Environmental Modelling and Software 155 (2022) 105426

Contents lists available at ScienceDirect

Environmental Modelling and Software

journal homepage: www.elsevier.com/locate/envsoft

Exploring the black box: Applying macro decomposition tools for scenario comparisons

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ARTICLE INFO

Keywords:
Greenhouse-gas emissions reduction scenarios
Integrated assessment models
Climate change mitigation
Decomposition methods
1.5C warming scenarios
Energy efficiency

ABSTRACT

To illustrate the power and utility of macro-level decomposition tools, this article presents a structured comparison of two all-sector global modeling exercises that assess emissions reductions compatible with climate stabilization at roughly 1.5C above pre-industrial levels. It uses an expanded Kaya Identity combined with the LMDI (Logarithmic Mean Divisia Index) method to decompose the effects of key drivers of changes in emissions over time in these scenarios.

The most important drivers of emissions reductions include final energy intensity of economic activity, the fraction of primary energy delivered by fossil fuels, and emissions from non-CO_2 warming agents. Land-use change and the carbon intensity of fossil energy are also important. The article suggests additional data modelers should release to allow more rapid analysis of results and ways to facilitate cross-study comparisons (such as adopting "best of breed" sectoral models instead of relying solely on in-house expertise for model development).

Topics: Global change; Climate change; Emissions reduction modeling; Model comparisons; Energy resources; Environmental policy; Environmental technology; Energy Policy.

1. Introduction

To illustrate the kinds of insights available from the use of recently developed macro-level decomposition tools, this article compares the results from two high-profile all-sector global climate mitigation modeling exercises. The intervention cases for many such scenarios rely heavily on carbon capture, don't include changes in projected end-use service demands, and are not aggressive enough to achieve climate stabilization as embodied in the Paris accord of "well below 2 Celsius above pre-industrial levels" (IPCC, 2022).

We chose to explore two "edge cases" that assess the potential for emissions reductions compatible with climate stabilization at roughly 1.5C above pre-industrial levels with modest or no deployments of carbon capture and storage (CCS) and some changes in service demands. There are comparatively few studies of such edge cases, but the ones we chose use two widely-cited models created by top-tier analytical teams. We also chose scenarios for which the public data were detailed enough for us to apply our macro decomposition tools, as described below. The lack of availability of key data for many such analyses is a constraint on applying these methods more widely, although data availability is gradually improving over time (IPCC, 2022).

We apply our systematic analytical framework to raise follow-on questions, highlight key issues, and propose areas for future research and practice. Previous comparative analyses have yielded real insights (IPCC, 2022; IPCC, 2018; Sognnaes et al., 2021), but we are convinced that a more detailed and systematic decomposition approach will be even more advantageous to improving modeling practice. For example, such comparisons almost universally rely on the traditional "four factor" Kaya identity to decompose energy-sector trends, but as shown in previous work (Koomey et al., 2019) and in the analysis below, that convention masks important effects and can create confusion for policy makers. The tools and indicators on which we rely enable consistent comparisons with historical trends as well as allowing rapid visual discovery of differences in scenario outputs.

This article first presents methods, reviewing the Kaya identity and its offspring. It then shows results, digging into detail on key drivers for the two scenarios. The article then turns to potential future work and ends with a summary of conclusions. The Supplemental Information

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https://doi.org/10.1016/j.envsoft.2022.105426
Received 20 June 2021; Received in revised form 18 May 2022; Accepted 21 May 2022
Available online 2 June 2022
1364-8152/

gives more detail on technical methods and results.

2. Methods

To assess high-level drivers of change in the energy sector, we apply a well-established convention in emissions scenario analysis known as the Kaya Identity (Kaya, 1989) in our comparison of modeling studies. There are other decomposition methods commonly applied to assess sectoral change (for example as used in Chen et al. (2022)) but just examining high-level macro drivers can also yield important lessons, and we hope that climate solutions modelers will bring such decomposition methods into their workflows to support diagnostics, analysis, interpretive insights, and better scenario story telling (De Meyer et al., 2020; Guivarch et al., 2022).

As many researchers have realized over the years, the Kaya identity as it was originally introduced is incomplete. This section presents the original Kaya Identity then presents an expanded version of that identity and a more comprehensive "fully expanded decomposition" (including terms characterizing emissions outside the energy sector) laid out in detail in Koomey et al. (2019) and expanded further in Koomey et al. (2022).

2.1. Overview of the Kaya Identity and its offspring

The Kaya Identity illustrates the key drivers for fossil carbon dioxide emissions from the energy sector. This identity decomposes carbon emissions as a product of aggregate economic activity per year, energy intensity of economic activity, and carbon intensity of energy supplied. Professor Kaya presented this equation to help understand the implications of history and future scenarios in a simple "back of the envelope" way.

We show the familiar "four-factor" Kaya identity in Equation (1):

$$Carbon\ dioxide\ emissions = P \cdot \frac{GNP}{P} \cdot \frac{PE}{GNP} \cdot \frac{C}{PE} \quad (1)$$

where.

P is population in any year;

GNP is gross national product per year, a measure of economic activity;

PE is primary energy consumed per year, including conversion and energy transmission losses;

C is total net carbon dioxide emitted per year from the primary energy resource mix;

$\frac{GNP}{P}$ is the average income per person per year;

$\frac{PE}{GNP}$ is the primary energy intensity of the economy; and.

$\frac{C}{PE}$ is the net carbon dioxide intensity of supplying primary energy.

The Kaya identity reflects a more general identity that expresses impact (I) as a product of human population (P), affluence (A), and technology (T) (Ehrlich and Holdren, 1971, 1972). Population is the same in both the Kaya and IPAT identities, GNP/person represents affluence, and the other two terms characterize technology.

This formulation implies that a larger number of people with a higher income and more extensive use of certain technologies will have a greater impact on the environment. The effect of technology can be ambiguous – technologies that produce and combust fossil fuels are the primary anthropogenic source of carbon dioxide, while technologies for harnessing renewable energy and nuclear power, sequestering carbon, and improving efficiency can reduce or eliminate net anthropogenic carbon emissions.

In analyzing these studies we relied on methods developed for previous work (Koomey et al., 2019), enhanced and updated for this project as explored in a recent white paper (Koomey et al., 2022). We use graphics that summarize key drivers of emissions scenarios in the energy sector, expressed in the form of an **expanded Kaya identity**, in which we disaggregate key terms to address energy supply losses, the fraction of primary energy delivered by fossil fuels, and fuel switching among fossil fuels (this disaggregation is explained in more detail in the Supplemental information, part SI-1 and in Koomey et al. (2019)). We supplement the expanded Kaya identity with additional graphs that tell the complete high-level emissions story for each scenario.

The expanded Kaya identity, as described in Koomey et al. (2019), reads as shown in Equation (2):

$$C_{Fossil\ Fuels} = P \cdot \frac{GNP}{P} \cdot \frac{FE}{GNP} \cdot \frac{PE}{FE} \cdot \frac{PE_{FF}}{PE} \cdot \frac{TFC}{PE_{FF}} \cdot \frac{NFC}{TFC} \quad (2)$$

where

$C_{Fossil\ Fuels}$ represents carbon dioxide (CO_2) emissions per year from fossil fuels combusted in the energy sector.

P is population in any year.

GNP is gross national product per year (measured consistently using Purchasing Power Parity or Market Exchange Rates).

FE is final energy consumed per year.

PE is total primary energy consumed per year, calculated using the direct equivalent (DEq) method, as discussed in Koomey et al. (2019).

PE_{FF} is primary energy consumed per year associated with fossil fuels.

TFC is total fossil energy CO_2 emitted per year by the primary energy resource mix.

NFC is net fossil CO_2 emitted to the atmosphere per year after accounting for fossil sequestration.

The ratio GNP/P represents annual economic activity per person.

The ratio FE/GNP represents final energy intensity of economic activity.

The ratio PE/FE represents the Energy System Loss Factor (ESLF) which is a measure of total losses throughout the energy system supply chain.

The ratio PE_{FF}/PE we call the Fossil Fuel Fraction, which is the fraction of primary energy supplied by fossil fuels.

The ratio TFC/PE_{FF} we call the emissions intensity of fossil fuel production, changes in which measure fuel switching among fossil fuels (like switching power plants from being fired by coal to being fired by fossil gas, or switching from oils with higher life-cycle emissions to those with lower life-cycle emissions, as described in Gordon et al. (2015), Koomey et al. (2016) and Brandt et al. (2018).

The ratio NFC/TFC is an index characterizing the fraction of energy-sector emissions that reach the atmosphere, which is a measure of how much energy-sector fossil sequestration a scenario contains.

This identity allows us to disentangle key drivers affecting scenario results in the energy sector, and to show graphically which of these drivers are most important.

Because we care about all emissions that cause warming, we also need the more comprehensive relationship summarized in Equation (3), which includes all emissions in terms of carbon dioxide equivalent:

$$C^{eq}_{Total} = C_{Fossil\ Fuels} + C_{Industry} + C_{Land-use} + C^{eq}_{Non-CO2\ gases} - CS_{Biomass} \quad (3)$$

where.

$C_{Fossil\ Fuels}$ is defined in Equation (2).

$C_{Industry}$ represents carbon dioxide emissions per year from industrial processes (non-energy uses of fossil fuels that result in emissions, such as cement, steel, and aluminum production). Some models combine these emissions with fossil fuel combustion emissions, but they should be split out for clarity and internal consistency checks.

$C_{Land-use}$ represents net carbon dioxide emissions per year from changes in agriculture and land-use that are not associated with emissions reductions from biomass CCS. This term can be negative if there is significant reforestation or afforestation.

$C^{eq}_{Non-CO2\ gases}$ represents emissions per year of other greenhouse gases converted to CO_2 equivalent using relative factors of global warming potential (GWP).[1]

$CS_{Biomass}$ represents net negative emissions per year from sequestering carbon emissions associated with biomass combustion. In effect, such sequestration removes carbon from the biosphere, although the timing of biomass regrowth can vary greatly, introducing uncertainty into these negative emissions estimates. The emissions reductions from this source must also be carefully distinguished from other land-use changes.

If direct air capture of CO_2 is present in future scenarios (as seems likely) an additional term would be needed in Equation (3).

Substituting Equation (2) into Equation (3) we get Equation (4), which we refer to as our *fully expanded decomposition*:

$$C^{eq}_{Total} = P \cdot \frac{GNP}{P} \cdot \frac{FE}{GNP} \cdot \frac{PE}{FE} \cdot \frac{PE_{FF}}{PE} \cdot \frac{TFC}{PE_{FF}} \cdot \frac{NFC}{TFC} + C_{Industry} + C_{Land-use} + C^{eq}_{Non-CO2\ gases} - CS_{Biomass} \quad (4)$$

Equation (4) allows us to compare emissions savings in every sector from scenario modeling runs, assuming that those modeling exercises release sufficient data to calculate all terms in our fully expanded decomposition.

2.2. The studies

We identified two modeling studies that are recent, cover all sectors, and analyze similarly rapid emissions reductions:

1) *van Vuuren* et al. (2018). The reference scenario for this study is consonant with Shared Socioeconomic Pathway 2 (SSP 2) (Bauer et al., 2017; Fricko et al., 2017; Riahi et al., 2017), and we use van Vuuren's most aggressive intervention[2] scenario that includes carbon taxes, changes in service demand, and non-price policies sufficient to keep radiative forcing at 1.9 W/m^2 (roughly equivalent to 1.5 C above pre-industrial times).
2) *Grübler* et al. (2018). This study can also be compared to the SSP 2 reference case (Bauer et al., 2017; Fricko et al., 2017; Riahi et al., 2017), and its intervention case achieves 1.5 C. It focuses on technical, institutional, and social changes to enable a future world with vastly lower energy intensities than in more traditional scenarios. Lower energy use reveals possibilities for structural change on the supply side as well as aggressive climate action not dependent on carbon capture and much less dependent on high carbon taxes.

Both scenarios were included in the IPCC's latest Working Group III report (IPCC, 2022). These scenarios could be considered "edge cases" in that they describe scenario storylines that involve aggressive emissions reductions, rely in part on changes in service demands and have minimal or no CCS, but use different modeling constraints and assumptions.

In the following section we summarize results of applying our decomposition tools to these studies, In the Supplemental Information, we give a more detailed exposition of the decomposition results for readers who want to dig deeper.

3. Results

We begin at the highest level, examining drivers of changes in emissions in the reference cases and cumulative emissions savings in the intervention cases. We then discuss lessons revealed by the detailed dashboards for the two studies.

3.1. Reference case trends

We begin by decomposing the underlying drivers of emissions growth in the reference scenarios for the two studies, applying the Logarithmic Mean Divisia Index (LMDI) method (Ang, 2004) to the Kaya identity in the energy sector.[3] Fig. 1 shows the change in emissions attributable to each driver to 2100 relative to a 2020 base year (expressed in gigatonnes of CO_2 equivalent emissions, calculated component by component). We focus on the cumulative change in emissions because it is directly related to changes in global temperatures to first order (Lahn, 2020, 2021), although there are complexities when summing CO_2 equivalent emissions of different warming agents, so these results should be considered approximate.

This graph shows the sum of changes relative to the 2020 value in each year for each sector/driver. We apply the LMDI[4] approach to the energy sector Kaya identity for the reference case minus 2020 energy sector emissions to conduct the decomposition in the ten-year intervals the data allow. We then interpolate linearly between decadal values to get annual numbers and sum the difference for each component in every year to 2100. For the additive factors (other gases, land use, and industrial process emissions) we take the difference between the reference case for each factor in each year and its value in 2020, then sum those differences to 2100. This method gives an indication of the relative importance of each driver/sector over the analysis period.

Drivers shown above the zero-line push emissions up, while those below the zero-line push emissions down. The net changes in cumulative emissions for the scenarios are indicated by the black circles, which fall at about 1500 Gt CO_2e for van Vuuren and about 2100 Gt CO_2e for Grübler. Both scenarios represent SSP-2, but there are always differences in the underlying drivers depending on modeling practice.

The single biggest driver of emissions growth is increasing economic activity per person, which is about five times more important than the next largest category of emissions growth, population. Increased economic activity is mainly the result of improving economic conditions in developing countries, which is a consequence of societal development (and an appropriate outcome, given historical inequities in income growth). The third largest driver of emissions growth is "other gases", which is one reason why just focusing on the energy sector for emissions reductions doesn't give the full picture. The carbon intensity of fossil energy, which characterizes fuel switching among fossil fuels, also contributes to emissions growth in the Grübler reference case, indicating a modest shift towards more carbon-intensive fossil fuels over time.

Reductions in energy intensity of the economy are the dominant source of reductions in emissions over time in both reference case scenarios. The second most important source of emissions reductions for Grübler and the third most important for van Vuuren are changes in land-use, indicating that even in the reference case there are big changes in this source of emissions. Fossil fuel fraction also contributes modestly to emissions reductions over time in both cases.

[1] We convert emissions of the two major non-CO_2 greenhouse gases (methane and nitrous oxides) to CO_2 equivalents using 100-year global warming potentials (including climate feedbacks) from the IPCC's Sixth Assessment Report (IPCC, 2021), Table 7.SM.7. For both models we calculate total F-gas emissions in CO_2 equivalent using GWPs from the same source using the three major categories of such gases reported by the models: PFCs, HFCs, and SF_6.

[2] We prefer the term "intervention" to describe scenarios that diverge from the reference case because it is more general than "mitigation" and can in principle cover intervention scenarios that result in higher emissions (although such scenarios would be special cases).

[3] Details can be found in Supplemental Information, Part 1 (SI-1): Technical Methods.

[4] Ang (2004) shows LMDI methods 1 and 2. We choose method 1 because it is simpler and method 2 has no advantages for our analysis.

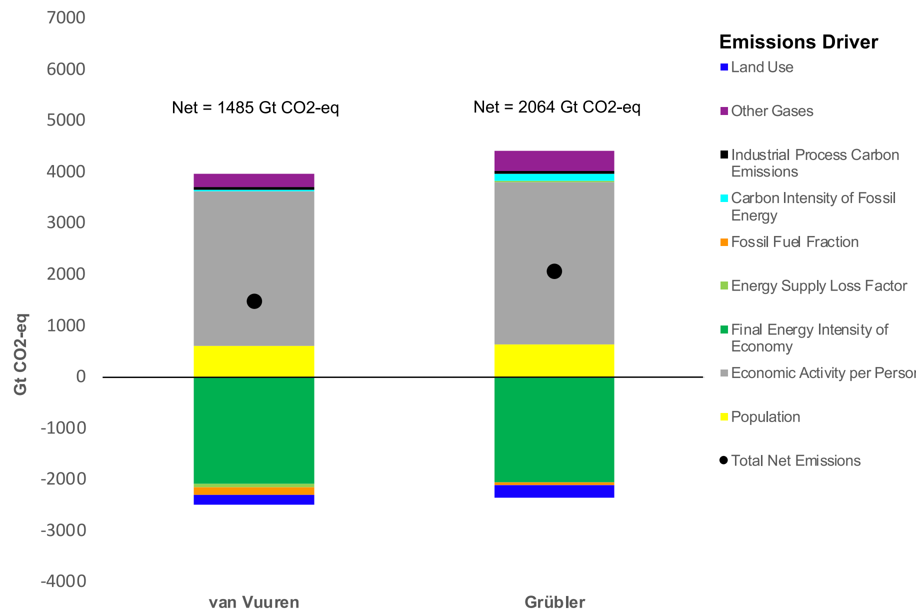

Fig. 1. Cumulative change in greenhouse gas emissions to 2100 for each reference case relative to 2020.
Industrial Process Carbon Emissions in the reference case are lumped in with energy sector emissions in the outputs for Grübler, so for that scenario we assume the same trajectory of industrial process emissions as van Vuuren. We use 100-year GWPs taken from Table 7.SM.7 in IPCC (IPCC, 2021)

3.2. Drivers of emissions reductions

We next summarize emissions *reductions* in the *intervention* scenario (compared to the reference scenario). Fig. 2 shows the attribution of cumulative emissions savings relative to the reference case to categories as per the previous graphs and equations (the same caveat about these results being approximate applies) for the 2020 to 2050 and 2050 to 2100 periods.

We've normalized savings to 100% of cumulative net emissions savings, and those absolute savings totals are shown at the top of each bar. When factors change in a way that drives net emissions *up* relative to the reference case (like for van Vuuren) then the bar exceeds 100% on the positive side and shows a corresponding bar below the zero line for the factor increasing emissions instead of decreasing it.

The Grübler intervention case shows improvements in the final energy intensity of the economy to be more important than for van Vuuren to 2050 but shows this component to be less important than for van Vuuren from 2050 to 2100, because of slowing improvements in emissions intensity in the later period (see further discussion below). Efficiency improvements also slow in the later period for van Vuuren, but the effect is not as dramatic.

For Grübler, the fossil fuel fraction is by far the most important driver of emissions reductions, accounting for about 30% of the total to 2050 and about 50% from 2050 to 2100. The contribution of fossil fuel fraction to total emission reductions also grows for van Vuuren. The van Vuuren scenario also trades off emissions reductions from changes in fossil fuel fraction against fossil CCS and greater emissions reductions from the carbon intensity of fossil energy than in the Grübler scenario.

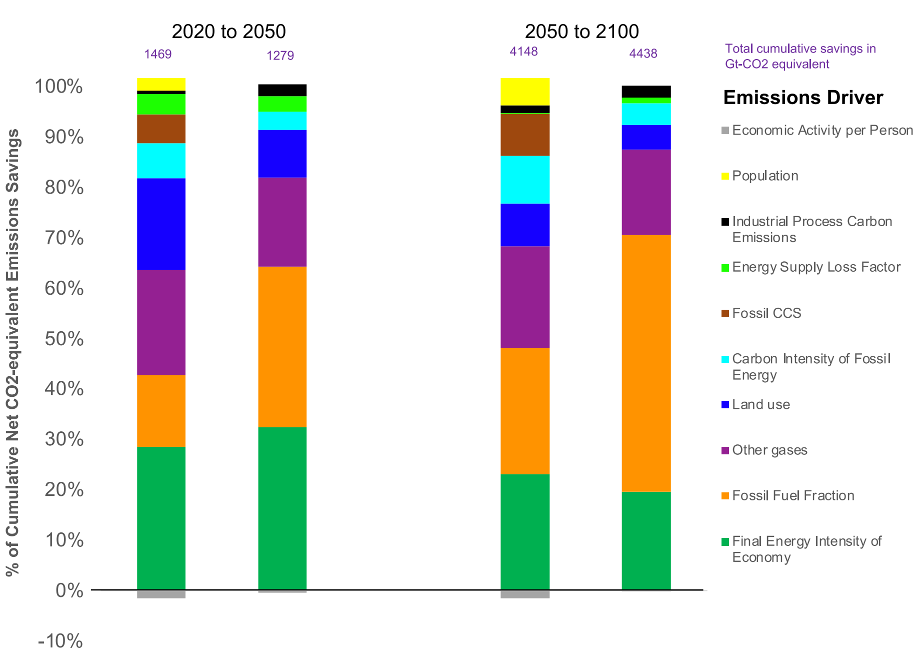

Fig. 2. Cumulative greenhouse gas emissions savings for each scenario.
For the Grübler intervention case we derive the implied industrial emissions by estimating energy sector emissions using primary energy consumption by fuel and IPCC emissions factors and subtracting that estimate from the total of energy sector and industrial emissions reported in the scenario outputs. We use 100-year GWPs taken from Table 7.SM.7 in IPCC(IPCC, 2021).

The contribution of "other gases" to total emissions reductions is about one quarter for van Vuuren and slightly less than one fifth for Grübler, and those percentage contributions remain roughly constant over the two analysis periods. Emissions reductions associated with changes in land-use are "front-loaded" in both scenarios, with significantly greater reductions in the first period. Five emissions reduction drivers comprise about 90% of cumulative reductions: final energy intensity of the economy, fossil fuel fraction, other gases, land use, and the carbon intensity of fossil energy.

The savings from "other gases" depends strongly on the assumption about global warming potentials (Smith and Wigley, 2000a, 2000b). In Fig. 2, we used the standard assumption of GWPs based on a 100-year lifetime, but a strong case can be made for also considering GWPs integrated over a 20-year period, especially for 1.5 C scenarios that reach net zero emissions in the next few decades.

Fig. 3 shows the results of altering the GWP for methane, N_2O, and F-gases to a 20-year time period (the GWP of carbon dioxide equals 1.0 by definition for any time period because GWP is measured relative to CO_2). Methane is the most important of the other gases and its 20-year GWP is two and a half times bigger than the 100-year value. For N_2O, the 20-year GWP is the same as the 100-year GWP, while for F-gases, some have 20-year GWPs that are lower than their 100-year GWPs, and some show the opposite. Taken together, these changes push savings from "other gases" to comprise thirty to forty percent of total cumulative emissions savings, up from twenty to twenty-five percent when using 100-year GWPs.

This result does not mean we can delay reductions in carbon dioxide, which take on increasing importance as time passes. It does mean that focusing on the other gases (particularly methane and other shorter lived warming agents) is a critical element of slowing climate change in the near term.

Interestingly, van Vuuren also shows emissions savings from a reduction in population growth. Previous research has documented that population growth affects emissions, but that changes in population growth are affected by many complex ethical and human factors related more broadly to societal development. O'Neill et al (2010) cautions that "the fact that a particular phenomenon is a quantitatively significant driver of emissions does not mean that it is also an important policy lever". Choices that affect societal development can also affect population (and thus emissions) but most scenarios avoid discussing such choices as explicitly driven by the goal of emissions reductions (Bongaarts and O'Neill, 2018). Van Vuuren states that the lower population estimates in this scenario are the result of aggressive policies promoting education, referencing Samir and Lutz (2017).

The van Vuuren scenario also indicates a small increase in emissions associated with improved economic activity per person, indicated by a small grey bar below the zero line. Grübler also shows this effect, but it's much smaller (10–20% of what's shown in the van Vuuren scenario). These effects appear to be related to economic benefits and co-benefits of various non-price policies, as distinct from implementation of the global carbon price.

3.3. Digging into the ratios dashboards

We show the results in the energy sector of our fully expanded decomposition for van Vuuren et al. and Grübler et al. in Figs. 4 and 5, respectively. Each pane in the dashboard characterizes one of the ratios in the expanded Kaya identity from Equation (2).

The green dotted lines show the path of the relevant ratio if it followed average historical growth rates for that ratio from 1900 to 2014, while the blue dotted lines show the path if it followed average historical growth rates from 1995 to 2014. The black lines indicate the path of the reference case, while the red line indicates the path of the intervention or mitigation case.

3.3.1. Population and economic activity

Population and economic welfare per person look roughly similar in both scenarios. Population growth diverges from historical trends, as expected from demographic studies in recent years (Samir and Lutz, 2017). Economic activity in the reference cases is assumed not to be significantly affected by associated changes in temperature, which is not necessarily a good assumption, but it's a common assumption for scenarios like these (IPCC, 2022; Bastien-Olvera, 2019; Christensen et al., 2018; Mann, 2022). The reduction in population and increase in

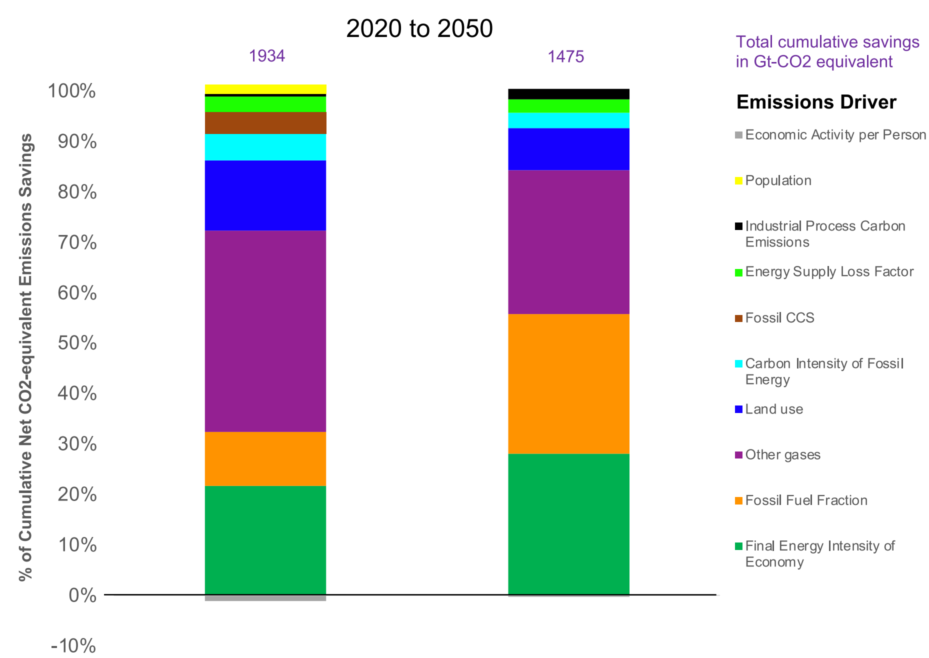

Fig. 3. Cumulative greenhouse gas emissions savings for each scenario (20-year GWPs for methane, N_2O, and F-gases).
These calculations use the same assumptions as for Fig. 2 but the GWP for methane, nitrous oxides, and F gases are switched to 20-year GWPs from 100 years as in Fig. 2. The 2020 to 2050 period corresponds roughly to a 20-year time period for estimation of the GWP. GWP data taken from Table 7.SM.7 in IPCC (IPCC, 2021).

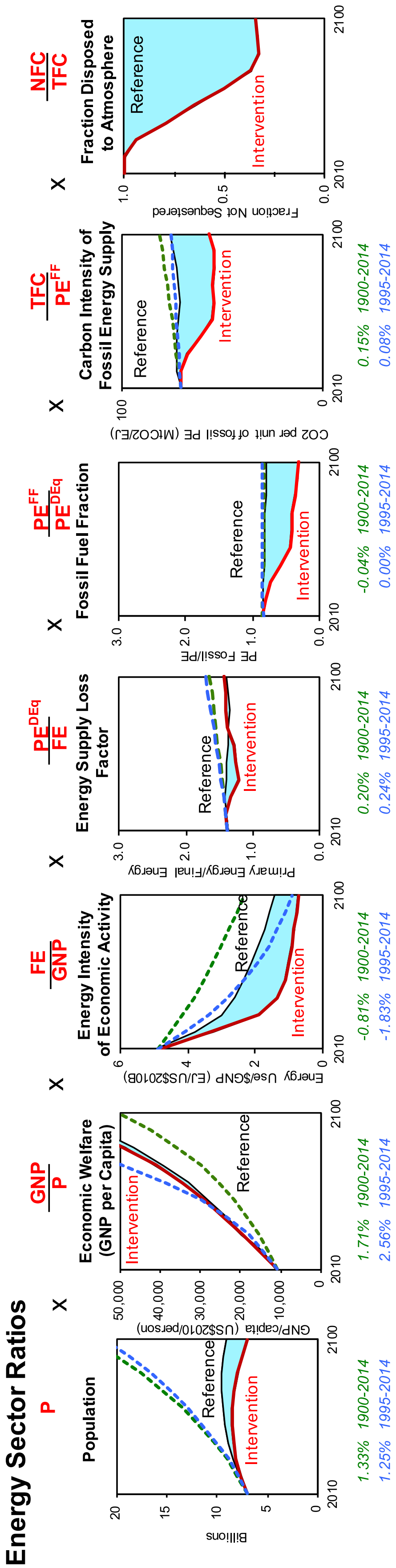

Fig. 4. Expanded Kaya identity ratios dashboard for van Vuuren et al., 2018

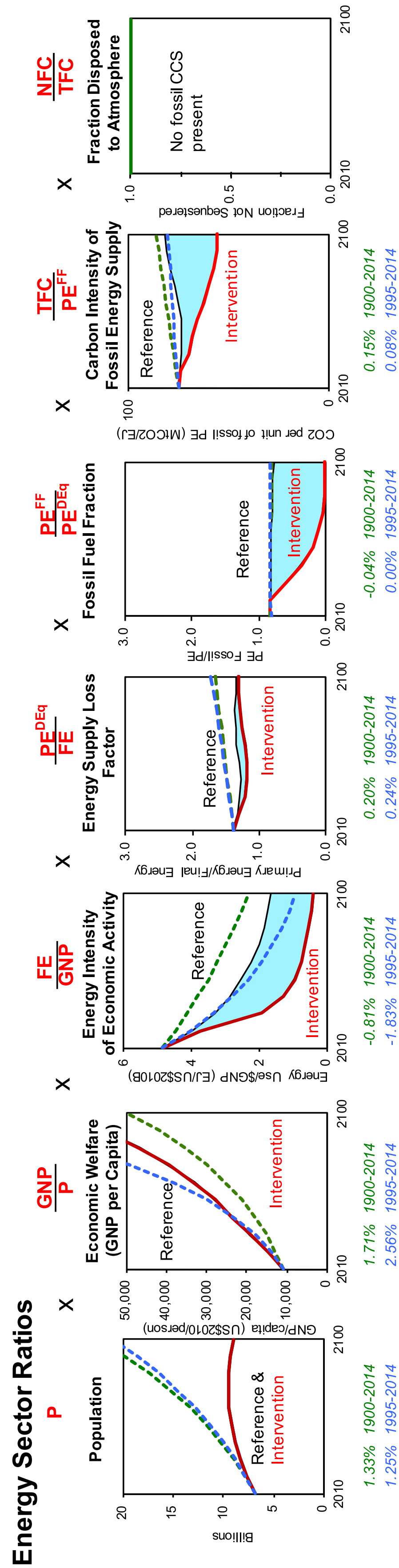

Fig. 5. Expanded Kaya identity energy sector ratios dashboard for Grübler et al., 2018

economic activity in the van Vuuren et al. intervention case show up clearly in the first two dashboard panes.

3.3.2. Final energy intensity of economic activity

Fig. 6 shows expanded panes for final energy intensity of economic activity for van Vuuren's and Grübler's scenarios. From 2010 to 2030, van Vuuren's intervention scenario shows a rapid decline in the final energy intensity of economic activity (FE/GNP), substantially exceeding historical trends as well as that of the reference scenario. From 2030 to 2040, the slope of the intervention scenario curve matches the historical rate of decline from 1995 to 2014 and flattens out further as the scenario progresses.

Grübler's scenario shows the same pattern, with an even steeper decline from 2010 to 2040, the rate of decline from 2040 to 2050 roughly matching that of the 1995 to 2014 period, with the curve then flattening, just like for van Vuuren. If Grübler's estimates for final energy intensity are correct, it would indicate the possibility of additional emissions reductions possible for the van Vuuren scenario through reduced energy intensities.

In the intervention scenario, declines in energy intensity (driven by improvements in energy efficiency, electrification, and changes in service demands) accelerate for the first few decades of the scenario and then slow down (as also shown in Figs. 4 and 5, above). The reasons for this pattern are not entirely clear, but as a general rule, demand-side technologies and practices (like energy efficiency and changes in activity levels) are represented in a much less detailed fashion in global energy models than are supply-side technologies, and bottom-up analyses of end-use efficiency tend to "run out" of efficiency later in these analyses because predicting technological change at a disaggregated level becomes increasingly difficult for later years (Wilson et al., 2012; Pye et al., 2020; Hardt et al., 2019; Napp et al., 2019). It is also possible that there are aggregate assumptions of physical limits buried in the models that curtail energy intensity improvements as each scenario progresses.

Whether such assumptions represent real physical limits (based on the 2nd law of thermodynamics) or simply modeling practice is not known, but we believe the importance of this issue warrants a much deeper dive into why climate mitigation scenarios exhibit this structural similarity in final energy intensity of economic activity. A deeper question is whether changes in the *structure* of economic growth (away from increases in physical consumption and toward increases in *knowledge-based goods* and *higher-quality physical goods*) can allow society to continue improvements in final energy intensity of economic activity far beyond what conventional models would indicate (McAfee, 2019). Answers to this question will vary greatly country by country.

As demonstrated by both scenarios, end-use energy intensity declines can make it possible to achieve emissions reductions with less widespread deployment of carbon capture and other supply side technologies. Hummel (2006) called this a reduction in "mitigation pressure" that allows for deeper emissions reductions than would be possible with accelerated supply-side options alone. Grübler et al. (2018) also allude to intensity reductions as an enabler of more rapid and more profound supply-side changes.

3.3.3. Energy supply system losses

As shown in Figs. 4 and 5 (above), energy supply losses to 2050 in both intervention cases are lower than in both reference cases, which is expected as more direct equivalent (non-combustion) energy sources enter the supply mix (Koomey et al., 2019; Nakicenovic et al., 2000). Energy supply losses in both intervention cases rise in the second half of the twenty-first century, with losses in the van Vuuren scenario exceeding those in the reference case as fossil CCS (which has higher system losses than conventional technologies) enters the supply mix. The Grübler scenario also shows rising supply losses in the intervention case over time but these losses remain lower than those in the reference case for the entire analysis period.

3.3.4. Fossil fuel fraction of primary energy

Fig. 7 shows expanded versions of the dashboard panes devoted to the fossil fuel fraction of primary energy. Both intervention scenarios show declines in this fraction, with van Vuuren approaching about one third of 2010 levels by 2100 and Grübler showing total fossil phaseout by about 2070 or so. This difference is primarily attributable to the use of fossil CCS in the van Vuuren scenario. Under strict emissions reduction goals, scenarios with CCS continue to use fossil fuels, while those without do not, which is one reason why fossil CCS is technology often favored by the fossil fuel industry.

3.3.5. Carbon intensity of fossil energy

Fig. 8 shows expanded panes from the dashboard characterizing the carbon intensity of fossil energy supply. This factor increases in both

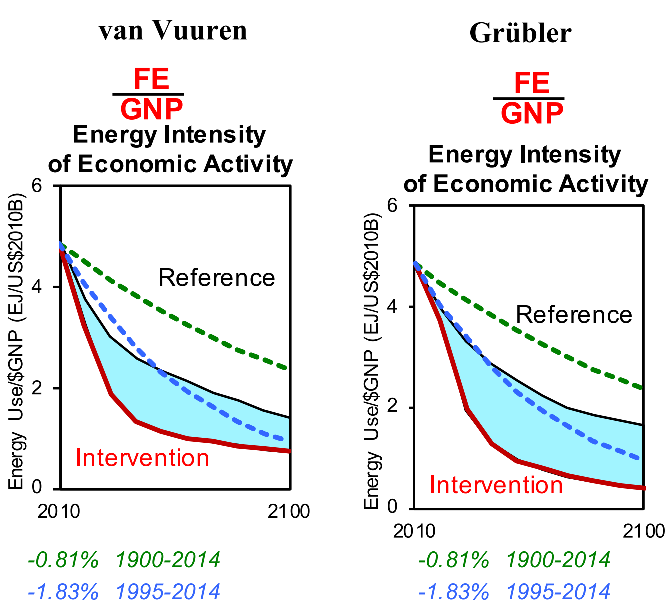

Fig. 6. Energy intensity of economic activity over time.

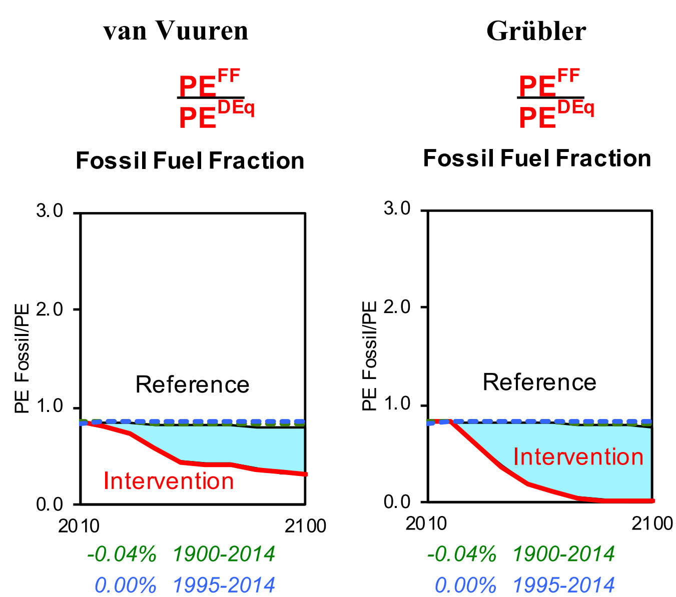

Fig. 7. Fossil fuel fraction of primary energy over time.

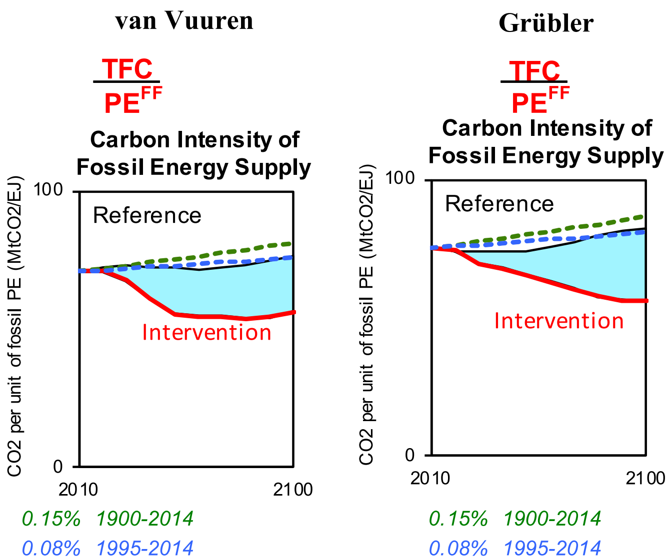

Fig. 8. Carbon intensity of fossil energy over time.

reference cases, indicating slightly more emissions-intensive use of fossil fuels over time. Both intervention cases trend towards the asymptote of natural gas emissions, but van Vuuren's scenario approaches that goal much more quickly. Additional emissions savings could thus be realized in the Grübler intervention scenario if the shift to natural gas happened as quickly as shown in the van Vuuren scenario. Why the carbon intensity of fossil fuel supply increases slightly towards the end of the analysis period for van Vuuren is a question worthy of further exploration.

3.3.6. Graphs of primary energy that summarize major trends in key drivers

One way to answer some of the queries raised above is by graphing primary energy over time by source, as shown in Fig. 9a and Fig. 9b for the van Vuuren and Grübler intervention cases, respectively. Graphs like these show trends in total primary energy. They also implicitly show trends in final energy because the energy supply loss factor is close to 1.0 throughout the analysis period for both scenarios. In addition, they implicitly show the fossil fuel fraction as well as the mix of fossil fuels contributing to meeting service demands in any year.

Fig. 9a (for van Vuuren) shows that total primary energy drops rapidly to 2040 (in part because of rapid improvements in the final energy intensity of economic activity and in part because of the rapid displacement of fossil combustion with direct equivalent sources, which avoids combustion losses). As improvements in final energy intensity slow down mid-century and carbon capture technologies with high system losses become more widely used, total primary energy starts rising, reaching 2020 levels by 2100.

Fossil gas consumption stays roughly constant to 2040 and then rises modestly to 2070, then falls to 2100. Petroleum use falls to mid-century then remains roughly flat, while coal use falls to mid-century and then rises to 2100. This latter finding explains why the carbon intensity of

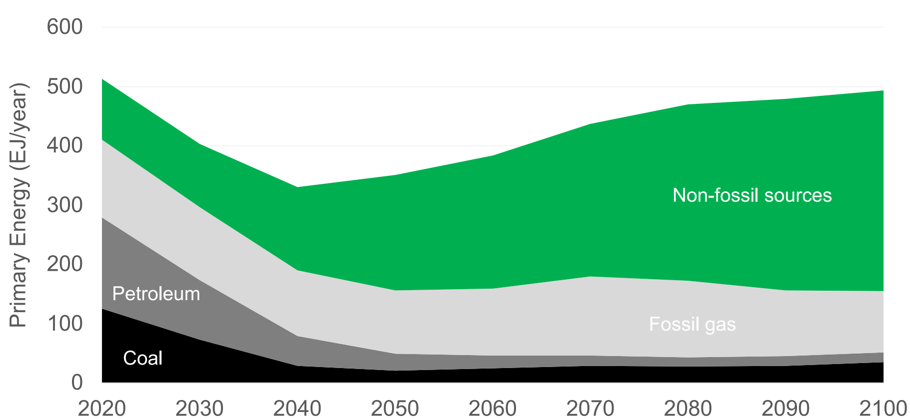

Fig. 9a. Primary energy by source over time in van Vuuren's intervention scenario.

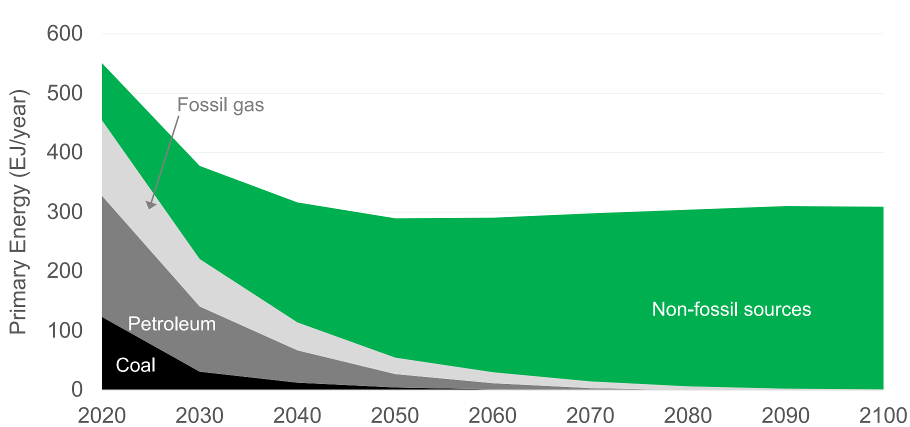

Fig. 9b. Primary energy by source over time in Grübler's intervention scenario.

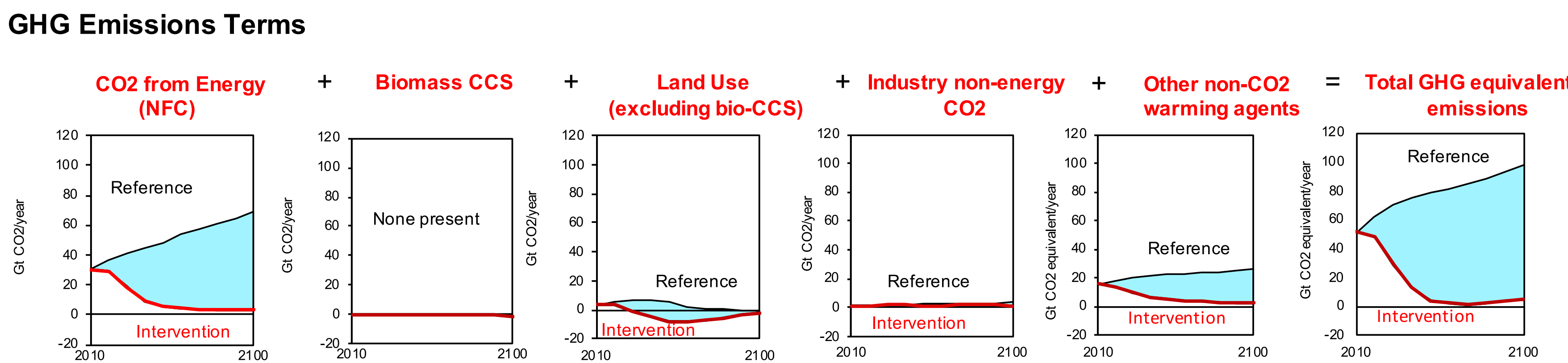

Fig. 10. Contribution of major sectors to emissions reductions for van Vuuren et al., 2018

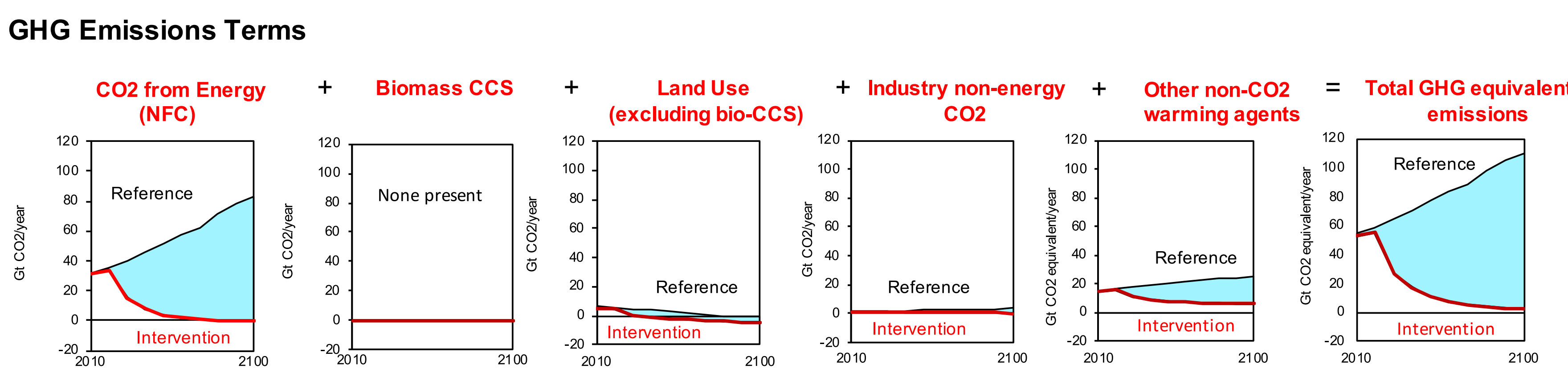

Fig. 11. Contribution of major sectors to emissions reductions for Grübler et al., 2019

fossil fuel supply goes up in the last couple of decades of the 21st century for this scenario.

Fig. 9b shows the same graph for Grübler, illustrating big differences with the van Vuuren intervention scenario. Primary (and final) energy decline substantially by mid-century and then remain roughly flat to 2100. Coal is almost completely gone by 2050, petroleum by 2070, and fossil gas by 2090.

Fossil gas represents a higher percentage of primary fossil energy supplied from 2020 to 2050 in the van Vuuren intervention case than in the Grübler intervention case, with this gap growing over time. These data explain why the carbon intensity of fossil energy supplied falls more rapidly early in the van Vuuren intervention case.

3.4. *Digging into the additive factors dashboard*

Now we turn to insights from our "additive factors dashboards", which show emissions changes over the analysis period by each factor identified in Equation (4) above, expressed in Gt CO_2 equivalent per year. Figs. 10 and 11 show that the energy sector is the largest contributor to emissions reductions, but other non-CO_2 warming agents and land use changes are also important. There are relatively small savings from industrial process emissions and none from biomass CCS in either scenario.

3.4.1. *Land-use change*

Fig. 12 shows expanded versions of the dashboard panes for carbon dioxide emissions from land-use changes, to make them easier to see. Some obvious questions emerge from casual examination of these graphs. What drives emissions in both references cases to decline over time (in the van Vuuren case after rising to 2030)? Why do net emissions in the van Vuuren intervention case become less negative after mid-century? What drives the rapid emissions reductions in the Grübler intervention scenario to 2030 and why then do emissions reductions proceed less rapidly after 2030?

3.4.2. *Industrial processes*

Fig. 13 shows expanded versions of the dashboard panes for carbon dioxide emissions from industrial processes (mainly cement). The reference cases are identical, taken from van Vuuren, because the SSP2 reference case used by Grübler doesn't split industrial process emissions from energy-sector emissions. The van Vuuren intervention case comes directly from that study's outputs, but we infer the intervention case for Grübler using fossil energy combustion and related emissions factors, then subtracting out inferred energy-sector emissions from the sum of energy-sector plus industrial process emissions.

Both intervention cases reflect changes in emissions from industrial processes, but it's not entirely clear whether such changes are consistent with the trajectory of energy infrastructure construction in these scenarios (this issue is a more general one that needs further attention from the modeling community). Additional transparency is needed with data related to industrial process emissions separate from energy-sector emissions, to ensure internal consistency of the scenarios. The van Vuuren intervention case also has unexplained oscillations that clearly warrant futher investigation.

3.4.3. *Non-CO_2 warming agents*

Fig. 14 shows expanded versions of the dashboard panes for carbon dioxide emissions from non-CO_2 warming agents like methane, nitrous oxide, and other pollutants using 100-year GWPs. The reference cases appear to be comparable but the intervention cases show much more rapid and effective mitigation of non-CO_2 pollutants in the van Vuuren scenario. If the van Vuuren assessment is correct, there is clearly room for more reductions in other warming agents in the Grübler scenario.

4. Recommendations for future work

We are hopeful that these decomposition tools can support and strengthen the next iteration of the IPCC's Working Group III report, due out in the mid to late 2020s, but that will depend on modelers integrating these tools into their workflows and and using them to generate insights, wh which should also speed up the process of developing scenarios and evaluating results.

4.1. *More studies of aggressive emissions reduction scenarios are needed*

In our view, there are too few scenarios with aggressive emissions reductions, and such emissions reductions are less well studied than they should be. These edge cases are the most likely to teach us something useful about what ultimate emissions reductions will be possible because they push the boundaries of our imagination.

The most comprehensive summaries of such scenarios are found in IPCC (2022) and IPCC (2018), but as with all fast-changing research areas, findings become obsolete quickly. As suggested by three of the comparisons above (improvements in the intensity of final energy use, the emissions intensity of fossil fuels and emissions from non-CO_2 warming agents), analytical focus on combining the best parts of the most aggressive scenarios from "best of breed" analyses can help policy makers map the true limits of what society can achieve.

We are also convinced that comparing analyses that are quite different in their underlying assumptions and drivers can yield important insights (Sognnaes et al., 2021). The two scenarios presented above are of a similar type but comparing scenarios like these to others that have different core assumptions about drivers and available technologies should be an important part of scenario decomposition efforts going forward.

4.2. *Addressing unanswered questions*

Use of the analytical tools highlighted above can help identify and diagnose unexplained trends and discontinuities. An example is the common pattern of accelerated energy intensity reductions in the first two or three decades of intervention cases, but a sudden slowing of those reductions around the mid-twenty-first century. Identifying and researching puzzles like these can lead to more rapid improvements in modeling practice as well as increased understanding of the true constraints holding back rapid climate action.

4.3. *We need more data*

We need more data from global energy models to do full decompositions to more fully understand the implications of individual studies and of the body of literature as a whole. The modeling community must routinely release more comprehensive data beyond what is now standard practice. Policy makers and funders can and should encourage more complete disclosure. Our experience indicates that more comprehensive, better defined, and more accurate data are needed in at least four areas:

1. **More disaggregated data:** To facilitate analysis and scenario comparisons, it is critical that data be disaggregated sufficiently. For example, industrial process carbon dioxide emissions should be reported separately from energy sector emissions. Methane and nitrous oxide emissions should at a minimum be split between those associated with fossil fuel production and those non-fossil emissions associated with industrial processes, agriculture, and other human activities. Finally, F-gases should be split and reported by species, not reported only as a total, otherwise it is hard to adjust for different global warming potentials and assess policy effects on different F-gases.

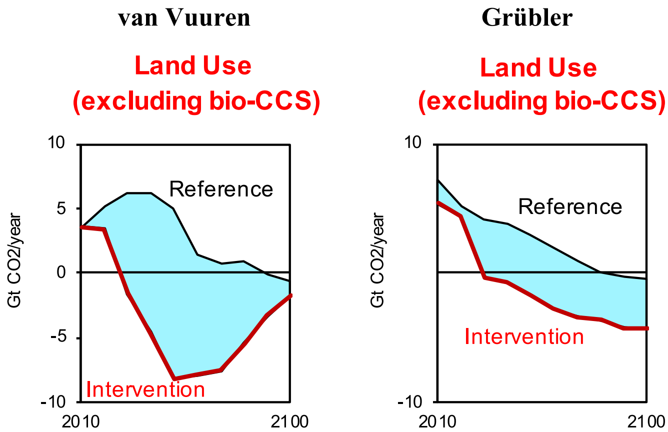

Fig. 12. Land-use emissions over time.

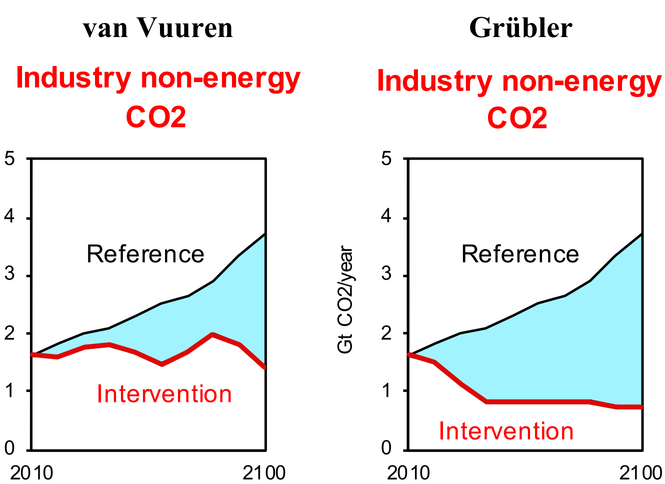

Fig. 13. Industry non-energy CO_2 over time.

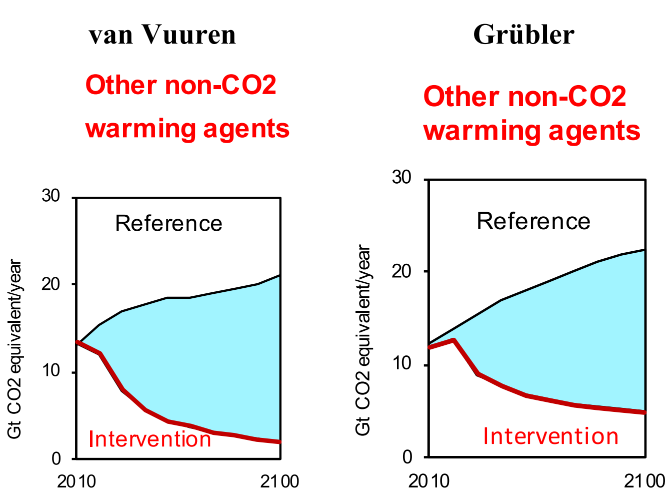

Fig. 14. Other non-CO_2 warming agent emissions over time.

2. **Endogenous treatment of industrial sector process emissions:** Industrial process emissions, most of which are associated with construction materials like cement, steel, aluminum, and glass, should be modeled as a function of the numbers and types of new energy production facilities, because the material requirements of future pathways can differ substantially (Pauliuk et al., 2017). Simultaneously modeling materials flows, process emissions, and the economic factors affecting expansion of certain industries (as in, for example (Cao et al., 2019) and (IEA, 2019)) is an approach more analysts should consider. Similarly, CCS for industrial sector process emissions should be tracked separately from energy-sector CCS.
3. **Electricity sector:** More detail on inputs and outputs to the electricity sector are also important, as electrification is a key component of many recent modeling exercises. With significant electricity generation being allocated to hydrogen production and power-to-gas in future scenarios, precise tracking is complicated but necessary. Care will be needed to ensure correct accounting and accurate characterization of energy supply losses for these technologies.
4. **Interactions between related sectors:** Scenario decomposition tools allow for more accurate characterization of iterations between linked sectors and technologies (like land-use, biofuels, biomass CCS, and agriculture) but consistent system boundaries and accurate data collection are essential to creating meaningful comparisons.

Decomposition tools can serve important diagnostic and research functions, but the results they produce are only as good as their input data. Understanding the inputs needed for comprehensive decomposition analyses can help researchers to organize and structure their models to produce the most useful results.

4.4. Integrating decomposition analysis into the modeling process

We built our decomposition tools in Microsoft Excel because they grew out of earlier work that used that platform (Hummel, 2006). As our work has progressed, we've come to realize that only tools that can be run by the modeling teams themselves and fully integrated into their workflows will gain wide acceptance and use, and that precludes an Excel model run by third parties. For this reason, we are turning our attention to creating an open-source Python library that will allow modelers to generate the decomposition results as part of their modeling process, integrated with tools now under active development by IIASA and other modeling groups (Huppmann et al., 2021). We hope that this effort will result in much more widespread use of these diagnostic analytical tools and speed up the process of scenario design, creation, and implementation.

5. Conclusions

Stabilizing global temperatures at well below 2 C will require immediate and sustained emission reductions, as well as retirement of fossil capital before it reaches its accounting lifetime (IPCC, 2022). The two scenarios we examine, while each aggressive in its own ways, contains only a subset of the possibilities. Modeling is a human process. Scenario analyses reflect the strengths, weaknesses, and knowledge of the modeling teams that create them.

Articles summarizing analyses contain different views of their results, but because each modeling team chooses what to emphasize, it is difficult to compare results across studies in a consistent fashion. Developing standardized comparison tools and integrating them into modeling workflows is one way to enable more rapid cross-study comparisons.

The modeling community should consider and implement ways to speed up comparisons and harmonization among modeling efforts, and funders should support this vital work, because it will allow us to identify more potentially promising pathways than we would be able to do in the absence of such efforts. Consistent comparisons of scenario drivers using systematic analytical tools can enable harmonization of resource potentials, technology costs, and deployment rates. With improved analytical tools, we are hopeful that scenario comparison exercises like the ones our decomposition tools enable will help inform development of rapid emissions reduction policies in the future.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jonathan Koomey, Koomey Analytics reports financial support was provided by World Resources Institute.

Acknowledgements

We are grateful for the financial support of World Resources Institute for this work. Many colleagues contributed comments, insights, and/or data along the way, including four anonymous reviewers, Tim Duane, Oliver Fricko, Arnulf Grübler, Mathijs Harmsen, Nate Hultman, Holmes Hummel, Daniel Huppman, Dan Kammen, Florentin Krause, Volker Krey, Amory Lovins, Glen Peters, Keywan Riahi, Joeri Rogelj, Simon De Stercke, Sven Teske, Detlef van Vuuren, David Victor, and John Weyant. Any errors are the responsibility of the authors.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envsoft.2022.105426.

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