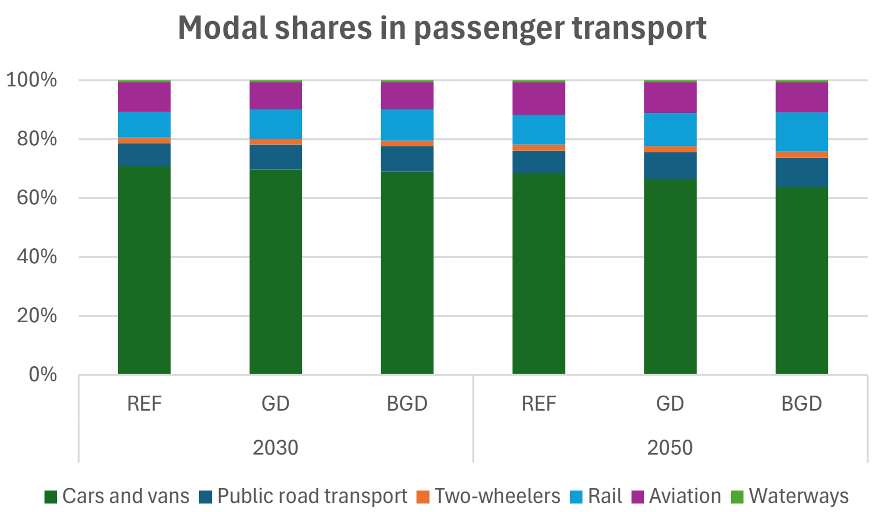


Figure 24. Modal shares in passenger transport in the EU27 in 2015-2050. Source: PRIMES-TREMOVE transport model

Examining the regional split of passenger road transport activity and projections for 2030 and 2050 (Figure 25), road transport activity in urban regions accounts for about 23% to 26% in 2030 and 17% to 26% in 2050, depending on the scenario. The shift to active modes corresponds only to trips below 7 km and is thus only a fraction of urban road transport activity. The reduction of the share of urban activity in total road transport activity in the BGD compared to the GD and the REF in 2050 is an outcome of the assumptions on additional behavioral changes reducing motorized travel in urban areas. In addition, there is a rebound effect of inter-urban activity increase, affected primarily by shared mobility and shift to public transport modes for inter-urban travel e.g. by coaches and high-speed rail, as a reduction of activity in urban areas makes a higher travel budget for other trip types available (e.g. longer distance trips).

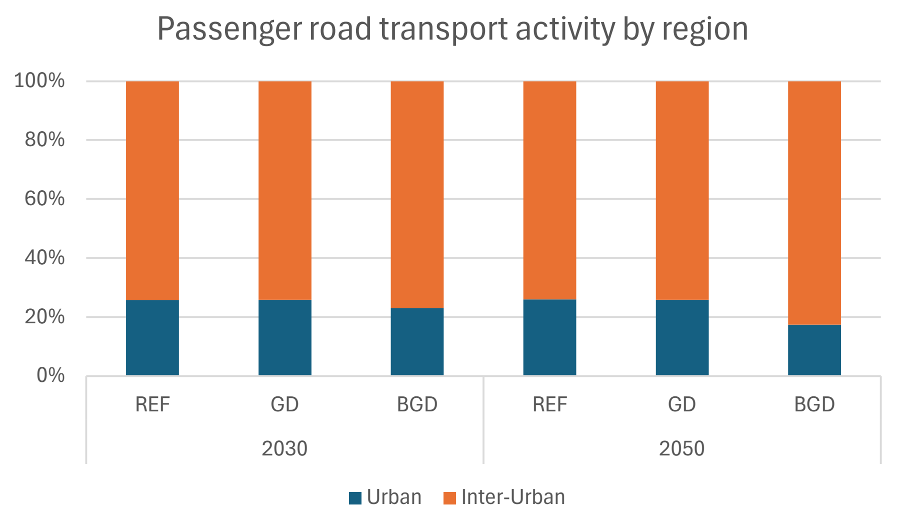


Figure 25. Regional split of passenger road transport activity in the EU27 in 2030 and 2050. Source: PRIMES-TREMOVE transport model

Figure 26 shows that passenger cars in urban areas are the main transport mode. They account for about 81-85% of motorized urban mobility in 2030 and between 69% to 84% of motorized urban mobility in 2050. In 2050, from about 1,170 Gpkm in the REF, passenger transport activity by cars in urban areas reduces to 1,140 Gpkm in the GD and to 590 Gpkm in the BGD.

In order to estimate the kilometers per day per passenger that could shift from passenger cars to active modes in the BGD scenario compared to the GD scenario, results of the scenario projections from PRIMES-TREMOVE are combined with data stemming from the analysis of ISGlobal on the DG MOVE's survey data (European Commission: Directorate-General for Mobility and Transport et al., 2022).

Specifically, the total projected reduction of about 550 Gpkm in the BGD compared to the GD corresponds to a total of 352 Gvkm, taking into account the occupancy factor of vehicles by country. On average, this translates to a reduction of travel by cars in BGD compared to GD of about 2.3 km/passenger/day in 2050. Note that the range is wide depending on the country (from 0.2 to 6 km/passenger/day). In 2020-2021, depending on the country, between 8% to 16% of kilometers driven by passenger cars were for trips less than 3 km and between 8% to 20% of kilometers driven by passenger cars were for trips between 3 and 7 km. These are the trips that could be replaced by active modes (i.e. walking for trips less than 3 km and cycling for trips between 3 km and 7 km).

Assuming that the same distance trip distribution applies in 2050, the additional reduction in the BGD compared to the GD that can be assigned to trips of less than 7 km that shift to active modes is about 0.5 km/passenger/day (range between countries 0.04 km/passenger/day to 1.5 km/passenger/day). The remainder is attributed to trips higher than 7 km, shift to public transport or activity loss.

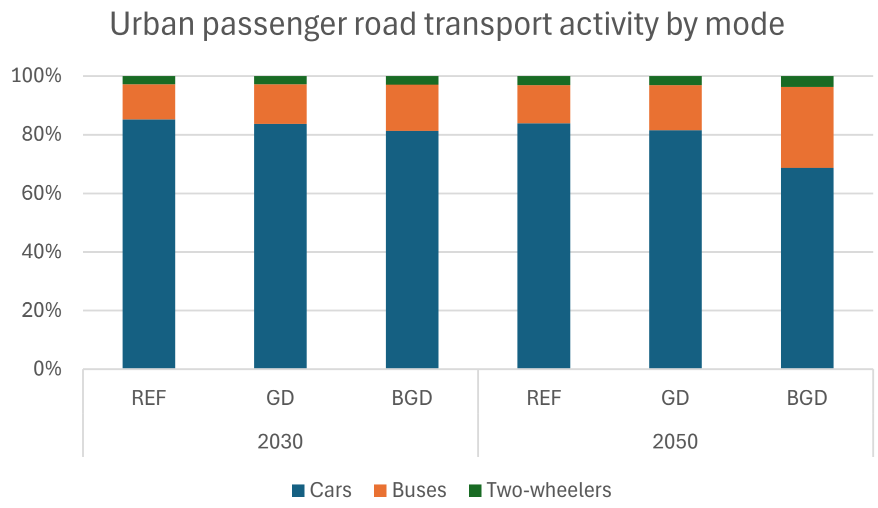


Figure 26. Modal split of passenger road transport activity in urban areas in the EU27 in 2030 and 2050. Note: Motorized travel only, i.e. excluding active modes. Source: PRIMES-TREMOVE transport model

Figure 27 presents the projection of final energy demand in transport in the three scenarios for the EU27 in the period 2015 to 2050. The reduction of energy demand in 2020 is due to the reduction of passenger transport activity. Energy demand reduces over time across all scenarios, driven by the penetration of more efficient transport technologies (e.g. efficient internal combustion engines, electric vehicles), and the shift to a more efficient transport system (e.g. modal shift to public transport modes). Steered by the Green Deal policies, the GD and BGD scenarios lead to notably lower energy demand compared to the REF: by 6% and 9% in 2030, respectively, and by 38% and 42% in 2050.

The reduction in final energy demand in transport is primarily due to the electrification of the transport system to the extent possible (i.e. increase of electric vehicles in the passenger car fleet, following the ICE ban after 2035) the increase of zero-emission vehicle technologies in the road freight transport segment (including fuel-cell trucks), and to some extent due to the use of more efficient public transport systems). In 2050, the energy demand in the BGD is about 6.5% lower than in the GD owing to the shift to active modes, higher vehicle occupancy and lifestyle changes (reduction of air travel, reduction of transport demand, and freight transport), without, however, any impact on the fuel mix, as both scenarios have a similar mix in 2030 and 2050 (Figure 28).

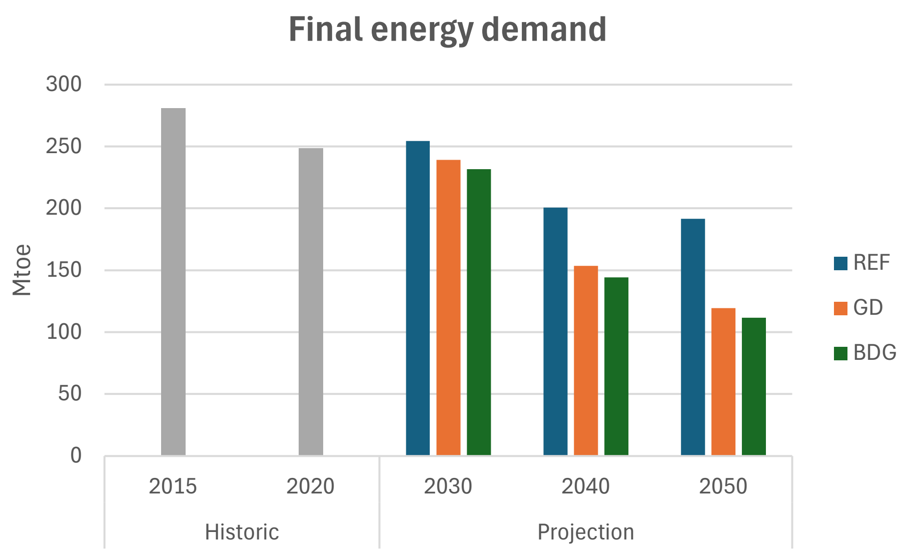


Figure 27. Final energy demand in transport in the EU27 in 2015-2050. Note: excluding extra-EU aviation, international maritime and other transport (not specified, pipelines, etc.). Source: PRIMES-TREMOVE transport model

In the REF by 2050, a substantial share of fossil fuels remains in transport as ICEs are projected to remain in circulation, using only a small share of biofuels in the fuel blend (Figure 28). Electricity in the REF makes up less than 20% of final energy demand. In contrast, electricity makes up almost 50% of the energy consumed in transport in the GD and the BGD. Besides biofuels, e-fuels are also used in road transport and in aviation and maritime due to the sectoral policies targeting the decarbonization of the sectoral fuel mix (i.e. FuelEU Maritime and REFUEL Aviation). The resultant emissions are presented in Section 6.

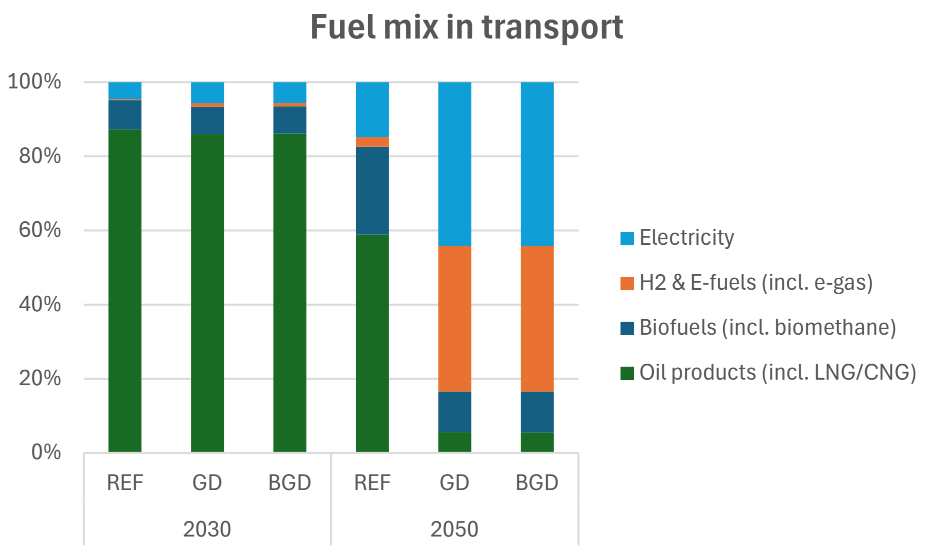


Figure 28. Final energy demand by fuel type in transport in the EU27 in 2015-2050. Source: PRIMES-TREMOVE transport model

5.4 Agriculture and diets

The food sector scenarios include several elements that affect both the supply- and demand side of food markets. The Farm to Fork measures as well as the increasing carbon value (see Section 3) tend to reduce supply for various reasons: Input use (fertilizers, pesticides) is reduced, and agricultural area is diverted to support biodiversity goals. At the same time the diet shift would reduce demand for animal products (in particular red meat), and indirectly also feed demand.

The shares of these two components differ. In the GD, the supply side measures dominate, and behavioral change is moderate. In the BGD, meanwhile, behavioral change dominates, and the further achievement and additional supply side mitigation is only supplementing. The simulated developments of agricultural drivers of emission changes for each respective variable are displayed in the line charts that follow.

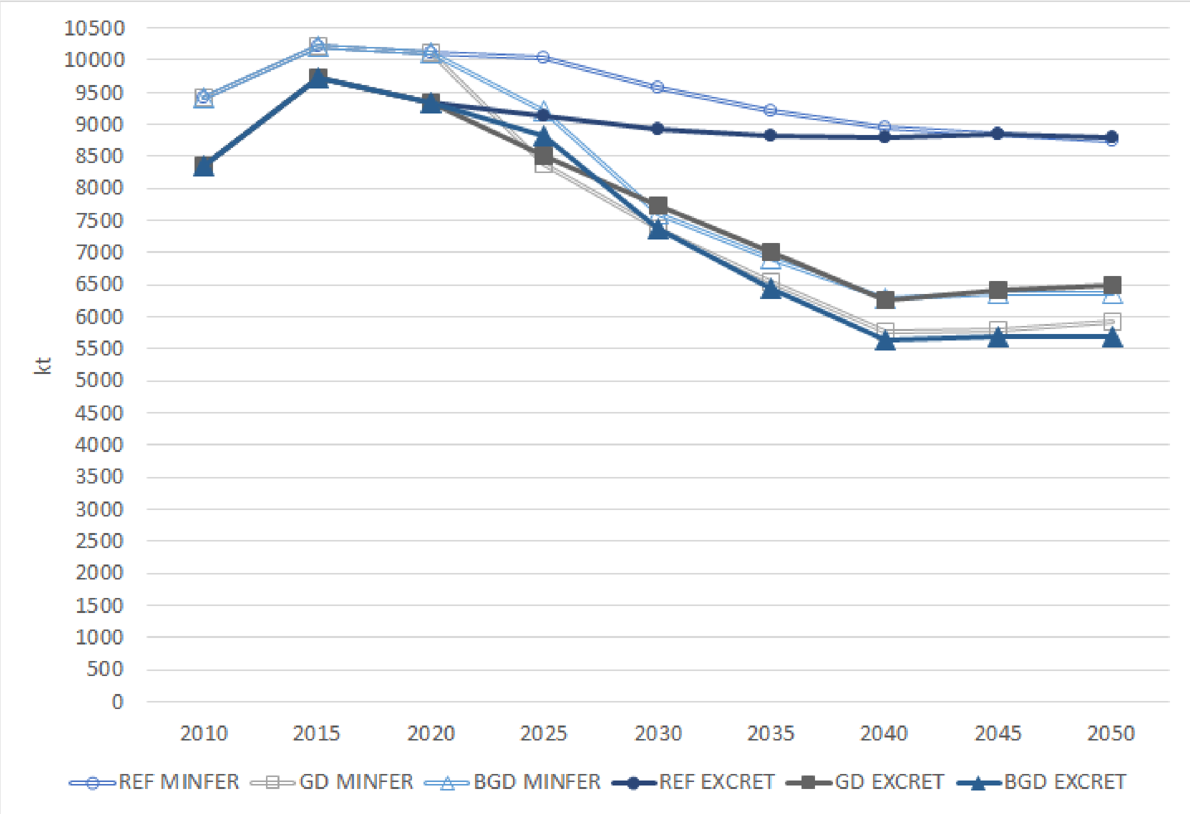


Figure 29. Nitrogen input from mineral fertilizer (MINFER) and manure from excretions (EXCRET) in EU27 [kt]

Figure 29 presents the two major sources of nitrogen, mineral fertilizer (light tone) and manure input from excretions (dark tone). Under REF we would expect a modest decline in mineral fertilizer use ("MINFER") and barely declining manure input ("EXCRET"). This would change drastically both under the GD and the BGD scenarios. However, while mineral fertilizer would show the stronger decline under the GD (light grey line), under the BGD it is the manure input that is declining the strongest (dark blue line). Key differences are higher carbon prices and stronger behavioral shifts away from meat and dairy consumption under the BGD, both contributing to a stronger decline (about 40%) than for mineral fertilizer (about 35%). Under the GD, the animal sector would be less affected such that a larger share of the required surplus reduction would be achieved through a cut in mineral fertilizer applications. Figure 30 and Figure 31 show the impacts on beef and poultry markets.

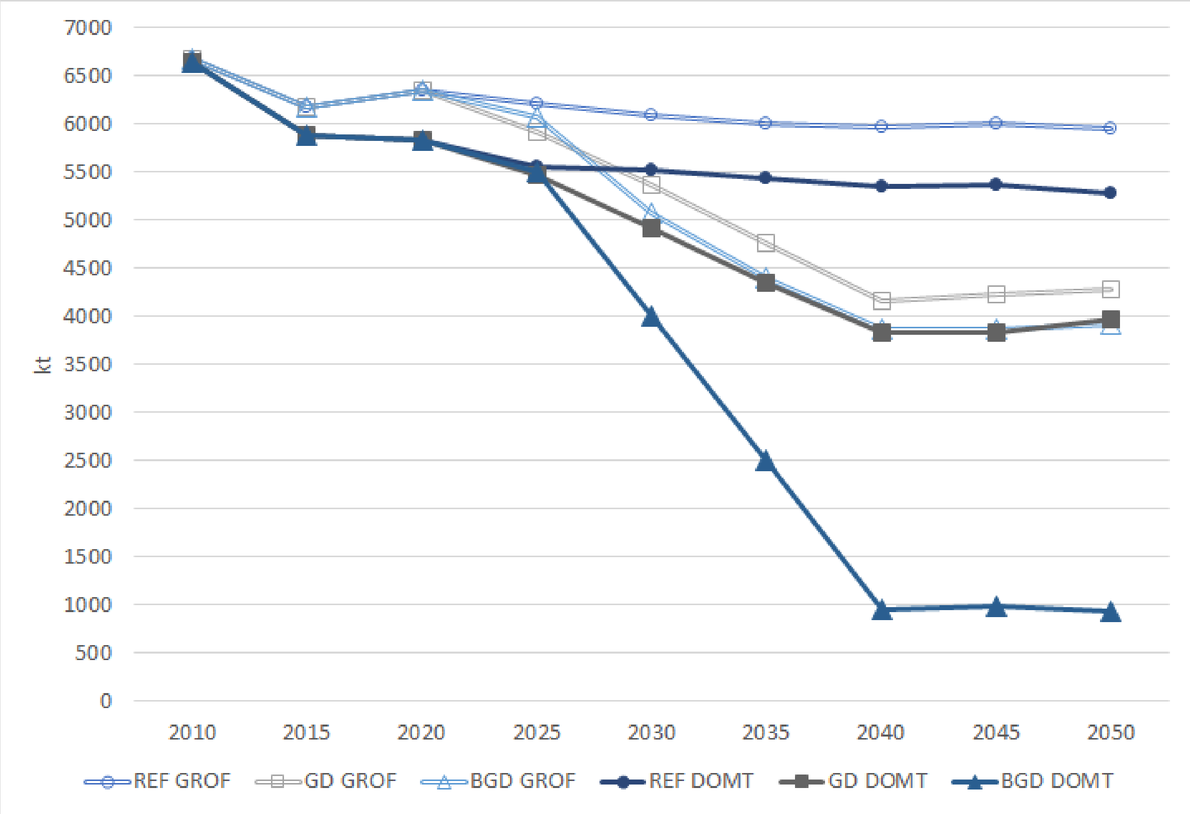


Figure 30. Gross production (GROF) and total domestic use (DOMT) for beef in EU27 [kt]

Under the REF a moderate decline both in supply ("GROF" = gross production on farms) and total domestic use ("DOMT") may be expected that leaves net exports almost constant at about 600 kt of beef from 2020 to 2050. This changes drastically under the GD and even more under the BGD. Meat supply ("GROF") declines stronger than demand ("DOMT") under the GD scenario by 2050 by about 40% as supply side drivers (nutrient surplus, carbon price) have stronger impacts than the diet shifts and waste reductions. Hence EU net exports of beef would decline, though slightly. This ranking is reversed under the BGD where strongly declining demand (more than 80% cut) would dominate the supply reduction and hence contribute to markedly higher EU net exports.

This picture is similar regarding the impacts on poultry markets shown in the next figure, but with some differences. First, there would be some expansion rather than a modest decline under the REF development. Furthermore, the impacts on poultry demand and supply are again strongest under the BGD, but these are evidently weaker than for beef as both the carbon price as well as the diet shifts would operate more moderately on poultry markets.

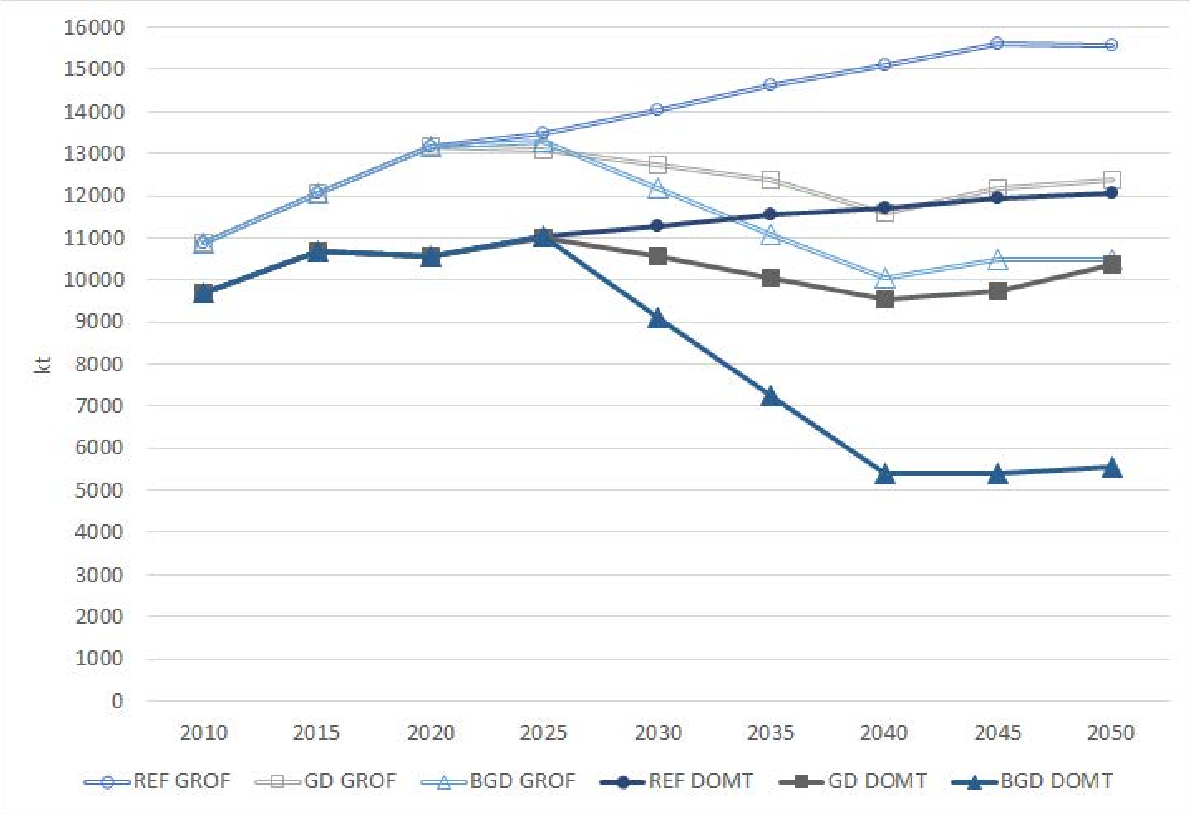


Figure 31. Gross production (GROF) and total domestic use (DOMT) for poultry meat in EU27 [kt]

The changes in supply also imply strong impacts on animal herds. Figure 32 displays pigs and cattle herds, as poultry herds are affected less strongly. In the graphical display of the developments the drop in aggregate pigs herd (“AgPigs”) under the BGD against the REF (-40%) catches attention, but the decline in the other cattle herd (“AgoCatt”) is of the same magnitude. Only the dairy herd (“DCOW”) is affected more moderately because this sector is rather profitable and hence not immediately abandoned with increasing carbon prices. Furthermore, EU dairies are quite export oriented and hence less dependent on EU demand than meats.

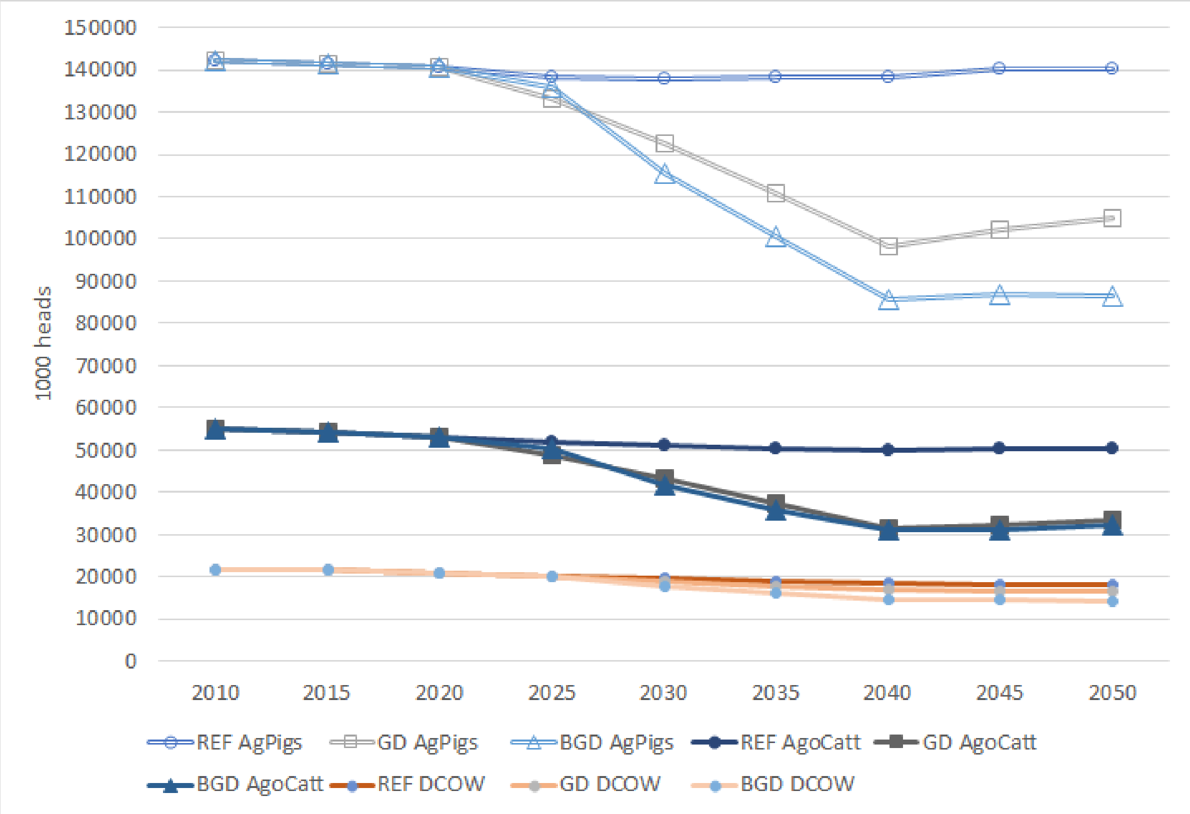


Figure 32. Pigs (AgPigs), dairy cows (DCOW) and other cattle (AgoCatt) herds in EU27 [1000 heads]

Selected cereal areas (“LEVL”) and yields (“YILD”) as a relevant model output also links both to the scenario specification as well as to the emission drivers. These are shown in Figure 33. Cereal yields may be observed to be declining markedly both under the GD and under the BGD scenarios. This decline is mostly driven by supply side changes such as the nutrient surplus constraint, declining yields from higher organic shares, and carbon price effects. Total cereal area is already declining in the REF and this decline is reinforced by increasing demand for new energy crops, the need to reduce productive land in favor of unproductive landscape elements and reduced feed demand. A smaller total cereal area then also contributes to savings in mineral fertilizer use, just like the constraint on the surplus per hectare. This translates into variegated emissions pathways, as detailed in Section 6.

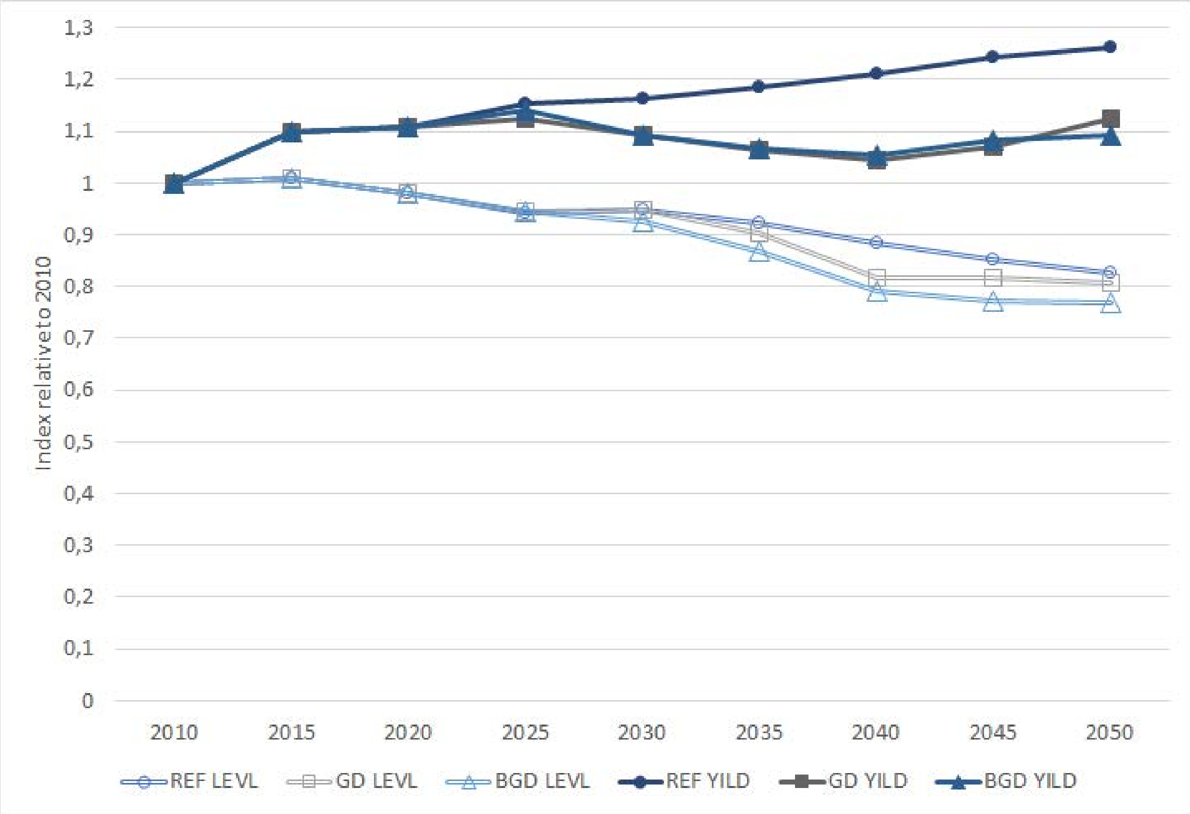


Figure 33. Cereal area (LEVL) and yields (YILD) in EU27 [index relative to 2010]

6. Emission trends

6.1 CO_2 emissions

One main indicator and outcome of the scenarios are total CO_2 emissions pathways. These comprise energy-related demand-side (Residential and Commercial sector, Transportation, Industry and Bunkers) and energy supply-side emissions, as well as emissions produced through industrial processes, but they exclude emissions from Agriculture, Forestry and Other Land Use (AFOLU) sectors.

Based on projections made with PRIMES presented in Figure 34 below, total EU27 CO_2 emissions are projected to decrease by 14% in 2030 and 53% in 2050 relative to 2020 under the REF scenario. In the GD case more substantial reductions are achieved as emissions fall by 32% in 2030 and 91% in 2050. In the BGD the reduction is very close to the GD case, 33% in 2030 and 91% in 2050, despite the differences in final energy consumption, as shown in Figure 12. Although the effect of behavioral changes is large on energy demand reduction, in a decarbonization environment the effect on CO_2 emissions is limited. Instead, the key driver of total CO_2 emission reductions in both 2030 and 2050 are decarbonization policies resulting in improvements in energy efficiency and increased uptake of renewable energy in both supply and demand sectors.

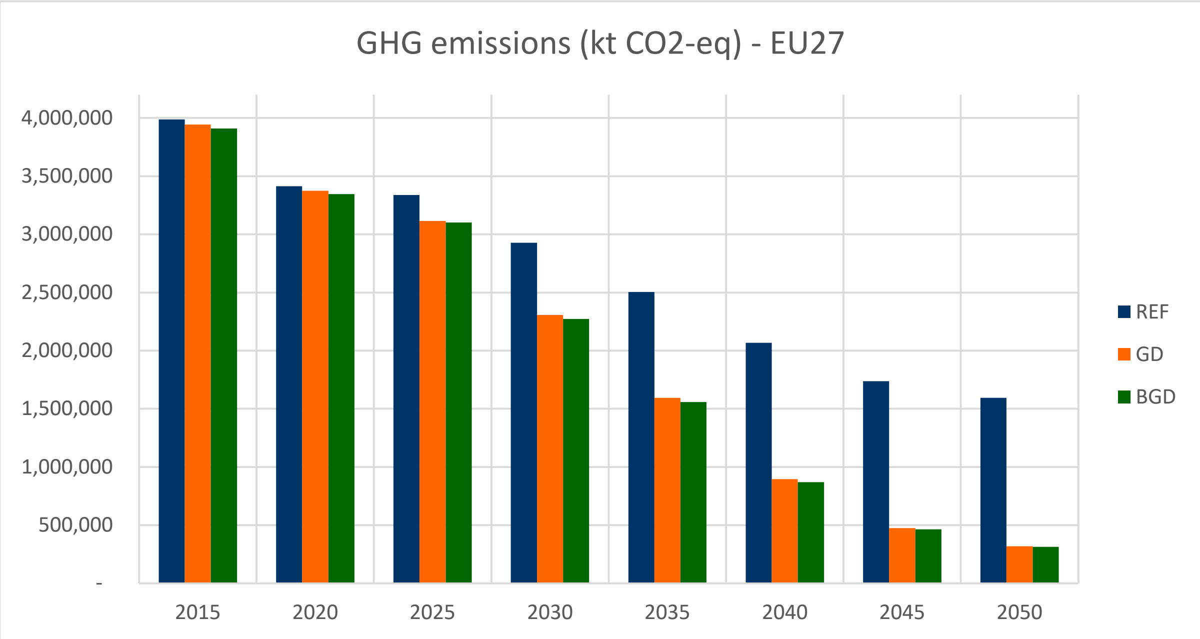


Figure 34. Total CO_2 emissions in REF, GD and BGD for the EU27[23]

[23] CO_2 emissions attributed to the construction of equipment and infrastructure (within the EU's territory) to support the low-carbon transition (e.g., renewable technologies, electrolyzers for hydrogen production, recharging stations for electric vehicles) are implicitly accounted in the PRIMES industrial module, which integrates the future supply of different materials.

The effect of these policies is particularly clear in the transport sector. Figure 35 shows the projections of CO_2 emissions in transport in the EU27 in 2015-2050, in the three scenarios. Increase in electrification and the penetration of clean fuels in the fuel mix shown above (Figure 28) lead to a drastically different trajectory between REF and the two decarbonization scenarios in terms of emissions (Figure 35). The reduction in emissions is already noticeable in 2030, where GD and BGD lead to 7% and 10% less emissions than REF. In 2050, CO_2 emissions in REF reach almost 340 $MtCO_2$, while in GD and BGD they are below 20 $MtCO_2$. Factors leading to the emissions reduction in GD and BGD are zero-emissions vehicle technologies and the penetration of clean fuel in the fuel mix (biofuels and e-fuels). Residual fossil fuels are responsible for the residual emissions as they remain in some segments and primarily aviation (Figure 36).

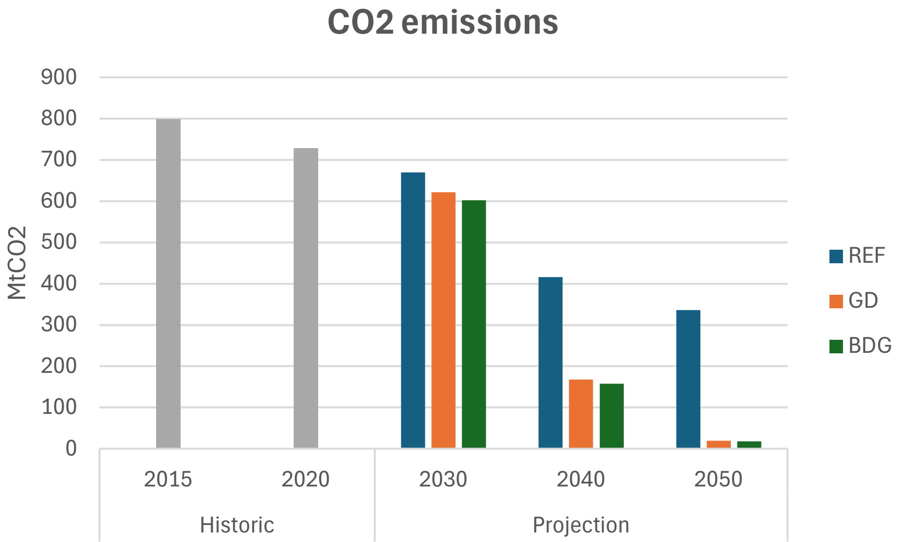


Figure 35. CO_2 emissions in transport in the EU27 in 2015-2050. Note: excluding extra-EU aviation, international maritime and other transport (not specified, pipelines, etc.). Source: PRIMES-TREMOVE transport model.

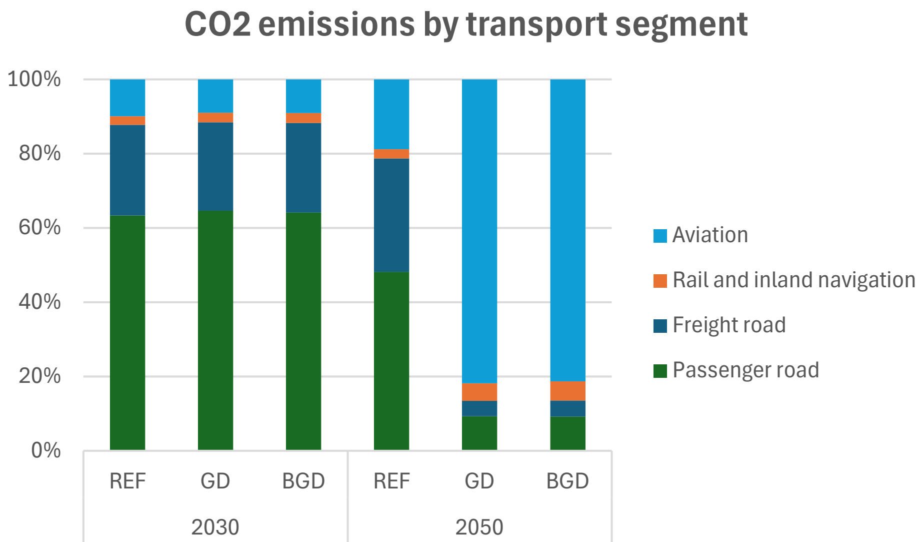


Figure 36 CO_2 emissions by transport segment. Source: PRIMES-TREMOVE transport model

As noted above, activity levels in BGD are lower than those of GD by 6.5% in 2050. However, this does not lead to an overall different trajectory in absolute terms, as in GD the transport system is largely directed towards more efficient transport modes and technologies and the fuel mix is largely decarbonized.

6.2 Air pollutant emissions

Beyond CO_2, the scenarios also differ in their air pollutant emissions. The three main scenarios—REF, GD and BGD—assume CLE conditions for air pollution controls which means that any differences between scenarios are exclusively driven by activity changes. The air pollution-specific scenario variant BGD90, meanwhile, introduces stricter emission controls for all precursors of $PM_{2.5}$. This demonstrates the remaining air pollution reduction potential that can be achieved through technical means.

Application rates of emission control technologies in all sectors for REF, GD and BGD represent the best knowledge of EU legislation and practice in each EU Member State as available to the GAINS modelling team. They have been reviewed and updated from the Third EU Clean Air Outlook (Klimont et al., 2022) and include the latest information from consultations with all Member States which took place in spring 2024 for the preparation of the Fourth Clean Air Outlook (Directorate-General for Environment (European Commission) et al., 2025). BGD90 enacts application rates of emission control technologies that are technically feasible yet exceed current policy frameworks and what is assumed in the previous scenarios, while still avoiding the costliest (and therefore least cost-effective) measures.

Emissions of $PM_{2.5}$ for the EU27 are shown in Figure 37. The main scenarios demonstrate a stepwise reduction between 2020 and 2050. Between 2020 to 2030, REF emissions decrease by approximately 34%, GD by 40% and BGD by 42%. In 2030, total $PM_{2.5}$ emissions in the GD scenario are approximately 8% lower than in the REF while BGD is about 12% lower. This relative difference is maintained in 2050, where scenarios converge towards similar overall reductions by 2050 compared to 2020: 61% (REF), 63% (GD), and 65% (BGD).

Combustion in the residential sector drives the majority of these emission reductions. Residential emissions decline by circa 47% between 2020-2030 in the REF, 53% in the GD, and 56% in the BGD. It remains the largest contributor in 2030 at 52% of REF total emissions decreasing from 64% in 2020, 50% of the GD, and 48% of the BGD. By 2050, this share falls to about 30% for REF, 27% for GD, and 25% for BGD. The proportional reduction in residential combustion remains largely consistent across all main scenarios. This suggests that residential combustion follows a similar trajectory regardless of overall policy stringency, indicating that these reductions are largely driven by factors beyond the specific policy measures that differentiate the scenarios.

BGD90 reveals significant remaining abatement potential for $PM_{2.5}$ across multiple sectors. In the residential combustion sector, BGD90 emissions are 25% lower than the BGD in 2030, a gap that increases to about 42% in 2050. These reductions are achieved through additional switches to cleaner heating and cooking technologies such as pellet stoves and boilers. Similarly, the BGD90 demonstrates mitigation potential for large industrial sources, with emissions lower than BGD across all years. A key technology for this sector is high-efficiency de-dusters.

Agricultural waste burning presents another area for additional abatement. While the main scenarios show largely similar emissions from this source, BGD90 achieves 63% lower emissions than BGD in 2030, a relative difference that stabilizes around approximately 76% in subsequent years. Although this sector's contribution is small in absolute terms, these reductions are easily achieved through bans on open field burning.

Other sectors show smaller variation between scenarios and over time, indicating limited scope for further $PM_{2.5}$ emission reductions at the EU27 level beyond the measures already captured in the main scenarios.

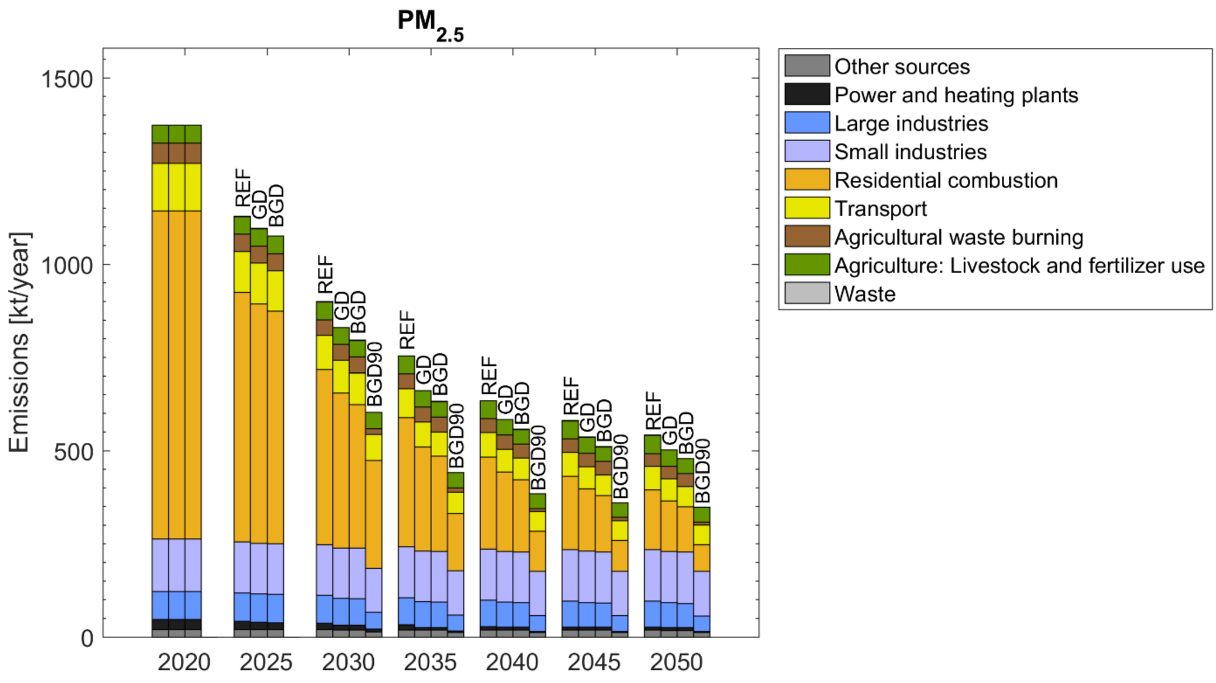


Figure 37. Emissions of primary $PM_{2.5}$ in the European Union as calculated in GAINS for the four scenarios

In some countries, the GD scenario accelerates transitions which would happen later in the REF scenario. Poland, displayed in Figure 38, is such a case. The transition to clean fuels for heating happens faster in the GD scenario. Between 2030 and 2035, total emissions in the GD fall from 123 kt to 63 kt, and BGD from 112 kt to 61 kt; 89% of this reduction is delivered by residential combustion in GD and 87% in BGD. This means that by 2035 both the GD and BGD scenarios see only about half the emissions from residential combustion compared to the REF. In later years this difference diminishes as REF catches up with the earlier transitions achieved under the GD and BGD. For example, already by 2040 GD achieving 7% lower total emissions than REF and BGD achieving 8% lower emissions than REF. BGD90 demonstrates that substantial further reductions are possible regardless of the speed of transition. Though, like the EU27, Poland's scenarios ultimately converge, the Polish case illustrates the variable speeds at which the GD delivers emissions reductions on a country level.

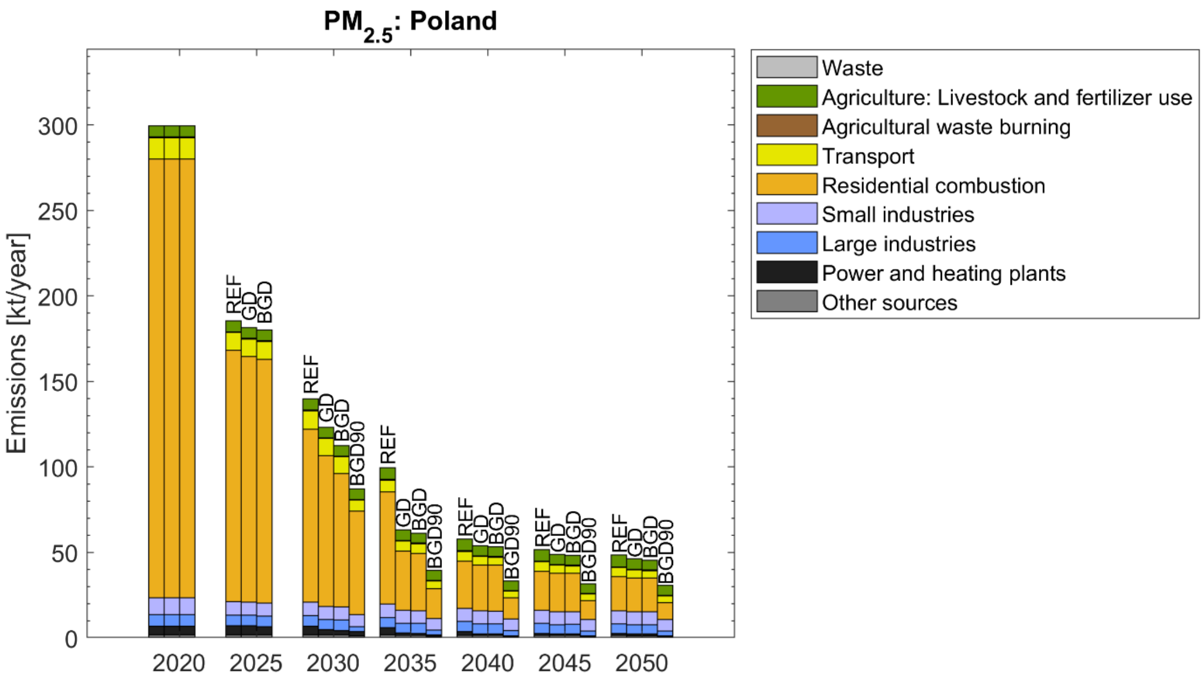


Figure 38. Emissions of primary $PM_{2.5}$ in Poland as calculated in GAINS for the four scenarios

Figure 39 reveals a continued decrease also in SO_2 emissions in the main scenarios. These scenarios deliver an emissions reduction between 2020 and 2050 of 58% (REF), 65% (GD) and 67% (BGD). Emissions in 2025 show a stepped reduction from the REF to GD to BGD, with each scenario achieving progressively lower levels. From 2030 onwards, GD and BGD reductions converge toward more similar emission levels. For example, absolute SO_2 emissions in 2035 are 575 kt for GD and 571 kt for BGD. This convergence continues through 2050, where GD emissions are 17% lower than REF and BGD achieves 20% lower—a difference of only 3 percentage points. This reduction is mainly driven by the power sector's transition away from coal, combined with increased application of best available emission control technologies. As power sector emissions decline, industrial process emissions become the dominant category since they are not expected to change significantly under the main scenarios.

However, BGD90 reveals that substantial mitigation potential remains in industrial sectors. BGD90 reduces total SO_2 emissions by about 40% in 2030, 48% in 2040, and 49% in 2050 compared to the BGD. These reductions are largely achieved through increased controls on large industries. Control options for this sector include flue gas desulfurization, and improved process controls.

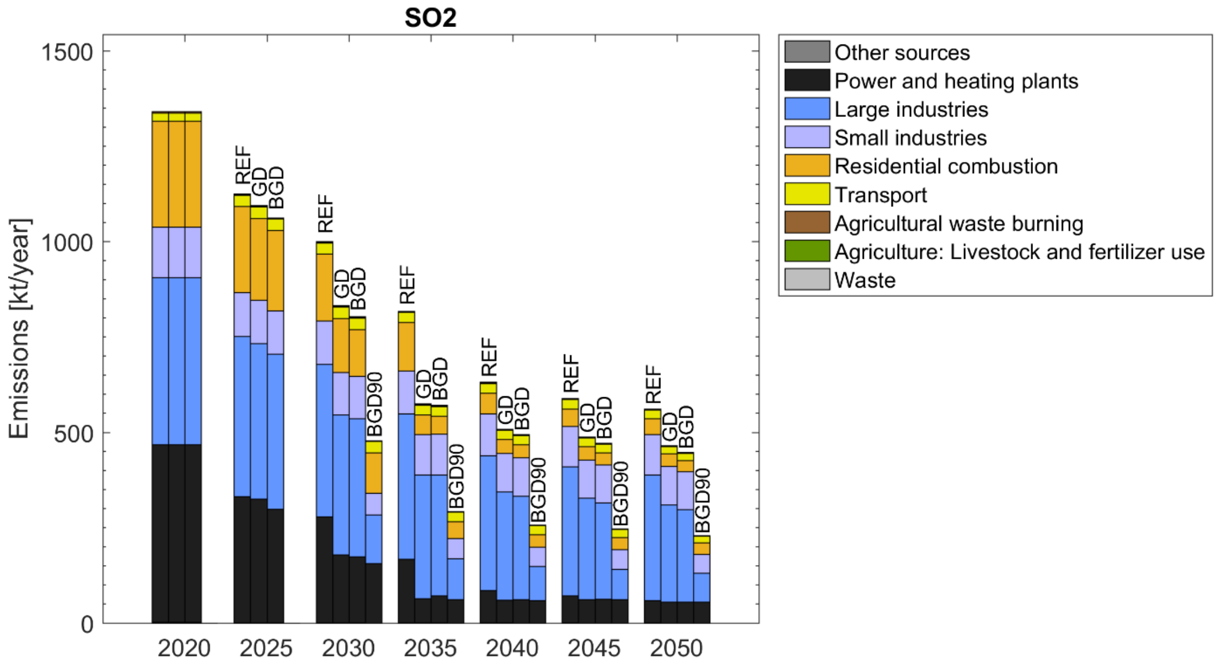


Figure 39. Emissions of SO_2 in the EU as calculated in GAINS for the four scenarios

Emissions of NO_x are shown in Figure 40. Between 2020 and 2050, total emissions decrease by 55% in the REF, 67% in the GD and 68% in the BGD. This translates into additional reductions by 2050, with the GD and BGD delivering 25% and 27% lower emissions respectively compared to the REF in the same year. Currently dominated by transport—mainly diesel cars, trucks, and mobile machinery—this pattern will change due to electrification and Euro-6/7 standards implementation.

Road transport drives early reductions. In 2020, transport accounts for about 38% of total NOx emissions. These sectoral emissions fall by 48% between 2020-2030 in REF alone which contributes to a 30% total NO_x reduction. The GD and BGD show similar transport emissions through 2030, then diverge modestly. By 2050, the contribution of road transport to total emissions is 8% in REF and about 2% in the GD and BGD.

By 2050, agriculture becomes the dominant NO_x source through soil emissions, which remain largely unchanged across all scenarios. The BGD90 also shows minimal agricultural improvements of less than 1% compared to the BGD, highlighting that technical mitigation options have been exhausted in this sector. Put differently, the BGD already largely exploits the technical control that are available to the BGD90 within the defined space of 90% gap closure.

The BGD90 reveals significant remaining potential beyond agriculture, reducing BGD emissions by 17% in 2030 and maintaining an approximate 19% relative reduction level through 2050. This potential is largely found in increasing air pollution controls for large industry with some found in small industry and residential combustion.

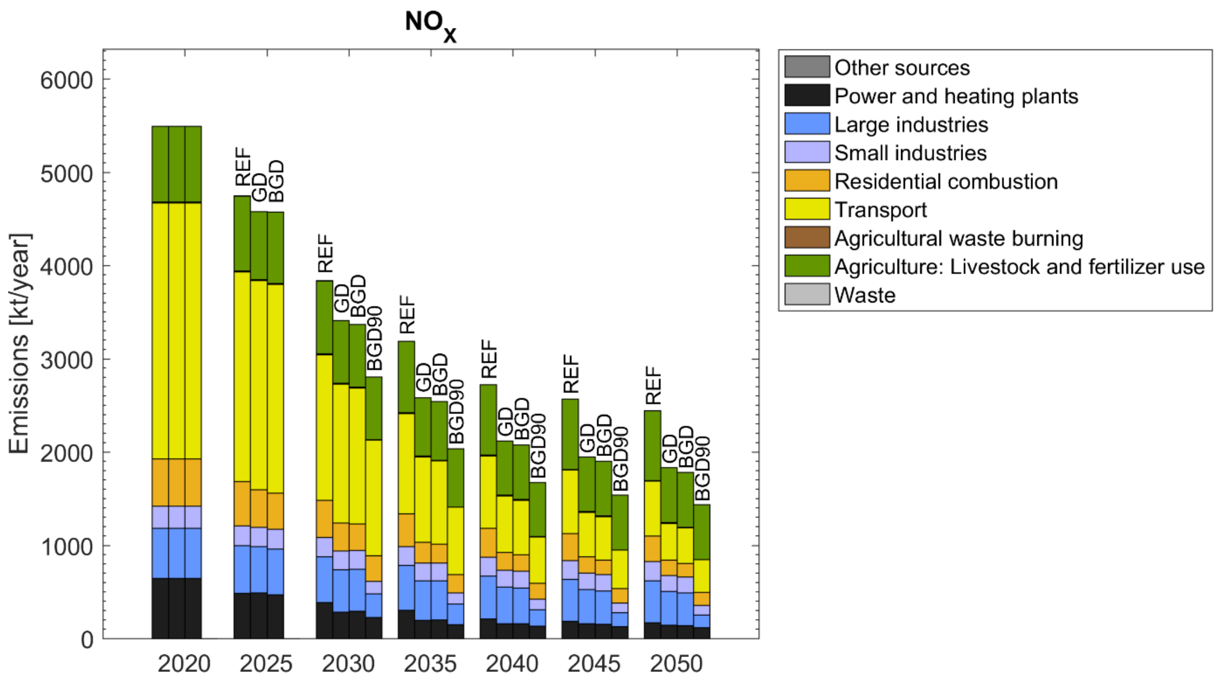


Figure 40. Emissions of NOx in the EU as calculated in GAINS for the four scenarios

Significant technical mitigation potential remains in agricultural livestock and fertilizer use. The BGD90 scenario consistently achieves approximately 20% lower agricultural emissions than BGD across all years. Available measures include low nitrogen feed, low emission housing, and air scrubbers for livestock, and low ammonia application and urea substitution for fertilizers. With all measures, agricultural NH_3 emissions in BGD90 are reduced by approximately 49% in 2050 compared to 2020 emissions in the main scenarios. In contrast, the waste sector shows no mitigation potential beyond REF, as seen in Figure 41. Emissions from this sector follow identical trajectories across all scenarios, starting at 165 kt NH_3 in 2030 and declining by approximately 1 kt per five-year timestep.

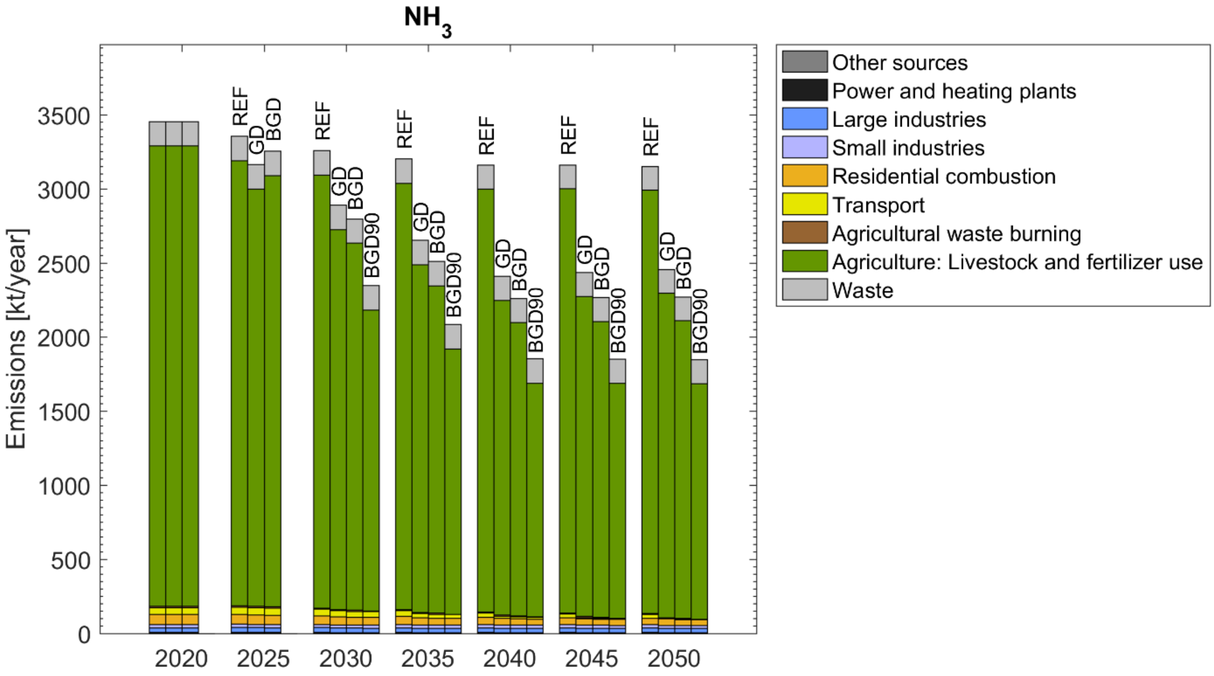


Figure 41. Emissions of NH_3 in the EU as calculated in GAINS for the four scenarios

The differences in agricultural activity levels discussed in relation to NH_3 also cause differences in emissions of NMVOCs between the scenarios as seen in Figure 42. Between 2020 and 2050, REF delivers approximately a 30% emissions reduction, GD delivers 37%, and BGD 40%. Since agriculture contributes only around 21% of total EU27 VOC emissions in 2020, the sector's impact on total emissions is smaller than its impact for NH_3—with GD and BGD total emissions approximately 11% and 14% lower than REF in 2050. Other sectors contribute modest additional reductions, including the residential sector through reduced biomass use and industry through decarbonization policies required to achieve the Green Deal targets.

BGD90 shows some remaining mitigation potential. In 2030, the difference in total emissions between BGD90 and BGD is about 7-9% and this remains roughly proportional through to 2050. This remaining mitigation potential comes primarily from 'Other sources', a sector which consists of solvent use and miscellaneous industrial processes. Control technologies include improved application techniques for e.g. paint and wood preservation and various other process optimizations.

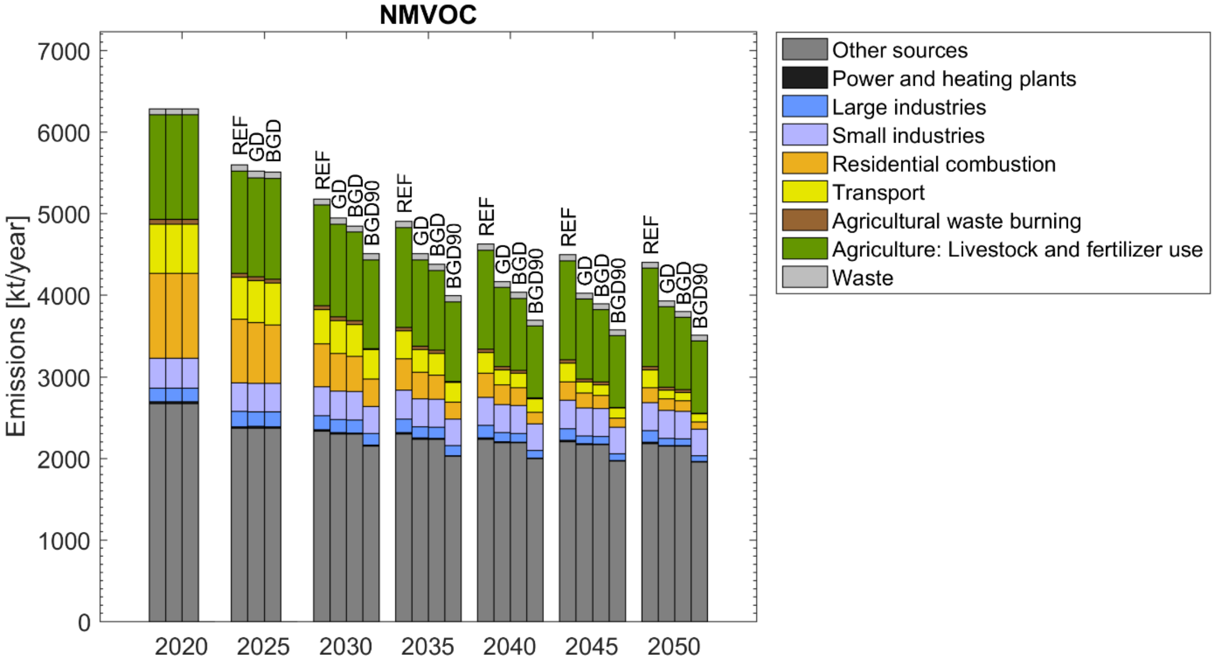


Figure 42.Emissions of NMVOCs in the EU as calculated in GAINS for the four scenarios

7. Conclusions

This report documents the emission scenarios developed for the Horizon Europe project CATALYSE. It is an updated version of the original report accompanying Deliverable D2.1 of the CATALYSE project: *Gridded emission scenarios for air pollutants in Europe until 2050*. The original deliverable report did not include the BGD90 scenario variant.

The main scenario space is defined by three main scenarios and a scenario variant:

- REF, a reference case prior to the development of the Green Deal
- GD, a scenario achieving the objectives of the Green Deal and considering all relevant EU legislation
- BGD, a scenario exploring further mitigation potential for GHG and air pollution emissions beyond the Green Deal, with a particular focus on behavioral changes regarding buildings, transport, and food & agriculture.
- BGD90, a scenario variant that introduces additional stringent air pollution emission controls on BGD assumptions to achieve 90% of the maximum technically feasible reductions of emissions of all air pollutants across EU27.

The scenarios have been developed using the linked framework of system models PRIMES-CAPRI-GAINS, with PRIMES and CAPRI models supplying the activity projections and GAINS estimating the associated emissions of all major air pollutants.

Total final energy consumption is significantly lower in the GD scenario than in REF, achieving a 13% reduction in 2030 and 37% reduction in 2050, while the BGD scenario reduces final energy consumption by 16% in 2030 with respect to REF and by 40% in 2050, respectively.

Such reductions are associated with significant decreases in GHG emissions in the main emissions scenarios. Already in the REF scenario, CO_2 emissions are projected to decrease by 14% in 2030 and by 53% in 2050 relative to 2020, while in the GD case emissions decrease by 32% in 2030 and by 91% in 2050 (the remainder would need to be balanced by negative emissions and additional uptake in vegetation in order to achieve carbon neutrality). The additional measures in the BGD scenario do not result in significant further reductions of GHG emissions beyond GD.

Emissions of air pollutants are expected to further decrease in the EU even in the REF case due to existing legislation. The strongest reductions are expected for $PM_{2.5}$ emissions (61%), followed by SO_2 (58%) and NO_x (55%), with smaller changes for NMVOC (30%) and NH_3 (9%). By 2050, the GD scenario delivers the largest reductions compared to REF for NO_x (25%), NH_3 (22%) and SO_2 (17%) with smaller changes in NMVOC (11%) and $PM_{2.5}$ (7%). Differences between the BGD and GD are modest; the BGD achieves a reduction of 27% for NO_x and 28% for NH_3 and 20% for SO_2, 14% for NMVOC and 12% for $PM_{2.5}$ in 2050 compared to REF. The sectoral drivers behind these reductions for each pollutant varies. Notable examples include residential combustion for PM2.5 whose sector contribution falls from 64% of total $PM_{2.5}$ emissions in 2020 to 30% in 2050 for the REF, 27% for the GD and 25% for the BGD, and transport for NO_x whose sector contribution falls from about 38% in 2020 to 8% in the REF and 2% in the GD and BGD in 2050.

The BGD90 scenario variant demonstrates remaining end-of-pipe emission control potential across multiple sectors. While some sectors like transport have largely exhausted their mitigation potential through electrification and fleet renewal, others—particularly the residential combustion sector, industry, and select agricultural practices—retain considerable room for additional control. These findings indicate that achieving a 90% emission gap closure is technically feasible, though the cost-effectiveness and implementation pathways for these additional measures would require further analysis.

The emission reduction potentials identified in these scenarios have important health implications. Direct health benefits can also be expected from the shift to more active mobility or to healthier diets, as contained in the GD and particularly BGD scenarios, while the additional insulation of buildings may cause detrimental side-effects on indoor air quality if poorly implemented. Health effects from these risk factors will be analyzed alongside air pollution for the main CATALYSE scenarios; in addition, sectoral variants can be built following specific assumptions in a given sector which are then not harmonized across all models and can be analyzed independently for the specific risk factor only. This comprehensive approach ensures that all health pathways are captured in evaluating the full benefits of emission reduction policies.

8. Data Availability

The dataset of gridded emissions used in this study is publicly available on Zenodo at: https://doi.org/10.5281/zenodo.17144194

The emission scenarios will also be made available in the GAINS model online interface (GAINS-Europe Data Explorer, https://gains.iiasa.ac.at/gains/GPV/index.login?logout=1).

References

Akimoto, K., Sano, F., & Oda, J. (2022). Impacts of ride and car-sharing associated with fully autonomous cars on global energy consumptions and carbon dioxide emissions. *Technological Forecasting and Social Change*, *174*, 121311. https://doi.org/10.1016/j.techfore.2021.121311

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., & Winiwarter, W. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software*, *26*(12), 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012

Amann, M., Borken-Kleefeld, J., Cofala, J., Hettelingh, J.-P., Heyes, C., Hoglund-Isaksson, L., Holland, M., Kiesewetter, G., Klimont, Z., Rafaj, P., Posch, M., Sander, R., Schoepp, W., Wagner, F., & Winiwarter, W. (2014). *The Final Policy Scenarios of the EU Clean Air Policy Package. TSAP Report #11* (No. TSAP Report #11). International Institute for Applied Systems Analysis.

Amann, M., Borken-Kleefeld, J., Kiesewetter, G., Rafaj, P., & Wagner, F. (2012). *Compliance with EU Air Quality Limit Values—A First Set of Sensitivity and Optimization Analyses. TSAP Report #8* (No. TSAP Report #8). International Institute for Applied Systems Analysis. http://www.iiasa.ac.at/web/home/research/researchPrograms/MitigationofAirPollutionandGreenhousegases/TSAP-SENSITIVITY-20121128.pdf

Amann, M., Purohit, P., Bhanarkar, A. D., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Kiesewetter, G., Klimont, Z., Liu, J., Majumdar, D., Nguyen, B., Rafaj, P., Rao, P. S., Sander, R., Schöpp, W., Srivastava, A., & Vardhan, B. H. (2017). Managing future air quality in megacities: A case study for Delhi. *Atmospheric Environment*, *161*, 99–111. https://doi.org/10.1016/j.atmosenv.2017.04.041

AMAP. (2015). *AMAP Assessment 2015: Black carbon and ozone as Arctic climate forcers*. Arctic Monitoring and Assessment Programme (AMAP). http://www.amap.no/documents/doc/amap-assessment-2015-black-carbon-and-ozone-as-arctic-climate-forcers/1299

Andreou, A., Fragkos, P., Pietzcker, R., Hasse, R., Hoppe, J., Rosemann, R., Müßel, J., Tsiropoullos, I., Tsanakas, N., Hughes, A., & Zisarou, E. (2023). *Report on the updated system models in mobility and residential demand and their results. Deliverable 6.1 of the CAMPAIGNers project funded under the*

European Union's Horizon 2020 research and innovation programme GA No: 101003815. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e503bf83cf&appId=PPGMS

Berg, N. J. van den, Hof, A. F., Wijst, K.-I. van der, Akenji, L., Daioglou, V., Edelenbosch, O. Y., Sluisveld, M. A. E. van, Timmer, V. J., & Vuuren, D. P. van. (2021). Decomposition analysis of per capita emissions: A tool for assessing consumption changes and technology changes within scenarios. *Environmental Research Communications*, *3*(1), 015004. https://doi.org/10.1088/2515-7620/abdd99

Bhanarkar, A. D., Purohit, P., Rafaj, P., Amann, M., Bertok, I., Cofala, J., Rao, P. S., Vardhan, B. H., Kiesewetter, G., Sander, R., Schöpp, W., Majumdar, D., Srivastava, A., Deshmukh, S., Kawarti, A., & Kumar, R. (2018). Managing future air quality in megacities: Co-benefit assessment for Delhi. *Atmospheric Environment*, *186*, 158–177. https://doi.org/10.1016/j.atmosenv.2018.05.026

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., De Vita, A., & Sakellaris, K. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy*, *134*, 110960. https://doi.org/10.1016/j.enpol.2019.110960

De Ceuster, G., Van Herbruggen, B., Logghe, S., & Proost, S. (2004). *TREMOVE 2.2 Model and Baseline Description*. European Commission DG Environment. https://www.asser.nl/upload/eel-webroot/www/documents/TREMOVEreport.Pdf

Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C., & Vandenbergh, M. P. (2009). Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(44), 18452–18456. https://doi.org/10.1073/pnas.0908738106

Dimitrova, A. K., Marois, G., Kiesewetter, G., Samir, K. C., Rafaj, P., & Tonne, C. (2021). Health impacts of fine particles under climate change mitigation, air quality control, and demographic change in India. *Environmental Research Letters*. http://iopscience.iop.org/article/10.1088/1748-9326/abe5d5

Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products (Recast) (Text with EEA Relevance), No. 2009/125/EC (2009). https://eur-lex.europa.eu/eli/dir/2009/125/oj

Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 Amending Directive 2003/87/EC to Enhance Cost-Effective Emission Reductions and Low-Carbon Investments, and

Decision (EU) 2015/1814 (Text with EEA Relevance.), CONSIL, EP, 076 OJ L (2018). http://data.europa.eu/eli/dir/2018/410/oj/eng

Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency (Text with EEA Relevance) (2018). https://eur-lex.europa.eu/eli/dir/2018/844/oj

Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast) (Text with EEA Relevance.), CONSIL, EP, 328 OJ L (2018). http://data.europa.eu/eli/dir/2018/2001/oj/eng

Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 Amending Directive 2009/33/EC on the Promotion of Clean and Energy-Efficient Road Transport Vehicles (2019). https://eur-lex.europa.eu/eli/dir/2019/1161/oj

Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 Amending Directive 2003/87/EC Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union and Decision (EU) 2015/1814 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading System (2023). https://eur-lex.europa.eu/eli/dir/2023/959/oj

Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 Amending Directive 2003/87/EC Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union and Decision (EU) 2015/1814 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading System (Text with EEA Relevance), EP, CONSIL, 130 OJ L (2023). http://data.europa.eu/eli/dir/2023/959/oj

Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the Deployment of Alternative Fuels Infrastructure Text with EEA Relevance, EP, CONSIL, 307 OJ L (2014). http://data.europa.eu/eli/dir/2014/94/oj/eng

Directorate-General for Agriculture and Rural Development (European Commission). (2023). *EU agricultural outlook 2023-2035*. Publications Office of the European Union. https://data.europa.eu/doi/10.2762/722428

Directorate-General for Energy (European Commission). (2019). *Clean energy for all Europeans*. Publications Office of the European Union. https://data.europa.eu/doi/10.2833/9937

Directorate-General for Environment (European Commission), IIASA, EMRC, MET Norway, TNO, e-misia, RIVM, & Logika Group. (2025). *Support to the development of the fourth clean air outlook: Final report*. Publications Office of the European Union. https://data.europa.eu/doi/10.2779/8768689

European Commission. (2020a). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Sustainable and Smart Mobility Strategy – putting European transport on track for the future*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

European Commission. (2020b). *Farm to Fork Strategy—For a fair, healthy and environmentally-friendly food system*. https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf

European Commission. (2020c). *The 2021 Ageing Report: Underlying Assumptions and Projection Methodologies - European Commission*. https://economy-finance.ec.europa.eu/publications/2021-ageing-report-underlying-assumptions-and-projection-methodologies_en

European Commission. (2022a). *Autumn 2022 Economic Forecast* [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6782

European Commission. (2022b). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS REPowerEU: Joint European Action for more affordable, secure and sustainable energy*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A108%3AFIN

European Commission. (2022c). *Fit for 55—The EU's plan for a green transition*. Consilium. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/

European Commission. (2024). *COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT Part 1 Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society* (No. SWD/2024/63 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52024SC0063

European Commission: Directorate-General for Climate Action, European Commission: Directorate-General for Energy, European Commission: Directorate-General for Mobility and Transport, De Vita, A., Capros, P., Paroussos, L., Fragkiadakis, K., Karkatsoulis, P., Höglund-Isaksson, L., Winiwarter, W., Purohit, P., Gómez-Sanabria, A., Rafaj, P., Warnecke, L., Deppermann, A., Gusti, M., Frank, S., Lauri, P., Fulvio, F., … Kalokyris, T. (2021). *EU reference scenario 2020 – Energy, transport and GHG emissions – Trends to 2050*. Publications Office. https://doi.org/10.2833/35750

European Commission: Directorate-General for Mobility and Transport, Armoogum, J., Garcia, C., Gopal, Y., Borgato, S., Fiorello, D., Maffii, S., Mars, K., Popovska, T., Schlemmer, L., Gayda, S., Bogaert, M., & Vincent, V. (2022). *Study on new mobility patterns in European cities – Final report. Task A, EU wide passenger mobility survey*. Publications Office of the European Union. https://doi.org/10.2832/728583

FAO. (2018). *The future of food and agriculture – Alternative pathways to 2050*. https://openknowledge.fao.org/server/api/core/bitstreams/e51e0cf0-4ece-428c-8227-ff6c51b06b16/content

FAO. (2022). *Crops and livestock products; FAOSTAT database.* FAO. https://www.fao.org/faostat/en/#data/QCL.

Feng, L., Smith, S. J., Braun, C., Crippa, M., Gidden, M. J., Hoesly, R., Klimont, Z., van Marle, M., van den Berg, M., & van der Werf, G. R. (2020). Gridded Emissions for CMIP6. *Geoscientific Model Development*, *13*(2), 461–482. https://doi.org/10.5194/gmd-13-461-2020

Florczyk, A., Corbane, C., Schiavina, M., Pesaresi, M., Maffenini, L., Melchiorri, M., Politis, P., Sabo, F., Freire, S., Ehrlich, D., Kemper, T., Tommasi, P., Airaghi, D., & Zanchetta, L. (2019). *GHS-UCDB R2019A - GHS Urban Centre Database 2015, multitemporal and multidimensional attributes*. https://doi.org/10.2905/53473144-b88c-44bc-b4a3-4583ed1f547e

Hamilton, I., Kennard, H., McGushin, A., Höglund-Isaksson, L., Kiesewetter, G., Lott, M., Milner, J., Purohit, P., Rafaj, P., Sharma, R., Springmann, M., Woodcock, J., & Watts, N. (2021). The public health implications of the Paris Agreement: A modelling study. *The Lancet Planetary Health*, *5*(2), e74–e83. https://doi.org/10.1016/S2542-5196(20)30249-7

Hordijk, L., & Amann, M. (2007). How science and policy combined to combat air pollution problems. *Environmental Policy and Law*, *37*(4), 336–340.

IEA. (2023a). *World Energy Balances—Data product*. IEA. https://www.iea.org/data-and-statistics/data-product/world-energy-balances

IEA. (2023b). *World Energy Outlook 2023*. International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2023

Karkatsoulis, P., Sourtzi, V., Paroussos, L., & Tsiropoulos, I. (2022). *newTRENDs D7.1 Focus Study report: Model developments to simulate sharing economy and new trends in transport*. https://newtrends2020.eu/wp-content/uploads/2022/12/newTRENDs_D7.1_Focus-Study-Report-Model-development-to-simulate-sharing-economy-and-new-trends-in-transport.pdf

Klimont, Z., Heyes, C., Rafaj, P., Hoglund-Isaksson, L., Purohit, P., Kaltenegger, K., Gomez-Sanabria, A., Kim, Y., Winiwarter, W., Warnecke, L., Schoepp, W., Lindl, F., Kiesewetter, G., Sander, R., & Nguyen, B. (2023). *Global gridded anthropogenic emissions of air pollutants and methane for the period 1990-2050* [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.10366132

Klimont, Z., Kiesewetter, G., Kaltenegger, K., Wagner, F., Kim, Y., Rafaj, P., Schndlbacher, S., Heyes C., Z., Denby, B., Holland, M., Borken-Kleefeld, J., Purohit, P., Fagerli, H., Vandyck, T., Warnecke, L., Nyiri, A., Simpson, D., Gomez Sanabria, A., Maas, R., … Anderl, M. (2022). *Support to the development of the third Clean Air Outlook*. International Institute for Applied Systems Analysis. https://circabc.europa.eu/ui/group/cd69a4b9-1a68-4d6c-9c48-77c0399f225d/library/4f014b48-eb5a-417c-88f2-abe6bb0abdc3/details

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., & Schöpp, W. (2017). Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, *17*(14), 8681–8723. https://doi.org/10.5194/acp-17-8681-2017

Koide, R., Lettenmeier, M., Akenji, L., Toivio, V., Amellina, A., Khodke, A., Watabe, A., & Kojima, S. (2021). Lifestyle carbon footprints and changes in lifestyles to limit global warming to 1.5 °C, and ways forward for related research. *Sustainability Science*, *16*(6), 2087–2099. https://doi.org/10.1007/s11625-021-01018-6

LBNL. (n.d.). *Products That Use Standby Power*. List of Standby Products. https://standby.lbl.gov/standby-power-data-metering

Meijer, J. R., Huijbregts, M. A. J., Schotten, K. C. G. J., & Schipper, A. M. (2018). Global patterns of current and future road infrastructure. *Environmental Research Letters*, *13*(6), 064006. https://doi.org/10.1088/1748-9326/aabd42

Mittal, S., Dai, H., Fujimori, S., Hanaoka, T., & Zhang, R. (2017). Key factors influencing the global passenger transport dynamics using the AIM/transport model. *Transportation Research Part D: Transport and Environment*, *55*, 373–388. https://doi.org/10.1016/j.trd.2016.10.006

OECD, Commission, T. E., Nations, F. and A. O. of the U., Programme, U. N. H. S., Organization, I. L., & Bank, T. W. (2021). *Applying the Degree of Urbanisation*. https://www.oecd-ilibrary.org/content/publication/4bc1c502-en

Pesaresi, M., Florczyk, A., Schiavina, M., Melchiorri, M., & Maffenini, L. (2019). *GHS-SMOD R2019A - GHS settlement layers, updated and refined REGIO model 2014 in application to GHS-BUILT R2018A and GHS-POP R2019A, multitemporal (1975-1990-2000-2015)—OBSOLETE RELEASE*. https://doi.org/10.2905/42E8BE89-54FF-464E-BE7B-BF9E64DA5218

Rafaj, P., Kiesewetter, G., Gül, T., Schöpp, W., Cofala, J., Klimont, Z., Purohit, P., Heyes, C., Amann, M., Borken-Kleefeld, J., & Cozzi, L. (2018). Outlook for clean air in the context of sustainable development goals. *Global Environmental Change*, *53*, 1–11. https://doi.org/10.1016/j.gloenvcha.2018.08.008

Rafaj, P., Kiesewetter, G., Krey, V., Schoepp, W., Bertram, C., Drouet, L., Fricko, O., Fujimori, S., Harmsen, M., Hilaire, J., Huppmann, D., Klimont, Z., Kolp, P., Aleluia Reis, L., & van Vuuren, D. (2021). Air quality and health implications of 1.5 °C–2 °C climate pathways under considerations of ageing population: A multi-model scenario analysis. *Environmental Research Letters*, *16*(4), 045005. https://doi.org/10.1088/1748-9326/abdf0b

Rao, S., Klimont, Z., Smith, S. J., Van Dingenen, R., Dentener, F., Bouwman, L., Riahi, K., Amann, M., Bodirsky, B. L., van Vuuren, D. P., Aleluia Reis, L., Calvin, K., Drouet, L., Fricko, O., Fujimori, S., Gernaat, D., Havlik, P., Harmsen, M., Hasegawa, T., … Tavoni, M. (2017). Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change*, *42*, 346–358. https://doi.org/10.1016/j.gloenvcha.2016.05.012

Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 Setting a Framework for Energy Labelling and Repealing Directive 2010/30/EU (Text with EEA Relevance.) (2017). https://eur-lex.europa.eu/eli/reg/2017/1369/oj

Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 Setting CO2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443/2009 and (EU) No 510/2011 (Recast) (Text with EEA Relevance)Text with EEA Relevance, OP_DATPRO (2019). http://data.europa.eu/eli/reg/2019/631/2023-12-03/eng

Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the Deployment of Alternative Fuels Infrastructure, and Repealing Directive 2014/94/EU (Text with EEA Relevance), 234 OJ L (2023). http://data.europa.eu/eli/reg/2023/1804/oj/eng

Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the Use of Renewable and Low-Carbon Fuels in Maritime Transport, and Amending Directive 2009/16/EC (Text with EEA Relevance), 234 OJ L (2023). http://data.europa.eu/eli/reg/2023/1805/oj

Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on Ensuring a Level Playing Field for Sustainable Air Transport (ReFuelEU Aviation) (Text with EEA Relevance) (2023). http://data.europa.eu/eli/reg/2023/2405/oj

Reis, S., Grennfelt, P., Klimont, Z., Amann, M., ApSimon, H., Hettelingh, J.-P., Holland, M., LeGall, A.-C., Maas, R., Posch, M., Spranger, T., Sutton, M. A., & Williams, M. (2012). From Acid Rain to Climate Change. *Science*, *338*(6111), 1153–1154. https://doi.org/10.1126/science.1226514

Replogle, M. A., & Fulton, L. H. (2014). *A Global High Shift Scenario: Impacts And Potential For More Public Transport, Walking, And Cycling With Lower Car Use. Background paper for the Eighth Regional EST Forum in Asia.* University of California, Davis and Institute for Transportation and Development Policy (ITDP). https://uncrd.un.org/sites/uncrd.un.org/files/8th-est_p7-bgp-01.pdf

Shahmohammadi, S., Steinmann, Z., King, H., Hendrickx, H., & Huijbregts, M. A. J. (2019). The influence of consumer behavior on energy, greenhouse gas, and water footprints of showering. *Journal of Industrial Ecology*, *23*(5), 1186–1195. https://doi.org/10.1111/jiec.12858

Shindell, D., Kuylenstierna, J. C. I., Vignati, E., Van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S. C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., … Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, *335*(6065), 183–189.

UNDESA. (2018). *World Urbanization Prospects: The 2018 Revision*. United Nations Department of Economic and Social Affairs. https://population.un.org/wup/

UNECE. (1999). *Convention on Long-Range Transboundary Air Pollution*. http://www.unece.org/fileadmin/DAM/env/lrtap/full text/1979.CLRTAP.e.pdf

UNEP. (2011). *Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers* (p. 78). United Nations Environment Programme (UNEP). http://wedocs.unep.org/handle/20.500.11822/8048

UNEP. (2017). *The Emissions Gap Report 2017: A UN Environment Synthesis Report* (p. 89). United Nations Environment Programme. https://www.unenvironment.org/resources/emissions-gap-report

UNEP/WMO. (2011). *Integrated Assessment of Black Carbon and Tropospheric Ozone* (p. 285). http://wedocs.unep.org/handle/20.500.11822/8028

United Nations Environment Programme. (2016). *A framework for shaping sustainable lifestyles: Determinants and strategies*. United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/9995

van de Ven, D.-J., González-Eguino, M., & Arto, I. (2018). The potential of behavioural change for climate change mitigation: A case study for the European Union. *Mitigation and Adaptation Strategies for Global Change*, *23*(6), 853–886. https://doi.org/10.1007/s11027-017-9763-y

Venturini, G., Tattini, J., Mulholland, E., & Gallachóir, B. Ó. (2019). Improvements in the representation of behavior in integrated energy and transport models. *International Journal of Sustainable Transportation*, *13*(4), 294–313. https://doi.org/10.1080/15568318.2018.1466220