Universitat Autònoma de Barcelona

The end of energy abundance: Embracing biophysical limits to a low-carbon energy transition

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Summary

There is broad scientific consensus that to avoid catastrophic climate change, global warming should be stabilised well below 2 °C compared to the pre-industrial period. Alarmingly, the window of opportunity to bring down greenhouse gas emissions in line with this objective is rapidly closing. Existing climate mitigation literature agrees that the time when gradual emission reductions could address the issue of climate change is over, and that nothing short of a profound transformation of the energy system, economy, and lifestyles is required to accomplish the necessary emission reductions.

Multiple scenarios have been produced by integrated assessment models (IAMs) that explore different mitigation avenues to accomplish a low-carbon energy transition. In this thesis, I analyse whether existing scenarios adequately represent biophysical constraints to the transition. Moreover, I explore if existing scenarios consider the full range of mitigation options to reduce emissions, and whether the scenarios assume adequate energy to enable a flourishing life for all. Finally, I discuss potential implications that a transition to a low-carbon energy system may have for the economy.

Existing mitigation scenarios estimate emissions and energy pathways that would be compatible with limiting global warming to 1.5–2 °C. However, at present, these scenarios do not estimate the amount of energy needed to build and maintain a low-carbon energy system, nor the amount of greenhouse gas emissions that would be associated with such a transition. This is a major gap in the literature, as it remains unclear how much of the remaining carbon budget would be tied to the transition, and how much of it would effectively remain for society to produce goods and provide services using fossil fuels. I calculate that the emissions associated with the transition could range from 70 $GtCO_2$ to 395 $GtCO_2$, with a cross-scenario average of 195 $GtCO_2$. This corresponds to approximately 0.1 °C of additional global warming.

I show that the transition could drive up the energy requirements of the energy system and may require a decrease in per capita net energy use of 10%–34% during the initial push for the transition. Nonetheless, in contrast to what has been argued in previous studies, a low-carbon energy transition would not necessarily lead to a decline in the Energy-Return-on-Energy-Invested (EROI) of the overall energy system in the long-term.

I conclude that a continued growth in energy use may be incompatible with the goal of avoiding dangerous climate change. Although use of negative emissions technologies may unlock additional energy from fossil fuels, the overall increase in available energy may be exaggerated in existing scenarios, due to overestimation of realistic mitigation potential and disregard of the high energy requirements of these technologies. Furthermore, use of negative emissions technologies may decrease the efficiency of energy provisioning to society, leading to increased economic expenditure for energy.

The conclusion that a low-carbon energy transition may limit the prospects of growth in energy use raises concern, as energy is a key requirement to produce goods and services. How do existing mitigation scenarios address the socioeconomic implications of this energy constraint?

I find that existing mitigation scenarios perpetuate the striking inequalities of energy use between the Global North and Global South. Lack of equitable convergence is further underlined by the scenarios that assume negative emissions. Although these scenarios allow for higher global energy use, the additional energy is overwhelmingly allocated to the countries in the Global North, which have the highest per-capita energy consumption. Moreover, existing mitigation scenarios do not consider that limits to energy growth may have a negative effect on the economy. On the contrary, mitigation scenarios typically assume economic growth is to increase in the future, despite lower energy use. To square economic growth with decreasing energy use, mitigation scenarios assume rapid and unprecedented improvements in the efficiency of energy use in the global economy. However, feasibility of accomplishing such improvements has been fiercely contested. To explore if there are alternative pathways to accomplishing a low-carbon energy transition, I outline a series of scenarios that assume lower rates of global economic growth. I demonstrate that lower economic growth makes it possible to accomplish sufficient emission reductions with more moderate energy efficiency improvements and a slower build-up of a low-carbon energy system. I discuss the concerns regarding negative implications that lower growth may have on social wellbeing and the ability to pay for the transition. I argue that post-growth policies focused on wealth redistribution may lead to desirable social outcomes without compromising the aim of avoiding dangerous climate change.

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Academic achievements are often attributed to one person alone, which I adamantly reject. While it may be true that I am the main protagonist in this story, none of my achievements would be possible without the indispensable support of family, friends, colleagues, and the broader community to which I belong.

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Chapter 1
Introduction

Climate change is widely recognised as one of the greatest threats of our times (European Commission, 2019). The goal to stabilise the rise in global temperatures to well below 2°C has been written into the Paris Agreement (UNFCCC, 2015), which lays out the framework for global mitigation action. Nevertheless, decades of research and awareness-building about climate change's impacts have produced little success as global emissions continue to rise. Despite all the talk of pulling the emergency brake on the use of fossil fuels, the foot is still firmly pressing the accelerator. The absence of meaningful climate action has made it increasingly challenging to stay on the path of the goals of the Paris Agreement. The 2022 IPCC report on *Mitigation of Climate Change* affirms that to limit global warming to 1.5 °C (2°C), global emissions must be reduced by half (quarter) by 2030 (IPCC, 2022a). Achieving such emission reductions will require a profound decarbonisation of our economies, lifestyles and energy systems (IPCC, 2018a). How would a society that has succeeded in avoiding dangerous climate change look? More importantly, what pathways of a low-carbon energy transition can lead us there?

This thesis assesses the existing literature on mitigation scenarios and investigates whether these scenarios adequately capture the range of possible low-carbon energy transitions, and if not, which feasible alternatives are left unexplored? The standpoint from which the scenarios are analysed is a combination of biophysical and socio-economic constraints to a low-carbon energy transition that may forestall or limit the range of possible transitions. Here, the biophysical constraints are best described by a combination of geophysical and ecological responses to the rising greenhouse gas concentrations in the atmosphere, which define the number of emissions that can be emitted before exceeding the global warming threshold inscribed in the Paris Agreement. Socio-economic constraints refer to society's capacity to accomplish a low-carbon energy transition. The overlap of biophysical and socio-economic constraints defines the possibility space for a low-carbon energy transition. Here, I study a low-carbon energy transition in relation to these constraints to reflect on a recurring question in the debate on scalability and sustainability, which is: can the global society keep biophysical and ecological limits in check only by changing energy technologies that power the energy and economic systems, or must it also limit energy use and economic production to accomplish a low-carbon energy transition?

The introduction begins with an overview of the epistemological frameworks used in the thesis, followed by a presentation of four main research questions. Finally, the introduction concludes with a summary of the chapters that are organised around the respective research questions.

1.1 Theoretical approaches and methods

My contribution to the literature on low-carbon energy transitions mainly draws from the theoretical foundations of ecological economics, which approaches sustainability by analysing material and energy exchanges between nature and the economy. However, methods of ecological economics have yet to be developed into a model that can integrate the analysis of multiple dimensions of social and natural systems.

To address this methodological gap, I develop an ecological economics model that estimates the flows of energy and emissions associated with a low-carbon energy transition and use this model to reanalyse the scenarios produced by integrated assessment models (IAMs), which currently do not represent biophysical flows. By estimating energy and emissions associated with a low-carbon energy transition, I analyse how the existing mitigation scenarios may change after considering the transition's biophysical requirements. Moreover, I explore how existing scenarios may change if their socio-economic developments were modelled from the assumption of lower economic growth and equitable convergence in the global economy.

1.1.1 Ecological economics

Ecological economics is a transdisciplinary field of research focusing on the interrelationships between the human economy and natural ecosystems. Ecological economists see the economy and nature as much more intertwined than commonly conceptualised in mainstream economics, which values nature for the resources it provides and for its capacity to absorb waste and pollution (Røpke, 2004). Ecological economists reject the ontological separation of nature and the economy, emphasising that human economy is "embedded in nature" (Røpke, 2005). According to ecological economists, the mainstream analysis of the economy in terms of monetary flows offers only a superficial description of economic processes, as it overlooks the underlying biophysical base of energy and matter. Moreover, ecological economists reject the appreciation of nature according to the inputs of production it can provide to the economy but emphasise the intrinsic values of healthy and resilient ecosystems, which form the basis of biophysical provisioning systems (O'Neill et al., 2018). Instead, they argue that biophysical provisioning systems cannot be replaced with human capital and therefore warn that the deterioration of ecosystems may decrease nature's capacity to support life on Earth (Costanza, 1989).

1.1.1.1 Core ideas of ecological economics

Ecological economics emerged as a separate thread of economic thought in the late 1960s and early 1970s, an era of profound change in both science and geopolitics, which have decisively shaped the core assumptions of ecological economics. Beginnings of ecological economics coincide with early warnings of growing environmental pressures from industrialisation and their dangers for ecosystems and human health, with arguably the most notable work of that time being The Silent Spring (Carson, 1962). The Limits to Growth, published by the Club of Rome, argues that the industrial era, marked by the exponential growth of resource use and wealth generation, may soon come to an end due to the fast-approaching exhaustion of resources and growing impacts of pollution (Meadows et al., 1972). This was also the beginning of the post-colonial era when former colonies won sovereignty over their economic affairs but failed to improve the living conditions of their citizens, which raised questions about the possibilities of prosperous global development. Finally, the oil crisis of 1973, which marks the end of the era of cheap fossil energy, highlights energy's importance for the economy and brings the topic of energy resource scarcity to the heart of ecological economics.

1.1.1.1.1 Limits to growth

Since its beginnings, the principal argument of ecological economics has been the notion of limits to the growth of the human economy. Ecological economists argue that since the biosphere is limited in space, energy and matter, the fact that the economy is embedded within the biosphere means the size of the economy must be limited as well (Boulding, 1966; Daly, 1992). Economic activity is constrained by the finite availability of natural resources and the negative implications of waste and pollution. Although industrial production can become more efficient over time, this cannot eliminate the problem of waste and pollution, as all final goods deteriorate over time and thereafter enter the waste stream (Ayres and Kneese, 1969).

The notion of limits is still at the centre of the debate between ecological economists and their mainstream counterparts as it outlines their different perceptions of the severity of the ecological crisis and the availability of possible solutions. Contrary to mainstream economists who believe that clean technologies and pollution pricing can sufficiently reduce environmental impacts from economic activity, ecological economists argue that these efforts are bound only to be successful if they form a part of a broader developmental shift away from the growth-oriented industrialised economy. The scepticism of ecological economists originates from the fact that the current economy dramatically exceeds the planetary boundaries within which the human economy can sustainably operate (Rockström et al., 2009). For the global economy to stay within these boundaries again, it would have to break with the historical relationship between economic growth and growing demand for materials, energy, and pollution. The possibility of a sufficient absolute decoupling whereby the economy continues to grow while the demand for resources and pollution steadily decline year after year is a dubious proposition, given limited evidence of it happening anywhere in the world (Brockway et al., 2021; Hickel and Kallis, 2020).

This thesis addresses the notion of limits in terms of a low-carbon energy transition. *Chapters 2* and *3* are dedicated to investigating how much energy could be provided to society as the energy system moves away from fossil fuels. *Chapter 5* focuses on illustrating scenarios of lower economic growth to explore the possibility of achieving emission reductions consistent with the Paris Agreement without the unprecedented decoupling of economic growth from energy use. *Conclusions* integrate the findings to deliberate on how the transition may constrain the economic prospects for continued expansion.

1.1.1.1.2 Redundance of economic growth in the pursuit of human well-being

The notion of limits to the scale of the human economy is deeply unpopular with mainstream economists, who argue that a world of limits to economic growth is inevitably a world dominated by poverty and deepening inequalities (Milanovic, 2017; Roser, 2021a). The conception that growth is a prerequisite for well-being originates from the post-war period of high growth, which saw the establishment of the modern welfare state.

Ecological economists reject the framing of growth as the panacea for solving the issues of poverty and inequality. The past two decades of growth have resulted in minor improvements in the global indicators of social-wellbeing, yet have substantially increased the overshooting of the planetary boundaries (Fanning et al., 2021). Meanwhile, in many high-income countries, the economy already provides enough for a decent life for all (Dietz and O'Neill, 2013; Jackson, 2016). The proposition that good life is not dependent on growth is supported by the life-satisfaction surveys, which reveal that citizens of high-income countries do not perceive their lives to improve with the growth in income over time (Easterlin et al., 2010). Rather than depending on income growth, people's life satisfaction varies depending on their relative social position.

If scarcity is not the root cause of poverty, the solution cannot be found in more growth but in a more equal distribution of resources. Unfortunately, recent studies reveal staggering levels of global inequality in terms of access to energy services (Oswald et al., 2020). However, on a positive note, the exuberant energy use of the world's richest 5%, which use more energy than 50% of the world's poorest combined, means that with the right set of redistributive policies, the current size of the energy system can provide more than enough energy for decent living conditions for all (Millward-Hopkins, 2022; Millward-Hopkins et al., 2020).

Chapters 4 and 5 of this thesis approach the question of growth and wellbeing by investigating how energy trajectories for the Global North and the Global South in existing mitigation scenarios compare to the decent energy threshold. I outline a post-growth scenario of equitable convergence to explore if sufficient energy for decent living can be provided to everyone in circumstances of lower global energy availability.

1.1.1.2 Estimating the biophysical throughput of the economy

Inspired by thermodynamics, ecological economists conceptualise the interrelationships between nature and the human economy by analysing the energy and material throughputs of the economic system (Daly, 1968; Georgescu-Roegen, 1986). Accordingly, they approach sustainability research by investigating the scale of energy and material requirements of the economy and exploring how this scale compares with the ecosystems' capacity to replenish resources extracted and absorb waste from the economy.

Different accounting methods have been developed to quantify the biophysical throughput of the human economy. One notable example is the material and energy flow analysis (MEFA) which traces biophysical flows along commodity supply chains by adhering to the mass-balance principle, which stipulates that the mass of resource inputs must equal the sum of accumulated stocks and the ensuing flow of waste (Haberl et al., 2019). MEFA offers a framework to analyse the economy's dependence on different resources and the associated generation of waste (Steinberger et al., 2013). Another widely used approach is the life-cycle analysis (LCA), which aims to encompass the environmental impacts associated with products in different stages of their lifespan (from cradle to grave) (Arvesen et al., 2018). Finally, net energy analysis investigates the importance of energy systems for the economy by looking at the efficiency of energy provision from the primary energy stage, where energy resources are extracted, to the useful energy stage, where energy is used to perform work for society (Murphy and Hall, 2010). Ecological economists believe that mainstream environmental economics' focus on the gross energy supply misses the main purpose of energy systems: to facilitate energy services to society and not to extract energy (Cleveland et al., 1984). Energy return on energy invested (EROI) is used to analyse the efficiency of energy provision to society by comparing the net energy available to perform useful work with the energy requirements of the energy system to extract, convert, and deliver the net energy to the society (Lambert et al., 2014).

In *Chapters 2 and 3* of this thesis, I apply the net energy analysis to calculate the EROIs of different energy technologies and the overall energy system. I compare the EROIs in different scenarios of a low-carbon energy transition to assess the efficiency of energy provision compared to the present-day efficiency and estimate how much net energy will be available to society.

1.2 Integrated assessment models

Integrated assessment models (IAMs) have been used prominently in the IPCC literature to produce a range of possible climate mitigation scenarios (IPCC, 2018b, 2022a) and have been instrumental in informing the public about possible solutions to climate change. These scenarios explore a range of socio-economic and technological responses in different sectors of the economy and across different global regions to limit global warming (Riahi et al., 2017; Rogelj et al., 2018).

IAMs are designed to study interactions between society, the biosphere and climate. At the heart of IAMs is a model of the socio-economic system, which features the evolution of the human population (KC and Lutz, 2017), and the economy in terms of the Gross Domestic Product (GDP) (Dellink et al., 2017; Leimbach et al., 2017). Population and economic activity in the models are linked to the energy and food systems, which are modelled in terms of energy (Bauer et al., 2017) and land use (Popp et al., 2017). Environmental impacts from human activities are represented in the models by greenhouse gas emissions and other pollutants linked to the climate system's global warming response (Meinshausen et al., 2011).

IAMs produce mitigation scenarios based on socio-economic narratives, which describe how social and economic systems develop in the future. These storylines are developed into quantitative indicators that guide the models' representation of socio-economic developments. IAMs are then used to analyse the implications of specific socio-economic developments for energy, land use, and environmental impacts.

The primary purpose of mitigation scenarios is to anticipate mitigation challenges associated with socio-economic developments and analyse policies that could reduce emissions. IAMs approach the design of mitigation scenarios by estimating the cost-optimum deployment of different mitigation solutions to meet the relevant climate targets (McCollum et al., 2018). Therefore, resulting emissions and energy pathways represent scenarios where adequate emission reductions can be achieved at the lowest mitigation cost.

While cost-optimisation of mitigation costs in scenarios is advantageous, as it may help guide the policymakers to prioritise the mitigation policies by order of their effectiveness, it glosses over challenges of the transition which are not related to financial requirements but go back to material and energy resources required to transform the energy system. The origin of this problem runs more profound in that existing IAMs do not account for the biophysical requirements of a low-carbon energy transition (Capellán-Pérez et al., 2019; Pauliuk et al., 2017; Sgouridis et al., 2016). Moreover, IAMs typically emphasise mitigation solutions at the production end of the economic and energy systems but tend to underestimate demand-side solutions, which require structural changes in the economy and lifestyles (Creutzig et al., 2018; Pye et al., 2021). Finally, IAMs do not consider the impediments from different political and social views of the transition that may not always be compatible with cost-optimal mitigation solutions (Riahi et al., 2015).

There is a broader issue here, which concerns a limited representation of mechanisms of socio-economic developments in IAMs. For example, changes in energy use and food prices are typically one of the few modelled socio-economic indicators. At the same time, other critical developmental indicators such as GDP, income distribution, and population are, in fact, not modelled but are pre-defined by the underlying assumptions of scenario narratives and therefore do not change due to climate impacts and changes to energy supply. Moreover, the scope of narratives considered in existing scenarios is limited to the narratives that combine social and environmental sustainability with high economic growth (O'Neill et al., 2017), while narratives of ambitious sustainability at low economic growth are not considered (Otero et al., 2020). As a result, existing scenarios leave much of the possible scenario space unexplored.

Despite their shortcomings, IAMs describe the fundamental implications of a low-carbon energy transition for the economy and climate. They represent a broad scope of possible mitigation policies, including demand-side solutions, which are compatible with the core beliefs of ecological economics. Here, I use the mitigation scenarios produced by IAMs as a data source for the analysis from the ecological economics perspective in all chapters. The aim of my analysis is then to estimate how these scenarios would look like and how they would benefit if they incorporated explicit modelling of biophysical flows.

1.3 How to partition the remaining carbon budget?

1.3.1 The “safe” level of global warming

Climate scientists have debated the extent to which global warming can be accepted without risking disastrous consequences for humanity since the early 1990s. The difference in opinion essentially came down to the choice between the limits of 1°C or 2°C of global warming above pre-industrial levels.

The 1°C goal was defended following the evidence suggesting a collapse of polar icecaps (Hansen et al., 2008), and the destruction of most vulnerable ecosystems, such as coral reefs and wetlands (Frieler et al., 2013; Rijsberman and Swart, 1990) at the higher temperatures. Accordingly, the 1°C and the corresponding atmospheric concentrations of CO_2 of 350 ppm (particles per million) were defined by some scientists as the boundary for a safe operating space for humanity (Rockström et al., 2009). Moreover, in international climate diplomacy, the target has been defended for a long time by many developing nations (World People’s Conference on Climate Change and the Rights of Mother Earth, 2010), including the small island states (The Alliance of Small Island States, 2015), whose existence is threatened by the rising seas.

On the other side of the debate, the limit of 2 °C was typically framed as a balanced objective between the costs of mitigation and climate damages (Stern, 2007). The problem with the 1°C target, it was argued, is that it was not feasible politically. Moreover, even extreme emission reduction measures could not ensure meeting the 1°C goal, as such warming may have been unavoidable already by the committed warming from historical emissions in the 1990s (Rijsberman and Swart, 1990). Contrary to the 1°C, the 2°C target was considered achievable, as it allowed for more gradual emissions reductions in the developed countries like the EU, which was an adamant supporter of this target at the international climate summits (European Union Council, 2010). However, some scientists recognised 2°C as the upper limit beyond which grave damage to ecosystems and non-linear response of the climate system was expected to increase rapidly (Parry et al., 2001; WGBU, 1995).

Ultimately, the rationale for the 1°C threshold has faded as the accelerated global warming broke through the respective temperature threshold by the time of the Paris climate summit (Dvorak et al., 2022) when 2°C became the defining limit for climate mitigation. The Paris Agreement features the pledge to pursue efforts towards limiting global warming to 1.5°C. However, this was arguably to appease the developing nations, as current global mitigation is critically insufficient even to meet the 2°C target (Matthews and Wynes, 2022), yet alone the 1.5 °C that is likely to be exceeded by 2035 (IPCC, 2022b).

1.3.2 Remaining carbon budgets

The amount of emissions that can still be emitted to meet the Paris Agreement targets depends on the present state of global warming and the climate system's sensitivity to the additional emissions (Millar et al., 2017).

IPCC reports that the average global temperature from 2011 to 2020 was 1.1 °C higher than the pre-industrial average (IPCC, 2022b). To this value, we must add the committed future warming, estimated at 0.2 °C (Dvorak et al., 2022), which specifies by how much the climate is expected to heat up before the mean global temperature and the enhanced global heating reach an equilibrium, assuming that fossil-fuel emissions were suddenly cut to zero (Mauritsen and Pincus, 2017). In other words, the committed future warming tells us how much global warming is already in the pipeline. Furthermore, it implies that the margins of additional warming that would still be consistent with the targets of the Paris Agreement are smaller than it seems from the point of present-day global warming.

The climate system's response to the increased greenhouse gas concentrations in the atmosphere determines the link between the temperature and emissions, which is commonly illustrated by the concept of the carbon emissions budget. The carbon budget tells us how much anthropogenic greenhouse gas emissions can still be emitted into the atmosphere before we exceed a specific global warming temperature (Peters, 2018), assuming no additional feedback to the climate system will be triggered by increasing temperatures that could accelerate global warming (Rogelj et al., 2019). The biophysical limit of the carbon budget is then estimated from the near-linear historical response of global warming to the cumulative amount of anthropogenic CO_2 emissions (Tokarska and Gillett, 2018; Van Vuuren et al., 2016), whereby the Earth tends to warm up by 0.1 °C for every 220 gigatonnes of CO_2 emitted ($GtCO_2$) (Damon Matthews et al., 2021). The remaining carbon budget in 2020 is estimated at 500 $GtCO_2$ for 1.5 °C and at 1150 $GtCO_2$ for 2°C of global warming above pre-industrial values (IPCC, 2022a). At the current annual emissions of 40.5 $GtCO_2$, these carbon budgets would be “spent” in 12 and 28 years, respectively. However, the size of the carbon budget could be smaller or bigger than suggested by the numbers above, depending on the mitigation of non-CO_2 emissions, such as methane and black carbon (Rogelj et al., 2015b).

Carbon budgets are typically framed as a fixed biophysical constraint on anthropogenic emissions. However, the amount of anthropogenic emissions can exceed the value of the carbon budget through negative emissions that remove CO_2 from the atmosphere (Kriegler et al., 2018). In theory, if society accomplished net negative emissions, where negative emissions would exceed the positive anthropogenic emissions, global warming could even be reversed (Zickfeld et al., 2016); however, questions remain regarding the ecosystem and ocean feedback on reduced CO_2 that may reduce the effectiveness of negative emissions (Jones et al., 2016; Tokarska and Zickfeld, 2015). Even if substantial negative emissions could be realised, this would only relax the constraint of the carbon budget and not eliminate it.

1.3.3 Emissions associated with the transition

If the carbon budget sets the limit to total anthropogenic emissions, the question is how to approach the reduction of emissions. Existing mitigation scenarios allocate the remaining emissions between a few large sectors of the economy, such as industry, transportation, and agriculture, by estimating the costs of mitigation in each of these sectors and pursuing the most cost-effective way to accomplish the required emissions reductions (Klein et al., 2014; Riahi et al., 2021).

In doing so, existing scenarios describe the transition from the perspective of how the remaining carbon budget could be partitioned between different sectors of the economy. However, they do not break these budgets into specific economic activities, goods, and services (Mastrucci et al., 2020). While providing a valuable illustration of the mitigation challenge across the economy, the scenarios do not estimate how much economic activity in each sector will be directed towards a low-carbon energy transition and what implications the transition may have for societal energy use.

This is a critical blind spot in existing scenarios, as a rapid build-up of low-carbon energy infrastructure and a significant overhaul of energy-consuming devices, gadgets, and utilities will require a substantial amount of energy and could result in major emissions since the current energy system is dominated by fossil fuels (Di Felice et al., 2018; Heinberg and Fridley, 2016) (see Figure 1.1). Therefore, a common interpretation of the carbon budget as the amount of emissions that can still be emitted before we accomplish the transition to net-zero emissions misses out on an essential point: if a substantial part of the carbon budget needs to be used for the transition to a net-zero society, the amount of carbon that can be emitted for consumption and that is not directly related to the transition may, in reality, be much lower.

To address this research gap, *Chapter 2* includes calculations of how much emissions will be associated with a low-carbon energy transition and how much CO_2 could still be emitted from other energy uses. I find these emissions to be substantial, and conclude that they impose a tight constraint on the emissions from energy use during the transition.

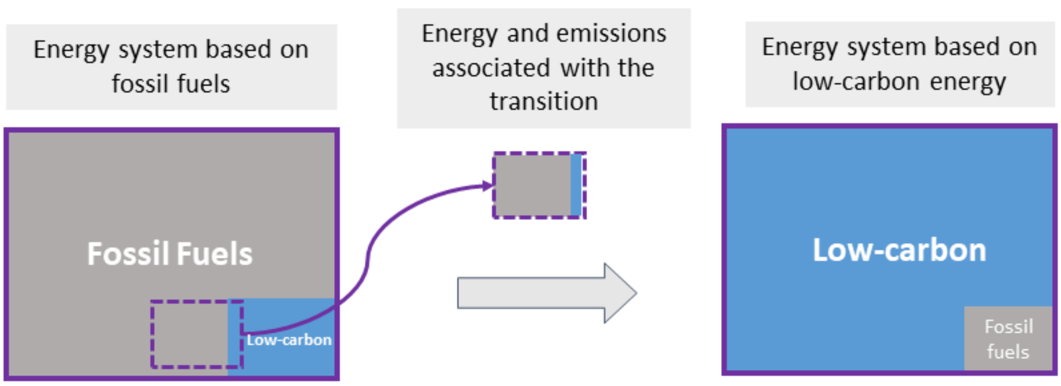

Figure 1.1: Transition to a low-carbon energy system (on the right) will itself result in CO_2 emissions because the energy required to build the low-carbon infrastructure and to produce low-carbon machines and gadgets, such as electric vehicles, will come from the energy system that is still dominated by fossil fuels (on the left).

1.4 How to transform the energy system?

The literature on climate mitigation covers several mitigation options to reduce carbon emissions from energy, including decarbonisation of energy generation, improved efficiency of energy use, adoption of low-energy and low-carbon lifestyles, and deployment of negative emissions (Warszawski et al., 2021). The first option aims to reduce the carbon intensity of energy generation, the second and the third options envision measures to decrease energy demand, and the fourth option is assumed to offset the remaining carbon emissions.

From an engineering point of view, the energy system's decarbonisation appears straightforward. If the root cause of global warming is carbon dioxide emitted due to the widespread use of fossil fuels from energy generation, the solution to the problem is to substitute fossil fuels with alternative energy technologies that emit low or, preferably, no emissions. Three types of "clean" energy generation technologies can play a part in a low-carbon energy transition: renewables, nuclear energy, and fossil fuels with carbon capture and (CCS) storage.

Renewables and nuclear energy emit no emissions when generating energy, meaning they could become *zero-carbon technologies*, if no carbon were emitted during the construction, operation and maintenance of these energy technologies. The exception here is renewable bioenergy, which emits carbon during biomass combustion. However, bioenergy can be carbon neutral over the long term if an equal amount of carbon emitted is captured by the regrowing vegetation. Likewise, fossil fuels with CCS can be considered a low-carbon technology, provided they remove most of the emitted CO_2 in combustion and then store it in geological deposits (Herzog, 2018). Besides low-carbon and zero-carbon technologies, there are also negative emissions options. Negative emissions capture CO_2 from the atmosphere to offset positive emissions from fossil fuels, allowing for a less dramatic reduction of emissions from fossil fuels (Rosen, 2018).

Even though renewables, nuclear energy, and biomass technologies have been available for decades, the average annual growth of all these low-carbon energy technologies from 2010 to 2020 of 1.2 EJ per year has been outpaced by three times faster growth in fossil fuels (IEA, 2021a). The problem, to be precise, is not that the global economy is still dependent on fossil fuels but that it has become increasingly dependent on fossil fuels. Therefore, a decisive shift towards a low-carbon energy system is needed. However, how could such an energy system look in terms of energy technologies used and the scale of energy it could generate?

1.4.1 Transition to a renewable energy system

The principal obstacle to a rapid transition to renewables is society's dependence on fossil fuels, which has been established by centuries of the utilisation of fossil fuels and the fundamental role they played in industrial and urban development (Smil, 2017). As a result of such a historical trajectory, existing infrastructures, established social norms, and provision of services in the economy largely depend on reliable fossil fuel supply. Integrating renewables into a system designed to run on fossil fuels is challenging, as the renewables generate electricity but are not helpful in producing liquid fuels or gases required in the infrastructures and machines running on combustion engines. The imperfect substitutability of fossil fuels and renewables (Kaya et al., 2017) pulls society to remain locked into relying upon infrastructures and act within the choice architectures designed for fossil fuels for as long the infrastructure is adjusted and people adapt their lifestyles to the options that can be provided in a low-carbon energy system (Creutzig et al., 2022).

Transitioning to a renewable energy system requires overarching electrification of energy services (Kriegler et al., 2014). However, contrary to conventional energy systems, which can adjust energy supply in real-time by varying the combustion of fuels in power plants, renewable energy is obtained from variable flow resources of sun, wind, and water, the availability of which changes over time with natural conditions. Therefore, to provide a reliable energy supply, a renewable energy system must store the surplus of energy generated during favourable natural conditions. and supply the energy stored when the natural flows of renewable resources are insufficient to meet the demand.

While 100% renewable energy systems are already used in self-sufficient energy systems for small communities, opinions diverge if this could be upscaled to the general energy system. Some authors claim that building a 100% renewable energy system is conceivable and cost-effective (Bogdanov et al., 2021; Jacobson et al., 2018), but others raise concerns about the feasibility of building sufficient energy storage, pointing to the fact that most storage solutions in these studies are based on unproven technologies (Clack et al., 2017), and that the material requirements required for currently available storage solutions (in the form of lithium batteries) would exceed all the known mineral reserves of lithium globally (Renner and Giampietro, 2019). Similar concerns were identified concerning the reserves and mining capacity of “rare-earth” minerals required for low-carbon energy generation, as the supply of these minerals is unlikely to match the speed at which renewables must be built to replace fossil fuels (Garcia-Olivares et al., 2012; Valero et al., 2018). Moreover, new mining projects and big energy projects are often opposed by the public due to the adverse social and environmental impacts of mineral extraction and land-grabbing (Lèbre et al., 2020), suggesting that renewables are not an unlimited source of energy and that a low-carbon energy transition may require the society to adjust to lower energy availability.

In theory, the drawbacks of renewables could be lessened by expanding the use of nuclear energy. However, the existing scenarios, on average, assume nuclear energy to represent only 8% of the total final energy in 2100 (Huppmann et al., 2019). Moreover, nuclear energy is unlikely to become a significant driving force of a low-carbon energy transition because it is a complex technology with substantial upfront costs and long construction times. Only a few companies worldwide have the knowledge and equipment to construct and supply nuclear fission power plants, making it difficult to increase the production of nuclear fission reactors even if there is a global rise in demand. Furthermore, nuclear power plants typically take over a decade to construct, so even an ambitious global initiative to promote nuclear energy would not have any impact on global emissions by 2035, which may be too late to meet the goals of the Paris Agreement.

1.4.2 Decarbonisation by relying on CCS and negative emissions

IAMs typically do not model a low-carbon energy transition as a transition to a 100% renewable energy system but use a broader range of low-carbon technology options, which include fossil fuels with CCS and negative emissions. The main advantage of including these technologies in the energy supply mix is that they allow for a more gradual reduction of fossil fuels and therefore reduce the risks of disruption in the provision of energy services. These disruptions are of particular concern for the sectors of aviation, steel and cement production (Davis et al., 2018; Luderer et al., 2018), where renewable electricity cannot replace fossil fuels in all of the industrial processes and activities. Moreover, using fossil fuels for electricity generation makes it easier to balance supply and demand by decreasing the need for energy storage.

Even though fossil fuels with CCS are direct substitutes for conventional fossil fuels, this technology requires substantial investments in infrastructure, as the existing systems would have to be retrofitted with the facilities for capturing, transporting, and storing carbon. Furthermore, CCS can only be extended to industrial users of fossil fuels but cannot be used in small combustion engines used in buildings and transportation. An additional limiting factor of CCS technologies is that they are not a zero-carbon technology, as they can only capture up to 90% of emissions from the combustion of fossil fuels (Sgouridis et al., 2019). Overall, CCS technologies are more costly and carbon-intensive than renewables (Babacan et al., 2020; Hertwich et al., 2015), which diminishes their deployment potential in a low-carbon energy transition constrained by a limited carbon budget.

This leaves us the option of expanding the carbon budget with negative emissions. In addition, negative emissions could be used to offset fossil fuels from challenging economic activities to decarbonise (Rogelj et al., 2015a). However, numerous researchers have objected to the large-scale reliance on negative emissions in existing mitigation scenarios, as the technologies that would allow negative emissions to become a game-changer for mitigation have not yet been proven to work at relevant scales (Anderson and Peters, 2016). Furthermore, relying on large-scale use of negative emissions is risky, as it may lock us into overshooting the Paris goals if large-scale reliance on negative emissions proves unfeasible (Realmonte et al., 2019). Finally, large-scale reliance on negative emissions has been associated with significant sustainability risks, including biodiversity loss (Heck et al., 2018), increased pollution with nitrogen and phosphorus (Humpenöder et al., 2018), and high requirements for energy and material resources (Chatterjee and Huang, 2020), revealing that negative emissions may shift impacts from climate change to other environmental problems. Due to the risks and unreliability of negative emissions, the consensus has been building up that these technologies should not be considered as a substitute for low-carbon energy technologies but rather a complementary mitigation option if negative emissions become viable and socially acceptable (Warszawski et al., 2021). However, the question remains of how much negative emissions could realistically be achieved without deleterious negative impacts. I deliberate on the issue of the scalability of negative emissions in *Chapter 3*.

1.4.3 Improving energy efficiency

Existing scenarios suggest the critical difference between a transition towards a 100% renewable energy system and a transition incorporating fossil fuels with CCS and negative emissions is the energy system's size. Scenarios describing a transition to a 100% renewable energy system assume global energy use to decrease (Grubler et al., 2018; Keyßer and Lenzen, 2021) or to be maintained at the present-day level of energy use (Van Vuuren et al., 2018a). Meanwhile, scenarios that assume a large-scale use of CCS and negative emissions project continued growth in energy use (Fuhrman et al., 2020; Kriegler et al., 2017).

A low-carbon transition to renewables is associated with less energy being available because the growth rates of renewables, assumed to be achievable in the scenarios, cannot match the speed at which the use of fossil fuels needs to decrease during the transition to keep the emissions within the carbon budget (Krey et al., 2016). Therefore, only a large-scale deployment of negative emissions and CCS can unlock the extra energy from fossil fuels and thus avoid decreasing energy supply during a low-carbon energy transition.

Lower energy availability could speak against the transition towards renewables, given the historical precedence of economic downturns following the periods of energy supply shortages in the 1973 and the 1978-1979 periods. However, existing scenarios avoid the negative impacts on the economy because they assume major energy efficiency gains that allow the economy to grow despite the lower energy availability (Grubler et al., 2018). To accomplish a lower energy demand, scenarios assume a dramatic change from historical improvements in energy intensity (energy use per unit of GDP), from -1.5% per year (the average from 2010 to 2020), to less than -4.0% per year during the next decade (Heun and Brockway, 2019).

Yet, the scenarios are as ambiguous as they are ambitious in explaining how such dramatic energy efficiency improvements are to be accomplished. Often, the underlying assumptions in scenarios only refer to efficiency improvements in energy technologies and buildings, therefore leaving a series of complementary demand-side solutions, as described in the “avoid-shift-improve” framework, underexplored (Creutzig et al., 2018; Pye et al., 2021). Moreover, the scenarios do not account for rebound effects that tend to undo most technologically driven efficiency gains (Brockway et al., 2021; Exadaktylos and Van Den Bergh, 2021). For example, the scenarios represent efficiency improvements in transportation by assuming the technological switch from a petrol to an electric car but ignore the possibility of reducing energy demand by shifting to a more efficient organisation of transportation, for example, by increasing access to public transportation, or by incentivising behavioural changes that could decrease the demand for mobility (Brand et al., 2019).

1.4.4 EROI and net energy during the transition

Another problem is the definition of energy efficiency used in existing scenarios which refers to the generated value (in GDP) per unit of energy used, therefore only describing the efficiency from the point of energy consumption. By framing energy efficiency as to how much energy is required to produce economic value, scenarios overlook the implications of losses and energy requirements for the energy system to maintain energy supply to society.

While this may not have been a critical oversight so far, as the energy system has remained unchanged for decades, a low-carbon energy transition implies a complete overhaul of the system towards low-carbon technologies with different capital, labour, and energy requirements than the existing fossil fuel technologies. As a result, there are concerns that low-carbon technologies may have a lower energy return on energy invested (EROI) compared to fossil fuel technologies, meaning the low-carbon energy system could take up a more significant share of energy generated and leave less net energy for societal consumption (Castro and Capellán-Pérez, 2020; King and Van Den Bergh, 2018).

Risks of a declining EROI of the energy system during the transition are uncertain, as some researchers argue that a low-carbon energy transition could bring society close to the minimum EROI required for industrialised society (Capellán-Pérez et al., 2019; Sers and Victor, 2018; Trainer, 2018), while others argue the EROI is unlikely to change substantially (Brockway et al., 2019), or may even increase in the future (Steffen et al., 2018). The high stakes of the EROI during the transition commend the net energy research for being incorporated in future mitigation scenario analyses.

In this thesis, I compare different low-carbon energy technologies in terms of their implications on the possible energy futures that are compatible with the goals of the Paris Agreement. The key question that I address is: how much energy would be available to society under different mitigation scenarios during the transition? *Chapter 2* of this thesis explores whether a low-carbon energy transition leads to an inevitable reduction in the net energy available to society and if the substitution of fossil fuels with low-carbon alternatives could result in a decline in the EROI of the energy system. To do so, I calculate the energy requirements of different energy technologies over time and measure the share of the total energy going for the energy system. In *Chapter 3*, I estimate by how much the deployment of negative emissions could increase the energy available to society during the transition and analyse the impacts of such technologies on the efficiency of energy provision.

1.5 Energy for whom?

One of the biggest challenges of the energy transition is to square the sustainable development goal of preventing dangerous climate change (UN, 2015a), with the aim of providing sufficient energy for decent living conditions to all global citizens (UN, 2015b). Two factors make this challenge difficult to overcome. First, the existing inequalities in energy use, as the world's wealthiest 5% of individuals use more energy than the poorest half of the global population combined (Oswald et al., 2020). Second, the limits to increasing energy use, as the energy available to society could be limited due to the insufficient capabilities of building-up low-carbon energy infrastructure to replace fossil fuels and the significant energy requirements of negative emissions options.

These constraints may leave the current approach of increasing energy access by growing energy generation unfeasible to continue during the transition. Instead, what may be necessary is to share the energy generated more equitably by reducing the energy use of the most affluent consumers to allow the energy use of the world's poorest to increase above the decent living energy threshold per capita, estimated at ~20 gigajoules per year (Kikstra et al., 2021; Millward-Hopkins et al., 2020). In theory, this goal can be accomplished, as the global average per-capita energy use of 55 gigajoules per year exceeds the minimum threshold by almost three-fold. However, it would require an ambitious global convergence in energy use (Grubler et al., 2018; Kuhnhenn et al., 2020).

Reducing energy consumption from the world's most affluent to allow access to essential energy services to the world's poorest may support climate mitigation action. While the provision of basic needs is found to be only weakly correlated with emissions (Rao et al., 2014; Steinberger et al., 2020), the same cannot be said about growing affluence that is typically associated with high-energy and high-emissions consumption choices (Wiedmann et al., 2020).

In *Chapter 4*, whose development was led by Jason Hickel, I investigate to what degree these scenarios represent the futures where energy use of the world's poorest increases above the threshold of decent living energy.

1.6 Is post-growth conducive to a low-carbon energy transition?

Existing scenarios associate ambitious mitigation with high economic growth (Dellink et al., 2017; Leimbach et al., 2017), in fact, all the scenarios in the IPCC literature that manage to stabilise global warming at 1.5–2 °C are scenarios of high economic growth. However, there are several problems with the link between economic growth and successful climate outcomes, which diminish the useability of existing scenarios to inform policymakers on the low-carbon transition.

First, existing scenarios assume a direct relationship between economic growth and mitigation capacity on grounds that growth drives the research and development of advanced mitigation technologies (Calvin et al., 2017; Kriegler et al., 2017; O'Neill et al., 2017). However, ambitious mitigation can also be pursued with existing technologies, such as renewables, trains, and bicycles. Moreover, mitigation depends not only on the development of new technologies but also on consumer lifestyles and climate policy factors that are independent of economic growth. Finally, substantial emission reductions can be accomplished via behavioural shifts, such as the adoption of sustainable diets (Bodirsky et al., 2022; van Vuuren et al., 2017).

Second, existing scenarios associate lower growth with high mitigation challenges (Fujimori et al., 2017). However, most of the challenges assumed in these scenarios, such as high population growth, low education, and low priority for environmental action, are unrelated to economic growth. As shown in most high-income countries, conditions of low population growth, high education, and high priority for environmental action can just as well occur at lower economic growth (Burgess et al., 2021).

Third, the growth rates realised over the past fifteen years do not resemble those assumed in existing scenarios. Suppose we consider the recent trend in the ageing demographics and accumulating debt. In that case, long-term effects from the pandemic and supply shortages, an upward swing in the GDP rate in the years to come seems a doubtful proposition at best (Burgess et al., 2020). However, the coming years also happen to be the last chance to bend the emissions curve in line with the pledges of the Paris Agreement. Irrespective of whether scenarios of lower growth are desirable or not, they may represent a likely circumstance in which the future of our planet will be decided. It would be irresponsible not to explore the possibilities of a low-carbon energy transition in a lower-growth world, as asserting that ambitious mitigation is impossible for as long as the global economy continues to stagnate may lock us in the path towards dangerous climate change.

Finally, by associating a low-carbon energy transition with high growth outcomes, existing scenarios represent only one side of the ongoing argument in the community of climate mitigation researchers. As my fellow co-authors and I pointed out in the article *Urgent need for post-growth scenarios* (Hickel et al., 2021a), IPCC scenarios only represent the narratives that assume significant absolute decoupling between the emissions and growth, even though the possibility of sufficient absolute decoupling has been contested at length in the literature (Haberl et al., 2020; Hickel and Kallis, 2020; Parrique et al., 2019). Meanwhile, the other side of the debate, represented by the post-growth (Jackson, 2019), degrowth (Kallis et al., 2020) and sufficiency (Millward-Hopkins et al., 2020) literature, is still omitted from the scenarios of successful mitigation produced by IAMs, despite the fact that these narratives have been common-place in the climate mitigation debate since "The Limits to Growth" was published in 1972. Moreover, multiple variants of conceptual low-growth scenarios have been developed that could be extended into a climate mitigation scenario, such as the "Post-growth" scenario by Nieto et al. (Nieto et al., 2020), the "Beyond economic growth" scenario by Otero et al (Otero et al., 2020), and the "Degrowth" scenario by D'Alessandro et al. (D'Alessandro et al., 2020).

To address this research gap and analyse the difference that low-growth scenarios could make, I explore in *Chapter 5* a range of low-growth scenarios that combine the assumption of lower growth rates with different levels of climate action. Finally, I deliberate on possible socio-economic challenges presented by a low-growth transition and outline post-growth policies that could make it possible to accomplish emission reductions and desirable social outcomes without economic growth.

1.7 Preview of the chapters

In *Chapter 2*, I reveal the concern that a low-carbon energy transition may itself become a substantial source of emissions, as the energy required to build the low-carbon infrastructure, machines and gadgets will come from the current energy system based on fossil fuels. I, therefore, ask the question: how much of the remaining emissions are tied to the low-carbon energy transition, and how much of these emissions are left for the provision of energy services from fossil fuels? The analysis in this chapter provides an in-depth review of different avenues of a low-carbon energy transition explored in the literature. I identify the size of the energy system and the choice of different low-carbon technologies to be the key differentiating characteristic between alternative transitions. I reveal that the growth in energy generation needs not to be reflected in an equal growth in energy to perform useful work for society. Finally, I argue that existing scenarios wrongly conflate energy generation with net energy available to society because they do not model how much generated energy needs to be used to build up and sustain the energy system.

My analysis suggests that a low-carbon energy system need not have a lower EROI than the existing energy system based on fossil fuels. However, as assumed in most of the existing scenarios, a rapid build-up of low-carbon energy infrastructure may face substantial constraints, as it would require a major shift of energy towards the renewable industries, leaving less energy for other sectors. Moreover, I find that substantial use of negative emissions leads to a long-term decline in the EROI of the overall energy system.

In *Chapter 3*, I extend the analysis by investigating what impact would a large-scale deployment of negative emissions have on the net energy for society. I find that a realistic carbon sequestration potential from negative emissions options tends to be significantly overestimated in existing scenarios. In contrast, the energy requirements for negative emissions tend to be underestimated. As a result of substantial energy requirements for negative emissions, the amount of net energy delivered to society in these scenarios is much lower than the total energy generated. As a result, the 21st century may mark the end of growth in energy use, irrespective if the transition is directed towards a 100% renewable energy system or large-scale use of fossil fuels with CCS and negative emissions.

In *Chapter 4*, I turn from the analysis of future energy availability to the question of future energy distribution between different global regions. Current global energy generation could provide sufficient energy services for a decent life for all citizens if distributed more equally. I then explore if existing mitigation scenarios represent the futures of equitable energy convergence.

Finally, in *Chapter 5*, I deliberate on the relationship between economic growth and emissions. Existing scenarios see low-carbon transitions to be viable only under the conditions of high economic growth. However, the global economy after the financial crisis of 2008-2009 has been characterised by a gradual decline in global economic growth, a trend which may continue over the coming years. To expand the range of conceivable low-carbon transitions, I design a series of low-growth mitigation scenarios and show that in conditions of lower economic growth, adequate emissions reductions could be within reach of the existing climate pledges.

Chapter 2
Energy requirements and carbon emissions for a low-carbon energy transition[1]

Abstract

Achieving the Paris Agreement will require massive deployment of low-carbon energy. However, constructing, operating, and maintaining a low-carbon energy system will itself require energy, with much of it derived from fossil fuels. This raises the concern that the transition may consume much of the energy available to society, and be a source of considerable emissions. Here we calculate the energy requirements and emissions associated with the global energy system in fourteen mitigation pathways compatible with 1.5 °C of warming. We find that the initial push for a transition is likely to cause a 10–34% decline in net energy available to society. Moreover, we find that the carbon emissions associated with the transition to a low-carbon energy system are substantial, ranging from 70 to 395 $GtCO_2$ (with a cross-scenario average of 195 $GtCO_2$). The share of carbon emissions for the energy system will increase from 10% today to 27% in 2050, and in some cases may take up all remaining emissions available to society under 1.5 °C pathways.

[1] This chapter corresponds to the article: Slameršak, A., Kallis, G. & O'Neill, D.W. Energy requirements and carbon emissions for a low-carbon energy transition. *Nat Commun* **13**, 6932 (2022). https://doi.org/10.1038/s41467-022-33976-5

2.1 Introduction

The IPCC's Special Report on Global Warming of 1.5 °C concludes that we can still meet the 1.5 °C target, and that by doing so we would reduce climate impacts and limit the risk of exceeding the tipping points of the climate system (IPCC, 2018b). The report provides a range of low-carbon energy pathways compatible with limiting global warming to 1.5 °C. However, at present, there is no estimate of how much energy would be needed to build and maintain a low-carbon energy system, or what amount of greenhouse gas emissions would be associated with such a transition (Daly et al., 2015; McDowall et al., 2018; Scott et al., 2016). This is an important gap in knowledge, as previous research suggests that rapid growth of low-carbon infrastructure could use a substantial amount of the global energy supply (Carbajales-Dale et al., 2014; Sgouridis et al., 2016). Moreover, since the global energy supply is currently derived mostly from fossil fuels, the transition itself may become a source of significant emissions (Di Felice et al., 2018; Heinberg and Fridley, 2016).

Some studies suggest that renewables have a lower energy return on energy invested (EROI) compared to the current energy system (Capellán-Pérez et al., 2019; Trainer, 2018). Lower EROI implies less energy delivered to society relative to the energy required to supply the energy, leading these studies to conclude that a low-carbon energy transition may result in less energy available to society. The energy required for the transition might push society into an "energy–emissions trap", where achieving ambitious climate mitigation could lead to a period of reduced energy availability (Jackson and Jackson, 2021; King and Van Den Bergh, 2018), and at the same time also consume a large share of the remaining carbon budget (Sers and Victor, 2018). Recent studies, however, find the hypothesis of lower energy availability might be exaggerated due to overestimating the EROI of fossil fuels (Brockway et al., 2019; Diesendorf and Wiedmann, 2020) and underestimating improvements in the EROI of renewable energy technologies (Louwen et al., 2016; Steffen et al., 2018).

Alongside EROI, life-cycle assessment is another accounting technique that has been used to quantify climate change impacts from different energy generation technologies. However, life-cycle studies typically only estimate the impacts of present-day energy technologies applied to a particular case study (Babacan et al., 2020; Berrill et al., 2016; Raugei et al., 2020). Life-cycle assessment has rarely been used in a dynamic analysis where the impacts of technologies change over time, or to assess the cumulative impacts of decarbonising the entire global energy system.

A notable exception is a study by (Pehl et al., 2017) who used a dynamic approach to estimate the energy requirements and emissions for the construction, operation, and maintenance of power plants. The authors combined a dynamic life-cycle assessment framework with an Integrated Assessment Model (IAM), estimating that emissions associated with power plants would lead to 82 $GtCO_{2eq}$ of cumulative emissions from 2010 to 2050. In another study, Di Felice et al. conducted a life-cycle assessment of the indirect emissions associated with the EU's renewable energy strategy, calculating that 25 $GtCO_{2eq}$ would be emitted in the decarbonisation of the EU's electricity generation from 2020 to 2050 (Di Felice et al., 2018). These studies, however, only cover electricity generation, which currently represents just ~20% of global final energy use. Moreover, each study only analysed one specific low-carbon pathway.

Here, we estimate how much energy would be required, and how much carbon would likely be emitted, to construct, operate, and maintain the global energy system during a low-carbon energy transition. Our study separates between the energy and emissions associated with the energy system, and the energy and emissions remaining for other societal uses. We thus provide complementary information to existing mitigation pathways. Moreover, by modelling dynamic changes in the EROI of the energy system in fourteen different mitigation pathways produced by six IAMs, we provide a holistic picture for a range of distinct energy transitions, all in line with the ambitious goal of stabilising global warming below 1.5 °C. We also assess the energy–emissions trap hypothesis, considering the latest literature on the EROIs of different energy technologies. In doing so, we follow a consumption-based accounting approach using an EROI analysis to estimate both direct (on-site) and indirect (upstream) energy use and emissions associated with constructing, operating, and maintaining the energy system and the energy supply for society. Based on our results, we suggest that the energy requirements and emissions should be explicitly modelled in the next generation of low-carbon mitigation pathways.

2.2 Results

2.2.1 Estimating energy requirements and emissions

We refer to the energy that would be required during a low-carbon energy transition as the "energy for the energy system" and the carbon that would be emitted as the "energy system emissions". Energy for the energy system includes the energy required for the construction (including decommissioning), operation, and maintenance of energy facilities like power plants, mines, and refineries as well as the energy required to transport the energy carriers from the point of extraction to the end user.

To estimate the energy for the energy system, we apply the method of net energy analysis, calculating energy return on energy invested (EROI) at the final energy stage. EROI at the final energy stage tells us how much of total final energy is used by the energy system to extract, process, convert, and deliver a unit of energy to the point of use for society (Castro and Capellán-Pérez, 2020; Murphy et al., 2011; Murphy and Hall, 2010). Net energy at the final energy stage is defined as the difference between total final energy and the energy for the energy system and represents the part of energy production that can be used for societal work (Carbajales-Dale et al., 2014). We calculate EROIs and the energy for the energy system for twenty-seven energy conversion technologies, which cover the entire energy system, from 2020 to 2100 (see Methods). We distinguish between four different energy carriers (electricity, gases, liquids, and solids), following the approach of Arvesen et al. (Arvesen et al., 2018). To obtain the share of energy for the energy system, we divide the energy requirements of the energy system by total final energy.

In our calculations, we combine a range of EROI estimates of present-day energy technologies (see Supplementary Figures 2.1 and 2.2 and Supplementary Table 2.1), with projections of future changes in EROI due to technological improvements that we estimate using energetic experience curves(Steffen et al., 2018). To account for the range of present-day estimates, the uncertainty of technological change, and resource availability, we report estimates of the energy requirements for each energy technology using low, median, and high EROI values representing the first, second, and third quartiles of the inter-quartile range of our estimates, respectively (see Methods). There is a divergence in EROI values in different studies, which can be traced to the distinct definitions of energy system boundaries, which can vary depending on the research objectives pursued (Palmer and Floyd, 2017). As a result, EROI values are often not directly comparable between different energy carriers and between different studies(Palmer, 2019). To address this shortcoming, we apply a consistent energy system boundary to all energy technologies. This boundary extends from the point of extraction (primary energy stage) to the point of use (final energy stage), as suggested by EROI analysts (Brockway et al., 2019; Raugei, 2019).

To represent a range of plausible EROI transitions, we develop three EROI scenarios. In the high-EROI scenario, we assume a fast increase in the EROI of renewables from the high end of present-day EROI values. In this scenario, we assume the EROI of bioenergy at the primary energy stage remains near the median of present-day values. This scenario can be interpreted as a future of high innovation and broad policy support for renewables, alongside efficient and sustainable harvest of biomass for energy. In the low-EROI scenario, we assume a gradual increase in the EROI of renewables from the median of present-day

EROI values, with the EROI of bioenergy remaining near the lower end of present-day values. Such a scenario corresponds to a future of moderate innovation and balanced policy support for renewables, and low efficiency in the management of bioenergy. In the median-EROI scenario, we assume a gradual increase in the EROI of renewables from the median of present-day EROI values, with bioenergy remaining near the median of present-day values. In all three scenarios, we assume a gradual decline in the EROI of fossil fuels at the primary energy stage from the present-day median value towards the present-day low-EROI value, in line with historical trends and the existing literature (Brockway et al., 2019; Dale et al., 2011; Sgouridis et al., 2016). For a detailed overview of the assumptions across all of the EROI scenarios see Supplementary Tables 2.2–2.7 and Supplementary Figures 2.1 and 2.2.

We calculate energy system emissions for different 1.5 °C–compatible mitigation pathways as the product of energy for the energy system and the carbon intensity of the energy system. We divide the energy for the energy system into four energy carriers that each have different carbon intensities, and distinguish between three life-cycle stages: construction, operation and maintenance, and decommissioning at the end of lifetime. The carbon intensity of energy carriers changes over time, primarily depending on the share of conventional fossil fuels (i.e. fossil fuels technologies without carbon capture and storage) in the energy mix of each carrier. By combining the effects of technological improvements in the EROIs of energy technologies with changes in carbon intensity due to the declining share of fossil fuels, we capture the dynamic evolution of carbon emissions associated with the energy system over time.

We illustrate our findings using the four illustrative pathways from the IPCC's Special Report on Global Warming of 1.5 °C*.* Three of these pathways were taken from the Shared Socioeconomic Pathways (SSP-1.9) scenario study (Rogelj et al., 2018), while one originates from the Low Energy Demand scenario (LED) (Grubler et al., 2018). These pathways represent the archetypes of different possible futures in terms of energy use, greenhouse gas emissions, and preferences for energy conversion technologies, yet all manage to stabilise global warming below 1.5 °C (see Table 2.1). LED and S1-A are pathways of rapid decarbonisation, achieved by phasing out more than 50% of fossil fuel energy by 2040, accelerating growth in renewable energy, and decreasing energy demand. S5-R is a pathway of slower decarbonisation, long-term growth in final energy, and large-scale carbon removal (which compensates for the higher emissions at the beginning of the transition). S2-M is a "middle of the road" pathway that combines decarbonisation with slow growth in final energy and moderate carbon removal. For a complete representation of different 1.5 °C–compatible futures, we also analyse ten additional pathways produced by Rogelj et al. (Supplementary Table 2.8), and present average values for all fourteen pathways (Rogelj et al., 2018).

Each pathway has different "total cumulative emissions", which depend on the quantity of carbon sequestration it includes (Peters, 2018). From the perspective that interests us here, the total cumulative emissions that are compatible with 1.5 °C of warming can be partitioned into energy system emissions and emissions for other societal uses. To obtain the share of energy system emissions in any given year, we divide energy system emissions by total emissions in that year (where the latter is obtained from the pathway data).

Table 2.1: The four IPCC illustrative pathways

Pathway	Scenario Assumptions	Energy Mix and Emissions
LED: Low Energy Demand (Grubler et al., 2018; IPCC, 2018b)	Moderate population growth. Moderate decrease in energy and material use. High innovation and fast adoption of sustainable technologies. Convergence to sustainable, low-carbon diets.	Average annual emissions reduction rate 2020-2040: 6.5% (rapid decarbonisation) Change in energy use (2020-2100): -44% Negative emissions from BECCS (2020-2100): 0 $GtCO_2$ Share of cumulative final energy (2020-2100): - Renewables: 42.8% - Nuclear: 6.9% - Fossil fuels: 37.3% - Bioenergy: 12.9%
S1-A: Sustainable Development (Riahi et al., 2017; Rogelj et al., 2018; van Vuuren et al., 2017)	Low population growth. Stable energy consumption and slow material growth. High innovation and fast adoption of sustainable technologies that improve energy efficiency. Convergence to low-waste and low animal share diets.	Average annual emissions reduction rate 2020-2040: 5.5% (rapid decarbonisation) Change in energy use (2020-2100): -7% Negative emissions from BECCS (2020-2100): 150 $GtCO_2$ Share of cumulative final energy (2020-2100): - Renewables: 44.1% - Nuclear: 5.6% - Fossil fuels: 39.9% - Bioenergy: 10.5%
S2-M: Middle of the Road (Fricko et al., 2017; Riahi et al., 2017; Rogelj et al., 2018)	Moderate population growth. Moderate growth in energy and material use. Gradual institutional and behavioural changes with slower technological innovation. Continuation of historical dietary transition trends.	Average annual emissions reduction rate 2020-2040: 5.0% (moderate decarbonisation) Change in energy use (2020-2100): +40% Negative emissions from BECCS (2020-2100): 415 $GtCO_2$ Share of cumulative final energy (2020-2100): - Renewables: 33.7% - Nuclear: 13.1% - Fossil fuels: 36.2% - Bioenergy: 16.9%
S5-R: Fossil-fuelled Development (Kriegler et al., 2017; Riahi et al., 2017; Rogelj et al., 2018)	Low population growth. High growth in energy and resource use. Delayed energy transition allowed by high innovation and large-scale adoption of negative emissions technologies. Diets with high animal shares and high waste.	Average annual emissions reduction rate 2020-2040: 3.8% (slower decarbonisation) Change in energy use (2020-2100): +76% Negative emissions from BECCS (2020-2100): 1190 $GtCO_2$ Share of cumulative final energy (2020-2100): - Renewables: 37.6% - Nuclear: 8.4% - Fossil fuels: 31.3% - Bioenergy: 22.8%

Note: The table summarises the fundamental assumptions and characteristics of the four alternative energy transitions that were selected as illustrative pathways in the IPCC's *Special Report on Global Warming of 1.5 °C*. The aim of the illustrative pathways is to show different possible futures that lead to a stabilisation of global warming. The pathways differ with regards to socioeconomic, behavioural, and technological assumptions. For the "SN-X" pathways, the number N refers to the scenario narrative from the SSPs, while the letter X denotes the model that produced a particular mitigation pathway. BECCS = bioenergy with carbon capture and storage.

2.2.2 Energy system emissions during the transition are substantial

We find that the cumulative carbon emissions associated with the energy system during the transition are substantial, and represent a considerable share of total cumulative emissions under different 1.5 °C–compatible scenarios (Figure 2.1). The fourteen-pathway average is 195 $GtCO_2$ for the median-EROI scenario, and ranges from 185 $GtCO_2$ for the high-EROI scenario to 290 $GtCO_2$ for the low-EROI scenario. These results correspond to an average of 21% of total emissions for the fourteen energy pathways under median-EROI assumptions, or 20% for high- and 31% for low-EROI assumptions.

Figure 2.1 shows the difference in cumulative energy system emissions among the IPCC's four illustrative pathways. Cumulative emissions for median-EROI values range from 70 $GtCO_2$ (12% of total cumulative emissions) for LED, which is a low-energy-demand/no-BECCS pathway, to 220 $GtCO_2$ (20% of total cumulative emissions) for S5-R, which is a high-energy/high-BECCS pathway. Generally, in slower decarbonisation pathways with higher energy use and higher deployment of BECCS, more carbon emissions are associated with the energy system during a low-carbon energy transition (see also Figure 2.3 and Supplementary Figure 2.3).

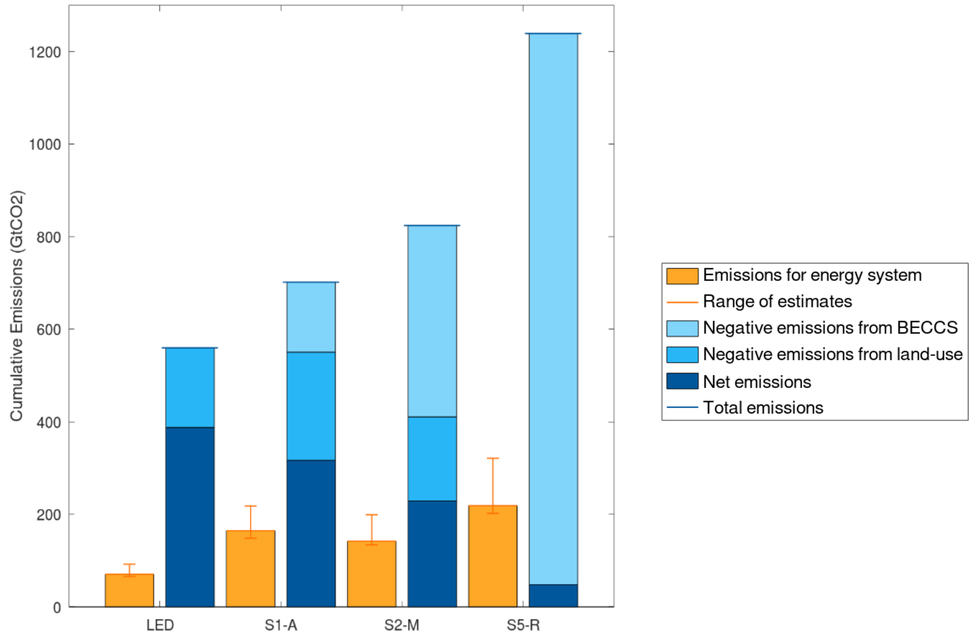

Figure 2.1: Energy system emissions for each of the four 1.5 °C illustrative pathways. Energy system emissions (orange columns) are compared to total cumulative emissions (blue columns). Orange whiskers indicate the range of energy system emissions from high- to low-EROI model runs. Net emissions in the atmosphere are equal to total emissions vented into the atmosphere minus carbon sequestration from BECCS and the land-use sector (AFOLU). Each pathway allows for different total carbon emissions (and hence different total cumulative emissions) as each pathway assumes different amounts of carbon sequestration and non-CO_2 greenhouse gas emissions. See Supplementary Figure 2.3 for all fourteen 1.5 °C pathways.

Energy system emissions become more important over time, as they take up an increasing share of total emissions, leaving less emissions for other uses in society. We estimate that the share of energy system emissions will increase to 2–5 times its current value by 2060, depending on different EROI assumptions (Figure 2.2). After 2060, the share of emissions stabilises in most pathways, as the pathways achieve a high degree of decarbonised energy. The share of emissions for the energy system in pathways S1-A, S2-M, and S5-R is much higher than in the LED pathway, which completely decarbonises its energy system. The fourteen-pathway average of energy system emissions increases from 10% of total emissions in 2006–2015 (for the median-EROI scenario), to 27% in 2050, and reaches 40% by the end of the century. For the low-EROI scenario, the share increases from around 12% in 2006–2015, to 39% in 2050, and 59% by the end of the century. In the high-EROI scenario the change is from 9% in 2006–2015 to 26% by 2050, and 31% by the end of the century.

The increase in the share of energy system emissions means that the decarbonisation of the energy system and energy supply is slower than the decarbonisation of the overall economy. A high share of emissions for the energy system may impose — particularly under the low-EROI scenario — a tight constraint on the “residual emissions” remaining for activities such as aviation, steel and cement production, and load-following electricity, which are difficult to decarbonise and currently generate approximately 9 $GtCO_2$ per year (Davis et al., 2018; Luderer et al., 2018). In the cases of some of the fourteen pathways, the energy system requires all of the residual emissions by 2080 under all three EROI scenarios — leaving no emissions for activities such as air travel, or steel and cement production.

A high share of energy system emissions in some of the pathways suggests the models may have been overly optimistic in their calculations of residual emissions. If this is the case, then the models need to either reduce the emissions allocated to other economic activities in society, or adjust their choice of energy technologies to reduce energy system emissions, as in the LED pathway. The pathways may be defended by assuming that technological innovation will make it possible to cut emissions to zero in the sectors that are difficult to decarbonise today. However, this assumption is highly speculative, given the essential role of fossil fuels in the production of steel and cement, which are critical materials in the economy (Arvesen et al., 2018; Hertwich et al., 2015).

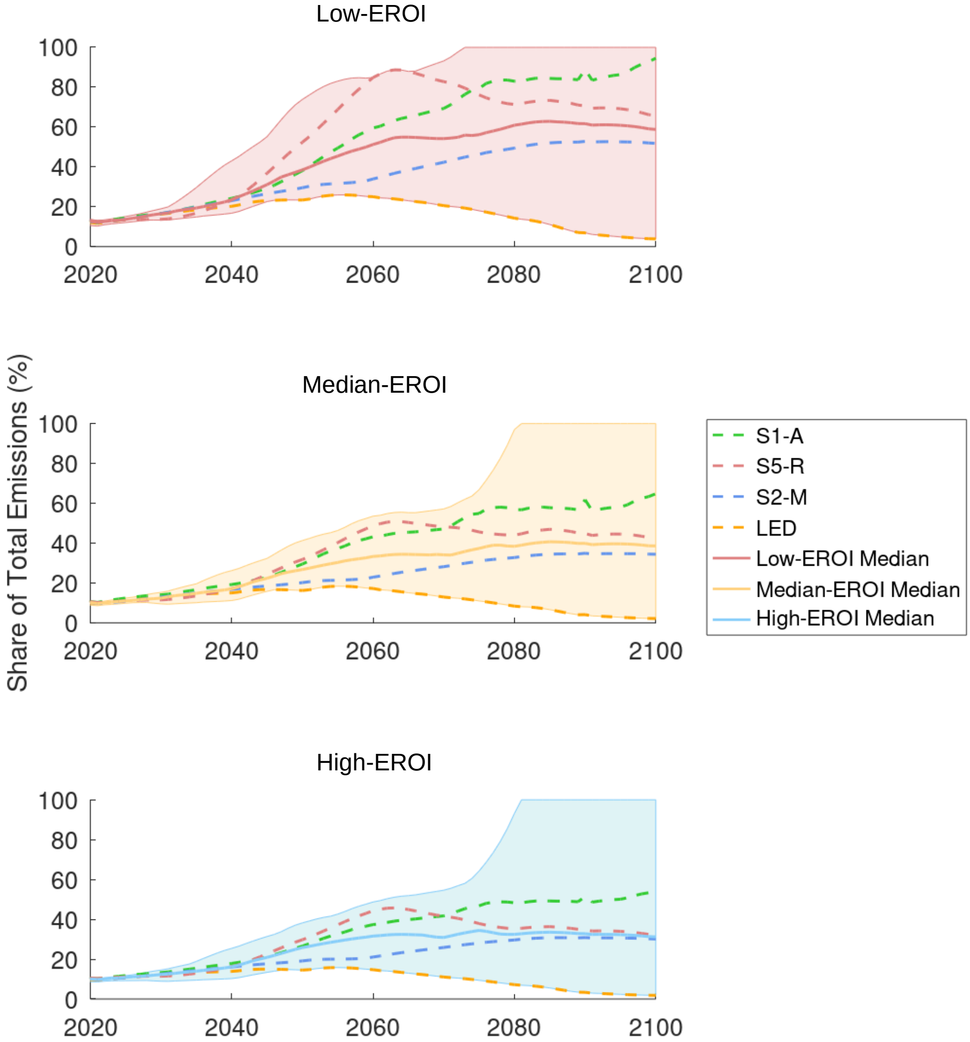

Figure 2.2: Share of energy system emissions over time, as a percentage of total emissions, for three different EROI scenarios (low, median, and high). In each plot, the solid line shows the median result of all fourteen pathways, while the result for each of the four illustrative pathways is plotted as a dashed line. The shaded envelopes show the full range of results for the fourteen pathways. If the values reach 100%, the energy system emissions exceed the total emissions in the respective pathway.

2.2.3 Energy transition leads to a small jump in emissions

Our results suggest that the upfront energy requirement to build a low-carbon energy system would only lead to a small jump in annual energy system emissions, with the most notable increase taking place in the pathways of higher energy use and continued reliance on fossil fuels beyond 2030 (e.g. S5-R; Figure 2.3). Average energy system emissions in the S5-R pathway from 2020 to 2030 are 4.0 $GtCO_2$ per year for the median EROI assumption, which is 1.0 $GtCO_2$ more than during the 2006–2015 period. Such an increase in emissions represents less than 3% of total carbon emissions in 2020, and does not undermine the target of keeping global warming below 1.5 °C.

Overall, the benefits of rapid decarbonisation far outweigh the extra emissions from the small jump. In pathways of rapid decarbonisation and lower energy use, the increase in emissions due to the upfront energy requirement of low-carbon infrastructure is small. In S1-A, emissions increase by only 0.6 $GtCO_2$ per year from 2020 to 2030 for the median-EROI scenario. Moreover, the phasing-out of fossil fuels leads to a rapid reduction in energy system emissions, starting as early as 2025.

Over the long term, the quantity of emissions depends on the amount of fossil fuels remaining in the energy system and the choice of low-carbon energy technologies in each of the pathways. Energy transitions that rapidly phase-out fossil fuels and prioritise renewables and nuclear energy over bioenergy technologies (BECCS in particular) achieve lower cumulative energy system emissions. The reason is that the emissions associated with renewables converge to zero (as in the LED pathway), while the emissions in pathways with BECCS only level off in the second half of the century (Figure 2.3). Pathways that combine an extended use of conventional fossil fuels with BECCS have higher energy system emissions, as they fail to completely decarbonise the energy supply. Moreover, BECCS is a low-EROI technology (see also Supplementary Table 2.1 and Figures 2.5-2.6). It has a low energy conversion efficiency and substantial energy requirements are associated with bioenergy supply (Fajardy and Mac Dowell, 2017, 2018). As such, BECCS has higher energy system emissions per unit of energy generated when compared to renewables (see Supplementary Figure 2.4).

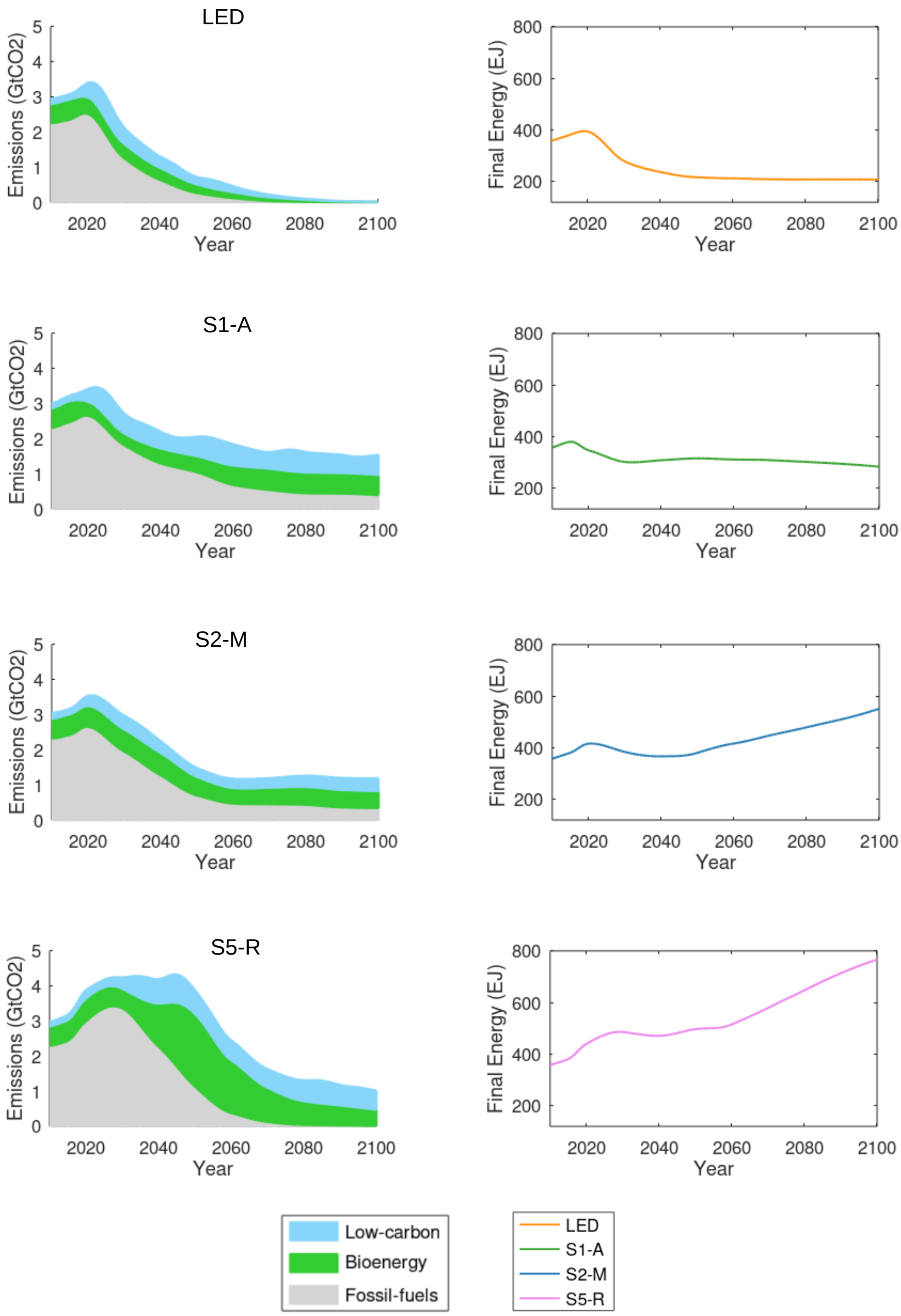

Figure 2.3: Energy system emissions and energy use in the four illustrative pathways. The left panel shows annual carbon emissions associated with the energy system under the median-EROI scenario. Energy system emissions are divided between three types of energy conversion technologies: fossil fuels, bioenergy, and low-carbon technologies that include renewables, hydrogen, and nuclear energy. The right panel shows the final energy consumption in the pathways.

2.3 Falling into the energy trap?

Our findings suggest that a low-carbon energy transition could drive up the share of total energy generation going towards the construction and operation of the energy system, and maintenance of the energy supply, compared to the current energy system. Consequently, a higher share of energy for the energy system would contribute to a decrease in net energy available to society. Depending on the mitigation pathway, the decrease in per capita net energy could be as low as 10% or as high as 34%.

2.3.1 Energy for the energy system

In pathways of lower energy use and rapid decarbonisation, the increase in the share of energy for the energy system would be most prominent during the initial push for the transition when the upfront energy requirements to construct low-carbon energy infrastructure would consume an increasing proportion of total final energy (Figure 2.4). In pathways of moderate and slower decarbonisation, the energy share increases during the second half of the century. The average share of energy for the energy system in the fourteen pathways for the median-EROI scenario during the 2020–2030 period is ~14%, with the highest increase occurring in the S1-A pathway, and the lowest in the S2-M pathway (Figure 2.4). A more substantial change is expected in the share of electricity for the energy system which can increase from the present-day value of 15% up to 25% (S2-A and S5-R pathways). The increase happens during the initial push for the rapid growth of these technologies, as the upfront electricity requirements for the manufacture of renewables consume much of the generated electricity.

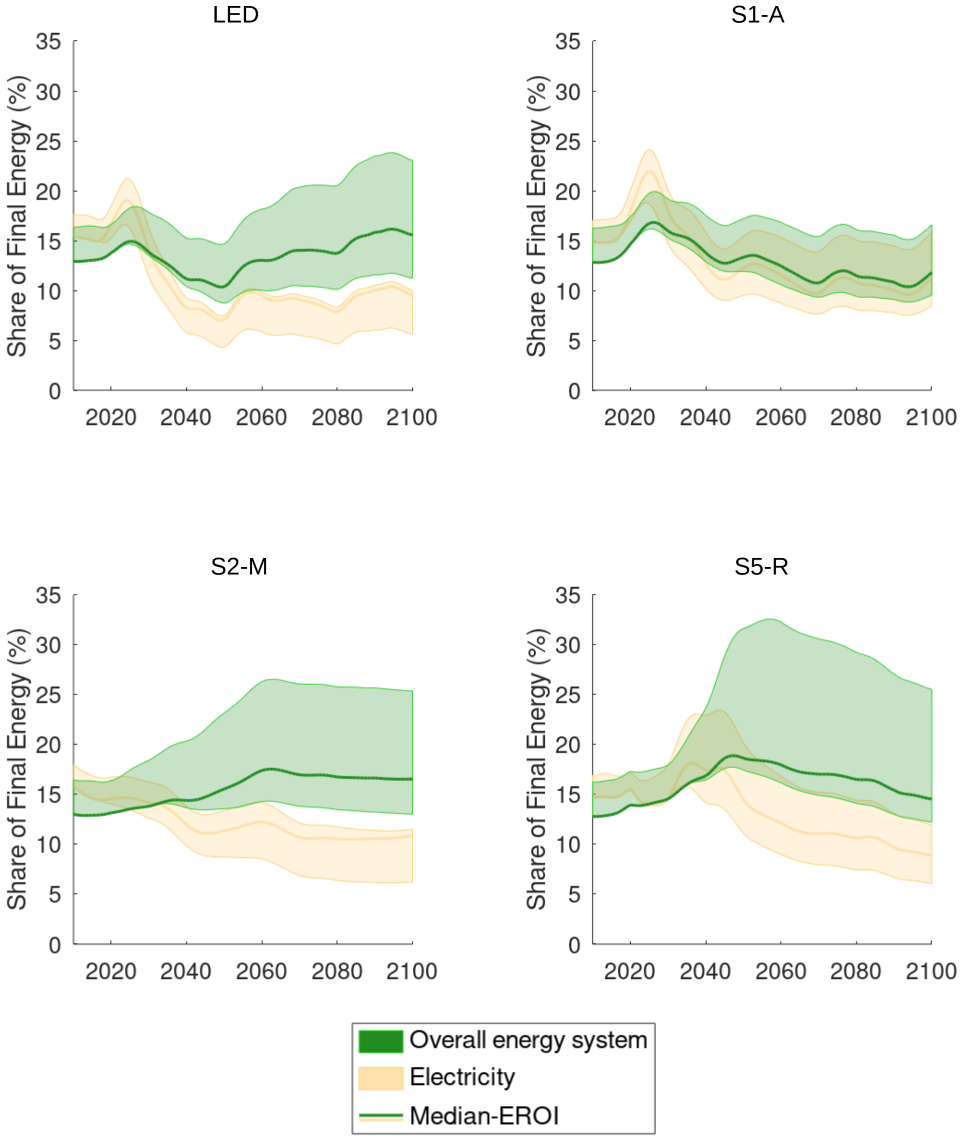

Figure 2.4: Share of energy for the energy system for the four illustrative pathways. The panel shows the share of the total final energy required for the energy system's construction and operation (in green). Additionally, the panel shows the share of final electricity required for the energy system (in yellow). All figures show a range of three estimates: high-EROI (upper boundary of the envelope), median-EROI (solid line), and low-EROI (upper boundary of the envelope).

2.3.2 EROI

In contrast to what has been argued in previous studies (Capellán-Pérez et al., 2019; Fabre, 2019; Jackson and Jackson, 2021; King and Van Den Bergh, 2018; Trainer, 2018), we find that a low-carbon energy transition would not necessarily lead to a decline in the EROI of the overall energy system in the long-term (green envelope plots in Figure 2.5). The EROI of the overall energy system depends on the choice of energy conversion technologies. EROI declines in pathways that prioritise bioenergy and fossil fuels with carbon capture and storage (e.g. S2-M and S5-R), and increases in pathways that focus on deploying renewable energy technologies (e.g. S1-A). The latter reflects the latest findings in the literature, which suggest that the EROI of renewable energy is comparable to (or higher than) the EROI of fossil fuels at present, and is likely to increase (Steffen et al., 2018), while the EROI of fossil fuels is likely to decrease (Brockway et al., 2019).

More substantial changes from the present-day values occur in the EROI of the two main energy carriers (Figure 2.5). The EROI of liquid fuels declines in the LED, S2-M, and S5-R pathways, as oil becomes increasingly substituted by biofuels which have a comparatively lower EROI. The exception is the S1-A pathway which does not assume the use of biofuels. Low EROI of liquid fuels during the transition means their production may require a similar amount of energy as the net energy these fuels provide to society. The EROI of electricity declines during the initial push for the transition. Findings reveal substantial differences in the EROI values of electricity between different power generation technologies (Figure 2.6). EROI values of low-carbon electricity decline during the initial push for a rapid expansion of these technologies, as the upfront electricity requirements for the manufacturing solar panels and wind turbines exceed the energy generated from the new energy infrastructure. However, this decline is only temporary as the EROI of low-carbon technologies increases rapidly only about a decade after their decline. Meanwhile, the EROI of fossil fuel electricity faces a gradual long-term decline provoked by a decreasing utilisation of fossil fuel power infrastructure and the declining EROI of fossil fuels at the point of their extraction. The EROI of electricity from bioenergy remains low throughout the transition and may drop below the EROI value of 1, meaning that these energy systems could use more energy to operate their energy supply chains than the amount of energy they deliver to society.

Our present-day EROI calculations are consistent with previous studies in the field (Figures 2.5 and 2.6), as only the EROI estimates of the two carriers from fossil fuels by Brockway et al. are higher than our present-day EROI estimates, which is due to methodological differences between our process-based approach and the input-output approach used by Brockway et al. (see the section "EROI estimates of different energy generation technologies" in Supplementary materials for more detail). In future projections, the EROI values vary between different illustrative pathways, demonstrating the critical effect of different endogenous modelling assumptions from different IAMs.

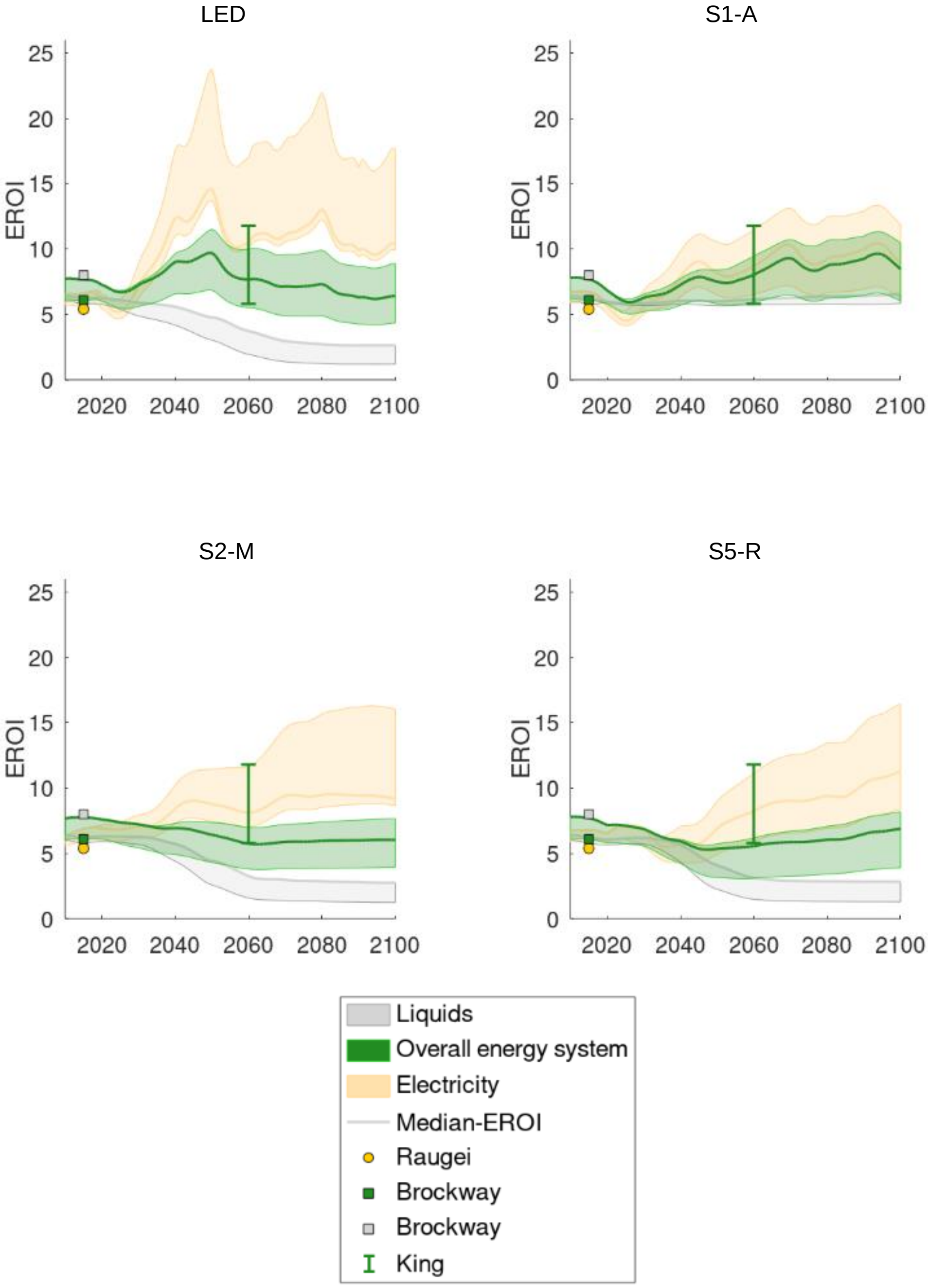

Figure 2.5: EROI of electricity, liquid fuels and the overall energy system for the four illustrative pathways. The panel shows the evolution of the EROI of the overall energy system and the energy carriers of electricity and liquid fuels (petroleum). All figures show a range of three estimates: high-EROI (upper boundary of the envelope), median-EROI (solid line), and low-EROI (lower boundary of the envelope). EROI estimates from peer-reviewed literature, summarised in Supplementary Table 2.2, are depicted next to our range of pathways.

Figure 2.6: EROI of different electricity generation technologies for the four illustrative pathways. The panel shows the evolution of the EROI of the various electricity generation technologies. Low-carbon electricity is provided by renewables and nuclear power. All panels show a range of three estimates: high-EROI (upper boundary of the envelope), median-EROI (solid line), and low-EROI (lower boundary of the envelope). EROI estimates from the peer-reviewed literature, summarised in Supplementary Table 2.2, are depicted next to our range of pathways.

2.3.3 Net energy

The net energy available to society declines in all of the pathways analysed, albeit at different rates and over different periods (Figure 2.7). In the S5-R pathway, the decrease is only temporary. Net energy primarily depends on the growth in final energy and less on the changes in energy for the energy system. Therefore, net energy declines substantially in pathways that increase energy for the energy system and reduce final energy. The global net energy per capita could drop by 14–16 gigajoules (28–34%) by 2030, compared to 2015, for pathways of rapid decarbonisation such as S1-A and LED.

Our results are similar to those of (King and Van Den Bergh, 2018), who estimated a 24–31% reduction in net energy per capita for the IEA low-carbon transition pathway. However, King and van den Bergh's reduction takes place over a more extended period (from 2015 to 2050). In contrast, our results indicate that a low-energy transition could lead to a significant reduction in net energy per capita in a single decade (Figure 2.7). In the pathways of slower decarbonisation (S2-M and S5-R), net energy per capita declines later, and by less, with a decrease of 10% by 2040 compared to 2030 in the median-EROI scenario. Net energy in these pathways only declines temporarily (until 2050), after which it returns to growth.

Considering the two main energy carriers, the initial push for the transition is associated with a rapid reduction in the availability of liquid fuels, which is only partly compensated by a growth in electricity available for society. In the pathways of rapid decarbonisation, net energy per capita from liquid fuels is estimated to decline by 5–10 gigajoules by 2030, while net electricity only increases by 1–2.5 gigajoules over the same period. Meanwhile, in the pathways of slower decarbonisation, a reduction of 4–6 gigajoules in liquid fuels is expected, while net electricity per capita could increase by 1.5–3 gigajoules. Electricity becomes the main energy carrier soon after the beginning of the transition (i.e., 2030), which confirms that all the scenarios assume widespread electrification of energy services throughout the economy.

All pathways suggest an inevitable decline in per capita net energy at the point of the most rapid overhaul of the energy system towards low-carbon energy. However, this finding does not mean that energy scarcity is an unavoidable feature of any low-carbon energy transition. The projected net energy decline during the initial push for the transition is not due to energy growth constraints in the models, but because the models assume more efficient energy use, which makes such pathways cost-effective (Grubler et al., 2018).

The prospect of more efficient energy use in society means that essential energy services such as heating, lighting, and transportation could still be provided even if less net energy were available. Access to essential energy services could be maintained in high-income countries and increased in lower-income countries at much lower net energy levels (Kikstra et al., 2021; Millward-Hopkins et al., 2020). Achieving a high quality of life could be possible at lower per-capita energy use by improving the efficiency of energy using technologies (e.g. by replacing gasoline-powered cars with electric cars), by shifting from consumption choices with higher energy intensities to options with lower energy intensities (e.g. from cars to bicycles), and by avoiding the most inefficient alternatives altogether (e.g. flying) (Creutzig et al., 2018).

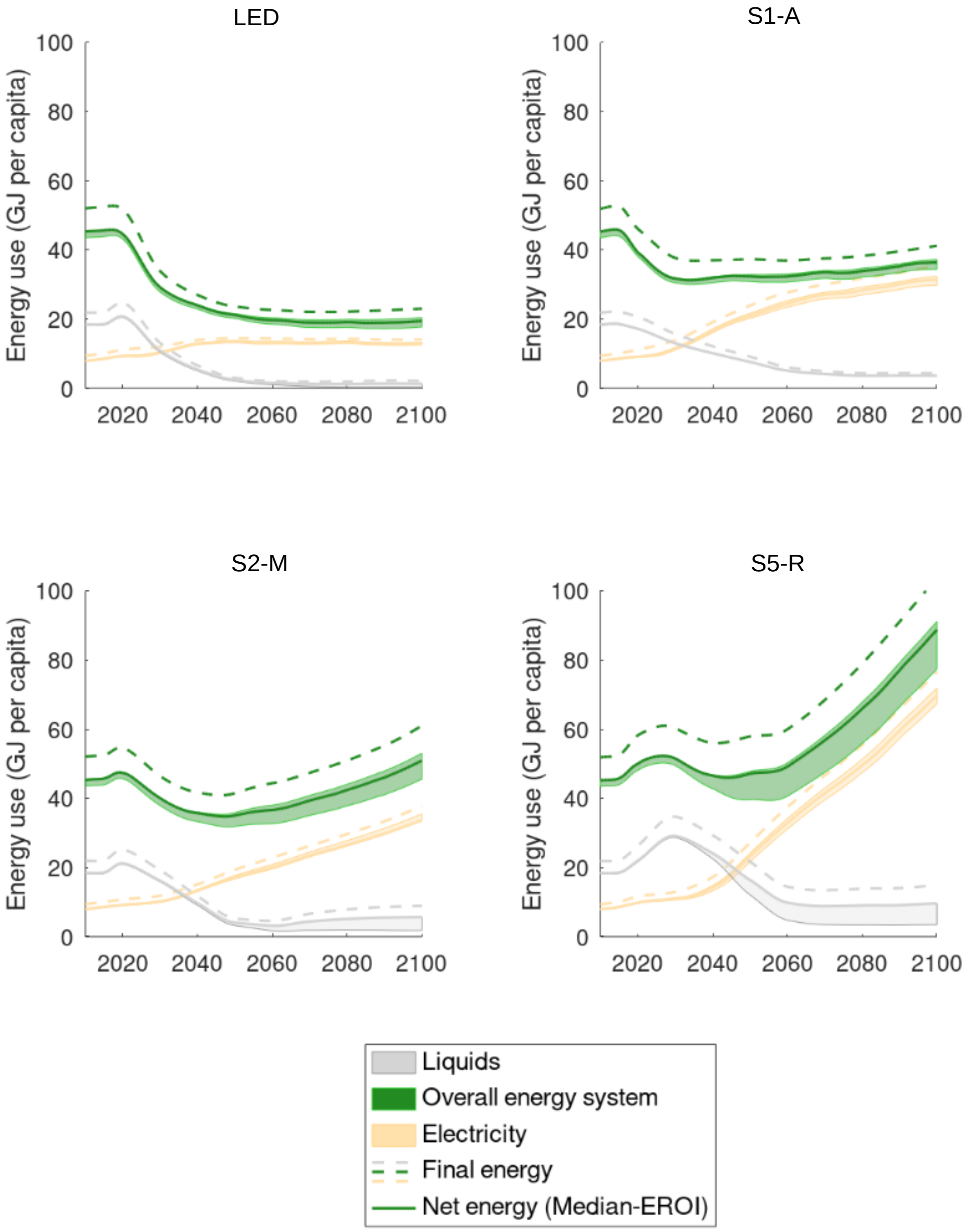

Figure 2.7: Net energy per capita in the four illustrative pathways. The panel shows the final energy per capita (dashed lines), and how much of it will be left for society as net energy per capita. The overall energy use (green) is depicted alongside the main energy carriers, which are electricity (yellow) and liquid fuels (grey). All panels show a range of three estimates: high-EROI (upper boundary of the envelope), median-EROI (solid line), and low-EROI (lower boundary of the envelope).

2.3.4 Factors driving energy system emissions

Our results suggest that energy system emissions are substantial, and increase as a share of total emissions over time. We use a panel data analysis (Supplementary Table 2.9) to analyse the underlying factors behind energy system emissions during the transition, while controlling for heterogeneity across the fourteen analysed pathways over time. Our analysis shows that energy system emissions depend on the growth in final energy use and the choice of energy technologies during the transition. A decrease in the overall EROI of the energy system contributes to an increase in energy system emissions during the initial push for the transition (from 2020 to 2040), but does not have a clear effect on emissions thereafter. The pathways that provide more energy to society have higher energy system emissions.

The different relationships in the two periods can be seen in Figure 2.8. The relationship between energy use and energy system emissions is particularly strong during the initial push for the transition (as shown by the orange markers in Figure 2.8a). From 2020 to 2040, a 100 EJ increase in annual energy use is associated with a 0.8 $GtCO_2$ increase in annual energy system emissions. The relationship weakens after 2040 as the energy system is gradually decarbonised (see blue markers in Figure 2.8a). From 2041 to 2100, the share of energy from fossil fuels is the most important factor contributing to energy system emissions (Figure 2.8b and Supplementary Table 2.9).

In theory, energy system emissions could be decoupled from the scale of the energy system completely by fully substituting fossil fuels with energy from renewables and nuclear energy (Sgouridis et al., 2016). However, such a transition would require even more dramatic upscaling of these technologies than currently assumed in the IPCC literature (Keyßer and Lenzen, 2021). Moreover, this upscaling could be constrained by other factors, such as the supply of materials required for energy infrastructure(Garcia-Olivares et al., 2012; Sprecher and Kleijn, 2021). Such issues may be best addressed by improved models that explicitly calculate energy and material requirements of the transition, beyond what is covered by existing IAMs.

Finally, we find a weak relationship between the share of energy for the energy system (defined as 1/EROI) and energy system emissions from 2041 to 2100. During the latter years of the transition, the overall EROI of the energy system becomes a secondary factor for emissions (as shown by the wide scatter in the blue markers in Figure 2.8c). This is not to say that EROI is not a relevant factor, as a lower EROI means that the energy system requires a larger share of total energy. However, a lower EROI may be counterbalanced by a lower share of fossil fuels in the energy system (e.g. due to faster decarbonisation), or by lower energy use.

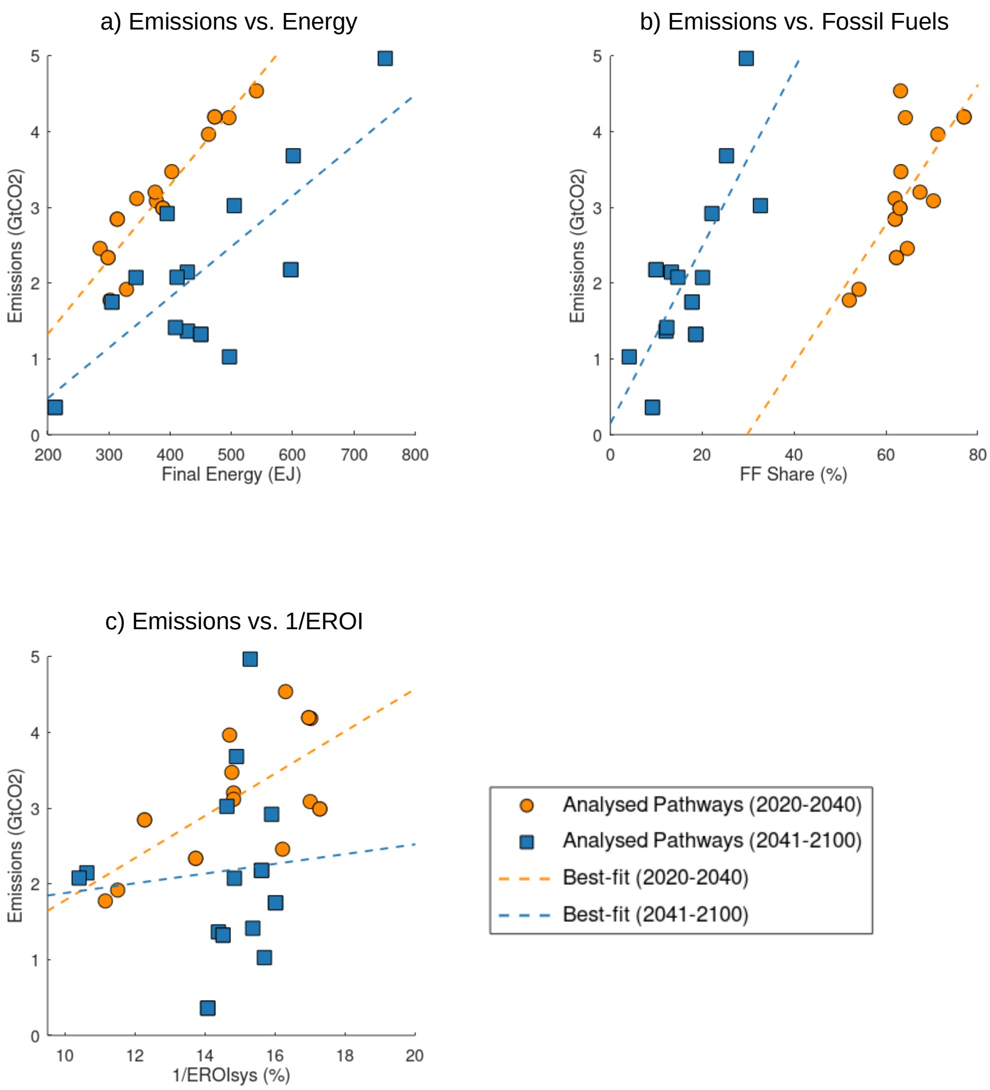

Figure 2.8: Analysis of factors affecting energy system emissions. The figure shows the relationship between average energy system emissions and different factors for each of the fourteen pathways compatible with 1.5 °C, for the median EROI assumption. Panel **a** shows average energy system emissions in relation to average annual energy use during the initial push for transition (2020–2040), and the period following this push (2041–2100). Panel **b** shows average energy system emissions in relation to the average share of energy generated from conventional fossil fuels, over the two periods. Panel **c** shows average energy system emissions as a function of the average share of energy for the energy system for the two periods.

2.4 Discussion

In this chapter, we have calculated the energy for the energy system, and the corresponding energy system emissions, for fourteen 1.5 °C–compatible mitigation pathways used extensively in the IPCC literature. Although energy for the energy system and energy system emissions are implicitly accounted for in these pathways, they are not quantified and reported as separate quantities. By providing a separate picture of energy system emissions we complement existing IAMs, yielding three core insights.

First, we find that energy system emissions are substantial. On average, we estimate that energy system emissions for a low-carbon transition would amount to 195 $GtCO_2$, which corresponds to ~5 years of global CO_2 emissions at their 2021 level. Based to the modelled linear relationship between total cumulative emissions and global warming (Damon Matthews et al., 2021), this figure implies that a low-carbon energy transition would lead to approximately 0.1 °C of global warming. Although the cumulative energy system emissions are substantial, their overall climate impact is small compared to the amount of carbon saved over the long term by rapid decarbonisation.

Second, we do not find a large jump in energy system emissions in the short run from intensifying efforts to decarbonise the energy system. On the contrary, we find energy system emissions to be higher in pathways that decarbonise slowly, that use more fossil fuels to produce energy in the short-term, and that rely on negative emissions technologies to compensate for higher cumulative emissions (Figure 2.3 and Supplementary Figure 2.4). Contrary to previous concerns about emissions associated with a transition to renewable energy increasing emissions in the short run, we identify a longer-term problem in pathways of slower decarbonisation and large-scale carbon removal, as energy system emissions in these pathways continue well into the future (Figure 2.3). Although modest on their own, these emissions are comparable in magnitude to the residual emissions from aviation, steel and cement production, and load-following electricity. Our results complement studies that find that carbon removal by BECCS is a much less efficient mitigation approach than assumed in existing pathways, due to upstream emissions from biomass supply chains (Creutzig et al., 2019b; Fajardy and Mac Dowell, 2017) and land use change (Harper et al., 2018; Heck et al., 2018).

Third, we find a comparable reduction in net energy, and in the share of energy available to society, during the low-carbon transition to that found in previous studies (King and Van Den Bergh, 2018). However, reductions in our study tend to come earlier (within the first decade of efforts), especially for mitigation pathways of fast decarbonisation. Pathways with faster decarbonisation and lower energy demand have lower energy system emissions, but this comes at the cost of lower net energy for society. Lower net energy does not need to lead to energy scarcity. A consensus is emerging regarding the enormous potential to use energy more efficiently (Cullen et al., 2011; Jacobson et al., 2018), and the possibilities of providing a decent life with much less energy than is currently consumed in wealthy nations (Millward-Hopkins et al., 2020; Oswald et al., 2020).

Generally, our study demonstrates the importance of calculating the energy requirements and emissions associated with the transition, to get a more complete picture of energy system dynamics and to inform on the remaining emissions available to society. Further research could explore the energy required and emissions associated with the replacement of machines and infrastructure at the consumption end of the energy system (e.g. electric vehicles, their charging stations, and energy storage solutions). Calculating such emissions would be worthwhile, as the transformation of the consumption end of the energy system could potentially take up a large part of the remaining carbon budget for 1.5 °C.

The research on energy transitions should go beyond the scenarios produced by IAMs, and also include scenarios from alternative "normative" energy modelling approaches (Keyßer and Lenzen, 2021; Sgouridis et al., 2016; Warszawski et al., 2021). IAMs focus on optimal-cost pathways of decarbonisation, and therefore do not cover the whole range of possible energy transitions (Ackerman et al., 2009). IAMs have been found to be biased towards technologies that are direct substitutes for conventional fossil fuels, such as BECCS and fossil fuels with carbon capture and storage (Kaya et al., 2017), which is why they tend to underestimate the realistic deployment potential of intermittent renewables (Pietzcker et al., 2017).

In our analysis, we find that a preference for direct substitutes for the conventional technologies leads to higher energy system emissions and lower net energy. A discussion of whether a low-energy transition based on renewables would be a preferable mitigation strategy is beyond the scope of this chapter. However, our analysis suggests that explicit modelling of energy system emissions and dynamic EROIs from different energy technologies could add support to the case for renewables over technologies relying on carbon capture and storage.

Questions remain regarding the extent to which the production-based approach of IAMs account for the upstream emissions associated with different energy generation technologies (Pehl et al., 2017), and also the extent to which IAMs capture effects from changes in the EROI of the energy mix (Palmer, 2018). Further research should explore the possibility of integrating EROI analysis into IAMs to produce internally more consistent energy and emissions pathways, which would likely change the models' choice of energy generation technologies. Such integration could involve EROI scenarios tailored to the narratives of the mitigation pathways, and link EROI calculations to specific narrative assumptions (e.g. about technological change, international cooperation, land use, and innovation).

Overall, our study demonstrates the importance of accounting for net energy and energy system emissions. Future mitigation pathways would be improved by explicitly modelling the energy requirements and emissions associated with a low-carbon energy transition. Doing so would allow us to better understand the trade-off between the energy and carbon required to transition to a low-carbon energy system, and what remains for other socio-economic activities outside of the transition.

2.5 Methods

2.5.1 Energy transition pathways

Fourteen 1.5 °C–consistent (RCP1.9) mitigation pathways were selected for this study. For illustrative purposes, we focus on four pathways (LED, S1-A, S2-M, and S5-R) from the IPCC's *Special Report on Global Warming of 1.5 °C*, which the IPCC selected as illustrative archetypes of alternative low-carbon transitions (IPCC, 2018b). These transitions are model interpretations of four distinct narratives that describe possible socioeconomic and technological developments in a world that limits climate change to 1.5 °C. The narratives are: Low Energy Demand (LED) (Grubler et al., 2018), Sustainability (S1) (van Vuuren et al., 2017), Middle of the Road (S2) (Fricko et al., 2017), and Fossil-fuelled Development (S5) (Kriegler et al., 2017).

To capture a wider range of assumptions and modelling frameworks beyond the four illustrative pathways, we complement the analysis with ten additional pathways, which were produced in the same study as S1-A, S2-M, and S5-R (Rogelj et al., 2018). Five of these are modelling representations of S1, three of S2, and one each of S4 and S5. S4 is also known as the "world of deepening inequality" narrative (Calvin et al., 2017).

2.5.2 Energy requirements and EROI

We estimate the energy for the energy system during transition by applying the analytical framework of Energy Return on Investment (EROI) at the final energy stage. EROI describes a ratio between the amount of net energy delivered to society (E_{NET}) and the total amount of energy that is required to extract, convert, and deliver this energy (E_{REQ}), which we also refer to as the "energy for the energy system" (Hall et al., 2009; Murphy and Hall, 2010). EROI is a measure of energy system efficiency, as it compares the amount of energy that enters the productive economy with the energy that is associated with total (gross) energy production (Brockway et al., 2019; Raugei and Leccisi, 2016). The lower the EROI, the greater the energy requirements, and the lower the net energy that is available for productive socio-economic activities (see Equation 1).

$$\mathrm{EROI} = \frac{E_{\mathrm{NET}}}{E_{\mathrm{REQ}}} = \frac{E_{\mathrm{GROSS}} - E_{\mathrm{REQ}}}{E_{\mathrm{REQ}}} = \frac{E_{\mathrm{GROSS}}}{E_{\mathrm{REQ}}} - 1 \quad (1)$$

We define the system boundaries of our EROI analysis at the final energy boundary, also known as the point-of-use boundary, which describes the point where energy carriers enter the productive economy (Hall et al., 2014). $\mathrm{EROI}_{\mathrm{FIN}}$ includes all the direct inputs along the energy supply chain required to extract (E_{EXT}) and refine energy resources (E_{REF}), the energy used to transport the energy from the primary energy stage to the point of use for society (E_{TRA}), as well as the energy requirements associated with construction (E_{CON}), decommissioning (E_{DEC}), and operation and maintenance of energy infrastructure ($E_{\mathrm{O\&M}}$), such as power plants and refineries, as shown in Equation 2 (Castro and Capellán-Pérez, 2020):

$$E_{\mathrm{REQ}} = E_{\mathrm{EXT}} + E_{\mathrm{REF}} + E_{\mathrm{TRA}} + E_{\mathrm{CON}} + E_{\mathrm{O\&M}} + E_{\mathrm{DEC}} \quad (2)$$

Energy for construction refers to the energy that is used to manufacture and build energy infrastructure like power plants and refineries. Energy for decommissioning accounts for energy required to dismantle, remove, and dispose of obsolete energy infrastructure. Energy for operation and maintenance includes energy used to extract primary energy resources, and the energy required to convert primary energy into useful energy carriers and deliver them to the end-user. Energy for operation and maintenance also includes all of the energy inputs for the energy industry's own use, from the primary to the final energy stage.

By convention, energy conversion losses from primary to final energy and energy losses in distribution, transmission, and storage (E_{LOSS}) are not counted among the energy requirements of energy conversion technologies (Capellán-Pérez et al., 2019). These losses are already accounted for in the energy balances of the original data from the pathways and result in lower final energy relative to total energy generation. Moreover, the energy requirements do not include the raw energy embodied in energy resources (e.g. the heating value of gas) that are to be converted into useful carriers. The energy requirements only account for energy inputs that are needed to procure and process the resources into useful energy carriers, and to deliver these carriers to the end user. See Supplementary Figure 2.5 for a complete illustration of our energy system boundaries and the representation of energy flows from primary energy sources to net energy.

We estimate the energy requirements for twenty-seven energy conversion technologies that are represented in the mitigation pathways (see Supplementary Figure 2.1 and 2.2 for a detailed overview of all energy conversion technologies in our model). These technologies describe different pathways of energy conversion from fossil fuels and biomass alongside energy generated from non-biomass renewables, nuclear energy, and hydrogen. In our calculations of energy for the energy system, we distinguish between four types of energy carriers that are represented in the mitigation pathways: electricity, refined liquid fuels, gases, and solids (coal and combustible biomass).

2.5.2.1 Energy requirements of fossil fuel and biomass technologies

For energy conversion from fossil fuels and biomass, the main energy requirements are associated with the extraction, processing, and delivery of energy resources, whereas the construction, decommissioning, and operation and maintenance of the energy infrastructure represent only a small share of total energy requirements (Arvesen et al., 2018). By contrast, for non-biomass renewables almost all energy requirements are from upfront energy demand for the construction of energy infrastructure.

We estimate the energy requirements associated with construction as upfront energy invested during the first year of the energy facility's lifetime. Similarly, the energy required for decommissioning is accounted for at the end of the energy infrastructure lifetime. The remaining energy inputs that are associated with energy system operations are counted every year during the lifetime of the energy infrastructure.

To calculate the energy requirements to build, decommission, and operate and maintain the energy infrastructure, we follow the previous work of (Sgouridis et al., 2019). We calculate the energy required for the construction and the energy embodied in the energy generation machinery by estimating the energy intensity of capital (ε) and multiplying it first by the capital costs of infrastructure per unit of installed power (C_p), and second by the newly installed power capacity in the respective year (P_{NEW}), as shown in Equation 3. For infrastructure capital costs, we use values from the REMIND IAM documentation (Luderer et al., 2015), which are provided in $US2015. We estimate the energy intensity of capital at 4.52 TJ/million $US2015, after adjusting for inflation the estimate of 5.49 TJ per million $US2007 from the abovementioned study, using the producer price index from the PCU3336 industry group data (U.S. Bureau of Labor Statistics, 2019). Values of the parameters for different energy conversion technologies are listed in Supplementary Table 2.10.

$$E_{\mathrm{CON}}(t) = \varepsilon \times C_p \times P_{NEW}(t) \tag{3}$$

In our calculations of energy requirements associated with new energy infrastructure, we include the power capacity built to increase energy production as well as the capacity that replaces the infrastructure that is decommissioned at the end of its lifetime (τ), as shown in Equation 4:

$$P_{\mathrm{NEW}} = \begin{cases} \max\big(0, P(t) - P(t-1)\big)\,; t < \tau \\ \max(0, P(t) - P(t-1) + P_{\mathrm{NEW}}(t-\tau))\,; t \geq \tau \end{cases} \tag{4}$$

We calculate the energy for the operation and maintenance of energy infrastructure as a product of the energy intensity of capital and the operation and maintenance costs per unit of generated energy ($C_{\mathrm{O\&M}}$) multiplied by the total energy generated per year (E_{GEN}), as shown in Equation 5:

$$E_{\mathrm{O\&M}}(t) = \varepsilon \times C_{\mathrm{O\&M}} \times E_{\mathrm{GEN}}(t) \tag{5}$$

In estimating the energy required for the decommissioning of energy infrastructure at the end of its lifetime we apply the assumption of (Hertwich et al., 2015), who estimated that decommissioning represents roughly 10% of the energy required for construction (see Equation 6).

$$E_{\mathrm{DEC}}(t) = 0.1 \times E_{\mathrm{CON}}(t-\tau) \tag{6}$$

In the following steps, we describe the calculation of the energy requirements of processes for obtaining raw fuels before they are refined into useful energy carriers that can be delivered to end-users.

To estimate the energy used in extraction, mining, or harvesting of raw fuels, we collect a series of present-day EROI estimates at the standard energy system boundary (Raugei, 2019) (e.g. farm-gate or mine-mouth; denoted $\mathrm{EROI_{ST}}$) from the peer-reviewed literature, as listed in Supplementary Table 2.11. From the $\mathrm{EROI_{ST}}$ values of these selected studies, we calculate the lower, median, and upper interquartile range of the $\mathrm{EROI_{ST}}$ for each energy resource and use these values to determine a range of estimated energy requirements associated with appropriation of raw energy fuels. We assume the $\mathrm{EROI_{ST}}$ of fossil fuels will continue to decline over time. We model the decline by following the approach of (Dale et al., 2011; Sgouridis et al., 2016), who use the equation of exponential decline from present-day values $\mathrm{EROI_{ST}}(0)$ shown in Equation 7. This approach models the convergence of $\mathrm{EROI_{ST}}$

towards the minimum EROI ($\text{EROI}_{\text{ST,low}}$), which we assume corresponds to the lower interquartile range of present-day EROI estimates. The rate of decline (β_C) for each respective resource is calibrated from the historical trend for the EROI_{ST} of fossil fuels, as published by (Brockway et al., 2019).

$$\text{EROI}_{\text{ST}}(t) = \text{EROI}_{\text{ST,low}} + (\text{EROI}_{\text{ST}}(0) - \text{EROI}_{\text{ST,low}}) \times exp^{-\beta_C \times t} \tag{7}$$

EROI_{ST} compares the raw energy content of energy resources such as wood, coal, gas, and crude oil (E_{RAW}) with the energy required to obtain these fuels (E_{EXT}; see Equation 8), before they are converted into useful energy carriers. The efficiency of energy conversion (η_C) depends on the respective energy conversion technology and may change over time. In this study, we apply the energy conversion coefficients from the representation of energy technologies in the REMIND model (Bauer et al., 2011; Luderer et al., 2015). The model assumes energy conversion efficiency in new energy infrastructure improves over time. We combine Equations 8 and 9 to obtain an expression that links the energy requirements of extraction (or harvest or mining) to the efficiency of energy conversion and EROI_{ST} (Equation 10).

$$\text{EROI}_{\text{ST}}(t) = \frac{E_{\text{RAW}}(t)}{E_{\text{EXT}}(t)} \tag{8}$$

$$E_{\text{GEN}}(t) = \eta_C(t) \times E_{\text{RAW}}(t) \tag{9}$$

$$E_{\text{EXT}}(t) = \frac{E_{\text{GEN}}(t)}{\eta_C(t) \times \text{EROI}_{\text{ST}}} \tag{10}$$

In estimating the energy required for the refining or processing of fuels (E_{REF}) we refer to the calculations from previous studies. For the refining of crude oil, we use the estimates of energy intensity of refining in MJ per kg (μ_{REF}) from (Raugei and Leccisi, 2016) and the "Ecoinvent Life-cycle Inventories of Oil Refinery Processing" (Meili et al., 2018). For the processing of raw fuels from biomass, we use estimates of energy intensity from an extensive literature review by (Fajardy and Mac Dowell, 2017, 2018). We define the energy used in refining as a product of the mass of the respective fuel and the energy intensity of refining, as shown in Equation 11. We calculate the mass of the fuel by dividing the raw energy content of energy resources (E_{RAW}) by the higher heating value (HHV), described by Equation 12. We do not assume specific energy requirements for the processing of natural gas and coal, consistent with previous EROI and life-cycle studies (Raugei et al., 2018; Raugei and Leccisi, 2016).

$$E_{\text{REF}}(t) = M_{\text{FUEL}}(t) \times \mu_{\text{REF}} \tag{11}$$

$$M_{\text{FUEL}}(t) = \frac{E_{\text{RAW}}(t)}{\text{HHV}} \tag{12}$$

To calculate the energy requirements for transportation, we assess global trade routes of coal, gas, and crude oil in the year 2019, by using the flows of these fuels from the international trade balance sheets of the BP Statistical Review of World Energy 2020. For biomass, we use data on the global flows of wood pellets from (Junginger et al., 2019). We partition the trade routes (indexed with *l*) into different stages by transportation type, estimating the average trade distance in each route. For example, the oil route from Baghdad (Iraq) to Houston (USA) consists of an onshore pipeline of 970km from Baghdad to Ceyhan (Turkey), a sea freight route of 12,500 km from Ceyhan to Houston, and an onshore pipeline of 100 km on the US mainland. We assume that the energy intensities of fuel transport remain constant over time.

We calculate the energy used in each transportation route segment (indexed with *j*) by multiplying the amount of fuel transported by the energy intensity of the transportation type and the distance over which the fuel is transported, as shown in Equation 13. The parameters for the transportation types are obtained from the life-cycle inventory database EcoInvent v3.2 (Ecoinvent, 2020), and can be found among the parameters listed in Supplementary Table 2.10.

$$M_{\mathrm{FUEL,l}} \times \gamma_{\mathrm{TRA,j}} \times \mathrm{distance}_{l,j} \tag{13}$$

To estimate the average global energy intensity (ϵ_{TRA}) associated with the transportation of each fuel (in MJ/kg), we sum the energy use across the global trade routes and divide the sum by the global volume of trade flows (in tonne kilometres), defined as the global sum of transported fuel multiplied by the distance, as described in Equation 14:

$$\epsilon_{\mathrm{TRA}} = \frac{\sum_l \left(M_{\mathrm{FUEL,l}} \times \sum_j \gamma_{TRA,j} \times \mathrm{distance}_{l,j} \right)}{\sum_l \left(M_{\mathrm{FUEL,l}} \times \sum_j \mathrm{distance}_{l,j} \right)} \tag{14}$$

Finally, we obtain the energy required for the transportation of raw fuel by multiplying the mass of the fuel transported by the average global energy intensity of fuel transportation for each respective fuel, as shown in Equation 15:

$$E_{\mathrm{TRA}}(t) = M_{\mathrm{FUEL}}(t) \times \epsilon_{\mathrm{TRA}} \tag{15}$$

For a complete overview of our assumptions regarding the trade routes of coal, natural gas, crude oil, and biomass, and our calculations of the energy intensities of fuel transport, see Supplementary Tables 2.12–2.15.

2.5.2.2 Energy requirements of non-biomass renewables and nuclear energy

The largest energy requirements of non-biomass renewables (i.e. solar photovoltaics, wind, geothermal, and hydropower) are related to the manufacturing and construction of energy infrastructure (Arvesen et al., 2018; Hertwich et al., 2015). For renewables, the energy required for operation is much lower than technologies that produce energy from raw fossil fuels, as renewable sources do not require energy to be extracted, transported, and processed. For nuclear energy, the energy to maintain the energy supply chain also includes energy requirements for extraction, enrichment, and transportation of uranium. Here, the energy requirements for operating energy infrastructure and maintaining the energy supply are substantially higher compared to the construction of energy infrastructure.

To obtain estimates of the energy requirements of renewables and nuclear energy over the lifetime of each technology, we collected a series of present-day EROI estimates for each technology at the final energy boundary, from a number of peer-reviewed studies (see the studies listed in Supplementary Table 2.1). From these studies, we calculated the lower, median, and upper quartile of the range of EROI values for each energy source. These quartiles are classified as low, median, and high EROI estimates.

We divided the energy requirements between the energy required for construction (E_{CON}) and decommissioning (E_{DECOM}) of the energy infrastructure, and the annual energy requirements to operate the energy infrastructure and maintain the energy supply ($E_{\mathrm{O\&M}}$), following the approach of (King and Van Den Bergh, 2018). Energy requirements for operation are proportional to the total installed power (P) times the capacity factor (CF) divided by the EROI of the technology (King and Van Den Bergh, 2018), as shown in Equation 16. CF is a dimensionless ratio that compares the actual annual generation of energy to the maximum potential energy output. The parameter α_{tech} describes the ratio between the energy requirements of operation and the energy invested in construction over the lifetime of the technology.

$$E_{\mathrm{O\&M}}(t) = \frac{\alpha_{\mathrm{tech}} \times P(t) \times \mathrm{CF}(t)}{\mathrm{EROI}(t)} \tag{16}$$

As described in Equation 17, the energy requirements of construction are proportional to new installed power (P_{NEW}), times the capacity factor of the respective energy conversion technology (CF), multiplied by the lifetime of the technology (τ), and divided by the technology's EROI.

$$E_{\mathrm{CON}}(t) = \frac{(1 - \alpha_{\mathrm{tech}}) \times P_{\mathrm{NEW}} \times \mathrm{CF} \cdot \tau}{\mathrm{EROI}(t)} \tag{17}$$

Energy associated with decommissioning is assumed to represent 10% of the energy used for construction, following (Hertwich et al., 2015). Energy associated with decommissioning is accounted for in the last year of the energy infrastructure's lifetime, as shown in Equation 18:

$$E_{\mathrm{DEC}}(t) = 0.1 \times E_{\mathrm{CON}}(t - \tau) \tag{18}$$

We assume the historical trend of increasing EROIs of photovoltaic and wind power technologies will continue in the future. We model the EROI dynamics of these technologies by applying "energetic experience curves" (Louwen et al., 2016; Steffen et al., 2018), thus estimating the reduction in the energy requirements for construction, and operation and maintenance due to technological innovation. For a detailed explanation of how we calculated the future dynamics of EROI for photovoltaics, wind power, and hydrogen from electrolysis, see the "Note on EROI dynamics of wind and solar power" and the "Note on energy requirements for hydrogen from electrolysis" in the Supplementary Information. In estimating the energy requirements of hydropower, geothermal, and nuclear energy, we refer to the present-day range of EROI estimates, due to a lack of studies on EROI dynamics for these technologies.

2.5.2.3 EROI of the overall energy system

We calculate the EROI of the overall energy system at the final energy stage, by applying Equation 1, wherein we compare the total amount of gross final energy production to the sum of the energy requirements for all energy conversion technologies (here represented by the index *i*), as shown in Equation 19. We use the same approach to calculate the EROI of individual energy conversion technologies and the EROI of different carriers, such as the EROI of electricity from renewables.

$$\mathrm{EROI}_{\mathrm{SYS}} = \frac{E_{\mathrm{GROSS}}}{\sum_i E_{\mathrm{EXT,i}} + E_{\mathrm{REF,i}} + E_{\mathrm{TRA,i}} + E_{\mathrm{CON,i}} + E_{\mathrm{O\&M,i}} + E_{\mathrm{DEC,i}}} - 1 \qquad (19)$$

We test our model by comparing our estimates of the EROI of the overall energy system with the results from the EROI literature. The note on “EROI estimates of different energy carriers” in the Supplementary Information demonstrates that our calculations of the EROI at the final energy stage are consistent with estimates from previous studies.

EROI values differ greatly depending on the energy system boundaries that the analyst uses (Hall et al., 2014; Murphy et al., 2011). For example, some studies measure energy delivered at the point of energy extraction, while others calculate energy delivered to the end user, which is an expanded analytical boundary of the system. Expanding the boundary results in lower EROI values, as it includes the additional energy required to convert the raw resource into useful energy and move it or store it. We selected studies to match a consistent system boundary, which includes the energy investments for energy resource extraction, resource transportation, resource processing, the construction of energy conversion facilities, and the energy required for the operation of the facilities.

We assume a global average EROI for each energy conversion technology. We do not take into account regional differences in production and transformation processes (Raugei, 2019). However, the EROI of the entire energy system does change with improvements in energy conversion efficiencies, changes in the $\mathrm{EROI}_{\mathrm{ST}}$ of fossil fuels due to a declining abundance of these energy resources, and as the mix of energy technologies changes over time.

In our EROI scenarios, high-EROI values assumed for each energy technology are based on studies with favourable assumptions regarding resource abundance and deployment of the most efficient low-carbon energy generating technologies. Low-EROI values in turn assume lower resource abundance and limited technological improvement of low-carbon energy technologies. Median-EROI values represent a balanced, middle-of-the road EROI trajectory. For a detailed overview of EROI assumptions for different energy technologies see Supplementary Tables 2.3-2.7.

2.5.3 Net energy

To calculate net energy per capita, we divide the difference between gross final energy and the total energy requirements of the energy system (as shown in Equation 1), by the global population projections in the mitigation pathways.

2.5.4 Energy system emissions

Estimating the carbon emissions associated with the build-up of the energy system and operation and maintenance of the energy supply during transition is crucial for assessing different mitigation pathways. If a substantial amount of the remaining carbon budget goes to decarbonising the energy system, this may significantly affect the projections of energy use and emissions in the end-use energy sectors. Future energy system emissions depend on changes in the energy requirements of the energy system and the carbon intensity of the energy for the energy system. Energy system emissions decrease with the decarbonisation of the energy supply and a reduction in energy requirements.

To calculate the emissions associated with the construction of energy technologies, and operation and maintenance of the energy supply over time, we first separate the energy requirements associated with the construction, decommissioning, and operation and maintenance of the energy supply for each energy technology into the four energy carriers: electricity, gases, liquid fuels, and solids. This step is crucial to adequately quantify energy system emissions, as the carbon intensities of different energy carriers can differ substantially (Pehl et al., 2017), especially given that electricity can be decarbonised much faster than other carriers. We count hydrogen among the liquid fuels, assuming that most hydrogen will be destined to replace liquid fossil fuels. In decomposing the energy requirements into different energy carriers we follow the approach of (Arvesen et al., 2018), who distinguish between the four abovementioned energy carrier types, for each of the three life-cycle assessment phases of construction, decommissioning, and operation (see Equation 20). The life-cycle phase of operation and maintenance includes both the energy requirements to operate the energy infrastructure as well as the energy required to maintain the energy supply. We use the life-cycle assessment database from Arvensen et al. to decompose the energy requirements into four energy carriers by multiplying the total energy requirements by the vector of the respective energy carriers shares, composed of electricity (*e*), gases (*g*), liquid fuels (*l*), and solids (*s*):

$$\mathbf{E_{REQ,i}}(t) = E_{\mathrm{REQ,i}}(t) \cdot \langle e, g, l, s \rangle_i \tag{20}$$

Energy requirements, decomposed into four energy carriers, are multiplied by the carbon intensity vector containing the carbon intensities of energy carriers ($\mathbf{CI}$), to obtain the energy system emissions from each respective energy generation technology, and the life-cycle phase, as shown in Equation 21.

$$\mathrm{CO}_{2,i}(t) = \mathbf{E_{REQ,i}}(t) \cdot \mathbf{CI}(t) \tag{21}$$

We calculate the carbon intensity of each carrier (c) by dividing the total carbon emissions from energy generation for each carrier by the total amount of energy generated by each carrier, as shown in Equation 21. Changes in the carbon intensities of energy carriers in the mitigation pathways over time are depicted in Supplementary Figures 2.6 and 2.7.

$$\mathbf{CI}_{\boldsymbol{c}}(t) = \frac{\sum_i \mathrm{CO}_{2,i,c}(t)}{\sum_i E_{\mathrm{GEN},i,c}(t)} \tag{22}$$

Emissions from electricity generation are obtained directly from the original scenario data, whereas emissions from gases, liquids, and solids are calculated using the carbon intensities of energy conversion technologies (φ_i), which are endogenous to the REMIND model (see Equation 23). For an overview of the carbon intensity parameters, see Supplementary Table 2.10.

$$\mathrm{CO}_{2.i,c}(t) = \varphi_i \cdot E_{\mathrm{GEN},i,c}(t) \tag{23}$$

Cumulative energy system emissions are calculated as the sum of annual emissions from all of the energy generation technologies, over the period from 2020 to 2100. The share of energy emissions that is shown in Figure 2.2 is calculated by dividing energy system emissions by the total carbon emissions from energy generation.

We report negative emissions, realised by BECCS technologies, separately from (positive) anthropogenic emissions. Negative emissions realised in energy generation are therefore not counted in the calculation of the carbon intensities of the four energy carriers. We refer to the negative emissions data, as they are reported in the original scenario data. Mitigation pathways report the total amount of sequestered carbon by BECCS technologies (gross negative emissions), but do not separately report the positive emissions from BECCS. Positive emissions from BECCS include the emissions from land-use change, the emissions from fertilisers, the emissions associated with the construction and operation of the BECCS energy facilities, and the carbon emitted along the biomass supply chain (Hanssen et al., 2020).

Mitigation pathways use different reporting methodologies for the carbon removal by BECCS that in some cases combine gross carbon removal with removals in the land use sector (Vaughan et al., 2018). This makes it difficult to include the total positive emissions associated with BECCS in our energy system calculations. Here, we limit our analysis of energy system emissions to the emissions associated with the biomass supply and emissions from BECCS facilities, though emissions from land-use-change and fertilizer use may be an even bigger source of energy system emissions (Creutzig et al., 2019b; Harper et al., 2018). As a result, our estimates may considerably underestimate the energy system emissions in low-carbon energy transitions that assume a large-scale use of bioenergy, such as the S2 and S5 mitigations pathways.

2.5.5 Multiple regression panel data analysis

To quantify the factors driving energy system emissions, we selected three independent variables: final energy use, share of energy from conventional fossil fuels, and the share of energy for the energy system. Panel OLS multiple regression analysis was used to estimate the contribution of each of these factors. The estimated model is as follows:

$$\mathrm{CO}_{2.k}(t) = \gamma(t) + \beta_1 x_{1,k}(t) + \beta_2 x_{2,k}(t) + \beta_3 x_{3,k}(t) + \varepsilon_k(t) \qquad (24)$$

where $\mathrm{CO}_{2,\mathrm{k}}(t)$ is the energy system emissions for pathway *k* in year *t*, β gives the coefficients for the three independent variables *x*, and γ is the time-specific term that controls for unobserved heterogeneity over time, and ε is the error term. Time fixed-effects were included in the model, given that we are interested in how the relationship between independent variables and energy system emissions varies between different pathways. Robust standard errors controlling for heteroskedasticity, and autocorrelation were estimated after testing for their presence in the balanced panel dataset.

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2.7 Author contributions

All authors contributed to designing the project and writing up the results. A.S. led the project and the writing of the chapter, developed the model, collected and analysed the data, and produced the results, under the supervision of G.K. and D.W.O. G.K. had the initial idea for the project, discussed and refined the results with A.S, and contributed to the writing of the chapter. D.W.O. contributed to the analysis and discussion of the results, the preparation of visuals, and the writing of the chapter.

2.8 Data and code availability

Energy, capacity, emissions, and population data for energy transition pathways were obtained from the IAMC 1.5 °C Scenario Explorer repository (release 2.0) (Huppmann et al., 2019), available at: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/. Data for the LED pathway (Grubler et al., 2018) were obtained from the LED database: https://db1.ene.iiasa.ac.at/LEDDB/. Historical data on gross final energy from different energy carriers were taken from the online IEA Data and Statistics database, accessible at: https://www.iea.org/data-and-statistics. The data for energy system emissions, energy requirements for the energy system, net energy, and EROI generated in this study have been made available in the online data repository, accessible at: https://osf.io/v5nqg/?view_only=d28f6be45dc44dec884b0afa59098b76. The Octave code used to calculate energy system emissions and energy for the energy system will be made available by the corresponding author upon reasonable request.

2.9 Supplementary Information

2.9.1 Note on $EROI_{FIN}$ estimates from the literature and our study

2.9.1.1 EROI estimates of different energy generation technologies

Supplementary Figures 2.1 and 2.2 show the $EROI_{FIN}$ values from the literature next to our $EROI_{FIN}$ estimates for the twenty-seven energy conversion technologies used in this study. Besides comparing our EROI calculations to the estimates from literature, the figures also depict how the EROIs of technologies change over time. Comparing values from the literature to our estimates in the time-period from 2020 to 2030 shows that our calculations generally compare closely with the range of literature estimates. The two outliers are the EROIs for wind and photovoltaics (PV), in the period from 2020 to 2030, which are considerably lower in our calculations than in the literature estimates. This difference is because during the initial period of low-carbon energy transition, renewables see an exponential growth in deployment across the range of energy pathways, which results in substantial upfront energy requirements, while most of the energy payback takes place after 2030. The uneven balance between the upfront energy requirements and energy generation translates into a lower EROI of these technologies over the period of rapid growth in their deployment. In the period from 2040 to 2050, when the bulk of renewable infrastructure is already constructed, the EROI of renewables increases substantially due to (a) lower upfront energy requirements as the growth of wind and photovoltaics decrease relative to the energy they generate, (b) low energy requirements for the operation and maintenance of the energy infrastructure, and (c) technological improvements which decrease the energy intensity of construction, operation and maintenance.

Our calculations show that the EROIs of non-CCS fossil fuel and bioenergy technologies at the final energy boundary will decrease in the future both due to higher energy costs of extraction and lower utilisation of these technologies. Depletion of fossil fuels in the most accessible resource extraction sites will lead to a decline in the EROI of fossil fuels at the standard energy system boundary. At the final energy boundary, the EROI of non-CCS technologies decreases below the EROI of CCS technologies in our analysis because conventional fossil fuels, according to the SSP scenario data, become less utilised for energy generation later in the century (supposedly because they are less economic with a rising carbon price). With lower utilisation of fossil fuel technologies, the capacity factors of existing infrastructure decrease, while the phasing-out also comes with an energy cost for the decommissioning of the fossil infrastructure. Both factors result in lower energy return and lower EROI for conventional fossil fuel technologies. This result is the consequence of stranded fossil fuel investments in the future. Some power plants will work at reduced capacities, others will be closed down before the end of their life-time. Thus the “real-world” EROI of these technologies will decline beyond the “real-world” EROI of CCS technologies, which will still operate further into the future, as their carbon intensity is lower in comparison.

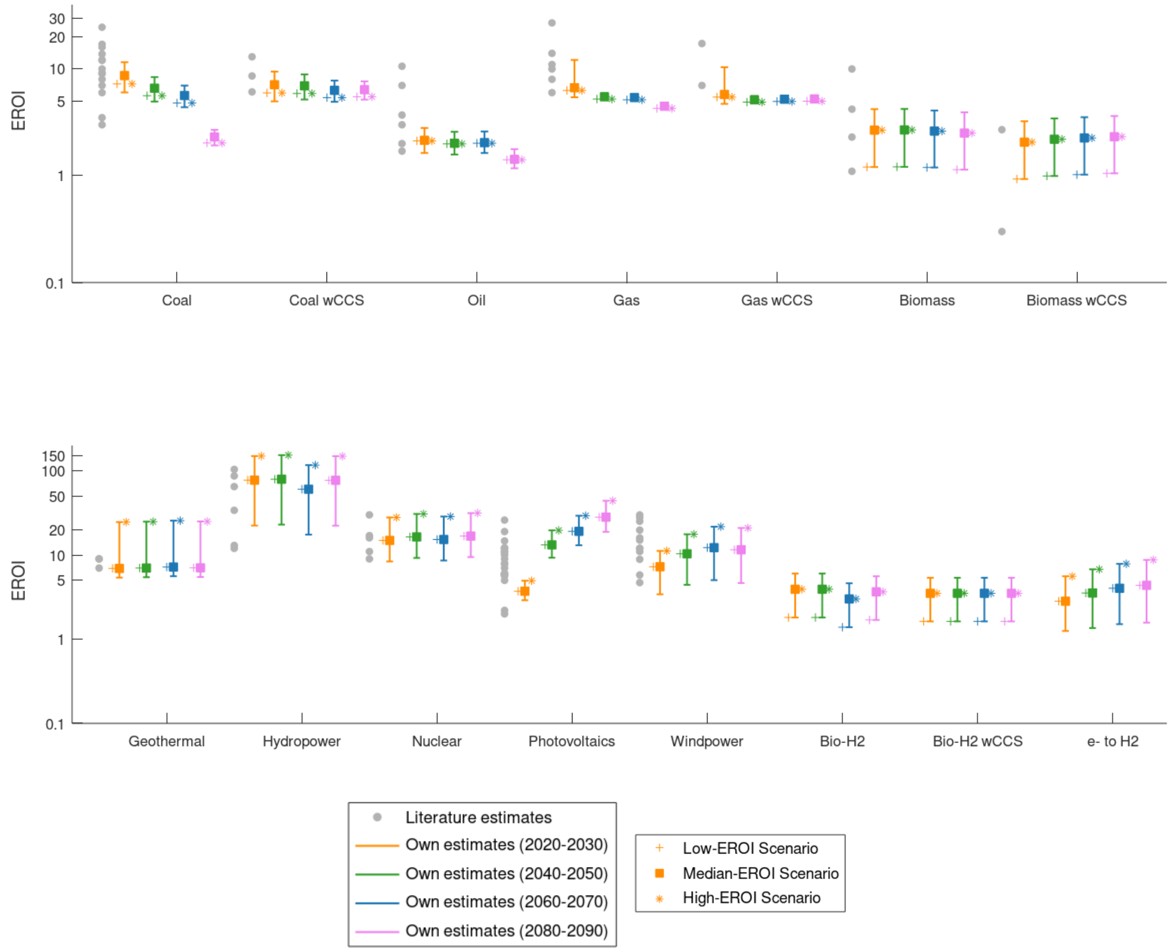
As shown by a range of estimates depicted in Supplementary Figures 2.1 and 2.2, alongside Supplementary Table 2.1, studies may produce different estimates of $EROI_{FIN}$ for a given energy conversion technology. There are three key reasons for different $EROI_{FIN}$ estimates in the literature.

The first is the use of different methodologies to account for energy requirements. EROI methods can omit important energy inputs in the calculation of energy requirements, leading to an overestimation of the $EROI_{FIN}$ of energy conversion technologies (Raugei, 2019). Typically, the process-based methods aim to include all the relevant direct energy inputs to the energy system, such as energy required for construction, decommissioning, and operation and maintenance of energy infrastructure. However, they tend to omit (some) indirect energy inputs, such as the energy required to produce the machinery that is involved in the construction of energy infrastructure or the energy required for exploration of energy resources or to provide for the human labour (Castro and Capellán-Pérez, 2020). In contrast, these indirect energy inputs are captured by input–output methodologies, which are therefore more complete at quantifying total energy requirements.

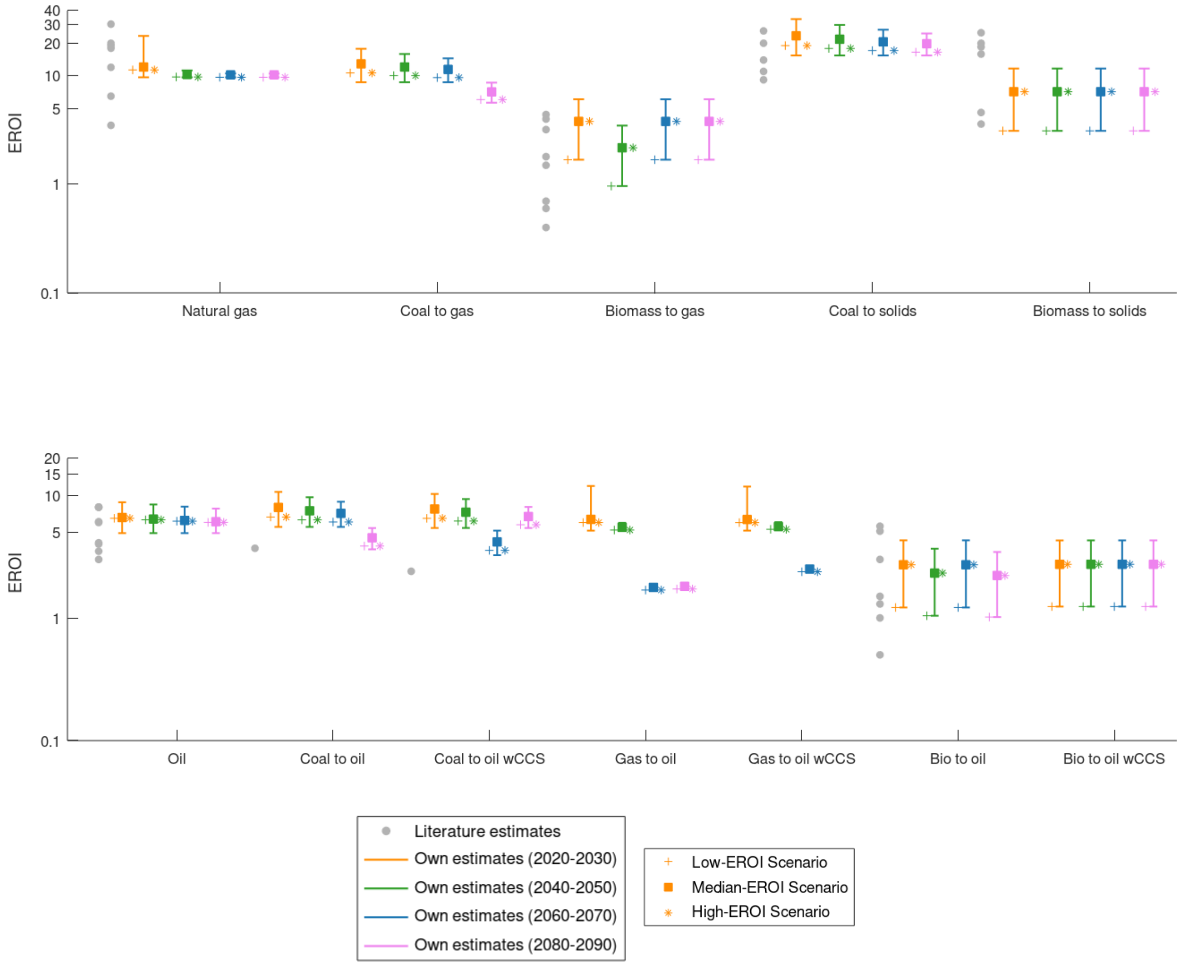
Comparisons between the two methodological approaches have shown that energy requirements estimated in studies using input–output analysis can exceed the energy requirements estimated in process-based studies by more than 100% (Guan et al., 2016; Song et al., 2009). However, input–output methodologies require highly detailed data on energy flows between different industries and across countries, which may not always be available and may therefore not be applicable in all case studies. For example, the input–output database used in the EROI study by (Brockway et al., 2019) describes energy flows between 163 industries across 49 different countries/regions. Such detailed analysis is not possible in our study, which is based on the mitigation pathway energy data from a single energy-system sector of the global economy. For these reasons our method of estimating energy requirements is largely derived from the studies using process-based methodologies like the study by (Raugei and Leccisi, 2016), which calculate the EROI of power-generation technologies in the United Kingdom.

Second, EROI may vary depending on the specific technological configuration of the energy conversion technology, or depending on the raw resource used, as indicated in Supplementary Table 2.1. For example, single-crystalline solar panels reportedly have a lower EROI than panels using cadmium telluride (Leccisi et al., 2016). Here, we simplify the calculations of the EROI of photovoltaics (PV) and wind power, which consist of multiple technological configurations, by using a single “representative technology” that aims to capture the average properties of the entire technological space. The energy requirements of the representative PV/wind-power technology are estimated by an inter-quartile range of EROI values from the case studies that feature different technologies listed in Supplementary Table 2.1.

Third, studies estimate the EROIs of energy conversion technologies in different geographical and temporal settings. Some studies estimate the EROI values of a particular energy generation project, whereas other studies estimate the average regional or global EROI values of a particular energy technology. A study design that quantifies the EROI of the best available technology under the most favourable conditions for energy generation will arrive at higher EROI estimates than a study aiming to quantify the global average EROI of that same technology. For example, the EROI of PV in a mid-latitude country is lower than in a low-latitude country because there is less solar irradiation in the mid-latitudes (Ferroni et al., 2017; Raugei et al., 2017).



Supplementary Figure 2.1: Dynamic $EROI_{FIN}$ of power generation and hydrogen technologies. The figure shows our EROI calculations for different power generation technologies and how they change over time. A range of EROI values from the peer-reviewed literature is shown next to our estimates. The full range of estimates is depicted by the error bar. The EROI values of different technologies that are used in our EROI-scenarios are shown with different markers. The depicted EROI values are averaged across fourteen scenarios and over the respective decade as indicated in the legend. For some technologies we did not find any EROI studies in the literature. Abbreviations: wCCS = with carbon capture and storage, Bio-H_2 = hydrogen from biomass, Bio-H_2 wCCS = hydrogen from biomass with carbon capture and storage, e- to H_2 = hydrogen from electrolysis.



Supplementary Figure 2.2: Dynamic EROI$_{FIN}$ of energy conversion into liquids, gases, and solids. The figure shows the range of our EROI calculations for different energy generation technologies and how they change over time. The full range of estimates is depicted by the error bar. The EROI values of different technologies that are used in our EROI-scenarios are shown with different markers. A range of EROI values from the peer-reviewed literature is shown next to our estimates. The depicted EROI values are averaged across fourteen scenarios and over the respective decade as indicated in the legend. For some technologies we did not find any EROI studies in the literature. Abbreviations: wCCS = with carbon capture and storage, Bio to oil = biomass into biofuels, Bio-to oil wCCS = biomass into biofuels with carbon capture and storage.

Supplementary Table 2.1: $EROI_{FIN}$ values from literature at the final energy (point-of-use) boundary.

Energy Conversion Technology	$EROI_{FIN}$ Value	Location/Type	Reference
Coal to electricity	3	Global[a]	(Brockway et al., 2019)
	3.5	UK[b]	(Raugei and Leccisi, 2016)
	7	Chile[b]	(Raugei, 2019)
	10	Indonesia[b]	(Raugei, 2019)
	12	Columbia[b]	(Raugei, 2019)
	6	USA[b]	(Raugei and Leccisi, 2016)
	8	Global[b]	(Kubiszewski et al., 2010)
	9-16	Global[b]	(Hall et al., 2014)
	9.2-13.8	Global[b]	(Sgouridis et al., 2019)
	17	Global[b]	(King and Van Den Bergh, 2018)
	12.2-24.6	Global[b]	(Raugei et al., 2012)
	6.0-11.9	*Global*	*Our present-day estimate*
Coal to electricity with CCS	6.1-8.6	Global[b]	(Sgouridis et al., 2019)
	13	Global[b]	(King and Van Den Bergh, 2018)
	4.9-9.5	*Global*	*Our present-day estimate*
Oil to electricity	1.7	UK[b]	(Raugei and Leccisi, 2016)
	2	Chile[b]	(Raugei, 2019)
	3	Colombia[b]	(Raugei, 2019)
	7	Global[b]	(King and Van Den Bergh, 2018)
	3.7-10.6	Global[b]	(Raugei et al., 2012)
	1.6-2.8	*Global*	*Our present-day estimate*
Gas to electricity	11-14	UK[b]	(Raugei and Leccisi, 2016)
	10	USA[b]	(Murphy and Hall, 2010)
	27	Global[b]	(Sgouridis et al., 2019)
	6	Global[b]	(Hall et al., 2014)
	8	Global[b]	(King and Van Den Bergh, 2018)
	5.4-15.9	*Global*	*Our present-day estimate*
Gas to electricity with CCS	17.3	Global[b]	(Sgouridis et al., 2019)

	7	Global[b]	(King and Van Den Bergh, 2018)
	4.7-12.2	*Global*	*Our present-day estimate*
Biomass to electricity	1.1	UK[b]	(Raugei and Leccisi, 2016)
	2.3-4.2	UK[b]	(Fajardy and Mac Dowell, 2018)
	10	Global[b]	(King and Van Den Bergh, 2018)
	1.2-4.1	*Global*	*Our present-day estimate*
Biomass to electricity with CCS	0.3-2.7[d]	UK[b]	(Fajardy and Mac Dowell, 2018)
	0.9-3.2	*Global*	*Our present-day estimate*
Geothermal electricity	9	Iceland[b]	(Atlason and Unnthorsson, 2013)
	7	Global[b]	(Kubiszewski et al., 2010)
	9	Global[b]	(Hall et al., 2010)
	7-9	*Global*	*Our present-day estimate*
Hydropower	34-87	UK[b]	(Raugei and Leccisi, 2016)
	12	Global[b]	(Kubiszewski et al., 2010)
	65-104	Global[b]	(Hall et al., 2014)
	13	Global[a]	(Castro and Capellán-Pérez, 2020)
	13-87	*Global*	*Our present-day estimate*
Nuclear electricity	30	UK[b]	(Raugei and Leccisi, 2016)
	9-16	Global[b]	(Kubiszewski et al., 2010)
	11-17	Global[b]	(Hall et al., 2014)
	9-30	*Global*	*Our present-day estimate*
Photovoltaics[c]			
cSi	2.2-5.7	UK[b]	(Raugei and Leccisi, 2016)
cdTe	5.8-14.7	UK[b]	(Raugei and Leccisi, 2016)
cSi	6-8	Columbia[b]	(Raugei and Leccisi, 2016)
cdTe	12-19	Columbia[b]	(Raugei and Leccisi, 2016)
cSi	5-11	USA[b]	(Raugei and Leccisi, 2016)
cdTe	11-26	USA[b]	(Raugei and Leccisi, 2016)
	9-10	Switzerland[b]	(Raugei et al., 2017)
	6	Global[b]	(Kubiszewski et al., 2010)

	6-12	Southern Europe[b]	(Raugei et al., 2012)
	10.4-12.2	Germany[b]	(Steffen et al., 2018)
	2.0-5.7	Global[a]	(Castro and Capellán-Pérez, 2020)
	7	Belgium[b]	(Limpens and Jeanmart, 2018)
	7.8[c]	Global[b]	(Louwen et al., 2016)
	6.0-9.5	*Global*	*Our present-day estimate*
Wind power[d]	15-28	Global (onshore)[b]	(Raugei and Leccisi, 2016)
	16-30	Global (offshore)[b]	(Raugei and Leccisi, 2016)
	19.8	Global (operational[b])	(Kubiszewski et al., 2010)
	25.2	Germany[b]	(Steffen et al., 2018)
	4.7	Global (offshore)[a]	(Castro and Capellán-Pérez, 2020)
	5.8	Global (onshore)[a]	(Castro and Capellán-Pérez, 2020)
	8.9	Global (onshore)[b]	(Dupont et al., 2018)
	12	Global (offshore)[b]	(Dupont et al., 2018)
	11-12	Belgium[b]	(Limpens and Jeanmart, 2018)
	5.8-18.0	*Global*	*Our present-day estimate*
Biomass to H_2	*1.8-6.0*	*Global*	*Our present-day estimate*
Biomass to H_2 with CCS	*1.6-5.4*	*Global*	*Our present-day estimate*
Electricity to H_2	1.7	Global (using PV electricity)[b]	(Sathre et al., 2014)
	2.3	Global (using PV electricity)[b]	(Sathre et al., 2016)
	<1.0	Global (using PV electricity)[b]	(Hacatoglu et al., 2012)
	1.4-6.0	*Global*	*Our present-day estimate*
Natural gas	30	UK[b]	(Raugei and Leccisi, 2016)
	12	USA[b]	(Yaritani and Matsushima, 2014)
	18	Global[b]	(Gagnon et al., 2009)
	19	Global[b]	(King and Van Den Bergh, 2018)
	20	Global[b]	(Hall et al., 2014)
	3.5-6.5	China[b]	(Feng et al., 2018)
	9.7-32.2	*Global*	*Our present-day estimate*
Coal to gas	*8.7-18.3*	*Global*	*Our present-day estimate*

Biomass to gas[e]			
Grass	0.6-3.2	Finland[b]	(Uusitalo et al., 2017)
Barley, Oat and Wheat Ethanol	0.4-1.5	Finland[b]	(Uusitalo et al., 2017)
Wood	0.7-4.0	Finland[b]	(Uusitalo et al., 2017)
Wood	1.8-4.4	Switzerland[b]	(Felder and Dones, 2007)
	1.7-6.1	*Global*	*Our present-day estimate*
Oil	6.1	UK[b]	(Raugei and Leccisi, 2016)
	3-4	California[b]	(Brandt, 2011)
	8	Global[a]	(Brockway et al., 2019)
	4.1	Global[b]	(Hall et al., 2009)
	8	Colombia[b]	(Raugei, 2019)
	6	Chile[b]	(Raugei, 2019)
	3.5-8	China[b]	(Feng et al., 2018)
	4.9-8.9	*Global*	*Our present-day estimate*
Coal to oil	3.7	China[b]	(Kong et al., 2015)
	5.4-10.5	*Global*	*Our present-day estimate*
Coal to oil with CCS	2.4	China[b]	(Kong et al., 2015)
	5.5-11.0	*Global*	*Our present-day estimate*
Natural gas to oil	*5.1-15.9*	*Global*	*Our present-day estimate*
Natural gas to oil with CCS	*5.1-10.5*	*Global*	*Our present-day estimate*
Biomass to oil[e]			
Ethanol from corn	0.5	USA[b]	(Hall et al., 2009)
Ethanol from corn	1.0	USA[b]	(Murphy et al., 2011)
Ethanol from corn	1.3	USA[a,b]	(De Castro et al., 2014)
Biodiesel	1.5	USA[a,b]	(De Castro et al., 2014)
Palm oil	3.0	Global[a,b]	(De Castro et al., 2014)
Ethanol from lignocellulosic feedstock	5.1-5.6	India[b]	(Mandade and Shastri, 2019)
	1.2-4.3	*Global*	*Our present-day estimate*
Biomass to oil with CCS	*1.0-3.7*	*Global*	*Our present-day estimate*
Biomass to solids[d]			

Biomass pellets	4.6	UK[b]	(Raugei and Leccisi, 2016)
Biomass pellets	3.6	UK and EU[b]	(Fajardy and Mac Dowell, 2018)
Biomass chips	15.9	UK and EU[b]	(Fajardy and Mac Dowell, 2018)
Biomass chips	18.5-25	Croatia[b]	(Pandur et al., 2015)
Solid wood	20	Global[b]	(Dale et al., 2012a, 2012b)
	3.1-11.7	*Global*	*Our present-day estimate*
Coal to solids	11	UK[b]	(Raugei and Leccisi, 2016)
	20	Chile[b]	(Raugei et al., 2018)
	26	Indonesia[b]	(Aguirre-Villegas and Benson, 2017)
	9.2-14	China[b]	(Feng et al., 2018)
	15.4-34.7	*Global*	*Our present-day estimate*

Notes: As indicated by location identifier, some studies estimate the $EROI_{FIN}$ of energy infrastructure at a specific location, whereas others aim to quantify the average regional or global $EROI_{FIN}$ of the energy conversion technology.

[a] Studies that use an input–output methodology to quantify energy requirements.

[b] Studies that use a process-based methodology to quantify energy requirements.

[c] Here, we estimate the EROI values of PV by converting the values of “energy payback time”, as calculated by Louwen et al.,(Louwen et al., 2016) into the $EROI_{FIN}$. To estimate $EROI_{FIN}$, we divide the expected lifetime of PV by its energy payback time, and multiply it with the conversion factor from primary energy to electricity of 0.311. This approach is consistent with the EROI convention of reporting the sum of energy inputs at the final energy boundary without converting them into primary energy equivalents.

[d] The EROIs of these energy generation technologies can differ depending on the specific technology (PV and wind power) or depending on the raw fuel (biomass type).

[e] Here, we estimate the EROI values of bioelectricity with CCS by converting the values of “electricity return on investment” (E_IROI), as estimated by Fajardy and Mac Dowell(Fajardy and Mac Dowell, 2018), into the $EROI_{FIN}$. The authors define the E_IROI as the “ratio of generated electricity to the electrical energy equivalent of energy inputs” (PEeq). To estimate the $EROI_{FIN}$ we divide the PEeq by the average power generation efficiency of the grid, which gives us a first order estimate of total energy requirements. This approach is consistent with the standard EROI convention of summing up all the energy inputs from different energy carriers at the final energy boundary without converting them into primary energy equivalents.

Supplementary Table 2.2: $EROI_{FIN}$ values from literature at the final energy (point-of-use) boundary.

Energy systems	Scenario assumptions	Estimated $EROI_{FIN}$	Reference
Solar and Wind (electricity only)	100% renewable power system in Australia, backed by storage. The study uses the EROI values of currently available technologies.	5.9	(Trainer, 2018)
Solar and Wind (electricity only)	100% renewable power globally by 2060 backed up by storage. The study models the evolution of EROI from renewable technologies over time.	From 3 to 5	(Capellán-Pérez et al., 2019)
Solar, wind and nuclear (electricity only)	100% low-carbon power system in Belgium, backed up by storage. The study uses the EROI values of currently available technologies.	5.4	(Limpens and Jeanmart, 2018)
Solar and wind (electricity only)	The study models the EROI in the energy system where 75% of the energy is provided from renewables by 2050.	6.2-6.8[2]	(Sgouridis et al., 2016)
Renewables, bioenergy, and nuclear represent approximately 60% of total energy generation, while fossil fuels represent 40%.	Energy system in 2050 from the IEA scenario that is consistent with 66% of staying below 2 °C. The study uses the EROI values of currently available technologies.	From 5.8 to 11.8	(King and Van Den Bergh, 2018)
Fossil fuels	The study calculates the existing EROI values of energy carriers generated from fossil fuels.	3 (electricity) 8 (petroleum and gas) 6.1 (all of the energy carriers combined)	(Brockway et al., 2019)
Fossil fuels represent 66% of power generation, nuclear 19%, biomass 5% and renewables 10%.	UK power grid in 2013.	5.4	(Raugei and Leccisi, 2016)

[2] Here, we convert the EROI values from (Sgouridis et al., 2016) which are reported in the primary energy equivalent of electrical energy, by dividing the original EROI values ranging from 20-22, by the average power generation efficiency of the UK grid. We use the efficiency of the UK grid from (Raugei et al., 2012) which is the original reference for the EROI of renewable energy technologies in the study of Sgouridis et al. This approach is consistent with the standard EROI convention of summing up all the energy inputs from different energy carriers at the final energy boundary without converting them into primary energy equivalents.

2.9.1.2 Overview of EROI assumptions for different energy conversion technologies

Here, we provide a transparent overview of the qualitative assumptions for the EROI scenarios of different energy technologies across the energy supply chain. Qualitative assumptions provide a rough sketch of the underlying social, political and technological contexts of the development and application of energy technologies in our EROI scenarios.

Supplementary Table 2.3: Fossil fuels

EROI scenario	Extraction	Transportation and distribution	Construction, and operation of infrastructure	Refining of crude oil	Distribution and transmission losses
High-EROI	$EROI_{ST}$ median and declining	Long trade routes	Energy required for the construction, and operation is assumed to be equal in all EROI scenarios, as these energy inputs assume only a small share of total energy requirements	Moderate energy intensity	Endogenously accounted in the IAM mitigation pathways
Median-EROI	$EROI_{ST}$ median and declining	Moderately long trade routes		Moderate energy intensity	
Low-EROI	$EROI_{ST}$ median and declining	Long trade routes		Moderate energy intensity	

Supplementary Table 2.4: Bioenergy

EROI scenario	Extraction	Transportation and distribution	Construction and operation of infrastructure	Biomass quality	Distribution and transmission losses
High-EROI	$EROI_{ST}$ median	Moderately long trade routes	Energy required for the construction, and operation is assumed to be equal in all EROI scenarios, as these energy inputs assume only a small share of total energy requirements	Moderate	Endogenously accounted in the IAM mitigation pathways
Median-EROI	$EROI_{ST}$ median	Moderately long trade routes		Moderate	
Low-EROI	$EROI_{ST}$ low	Long trade routes		Low	

Supplementary Table 2.5: Photovoltaics and wind energy

EROI scenario	Construction, operation and maintenance of infrastructure	Resource quality distribution	Distribution, transmission, and storage losses
High-EROI	High innovation results in a fast decrease of the energy required to construct, maintain and operate renewable energy systems	Resource management prioritises high energy yields over other objectives (e.g. conservation of nature reserves), and low public resistance to renewable energy projects result in high energy yields at the sites of most abundant resource density	Endogenously accounted in the IAM mitigation pathways
Median-EROI	Moderate innovation results in a moderate reduction of the energy required to construct, maintain and operate renewable energy systems	Resource management strikes a balance between high energy yields and oteher objectives. Public resistance to renewable energy projects is limited to the areas of high proximity to urban centres and areas of recognised ecological value. These conditions mean that energy yields of energy infrastructure are relatively high, but bellow the maximum tehnical potential	
Low-EROI	Moderate innovation results in a moderate reduction of the energy required to construct, maintain and operate renewable energy systems	Resource management strikes a balance between high energy yields and oteher objectives. Public resistance to renewable energy projects is limited to the areas of high proximity to urban centres and areas of recognised ecological value. These conditions mean that energy yields of energy infrastructure are relatively high, but bellow the maximum tehnical potential	

Supplementary Table 2.6: Nuclear energy, hydropower, and geothermal energy.

EROI scenario	EROI assumptions	Distribution and transmission losses
High-EROI	The upper quartile of present-day EROI values	Endogenously accounted in the IAM mitigation pathways
Median-EROI	Median of present-day EROI values	
Low-EROI	The lower quartile of present-day EROI values	

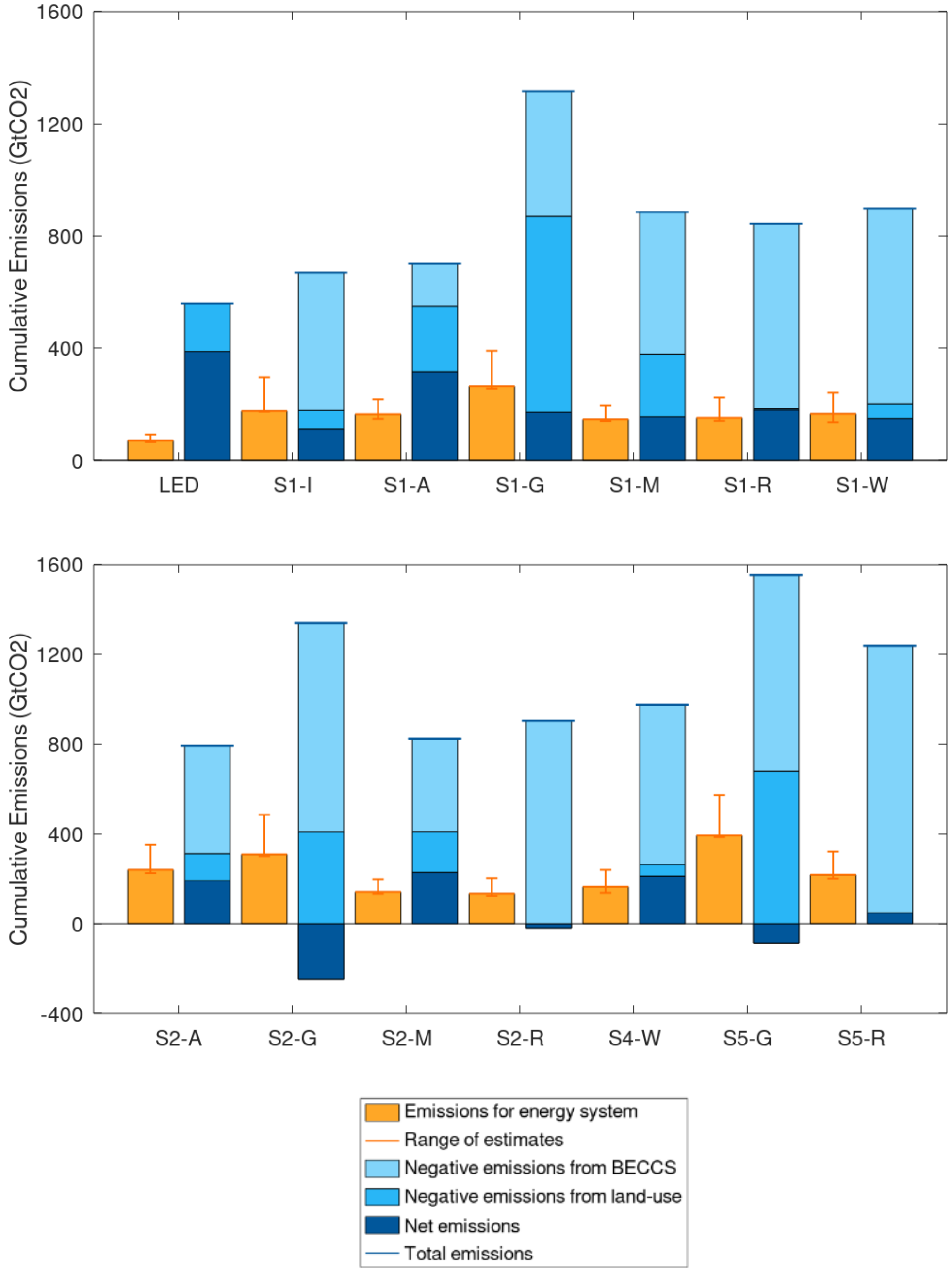
Supplementary Table 2.7: Hydrogen from electrolysis

EROI scenario	Energy system conversion efficiency	Distribution and transmission losses
High-EROI	High innovation leads to very high efficiency improvements of electrolysis and reduced energy requirements of a hydrogen fuel cell	Endogenously accounted in the IAM mitigation pathways
Median-EROI	Moderate innovation results in high efficiency improvements of electrolysis and lower energy requirements of a hydrogen fuel cell	
Low-EROI	High innovation leads to very high efficiency improvements of electrolysis and reduced energy requirements of a hydrogen fuel cell	

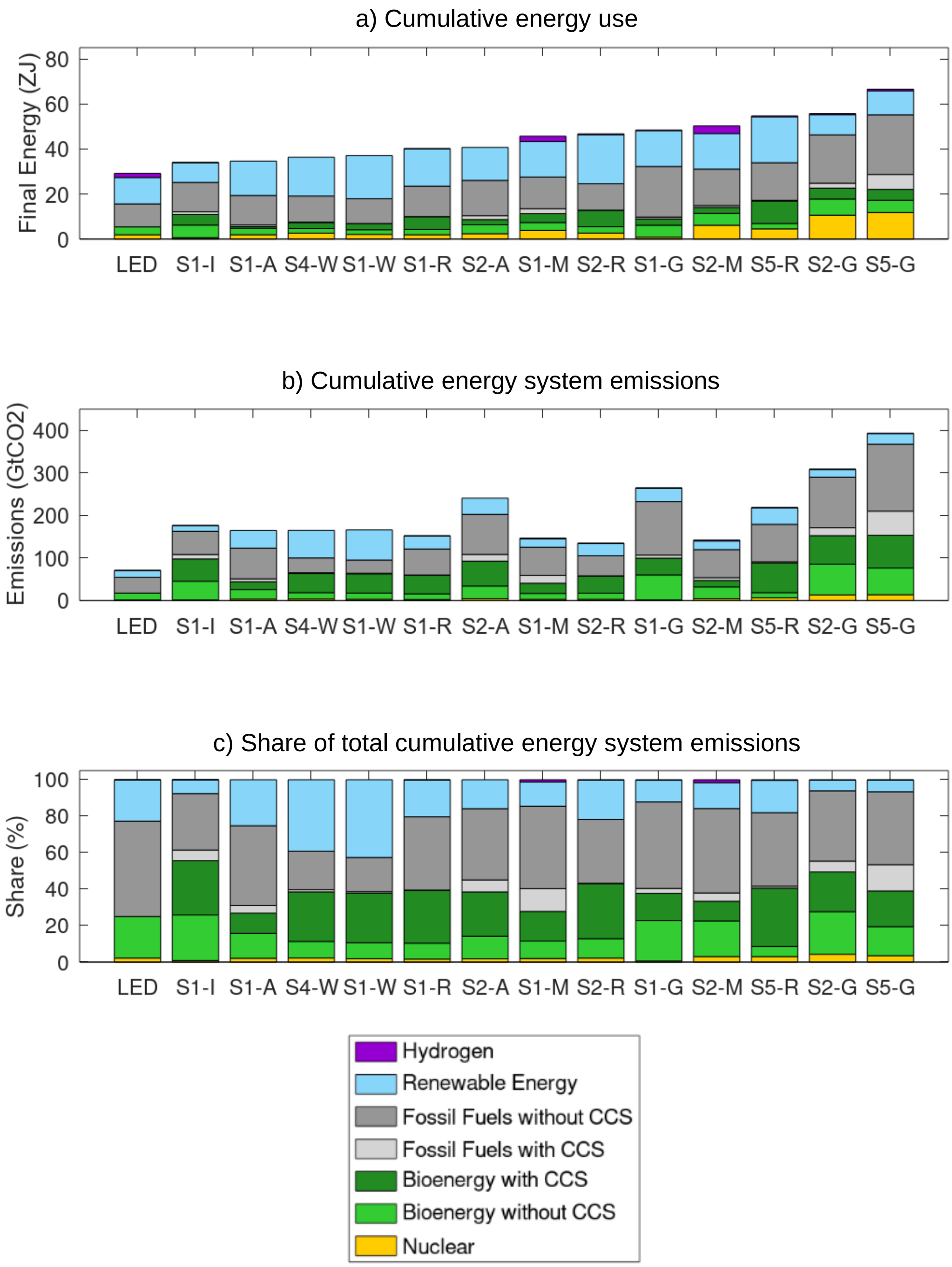
Supplementary Table 2.8: The fourteen scenarios used in our study

Scenario Narrative	Integrated Assessment Model	Abbreviations
LED - Low Energy Demand (Grubler et al., 2018; IPCC, 2018b)	MESSAGE GLOBIOM	LED
S1- Sustainable Development (Riahi et al., 2017; Rogelj et al., 2018; van Vuuren et al., 2017)	IMAGE	S1-I
	AIM	S1-A
	GCAM4	S1-G
	MESSAGE GLOBIOM	S1-M
	REMIND MAgPIE	S1-R
	WITCH	S1-W
S2 – Middle of the Road (Fricko et al., 2017; Riahi et al., 2017; Rogelj et al., 2018)	AIM	S2-A
	GCAM4	S2-G
	MESSAGE GLOBIOM	S2-M
	REMIND MAgPIE	S2-R
S4 – World of deepening Inequality (Calvin et al., 2017; Riahi et al., 2017; Rogelj et al., 2018)	WITCH	S4-W
S5 – Fossil-fuelled development (Kriegler et al., 2017; Riahi et al., 2017; Rogelj et al., 2018)	GCAM4	S5-G
	REMIND MAgPIE	S5-R

Note: The table provides a list of fourteen scenarios used in our study and their abbreviations. We group the scenarios according to their scenario narratives. Scenario narratives underpin the Shared Socioeconomic Pathways (SSPs) and outline different socioeconomic developments. SSP narratives lay out basic assumptions on technology developments, lifestyle changes and resource availability. The assumptions from SSPs are then used in integrated assessment models (IAMs) to produce the mitigation pathways that are compatible with the climate target of stabilising climate change below 1.5 °C by 2100. LED is a scenario that was produced after the release of the SSPs and is based on a “low-energy narrative” that is distinct from any of the SSP narratives.



Supplementary Figure 2.3: Energy system emissions for the fourteen scenarios compatible with 1.5 °C. Energy system emissions (orange columns) are compared to total cumulative emissions (blue columns). Orange error bars indicate the spread of energy system emissions calculations from high- to low-EROI scenarios.



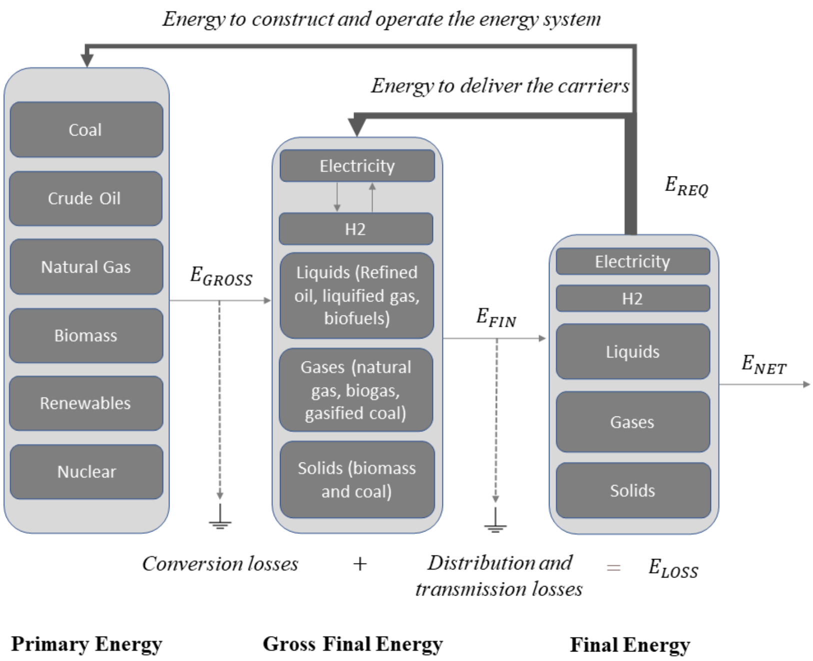
Supplementary Figure 2.4: Cumulative energy use and energy system emissions from different energy technologies for scenarios compatible with 1.5 °C. (a) Total amount of energy consumption in the period from 2020 to 2100. Individual technologies are aggregated together depending on the energy generation type. Scenarios in all the panels are ordered by energy consumption. **(b)** Total amount of energy system emissions for the median EROI assumption. **(c)** The share of emissions for the energy system from each energy source for the median EROI assumption.

Notes: The speed of decarbonisation in different scenarios can be approximated from the cumulative energy system emissions from fossil fuels without carbon capture and storage (Panel a). The speed of decarbonisation is roughly speaking inversely proportional to the cumulative use of fossil fuels without CCS (Panel b). Note that BECCS produces a relatively small amount of energy (Panel a), but represents a major source of energy system emissions in the majority of scenarios (Panels b and c).

Supplementary Table 2.9: Panel data analysis of the factors that drive energy system emissions

	Annual Energy System Emissions ($GtCO_2$/year)	
	2020–2040	**2041–2100**
Energy Use (EJ/year)	0.0081***	0.0042***
	(9.714e-05)	(0.0002)
Share of Conventional Fossil Fuels (%)	0.0120***	0.0896***
	(0.0018)	(0.0026)
1/EROI (%)	0.1397***	-0.0436***
	(0.00413)	(0.0096)
Constant	-2.7540***	-0.0069***
	(0.0544)	(0.0013)
Number of Observations	294	840
R^2 (Between Scenarios)	0.992	0.880

Note: We performed an OLS regression with time fixed-effects on average annual energy system emissions for three energy system emissions factors. We conducted separate analyses for the 2020–2040 and 2041–2100 periods. Robust standard errors are shown in parentheses. *** $p < 0.001$.



Supplementary Figure 2.5: Boundaries of net energy analysis and energy flows along the energy supply chain. The figure illustrates how different technologies convert energy from the primary energy stage to the final energy stage, where net energy is delivered to society. At the primary energy stage, raw resources are extracted, or harvested, before being sent to energy conversion or energy processing facilities like power plants and refineries at the secondary energy stage. This is the energy system boundary for calculating the EROI at the standard energy system boundary ($EROI_{ST}$). The secondary energy stage is where most of the useful energy carriers are generated. The total amount of energy generated at this stage is known as the gross final energy. A fraction of gross final energy is "lost" during the distribution and transmission to end users. A fraction of the remaining final energy is used by the energy system itself (e.g., for extraction, conversion, and the delivery of energy to the end users). Some of the final energy is also used by the industry to produce new energy infrastructure that replaces the obsolete infrastructure. The remaining energy that goes to society is defined as net energy.

Supplementary Table 2.10: Model parameter values

Parameter	Abbreviation	Specification	Value (min-max)	Unit	Reference
Energy intensity of capital	ε		4520	GJ/million $US2015	(Sgouridis et al., 2019)
Capital costs of infrastructure	C_p			$/ per kW of installed capacity	
		Coal to electricity	2200		(IAMC, 2019; Luderer et al., 2013)
		Coal to electricity wCCS	2800		(IAMC, 2019; Luderer et al., 2013)
		Oil to electricity	1000		Our assumption
		Gas to electricity	950		(IAMC, 2019; Luderer et al., 2013)
		Gas to electricity wCCS	1350		(IAMC, 2019; Luderer et al., 2013)
		Biomass to electricity	2450		(IAMC, 2019; Luderer et al., 2013)
		Biomas to electricity wCCS	3150		(IAMC, 2019; Luderer et al., 2013)
		Natural gas	0[a]		Our assumption
		Coal to gas	1440		(IAMC, 2019; Luderer et al., 2013)
		Biomass to gas	1200		(IAMC, 2019; Luderer et al., 2013)
		Oil	0[a]		Our assumption
		Coal to oil	1740		(IAMC, 2019; Luderer et al., 2013)
		Coal to oil wCCS	1820		(IAMC, 2019; Luderer et al., 2013)
		Gas to oil	1030		(Larson et al., 2012)
		Gas to oil wCCS	1230		(Larson et al., 2012)
		Biomass to oil	3000		(IAMC, 2019; Luderer et al., 2013)
		Biomass to oil wCCS	3600		(IAMC, 2019; Luderer et al., 2013)
		Coal to solids	0[a]		(IAMC, 2019; Luderer et al., 2013)
		Biomass to solids	0[a]		(IAMC, 2019; Luderer et al., 2013)
		Biomass to H_2	1680		(IAMC, 2019; Luderer et al., 2013)
		Biomass to H_2 wCCS	2040		(IAMC, 2019; Luderer et al., 2013)

Operation and Maintenance costs	$C_{O\&M}$			$/ per GJ of generated energy	
		Coal to electricity	4.0		(IAMC, 2019; Luderer et al., 2013)
		Coal to electricity wCCS	5.3		(IAMC, 2019; Luderer et al., 2013)
		Oil to electricity	7.0		Our assumption
		Gas to electricity	2.1		(IAMC, 2019; Luderer et al., 2013)
		Gas to electricity wCCS	2.9		(IAMC, 2019; Luderer et al., 2013)
		Biomass to electricity	5.1		(IAMC, 2019; Luderer et al., 2013)
		Biomas to electricity wCCS	6.9		(IAMC, 2019; Luderer et al., 2013)
		Natural gas	0[a]		Our assumption
		Coal to gas	1.4		(IAMC, 2019; Luderer et al., 2013)
		Biomass to gas	1.9		(IAMC, 2019; Luderer et al., 2013)
		Oil	0		Our assumption
		Coal to oil	4.2		(IAMC, 2019; Luderer et al., 2013)
		Coal to oil wCCS	5.0		(IAMC, 2019; Luderer et al., 2013)
		Gas to oil	1.2		Our assumption
		Gas to oil wCCS	1.5		Our assumption
		Biomass to oil	4.2		(IAMC, 2019; Luderer et al., 2013)
		Biomass to oil wCCS	5.4		(IAMC, 2019; Luderer et al., 2013)
		Coal to solids	0[a]		Our assumption
		Biomass to solids	0[a]		Our assumption
		Biomass to H_2	5.7		(IAMC, 2019; Luderer et al., 2013)
		Biomass to H_2 wCCS	6.8		(IAMC, 2019; Luderer et al., 2013)
Rate of decay	β_C			% per year	
		Coal		2.2	(Brockway et al., 2019)
		Gas		1.6	(Brockway et al., 2019)
		Oil		1.1	(Brockway et al., 2019)
Energy conversion efficiency	η_C			Dimensionless	

		Coal to electricity	(0.41-0.50)[b]		(IAMC, 2019; Luderer et al., 2013)
		Coal to electricity wCCS	(0.33-0.43)[b]		(IAMC, 2019; Luderer et al., 2013)
		Oil to electricity	0.35		(IPCC, 2007)
		Gas to electricity	(0.56-0.63)[b]		(IAMC, 2019; Luderer et al., 2013)
		Gas to electricity wCCS	(0.49-0.56)[b]		(IAMC, 2019; Luderer et al., 2013)
		Biomass to electricity	(0.37-0.46)[b]		(IAMC, 2019; Luderer et al., 2013)
		Biomas to electricity wCCS	(0.28-0.35)[b]		(IAMC, 2019; Luderer et al., 2013)
		Natural gas	1.0[c]		Our assumption
		Coal to gas	0.6		(IAMC, 2019; Luderer et al., 2013)
		Biomass to gas	0.55		(IAMC, 2019; Luderer et al., 2013)
		Oil	1.0[c]		Our assumption
		Coal to oil	0.40		(IAMC, 2019; Luderer et al., 2013)
		Coal to oil wCCS	0.40		(IAMC, 2019; Luderer et al., 2013)
		Gas to oil	(0.53-0.58)[b]		(Larson et al., 2012)
		Gas to oil wCCS	(0-53-0.58)[b]		(Larson et al., 2012)
		Biomass to oil	0.40		(IAMC, 2019; Luderer et al., 2013)
		Biomass to oil wCCS	0.41		(IAMC, 2019; Luderer et al., 2013)
		Coal to solids	1.0[c]		Our assumption
		Biomass to solids	1.0[c]		Our assumption
		Biomass to H_2	0.61		(IAMC, 2019; Luderer et al., 2013)
		Biomass to H_2 wCCS	0.55		(IAMC, 2019; Luderer et al., 2013)
Energy intensity of oil refinery per kg output	μ_{REF}		3.8[d] (2.8[d] -4.5)[d]	MJ/kg	(Meili et al., 2018) (Jing et al., 2020) (Raugei and Leccisi, 2016)
Higher heating value	HHV			MJ/kg	
		Coal	25.2		(Raugei and Leccisi, 2016)
		Natural gas	38.3		(Raugei and Leccisi, 2016)

		Oil (petroleum)	45.8		(Raugei and Leccisi, 2016)
		Biomass – miscanthus and wheat straw	18.4 (17.3-21.2)[e]		(Fajardy and Mac Dowell, 2017)
Energy intensity of transportation per tonne km	$\gamma_{TRA,j}$			MJ/tkm	
		Shipping (bulk)	0.11		(Ecoinvent, 2020)
		Shipping (tanker)	0.06		(Ecoinvent, 2020)
		Shipping (LNG)	0.37		(Ecoinvent, 2020)
		Oil pipeline offshore	0.63		(Ecoinvent, 2020)
		Oil pipeline onshore	0.18		(Ecoinvent, 2020)
		Gas pipeline offshore	0.35		(Ecoinvent, 2020)
		Gas pipeline onshore	0.35		(Ecoinvent, 2020)
		Truck >32tonnes	1.26		(Ecoinvent, 2020)
		Truck >16tonnes	1.93		(Ecoinvent, 2020)
		Rail	0.14		(Ecoinvent, 2020)
		Barge	0.52		(Ecoinvent, 2020)
Lifetime of infrastructure	τ			years	
		Coal to electricity	35		(IAMC, 2019; Luderer et al., 2013)
		Coal to electricity wCCS	35		(IAMC, 2019; Luderer et al., 2013)
		Oil to electricity	35		Our Assumption
		Gas to electricity	35		(IAMC, 2019; Luderer et al., 2013)
		Gas to electricity wCCS	35		(IAMC, 2019; Luderer et al., 2013)
		Biomass to electricity	40		(IAMC, 2019; Luderer et al., 2013)
		Biomas to electricity wCCS	40		(IAMC, 2019; Luderer et al., 2013)
		Natural gas	35		(IAMC, 2019; Luderer et al., 2013)
		Coal to gas	35		(IAMC, 2019; Luderer et al., 2013)
		Biomass to gas	35		(IAMC, 2019; Luderer et al., 2013)
		Oil	30		(CAPP, 2021)
		Coal to oil	35		(IAMC, 2019; Luderer et al., 2013)
		Coal to oil wCCS	35		(IAMC, 2019; Luderer et al., 2013)

		Gas to oil	35		(Larson et al., 2012)
		Gas to oil wCCS	35		(Larson et al., 2012)
		Biomass to oil	35		Our assumption
		Biomass to oil wCCS	35		Our assumption
		Coal to solids	45		(King and Van Den Bergh, 2018)
		Biomass to solids	35		Own assumption
		Biomass to H_2	35		(IAMC, 2019; Luderer et al., 2013)
		Biomass to H_2 wCCS	35		(IAMC, 2019; Luderer et al., 2013)
		Geothermal power	30		(IAMC, 2019; Luderer et al., 2013)
		Hydropower	70		(IAMC, 2019; Luderer et al., 2013)
		Nuclear power	40		(IAMC, 2019; Luderer et al., 2013)
		Photovoltaics	30		(IAMC, 2019; Luderer et al., 2013)
		Windpower	25		(IAMC, 2019; Luderer et al., 2013)
		Electricity to H_2	30		Own assumption
Operation share of energy requirements	α_{tech}			Dimensionless	
		Geothermal power	0.95		(Atlason and Unnthorsson, 2013)
		Hydropower	0		(Arvesen et al., 2018)
		Nuclear power	0.904		(Arvesen et al., 2018)
		Photovoltaics	0.01		(Arvesen et al., 2018)
		Windpower	0.1215[f]		(Arvesen et al., 2018)
		Electricity to H_2	1.0		Our assumption
Experience parameter	b			Dimensionless	
		Photovoltaics	0.235 (0.193-0.278)[g]		(Steffen et al., 2018)
		Windpower	0.015 (-0.036-0.066)[g]		(Steffen et al., 2018)
Energy stored on energy invested	ESOI	Hydrogen fuel cell	59 (65-68)[h]	Dimensionless	(Pellow et al., 2015)
Electrolyser efficiency	η_{lyz}		0.78 (0.70-0.85)[h]	Dimensionless	(Pellow et al., 2015)
Fuel cell efficiency	η_{FC}		0.60 (0.47-0.72)[h]	Dimensionless	(Pellow et al., 2015)
Hydrogen compression efficiency	η_{comp}		0.89 (0.93-0.96)[h]	Dimensionless	(Pellow et al., 2015)

Full H_2 system efficiency	η_{sys}		0.442 (0.303-0.591)[h]	Dimensionless	(Pellow et al., 2015)
Carbon intensity of energy conversion technologies	φ_i			tCO_2/GJ	
		Coal	0.0957		(IAMC, 2019; Luderer et al., 2013)
		Coal wCCS	0.00957		(IAMC, 2019; Luderer et al., 2013)
		Oil	0.0675		(IAMC, 2019; Luderer et al., 2013)
		Gas	0.0561		(IAMC, 2019; Luderer et al., 2013)
		Gas wCCS	0.00561		(IAMC, 2019; Luderer et al., 2013)
		Biomass	0		(IAMC, 2019; Luderer et al., 2013)

Notes: [a] Capital costs and operation and maintenance costs of energy infrastructure for indicated technologies are already accounted for in $EROI_{ST}$ at the standard boundary, therefore the value is 0.

[b] Minimum values of energy conversion efficiencies represent the technological efficiencies of energy infrastructure built in year 2005, whereas maximum values correspond to the efficiencies of infrastructure build after 2050, as assumed in the REMIND IAM documentation. For energy conversion efficiencies of energy infrastructure build between 2005 and 2050, we use a linear interpolation between the values of 2005 and 2050.

[c] Energy conversion efficiencies equal 1.0 when there is no energy conversion loss. We assume zero losses for natural gas and oil, as we use the data at the secondary energy stage which already accounts for conversion losses. We also assume zero losses for biomass and coal, which is consistent with the energy conversion in the majority of mitigation scenarios that were analysed.

[d] Lower value for energy intensity of oil refinery are taken from (Meili et al., 2018) median value is taken from (Jing et al., 2020) and the high value is taken from (Raugei and Leccisi, 2016).

[e] The range of HHV values for biomass is taken from the HHV values of miscanthus, and wheat straw, according to (Fajardy and Mac Dowell, 2018).

[f] Here, the operation share of energy requirements for wind power is estimated as an average of operation shares for offshore and onshore wind-power, calculated by (Arvesen et al., 2018).

[g] Experience parameters for PV and Wind power are calculated following the approach of (Steffen et al., 2018). We calculate the experience parameter b from the "invested energy data" provided in Figure 1 of the latter study. In the calculation of experience parameters, we do not account for the improved efficiency of energy generation, as these improvements and their effects on the EROI are already endogenously included in the energy generation data from the mitigation scenarios.

[h] Parameters of hydrogen generation from electrolysis were obtained from the Table 1 (compressor efficiency) and Table 3 (ESOI, electrolyser efficiency, and fuel cell efficiency) of the study by (Pellow et al., 2015). The system efficiency parameter was calculated using the Supplementary Equation 11 from the "Note on energy requirements of hydrogen from electrolysis", which was derived from the same study.

2.9.2 Note on EROI$_{ST}$ estimates from literature

We constructed a database of EROI values for different energy fuels at the standard energy system boundary by conducting a Google Scholar search using the following queries: "EROI + fuel type" (e.g. "EROI + biomass"), and "net-energy analysis". We collected all studies containing EROI calculations for the raw fuels included in our study. Furthermore, we manually checked the studies cited in the relevant EROI review literature (Dale et al., 2012b; Hall et al., 2014; Lambert et al., 2012; Murphy et al., 2011; Weißbach et al., 2013).

Of the 39 studies obtained, we eliminated studies with ambiguous EROI methodologies or boundaries that did not fit those defined in our study. We also excluded studies that used EROI estimates originating from studies we had already selected, to avoid double-counting. EROI data from the remaining 23 studies, listed in Supplementary Table 2.10, were used for the interquartile analysis producing low, median, and high-EROI$_{ST}$ estimates for the raw energy fuels in our model. The EROI$_{ST}$ values are used to calculate the energy required for the extraction, mining, or harvesting of raw fuels and should not be confused with the EROI$_{FIN}$ estimates reported in Supplementary Table 2.1, which include additional energy requirements for the conversion of raw fuels into useful energy carriers and their delivery to consumers at the final energy stage.

Supplementary Table 2.11: Overview of $EROI_{ST}$ estimates from the literature at the standard energy system boundary alongside our calculations

Energy resource	$EROI_{ST}$ value (min/median/max)	Location/Origin	Reference
Coal			
	46	USA	(Raugei and Leccisi, 2016)
	60	Colombia	(Raugei and Leccisi, 2016)
	27	UK	(Raugei and Leccisi, 2016)
	18	Russia	(Raugei and Leccisi, 2016)
	40-55	Global	(Hall et al., 2014)
	60	USA	(Hall et al., 2014)
	27	China	(Hu et al., 2013)
	80	USA	(Murphy and Hall, 2010)
	42	Global	(Dale et al., 2012a, 2012b)
	28	Global	(Lambert et al., 2012)
	42	Indonesia	(Aguirre-Villegas and Benson, 2017)
	65	Chile	(Raugei et al., 2018)
	23-58	Global	(Sgouridis et al., 2019)
	29	Global	(Brockway et al., 2019)
	27/42/59	**Global IQ-range[a]**	**Our calculation**
Oil	86	UK	(Raugei and Leccisi, 2016)
	10	Algeria	(Raugei and Leccisi, 2016)
	6	Nigeria	(Raugei and Leccisi, 2016)
	49	Norway	(Raugei and Leccisi, 2016)
	9	China	(Hu et al., 2013)
	25	Colombia	(Yáñez et al., 2018)
	24	Chile	(Raugei et al., 2018)
	18	Global	(Cleveland and O'Connor, 2011)
	13	Canada	(Poisson and Hall, 2013)
	11	USA	(Guilford et al., 2011)
	10-20	USA	(Murphy et al., 2011)

	24	Global	(Dale et al., 2012a, 2012b)
	17	Global	(Lambert et al., 2012)
	18	Global	(Gagnon et al., 2009)
	20	Global	(Hall et al., 2014)
	28	Global	(Brockway et al., 2019)
	11/18/24	**Global IQ-range[a]**	**Our calculation**
Natural Gas			
	78	UK	(Raugei and Leccisi, 2016)
	115	Norway	(Raugei and Leccisi, 2016)
	294	Netherlands	(Raugei and Leccisi, 2016)
	87	USA	(Sell et al., 2011)
	17	USA	(Yaritani and Matsushima, 2014)
	10	USA[b]	(Murphy et al., 2011)
	20	Canada[b]	(Lambert et al., 2012)
	9	China[b]	(Hu et al., 2013)
	13	Canada[b]	(Poisson and Hall, 2013)
	20	Canada[b]	(Lambert et al., 2012)
	11	USA[b]	(Guilford et al., 2011)
	53	Global	(Sgouridis et al., 2019)
	20	Global[b]	(Hall et al., 2014)
	18	Global[b]	(Gagnon et al., 2009)
	29	Global	(Brockway et al., 2019)
	13/20/78	**Global IQ-range[a]**	**Our calculation**
Biomass[c]			
Pellets	3.1	USA	(Raugei and Leccisi, 2016)
Chips	54	UK	(Raugei and Leccisi, 2016)
Straw	4.5	UK	(Raugei and Leccisi, 2016)
Solid biomass	20	Global	(Dale et al., 2012a, 2012b)
Chips	30	Croatia	(Pandur et al., 2015)
Chips	14.4	North Europe	(Moriarty and Honnery, 2016)

Wheat pellets	7.8/9.9/13.5[d]	EU	(Fajardy and Mac Dowell, 2017)
Switchgrass pellets	5.0/9.0/14.8[d]	EU	(Fajardy and Mac Dowell, 2017)
Miscanthus pellets	3.8/5.9/10.3[d]	EU	(Fajardy and Mac Dowell, 2017)
Willow pellets	2.1/2.5/2.7[d]	EU	(Fajardy and Mac Dowell, 2017)
Wheat pellets	7.8/9.5/13.5[d]	USA	(Fajardy and Mac Dowell, 2017)
Switchgrass pellets	5.0/8.1/14.8[d]	USA	(Fajardy and Mac Dowell, 2017)
Miscanthus pellets	3.8/5.6/10.3[d]	USA	(Fajardy and Mac Dowell, 2017)
Willow pellets	1.5/2.1/2.7[d]	USA	(Fajardy and Mac Dowell, 2017)
Wheat pellets	5.6/9.4/19.8[d]	Brazil	(Fajardy and Mac Dowell, 2017)
Switchgrass pellets	3.5/7.2/28.7[d]	Brazil	(Fajardy and Mac Dowell, 2017)
Miscanthus pellets	3.0/5.8/18.6[d]	Brazil	(Fajardy and Mac Dowell, 2017)
Wheat pellets	4.5/8.5/24.1[d]	China	(Fajardy and Mac Dowell, 2017)
Miscanthus pellets	3.2/13.3[d]	China	(Fajardy and Mac Dowell, 2017)
Switchgrass pellets	4.2/9.5/67.7[d]	China	(Fajardy and Mac Dowell, 2017)
Wheat pellets	4.3/9.5/13.1[d]	India	(Fajardy and Mac Dowell, 2017)
Miscanthus pellets	2.3/4.3/13.1[d]	India	(Fajardy and Mac Dowell, 2017)
Switchgrass pellets	2.2/5.4/25[d]	India	(Fajardy and Mac Dowell, 2017)
Dry Switchgrass	23	Canada	(Hall et al., 2011)
Dry Switchgrass	38	USA	(Hall et al., 2011)
Verge grass (natural drying)	45-60	Netherlands	(Voinov et al., 2015)
Willow chips (natural drying)	83-102	Netherlands	(Voinov et al., 2015)
Chips	**20/26/38**	**Global IQ-range[a]**	**Our calculation**
Pellets	**1.9/5.5/9.2**	**Global IQ-range[a]**	**Our calculation**
50% pellets, 50% chips	**3.6/9.1/14.9**	**Global IQ-range[a]**	**Our calculation**

Notes: [a] We use the range of EROI values of each energy resource from the literature to calculate the inter-quartile range of EROI values (IQ-range), consisting of: lower-quartile, median, and higher-quartile EROI values of the resource. We use these estimates in the model to calculate the energy requirements for the extraction, mining or harvesting of energy resources (raw fuels) before they are converted into useful energy carriers.

[b] EROI values for a combined extraction of oil and natural gas. Extraction of natural gas commonly takes place alongside extraction of crude oil, therefore, many studies analyse energy inputs associated with the extraction of oil and natural gas together and report a single EROI value for both fuels.

[c] EROI values of biomass include energy requirements of harvesting at the standard system boundary, and energy inputs associated with processing, drying, and chipping or pelleting of biomass.

[d] EROI estimates from Fajardy and Mac Dowel were adjusted by deducing from energy requirements the energy used in the transportation of biomass. This was done to avoid the double counting of energy used in transportation when calculating the EROI of energy conversion technologies from biomass using our method.

Supplementary Table 2.12: Energy requirements of the global transportation of liquid fuels, estimated from the analysis of major global trade routes of crude oil and oil products.

Trade Route[a]	Distances (tkm)				Trade flow in million tonnes and (%)[f]	Energy intensity of transport (MJ/kg)	References
	Onshore pipeline[b]	Offshore pipeline[c]	Sea freight[d]	Truck freight[e]			
Canada (Edmonton)–USA (Pine Bend in Minnesota)	1.88	0	0	0.1	269.4 (7.7%)	0.47	(NRCAN, 2020)
Middle East (Bagdad via. Ceyhan) - USA (Houston)	1.07 (0.97 in the Middle East and 0.1 in Houston)	0	12.5	0.1	52.8 (1.5%)	1.07	(Meili et al., 2018)
West-Africa (Onne) - USA (Houston)	0.24 (0.14 in Nigeria and 0.1 in USA)	0.02	11	0.1	33.8 (1.0%)	0.85	(Meili et al., 2018)
Mexico (Altamira)-US (Houston)	0.2	0.2	0.9	0.1	32.3 (0.9%)	0.35	(Meili et al., 2018)
Brazil (Sao Paulo)-China (Quingdao)	0.1	0.2	20.5	0.1	68.5 (2.0%)	1.50	(Sea Rates, 2021)
Russia (Taishet)-China (Skovorodino)	3.8	0	0	0.1	80.8 (2.3%)	0.81	(Global Energy Monitor, 2021)
Middle East (Abqaiq) – China (Shenzen)	0.1	0.02	9.4	0.1	244.8 (7.0%)	0.73	(Sea Rates, 2021)
West-Africa (Onne) - China (Shenzen)	0.14	0.02	17.3	0.1	91.8 (2.6%)	1.21	(Sea Rates, 2021)
Middle East (Mina via. Al-Ahmadi) - New Mangalore	0.1	0	3.6	0.1	158.9 (4.6%)	0.36	(Sea Rates, 2021)
West-Africa (Onne) - India (Jamnagar)	0.14	0.02	13.7	0.1	47.6 (1.4%)	0.99	(Sea Rates, 2021)
Middle East (Dubai) - Japan (Yokohama)	0.1	0	11.8	0.1	141.1 (4.1%)	0.86	(Sea Rates, 2021)
Middle East (Abqaiq) - Singapore	0.1	0.02	8	0.1	56.7 (1.6%)	0.64	(Sea Rates, 2021)
Long-distance oil transport to Europe	2	0.04	2.2	0.1	731.7 (21.0%)	0.65	(Meili et al., 2018)
Average energy for domestic transport[g]	0.6	0.04	0	0.1		0.26	Our calculation

Weighted average energy intensity of oil transport					**3480.9 (100%)**	**0.61+/-0.11[f]**	

Notes: [a] Selected trade routes represent some of the major destinations of global export and import of crude oil. We divide the trade routes into four transportation segments (onshore pipeline, offshore pipeline, freight by tankers, and freight by truck with the cargo capacity of 32 tonnes). Our approach broadly follows the methods and assumptions of (Meili et al., 2018)

[b] For distances of oil transport in pipelines we used the information on existing pipeline networks that was available in online documentation of pipeline networks, unless the distances were already provided in the study by (Meili et al., 2018) For trade routes where oil is delivered to the refineries that are situated nearby the ports, we assume the onshore pipeline value of 100 km.

[c] For trade routes where offshore oil fields represent the main share of oil extraction, we assume a generic offshore pipeline value of 200 km, whereas for trade routes where offshore represents a small share of oil extraction, we assume 20 km, following (Meili et al., 2018). For oil exports from oilwells based on the mainland, we assume the distance of offshore pipelines to be zero.

[d] For transportation across the open sea, we used the application "Sea Rates (Sea Rates, 2021)" which calculates the distances between ports.

[e] We assume an average global distance of delivery by a truck from the refinery to the final user of 100km.

[f] We match the selected trade routes with the volume of transported crude oil and oil products obtained from "Oil: Inter-area movements 2019" input and output table from the British Petroleum's (BP) *"Statistical Review of World Energy 2020"*(BP, 2020). According to the BP data tables on global oil production and trade, the selected trade routes transport 58% of globally produced crude oil and oil products. We calculate relative shares of global oil production that is transported over a selected trade route and use them as relative weights to calculate the average global energy requirement for transporting liquid fuels, as shown in Equation 13 of the Methods. The standard error of our global intensity estimate is assumed to be the double of the standard deviation of the energy intensities in the selected trade routes.

[g] Domestic transport of oil corresponds to the 22.4% of global oil production for which the extraction, refining and end-use take place within the same country. For domestic oil transport, we assume an average onshore pipeline distance of 600 km, which is consistent with the average distance of the domestic oil transport in pipelines in the USA (Strogen and Horvath, 2013), an average offshore pipeline distance of 40 km as suggested for Europe by (Meili et al., 2018) and 0 km of sea freight, as we consider that domestic transportation rarely involves transport over the sea.

Supplementary Table 2.13: Energy requirements of the global transportation of natural gas, estimated from the analysis of major global trade routes of natural gas.

Trade Route[a]	Distances (tkm)			Trade flow (million tonnes)	Share of global gas trade	Energy intensity of transportat (MJ/kg)	References
	Onshore pipeline	Offshore pipeline	Sea freight				
UK – Belgium	0.55	0.235	0				(Ecoinvent, 2020)
UK – Switzerland	0.7	0.235	0				(Ecoinvent, 2020)
UK – Netherlands	0.65	0.235	0				(Ecoinvent, 2020)
Netherlands-Austria	0.8	0	0				(Ecoinvent, 2020)
Netherlands-France	0.2	0	0				(Ecoinvent, 2020)
Netherlands – UK	0.25	0.235	0				(Ecoinvent, 2020)
Norway – Belgium	0.1	0.65	0				(Ecoinvent, 2020)
Norway – Switzerland	1.45	0.65	0				(Ecoinvent, 2020)
Norway - Czechia	0.75	0.65	0				(Ecoinvent, 2020)
Norway – Spain	1.55	0.65	0				(Ecoinvent, 2020)
Germany – Austria	0.7	0	0				(Ecoinvent, 2020)
Germany – Switzerland	0.85	0	0				(Ecoinvent, 2020)
Germany – Poland	0.5	0	0				(Ecoinvent, 2020)
European domestic	**0.7**	**0.235**	**0**		**5.28%**	**0.32**	(Ecoinvent, 2020)
Algeria – Switzerland[b]	2.1	0.1	1.1				(Ecoinvent, 2020)
Algeria - Spain[b]	1.2	0.1	0.6				(Ecoinvent, 2020)
Algeria – France[b]	0.7	0.1	2.5				(Ecoinvent, 2020)
Algeria – Italy[b]	1	0.1	1				(Ecoinvent, 2020)
Algeria - UK[b]	0.7	0.1	2.1				(Ecoinvent, 2020)
North Africa-Europe	**1**	**0.1**	**1.1**		**1.59%**	**0.79**	
Russia - Belgium	6.1	0	0				(Ecoinvent, 2020)
Russia - Sweden	5.6	0	0				(Ecoinvent, 2020)
Russia - Poland	3.7	0	0				(Ecoinvent, 2020)
Russia - Italy	6.4	0	0				(Ecoinvent, 2020)
Russia-EU[c]	**5.85**	**0**	**0**		**5.72%[c]**	**2.02**	(Ecoinvent, 2020)
USA (Ford Shale - Corpus Christi) – Europe (Rotterdam)[d]	**0.1**	**0.02**	**9.6**		**0.48%**	**3.66**	Our Calculation
Middle-East (Qatar)– Europe	**0.6**	**0**	**10.0**		**1.04%**	**3.91**	(Schori et al., 2012)

Central and South America domestic[e]	**0.6**	**0**	**0.4**		**4.2%**	**0.35**	Our Calculation
Alberta - Quebec (inside Canada)	**3800**	**9**	**0**				(Ecoinvent, 2020)
USA (inside)	**1000**	**0**	**0**				(Littlefield et al., 2019)
USA and Canada domestic	**1.3**	**0**	**0**		**24.6%**	**0.45**	Our Calculation
Middle East domestic	**0.2**	**0.02**	**0**		**14.2%**	**0.08**	(Ecoinvent, 2020)
Russia domestic[c]	**2.5**	**0**	**0**		**14.6%**	**0.86**	(Ecoinvent, 2020)
Russia (Siberia) – China (Shanghai)[f]	3	0	0		1.55%	2.42	Our Calculation
Qatar – China (Shanghai)	0.2	0	10.6[h]		0.44%	3.99	Our Calculation
Australia (North West Shelf) - China (Shanghai)[g]	0	0.12	5.7[h]		3.77%	2.15	Our Calculation
Malaysia (Bintulu) – China (Shanghai)[i]	0	0.15[i]	3,3[h]		2.04%	1.16	Our Calculation
China (average)	**1.4**	**0.1**	**4.1**		**7.8%**	**2.05**	Our Calculation
Weighted average energy intensity of natural gas transport					**100*%**	**0.76+/-0.18[j]**	

Notes: [a] Selected trade routes represent some of the most important natural gas pipelines and sea freight routes for liquified natural gas. We divide the trade routes into three transportation segments (onshore pipeline, offshore pipeline, freight by ships). To estimate the energy required in the transportation of natural gas, we first calculate median distances of natural gas across the transportation segments in each respective region. Estimates of median distances in the regions are indicated in bold letters in the Supplementary Table 2.6. To obtain the energy used in the transportation of natural gas in each respective region, we multiply median distances by the respective energy intensity coefficients, provided in Supplementary Table 2.3. We obtained the distances for most routes from the Ecoinvent v3.2 database, using the keywords: *natural gas, high pressure, import from "xxx"*.

[b] Natural gas from Algeria is transported to Europe in pipelines and in freight ships. The Ecoinvent database provides the joint average transportation distance from both transportation modes while considering the shares of natural gas that is transported in pipelines and in liquified natural gas (LNG) freight ships.

[c] In the calculations of energy requirements from trade routes that start in Russia, we also include the gas from other former countries of the Soviet Union (CIS countries).

[d] For the transportation of natural gas from the USA to Europe, we choose the Eagle Ford natural gas field, Texas and the main LNG export terminal in Corpus Christi (Global Energy Monitor, 2012), as Texas is the biggest producer of natural gas in the USA (EIA, 2021). Only a small fraction of natural gas is produced offshore, in the Mexican Gulf, therefore the average distance of offshore pipelines in the respective transportation routes is estimated at 20 km, following the assumptions of the Ecoinvent database.

[e] For the transportation of natural gas in Latin America in onshore pipelines we (conservatively) estimate an average distance of 650 km. According to the BP table of major trade movements of natural gas, around 90% of natural gas in this region is moved by land. For the remaining 10% which is transported in LNG freight ships, we chose the representative trade route from Pampa Melchorita (Peru) to Manzanillo (Mexico) with a distance of 4700 km according to the "Sea Rates" (Sea Rates, 2021) distance calculator.

[f] Estimated distance is taken from the documentation on the main line of the Power of Siberia 1 pipeline(Gazprom, 2021).

[g] For the transportation of natural gas from Australia, we chose the North West Shelf field, which is the main offshore source of natural gas in Australia. The local port Karratha is where natural gas is liquified and loaded onto ships(Woodside, 2021).

[h] For the open sea trade routes, we used the application "Sea Rates" which calculates the distances between ports.

[i] Malaysia's LNG terminal that is based in Bintulu is the country's largest export hub for natural gas (Monitor, 2021). We used Google maps to estimate the distance of the offshore pipelines in Sarawak to be 150 km. The distance from Bintulu to Shanghai was estimated using "Sea Rates".

[j] We match the selected trade routes with the volume of transported natural gas in pipelines and ships in the "*Natural Gas Trade Movements 2019*" input and output tables from the BP's *"Statistical Review of World Energy 2020"*(BP, 2020) According to BP's data tables on natural gas production and trade, the selected trade routes transport 80% of globally produced natural gas. We calculate relative shares of natural gas that is transported over a selected regional trade route and use them as relative weights to calculate the average global energy requirement for transporting natural gas, as shown in Equation 13 of the Methods. The standard error of our global intensity estimate is assumed to be the double of the standard deviation of the energy intensities in the selected trade routes.

Supplementary Table 2.14: Energy requirements of the global transportation of coal, estimated from the analysis of major global trade routes of coal.

Trade Route[a]	Distances (tkm)				Trade flow (EJ)[b]	Share of global coal production [c]	Energy intensity of transport (MJ/kg)	References
	Train	Barge	Lorry (16-32 tonnes)	Freight ship (bulk)				
Domestic Transport					**132.30**	**79.0%**	**0.15**	(Ecoinvent, 2020)
Indonesia	0.15	0.15	0.05	0	5.87	3.50%	2.57	(Ecoinvent, 2020)
Latin America	0.2	0	0.008	0	0.43	0.26%	1.03	(Ecoinvent, 2020)
Australia	0.01	0.05	0	0	3.46	2.06%	0.59	(Ecoinvent, 2020)
China	0.645	0.09	0.005	0	79.48	47.43%	1.03	(Ecoinvent, 2020)
Europe	0.45	0.3	0	0	6.29	3.75%	1.36	(Ecoinvent, 2020)
India	0.42	0	0.05	0	12.73	7.60%	1.41	(Ecoinvent, 2020)
North America	0.38	0.03	0.005	0	12.26	7.31%	1.14	(Ecoinvent, 2020)
Russia	0.8	0	0	0	5.02	3.0%	0.50	(Ecoinvent, 2020)
South Africa	0.21	0	0.16	0	4.18	2.49%	2.18	(Ecoinvent, 2020)
International Transport					**35.28**	**21.0%**	**0.89**	(Ecoinvent, 2020)
Australia - Europe	0.25	0	0	23	6.3	0.39%	2.18	(Ecoinvent, 2020)
Australia – East Asia (China)	0.25	0	0	9	1.71	3.76%	0.70	(Ecoinvent, 2020)
Australia - Indonesia	0.25	0	0	5	0.15	0.01%	2.00	(Ecoinvent, 2020)
Australia - Latin America	0.25	0	0	9	0	0.001%	1.12	(Ecoinvent, 2020)
Australia - South Africa	0.25	0	0	12.5	0.83	0.03%	0.79	(Ecoinvent, 2020)
Australia - India	0.25	0	0	10	6.47	0.50%	1.40	(Ecoinvent, 2020)
Indonesia -East Asia China)	0.4	0	0	4	0.07	3.86%	0.85	(Ecoinvent, 2020)
Indonesia - Europe	0.15	0.15	0.05	18	0	0.04%	1.40	(Ecoinvent, 2020)
Indonesia - North America	0.15	0.15	0.05	18	2.61	0.01%	1.07	(Ecoinvent, 2020)
Indonesia - India	0.15	0.15	0.05	4.6	0.25	1.56%	1.62	(Ecoinvent, 2020)
Latin America – East Asia (China)	0.8	0	0.008	17	0.84	0.15%	0.50	(Ecoinvent, 2020)
Latin America - Europe	0.8	0	0.008	9	0.03	0.50%	0.61	(Ecoinvent, 2020)
Latin America - India	0.8	0	0.008	20	0.3	0.02%	1.27	(Ecoinvent, 2020)
Latin America - North America	0.8	0	0.008	6	1.29	0.18%	2.11	(Ecoinvent, 2020)
North America – East Asia (China)	0.38	0.03	0.005	12	0.96	0.77%	1.43	(Ecoinvent, 2020)
North America - Europe	0.38	0.03	0.005	7	0	0.57%	2.57	(Ecoinvent, 2020)
North America - India	0.38	0.03	0.005	16	6.47	0.24%	0.59	(Ecoinvent, 2020)
North America - Latin America	0.38	0.03	0.005	9	0.23	3.86%	1.03	(Ecoinvent, 2020)
North America - South Africa	0.38	0.03	0.005	14	2.73	0.14%	1.36	(Ecoinvent, 2020)
Russia – East Asia (China)	2	0	0	2	2.54	1.63%	1.41	(Ecoinvent, 2020)

Russia – Europe	2	0	0	3	0.22	1.52%	1.14	(Ecoinvent, 2020)
Russia – India	2	0	0	9	0.16	0.13%	0.50	(Ecoinvent, 2020)
South Africa – Europe	0.76	0	0.16	15.4	0.03	0.10%	2.18	(Ecoinvent, 2020)
South Africa – Latin America	0.76	0	0.16	9.25	6.3	0.02%	1.63	(Ecoinvent, 2020)
Weighted average energy intensity of coal transport					**167.58**	**100%**	**0.28 (0.18-0.48)[c]**	

Notes: [a] Selected trade routes represent the most relevant global trade routes of coal. We divided the trade routes into four transportation segments (train, lorry, freight by ship, and freight by barge), following the methodology from the Ecoinvent v3.2 database. Energy requirements for transportation using conveyor belt are neglected as they are one order of magnitude lower than the other means of transportation. We obtained the distances for domestic trade routes from the Ecoinvent v3.2 database, using the keywords: *market for hard coal*. For international trade routes, we used the keywords: *hard coal, import from "destination"*, also from the Ecoinvent v3.2 database.

[b] We match the selected international trade routes with the volume of transported coal obtained from "*Coal: Inter-area movements 2019*" input and output table from the BP's "*Statistical Review of World Energy 2020*" (BP, 2020). According to BP's data tables on global coal production and trade, selected trade routes represent 21% of globally produced coal. The remaining 79% of global coal production is transported and consumed domestically.

[c] We calculate relative shares of globally produced coal that is transported over a selected trade route and use them as relative weights to calculate the average energy use for the domestic and international transport of coal, as shown in Equation 13 of the Methods. For the lower-range estimate of energy intensity of global transportation of coal, we deduct from the average energy intensity the standard error of the energy intensity of domestic coal transport. For the upper range estimate we add to the median energy intensity of transporting coal, the standard error of the energy intensity of the international coal transport. The standard errors of the domestic and international energy intensity of coal transport is calculated as the standard deviation of the energy intensities of the selected trade routes.

Supplementary Table 2.15: Energy requirements of the global transportation of biomass, estimated from the data on global trade in biomass pellets.

Trade Route[a]	Distances (tkm)[b]			Trade flows (ktonne)	Share of global pellet production	Energy intensity of transport (MJ/kg)[c]
	Truck (<32 tonnes)	Train	Freight ship			
Canada – USA	0.1-0.4		0	**185**	**0.80%**	0.13-0.50
Canada – Europe	0.1-0.4		7	**1290**	**5.60%**	0.90-1.27
Canada – Japan	0.1-0.4		12	**80**	**0.35%**	1.45-1.82
Canada – South Korea	0.1-0.4		12	**50**	**0.21%**	1.45-1.82
USA – Europe	0.1-0.4		7	**4550**	**19.78%**	0.90-1.27
Europe domestic	0.1-0.4		0	**6680**	**29.04%**	0.13-0.50
Russia – Europe	0	2-4	3	**1115**	**4.85%**	2.85-5.34
Russia – South Korea	0	2-4	2	**70**	**0.30%**	2.74-5.26
Malaysia – South Korea	0.1-0.4		4	**115**	**0.50%**	0.57-0.94
Vietnam – South Korea	0.1-0.4		3	**600**	**2.60%**	0.46-0.83
Domestic	0.1-0.4		0	**8265**	**35.93%**	0.30-0.50
Weighted average intensity of biomass transport					**100%***	**0.36 - 0.74[c]**

Notes: [a] Trade routes as well as volumes of traded biomass are taken from the study by (Junginger et al., 2019) For transportation of biomass we could not apply the approach applied for other energy resources because biomass trade flows are not reported in the BP's "*Statistical Review of World Energy 2020*"report(BP, 2020).

[b] For transportation across the open sea, we assume the same distances as in the corresponding trade routes from the case study of coal (see Supplementary Table 2.7). For distances of biomass transportation via a truck or train, we base the range of our assumptions on the estimates from life-cycle analysis literature*:* (Fajardy and Mac Dowell, 2017), (Fajardy and Mac Dowell, 2018), (Pandur et al., 2015), (Raugei and Leccisi, 2016)*.*

[c] We calculate the relative shares of the global pellet production transported over a selected trade route and use them as relative weights to calculate the average energy intensity for biomass transportation, as shown in Equation 13 of the Methods. To obtain the energy used in the transportation of biomass in each respective trade route, we multiply the distances by the respective energy intensity coefficients, provided in Supplementary Table 2.3. Our estimates of average global energy intensity of biomass transport (0.36 – 0.74 MJ/kg) are comparable with the estimates from recent studies by (Hanssen et al., 2017) who estimated 0.96 MJ/kg for the trade route from USA to Europe or from (Raugei and Leccisi, 2016)*,* who estimated 0.4 – 0.6 MJ/kg for the trade route from USA to UK.

2.9.3 Note on EROI$_{FIN}$ dynamics in fossil fuels and biomass technologies

The EROI of energy technologies changes over time due to a range of factors. For depletable resources like oil and coal, energy requirements of extraction have increased over time due to declining resource abundance and are likely to continue to increase in the future (Dale et al., 2011; Sgouridis et al., 2019). This increase in energy requirements has led to a decline in the EROI of fossil fuels at the primary energy stage (Cleveland, 2005; Heun and de Wit, 2012; Hu et al., 2013). By contrast, research and innovation have improved the efficiency of energy conversion from primary to final energy, thereby increasing the amount of energy delivered per input of raw energy (EEA, 2018). Previous studies find that values of the global EROI of fossil fuels at the final energy stage have not changed significantly over the 1990-2010 period, suggesting the two opposite tendencies have cancelled each other out (Brockway et al., 2019; Steffen et al., 2018).

Here, we model the EROI dynamics of fossil fuels and biomass technologies at the final energy stage by assuming the energy requirements associated with extraction will continue to increase over time, as shown in Equation 7 of the Methods. We model the changes to the energy conversion of fossil fuels by referring to the improvements in energy conversion efficiencies assumed in the REMIND model, summarised in Supplementary Table 2.9. As shown in Equation 10 of the Methods, an increase in the conversion efficiency (η_C) increases the amount of energy delivered per unit of energy invested, as it decreases the required input of the raw resource per unit of generated energy, thereby increasing the EROI of these technologies. For energy intensities of energy requirements along the energy supply chain (E_{TRA}, and E_{REF}), we do not explicitly model dynamic changes, as there are no assumptions about these processes in the IAMs. However, improvements in energy conversion efficiencies decrease the energy requirements for maintaining the supply of raw fuels. Therefore, our EROI calculations broadly capture the underlying technological assumptions of the mitigation scenarios of low-carbon energy transition. Although we do not model the dynamics of all the processes, our range of energy intensities associated with the energy requirements can be read as best-case versus worst-case scenarios of energy requirements associated with the supply of raw energy fuels (see Supplementary Tables 2.3 and 2.4). The lower end of energy intensity parameters is based on the favourable assumptions that energy requirements in resource extraction, transportation, and processing or refining will decrease. Higher energy intensity parameters in turn assume a perspective of more costly operations of resource supply (e.g. longer trade routes, greater resource scarcity). The median energy intensity parameters describe a balanced, middle-of-the road scenario.

2.9.4 Note on EROI dynamics of wind and solar power

Historically, the EROIs of renewables have increased due to improvements in energy efficiency and declining energy requirements, achieved through technological innovation and the upscaling of power plant production (Diesendorf and Wiedmann, 2020; Louwen et al., 2016).

To model the dynamic evolution of the EROI of PV and wind power, we estimate the effects of technological innovation on the energy requirements of the construction, and operation and maintenance of these technologies, using the "energetic experience curves" approach by (Steffen et al., 2018). The experience curves approach is a well-established methodology for quantifying technological improvements with the increasing use of technologies (Creutzig et al., 2017; Louwen et al., 2016; Rubin et al., 2015). The underlying assumption of this approach is that the performance of a given technology increases proportionally to its uptake by society.

In our case study, the energy requirements of the technology decrease proportionally to the cumulative installed capacity of the technology in relation to the present-day energy intensities of construction, and operation and maintenance $\theta_{\mathrm{CON,0}}$ and $\theta_{\mathrm{O\&M,0}}$, as shown in Supplementary Equations 1 and 2. The rate of improvement is determined by the experience rate (*b*), which we calculate from the "invested energy data" provided by Steffen et al., in Fig. 1 of their article. We obtain the present-day energy intensities of construction and operation per installed unit of power, by dividing the energy requirements for operation and the requirements of construction by the power capacity, as described in Supplementary Equations 3 and 4.

$$\theta_{\mathrm{CON}}(t) = \theta_{\mathrm{CON,0}} \cdot \left(\frac{P_{\mathrm{CUM}}(t)}{P_{\mathrm{CUM,0}}}\right)^{-b} \quad (1)$$

$$\theta_{\mathrm{O\&M}}(t) = \theta_{\mathrm{O\&M,0}} \cdot \left(\frac{P_{\mathrm{CUM}}(t)}{P_{\mathrm{CUM,0}}}\right)^{-b} \quad (2)$$

$$\theta_{\mathrm{CON,0}} = \frac{0.9 \cdot (1 - \alpha_{\mathrm{tech}}) \cdot \mathrm{CF_0} \cdot \tau}{\mathrm{EROI_o}} \quad (3)$$

$$\theta_{\mathrm{O\&M,0}} = \frac{\alpha_{\mathrm{tech}} \cdot \mathrm{CF_0}}{\mathrm{EROI_0}} \quad (4)$$

We do not apply the experience curve approach to estimate improvements in energy conversion efficiencies, as these improvements and the effects on the EROI of PV and wind power are already endogenously accounted for in the scenario data of generated energy.

By calculating the energy intensity of construction and operation of renewables, over time, we can estimate the future energy requirements of PV and wind power, as well as the EROIs of these technologies as shown in Supplementary Equations 5 and 6.

$$E_{\mathrm{CON}}(t) = \theta_{\mathrm{CON}}(t) \cdot P_{\mathrm{NEW}}(t) \qquad (5)$$

$$E_{\mathrm{OPR}} = \theta_{\mathrm{OPR}}(t) \cdot P(t) \qquad (6)$$

Finally, after including the energy requirements associated with decommissioning (see Equation 18 of the Methods), we obtain the equation for calculating the EROIs of PV and wind, as shown below:

$$EROI(t) = \frac{E_{\mathrm{GEN}}}{0.9 \cdot \theta_{\mathrm{CAP}}(t) \cdot P_{\mathrm{NEW}}(t) + \theta_{\mathrm{O\&M}}(t) \cdot P(t) + 0.1 \cdot \theta_{CAP}(t-\tau) \cdot P_{\mathrm{NEW}}(t-\tau))} \qquad (7)$$

However, the historical trend of improving EROIs of renewables may slow down or even reverse in the future due to several factors. EROI improvements may slow down with decreasing resource density (e.g. average wind power density), as the best sites are developed first and there are fewer sites with abundant resources (Miller and Keith, 2018). Moreover, the EROI of renewables may decline as their share in the energy mix increases due to intermittent variability in the energy supply from renewables, depending on the environmental conditions (Barnhart et al., 2013). During favourable conditions, the electricity generated from renewables may exceed the electricity demand, causing the overcapacity of renewable energy infrastructure as well as of the “conventional power plants” to be temporarily switched-off the energy grid. By contrast, to ensure reliable energy supply during unfavourable conditions, when renewables do not meet the electricity demand, the electric grid will have to be reinforced with additional power plants (overcapacity) and energy storage solutions (Delucchi and Jacobson, 2011; Sullivan et al., 2013), both of which are energetically costly and therefore decrease the EROI of the overall energy system (Castro and Capellán-Pérez, 2020).

Our calculations only allow for a rough estimation of energy investment in the construction, and operation and maintenance of intermittent energy delivery. As wind and solar power become more important sources in the energy mix, such intermittent energy sources will require additional energy investments due to energy losses from excess power supply (curtailment) and from the energy requirements of storage (Barnhart et al., 2013).

We account for factors that may lead to a decline in the EROI of renewables (e.g. overcapacity and energy storage) to the extent that these effects are represented in the data of mitigation scenarios for energy generation. Some scenarios take into consideration the need for additional installed power capacity. The storage solutions in the mitigation scenarios are explicitly only represented by hydrogen from electrolysis (Sullivan et al., 2013). For a description of our method of calculating the EROI of hydrogen from electrolysis, see the “Note on energy requirements of hydrogen from hydrolysis” (in Supplementary Information).

We only account for invested energy for the production side of the energy system, but not the energy required for the supporting energy infrastructure, like smart power-grids.

2.9.5 Note on energy requirements of hydrogen from electrolysis

Most of the mitigation scenarios analysed in this study include hydrogen in their basket of low-carbon energy carriers. These scenarios are LED, S1-I, S1-G, S1-M, S1-R, S2-G, S2-M, S2-R, S5-G, and S5-R. The hydrogen energy conversion technologies include: hydrogen from biomass, hydrogen from biomass with CCS, and hydrogen from electrolysis. Our calculation of energy requirements of hydrogen from biomass follows the general approach for biomass technologies, described in the Methods section: "Energy requirements of fossil fuels and biomass technologies".

To estimate energy requirements of hydrogen generated from electrolysis, we divide the amount of generated hydrogen by the EROI of hydrogen from electrolysis, as shown below:

$$E_{\mathrm{REQ}} = \frac{E_{\mathrm{GEN}}}{\mathrm{EROI}_{H2}} \qquad (8)$$

In estimating the EROI of hydrogen from electrolysis, we follow the approach of (Pellow et al., 2015). Here, EROI of hydrogen from electrolysis depends on the efficiency of energy conversion from electricity to hydrogen (η_{sys}), and the energy embodied in the production of the hydrogen fuel cell, reflected in the ESOI, alongside the energy requirements associated with the generation of electricity in the grid (EROI_e), as shown in Supplementary Equation 9.

$$\mathrm{EROI}_{H2} = \frac{\eta_{\mathrm{sys}}}{\frac{1}{\mathrm{EROI}_e} + \frac{1}{\mathrm{ESOI}}} \qquad (9)$$

Here, ESOI stands for "Energy stored on energy invested", defined as a ratio between the energy stored in a fuel cell over its lifetime and the energy that is required to manufacture and maintain the fuel cell. We calculate the EROI of electricity by summing the total amount of generated electricity, across all of the electricity generation technologies, and dividing it by the sum of the total energy requirements of electricity generation.

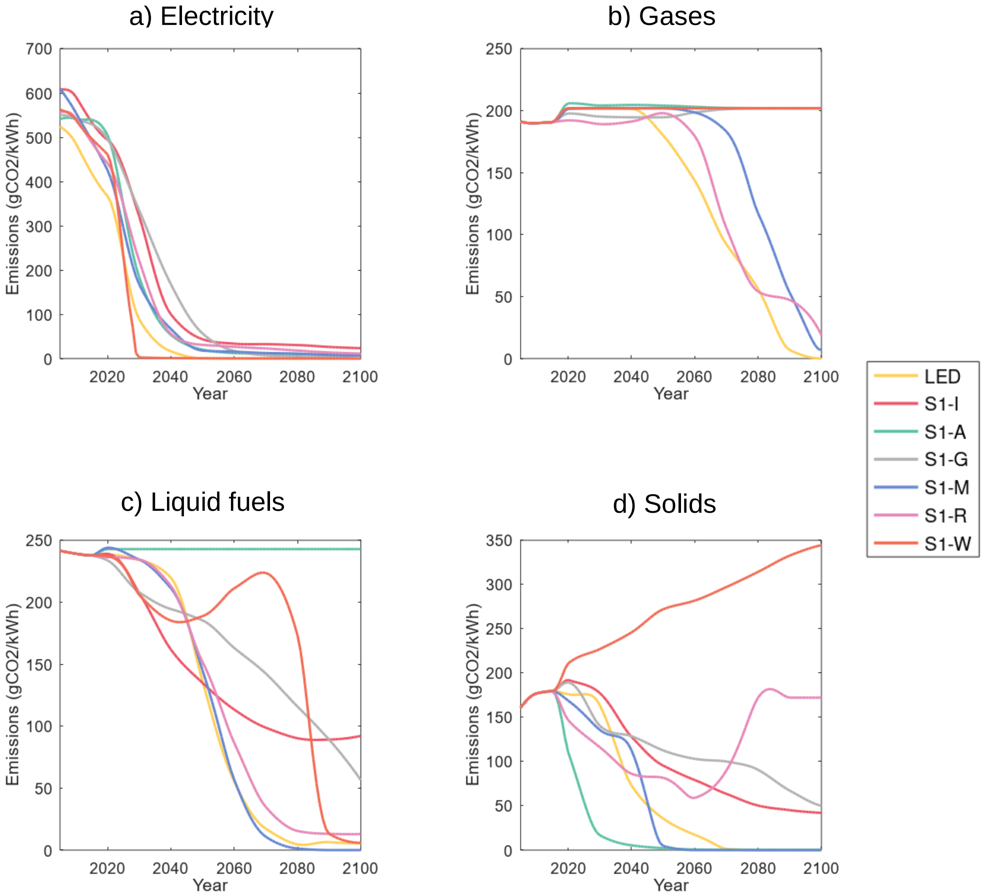
$$\mathrm{EROI}_e = \frac{\sum_e E_{\mathrm{GEN},e}}{\sum_e E_{\mathrm{REQ},e}} \qquad (10)$$

The system efficiency parameter depends on the efficiencies of the electrolyser (η_{lyz}), fuel cell efficiency (η_{FC}), and hydrogen compression (η_{comp}) as in Supplementary Equation 11 (Pellow et al., 2015):

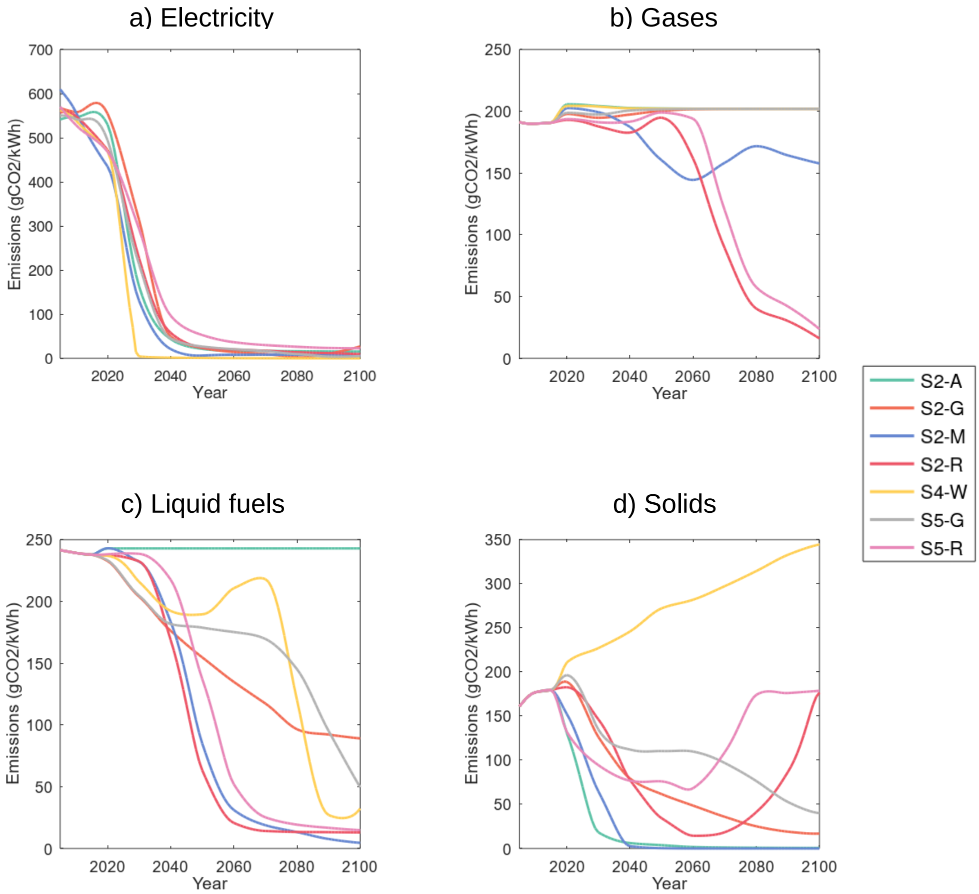
$$\eta_{\mathrm{sys}} = \frac{\eta_{\mathrm{lyz}}\eta_{\mathrm{FC}}}{1 + \eta_{\mathrm{lyz}}(\frac{1}{\eta_{\mathrm{comp}}} - 1)} \qquad (11)$$

In our estimates of the EROI of hydrogen from electrolysis, we conducted a sensitivity analysis on the efficiency parameters, using three assumptions: median, optimistic, and very optimistic. Parameter values were taken from (Pellow et al., 2015). The median assumptions resemble the efficiency parameters of best available technologies, whereas optimistic and very optimistic parameters represent different assumptions on the future technological innovation of hydrogen. Very optimistic parameters represent efficiencies that are close to their thermodynamic limit. The values of the efficiency parameters are provided together with the ESOI calculations in Supplementary Table 2.9.

2.9.6 Carbon intensities of the four energy carriers in the mitigation pathways



Supplementary Figure 2.6: Carbon intensities of energy carriers in the first group of pathways used in our study. Electricity undergoes the fastest decarbonisation amongst the four energy carriers across the scenarios. Gases, liquids, and solids are fully decarbonised only in some pathways (LED, S1-M, S2-M) whereas in others these carriers are either partially decarbonised or their carbon intensities even remain constant over time. These carriers are decarbonised in pathways that switch from fossil fuels to biomass, as their primary raw energy source, changing the traditional energy carriers of oil (petroleum), natural gas, and coal, for the alternatives such as biofuels, synthetic "biogases", and biomass pellets. Moreover, some scenarios (S1-M, S2-M, S1-R, S2-R, S5-R) decarbonise the energy services provided by liquid fuels by transitioning from oil to hydrogen-powered engines. The pathways that do not fully decarbonise all four energy carriers accomplish the emissions reductions by downsizing the use of the carriers of high carbon intensity, substituting them with decarbonised energy carriers, or by offsetting emissions using negative emissions from BECCS. The example of substation between carriers would be a transition from internal combustion engine vehicles to electric vehicles. For example, the S1-A and S2-A scenarios accomplish a rapid decarbonisation by assuming energy transition towards an energy system based on low-carbon electricity, thereby downscaling the importance of other carriers in the energy system. Carbon intensities of the second group of pathways are shown in Supplementary Figure 2.7.



Supplementary Figure 2.7: Carbon intensities of energy carriers in the second group of pathways used in our study.

Chapter 3
Avenues for a safe climate: Remove carbon from the atmosphere or reduce energy use?[3]

Abstract

Existing climate mitigation scenarios describe a range of potential futures, from a rapidly decreasing dependence on fossil fuels and lower global energy consumption to large-scale negative emissions that allow for the continued growth of global energy consumption. Here, we show that the difference in energy use between these two transitions has been exaggerated due to an unrealistic representation of negative emissions in existing scenarios. We find the realistic mitigation potential of negative emissions from bioenergy to be much lower than suggested in existing scenarios, with our estimates at 300 $GtCO_2$ compared to the cross-scenario average of 650 $GtCO_2$. Moreover, realising negative emissions at scale with alternative options may be highly energy intensive and could reduce the amount of energy available to society by more than 20%. Therefore, the use of negative emissions is unlikely to enable the continuation of growth in energy use, although, it can lessen the reduction in energy use required to limit global warming to 1.5–2.0 °C. However, using negative emissions may decrease the efficiency of energy provision to society, which could increase the economic expenditure for energy.

[3] This chapter presents results from work in preparation: Slameršak, A., O'Neill, D.W, Kallis, G., & Hickel, J. Avenues for a safe climate: Remove carbon from the atmosphere or reduce energy use? *Unpublished work in preparation*.

3.1 Introduction

Authoritative scientific reports produced by the Intergovernmental Panel on Climate Change (IPCC) establish that to minimise climate impacts and limit the risk of exceeding the tipping points of the climate system, we should limit global warming between 1.5 °C and 2.0 °C (IPCC, 2018b, 2022b). At the international policy level, the consensus on those global warming targets was written into the Paris Agreement (United Nations, 2015). To meet the Paris Agreement goals, we need to keep total carbon emissions within the carbon budget limit, estimated at 500 $GtCO_2$ for 1.5 °C and 1150 $GtCO_2$ for 2°C of global warming in 2020 (IPCC, 2022a). Staying within those carbon budgets will require a far-reaching and unprecedented transformation of our economies, lifestyles, and energy systems (IPCC, 2018c).

Scenarios produced by the integrated assessment models (IAMs) are widely used in the IPCC literature to explore a range of mitigation avenues that can accomplish such a transformation. However, these scenarios differ in their use of mitigation levers, including decarbonisation of energy supply, reduction of emissions from land use and agriculture, reduction of global energy use, and the deployment of negative emissions options that sequester carbon from the atmosphere (Warszawski et al., 2021). In these scenarios, negative emissions are used to offset the residual emissions from economic activities that are difficult to decarbonise, such as aviation and steel production (Davis et al., 2018; Rogelj et al., 2015a), and to reverse global warming if the temperature goal is exceeded (Hanna et al., 2021; Kriegler et al., 2018). Therefore, negative emissions alleviate the urgency of pressing hard on other mitigation levers, enabling a more gradual reduction of emissions and allowing for slower decarbonisation and higher energy use.

The latest IPCC report affirms that some negative emissions are necessary to stabilise global warming in all conceivable mitigation pathways (IPCC, 2022a; Luderer et al., 2018). The underlying question is not anymore if negative emissions are needed to stabilise global warming, but how much of these technologies can be deployed and whether their deployment can be met without major adverse impacts on society and nature. We reflect on these concerns by investigating the quantity of negative emissions that can realistically be deployed and how their deployment would affect the energy provision for society in the 21st century.

3.1.1 Negative emissions in the scenario literature

The drawbacks and risks of negative emissions options have been well documented in the literature. Numerous studies have been critical of negative emissions' role in mitigation scenarios. Researchers point out that negative emissions are still in the early stages of development and argue that such unproven solutions cannot form the backbone of mitigation (Anderson and Peters, 2016; Larkin et al., 2018). Furthermore, relying on negative emissions is risky (Minx et al., 2018) as it incentivises the deferral of mitigation, which can lead us to overshoot the Paris goals by up to 0.8 °C by 2100 if large-scale deployment of negative emissions fails (Realmonte et al., 2019). Moreover, negative emissions are more costly than conventional mitigation options such as renewable energy and energy efficiency improvements (Bednar et al., 2019). They require substantial resources for carbon sequestration (Smith et al., 2016). Furthermore, their effectiveness of carbon sequestration can be diminished by indirect emissions in the upstream supply of resources and energy (Fajardy and Mac Dowell, 2017; Gambhir and Tavoni, 2019) and from provoked land use change (Harper et al., 2018). Finally, negative emissions have been linked to major sustainability risks, including biodiversity loss (Heck et al., 2018), increased chemical pollution (Humpenöder et al., 2018), and high resource use (Chatterjee and Huang, 2020), which suggest that a successful realisation of negative emissions may shift the impacts from climate change to other environmental problems.

Some of the drawbacks of negative emissions are specific to individual negative emissions options. For example, bioenergy with carbon capture and storage (BECCS), which converts biomass into energy and stores the emissions from this process in geological deposits, requires vast amounts of land to be converted for energy crop plantations. To sequester ~20 $GtCO_2$ per year, as estimated in the high-end scenarios relying on BECCS, the demand for bioenergy exceeds 400 EJ (Kriegler et al., 2017), representing 70% of the global energy supply in 2020. This results in the appropriation of over 20 million square km (Smith et al., 2016; Turner et al., 2018), which is more than the surface area of Russia. Moreover, such expansion of bioenergy plantations would include lands that are currently sites of natural forests or are used for agriculture, which would drastically diminish biodiversity (Newbold et al., 2016; Powell and Lenton, 2013) or provoke shortages in global food supply (Fuhrman et al., 2020; Humpenöder et al., 2018).

Recent studies have addressed these concerns by 1) excluding energy crop plantations for BECCS from the areas of importance for agriculture and biodiversity (Creutzig et al., 2021; Hanssen et al., 2022; Humpenöder et al., 2018); 2) exploring alternative mitigation scenarios with lower dependence on negative emissions (Grubler et al., 2018; Holz et al., 2018; Van Vuuren et al., 2018b); 3) extending the portfolio of negative emissions options (Fuhrman et al., 2020; Realmonte et al., 2019). For example, Creutzig et al. estimate the sustainable mitigation potential of BECCS in the range from 0.5 to 5 $GtCO_2$ per year, the bioenergy potential below 100 EJ per year, and the sustainable land footprint of energy crop plantations at 0.5 million square km (Creutzig et al., 2021). Furthermore, Realmonte et al. show that the reliance on BECCS can be reduced by complementing this technology with direct-air carbon capture and storage (DACCS) (Realmonte et al., 2019).

Recognising substantial trade-offs of BECCS, the latest research has shifted its focus to investigating the carbon removal potential of DACCS. DACCS refer to technologies that capture CO_2 from ambient air by using liquid or solid sorbents that attract CO_2 molecules (Gambhir and Tavoni, 2019). The CO_2 from ambient air binds to the sorbent and is subsequently stripped from it to be sequestered in geological storage. Most of the sorbent can be recovered to repeat the chemical mechanism of carbon removal.

The advantage of DACCS over BECCS is its low impact on land, as the DACCS modules are small and can be deployed in areas with no negative impacts on food supply or biodiversity (Socolow et al., 2011). Land requirements of these technologies are expected to be two orders of magnitude smaller than the requirements of BECCS (Creutzig et al., 2019b). Assuming the demand for chemical sorbents and energy to power DACCS installations could be met, the negative emissions potential of these technologies could exceed 30 $GtCO_2$ per year, meaning DACCS could, in theory, offset all the current global energy-related CO_2 emissions (Friedlingstein et al., 2020).

Even though the feasibility of a large-scale deployment of BECCS has been challenged and alternative negative emissions options have been proposed, literature on ambitious mitigation scenarios is still dominated by scenarios that incorporate large-scale use of BECCS as one of their main mitigation levers. This is a significant research gap, as it implies that energy and emissions pathways in these scenarios may be a misleading illustration of achievable mitigation trajectories.

3.1.2 The realistic potential of negative emissions and implications for energy use

To analyse the implications of excessive reliance on BECCS, our study estimates the realistic negative emissions potential of BECCS and explores how energy pathways in the existing scenarios would change if negative emissions from BECCS were downscaled to the realistically achievable values. To quantify the realistic potential of negative emissions, we first analyse the maximum theoretical potential of negative emissions from BECCS, which refers to the hypothetical scenario where all the natural land, excluding the food crops from existing agricultural land, is dedicated to BECCS. We then estimate the realistic potential of negative emissions from BECCS for different land management scenarios, where only a part of global land is dedicated to BECCS. We find the realistic potential of negative emissions from BECCS to be in the range of ~300 $GtCO_2$, which is substantially less than assumed in most of the analysed mitigation scenarios.

Reduced mitigation potential from BECCS implies that a substantial share of negative emissions needs to be provided from alternative negative emissions options such as DACCS or that more emphasis needs to be on the other mitigation levers. Either way, the reduced role of BECCS for mitigation has important implications for energy pathways in the scenarios. We identify three reasons why an overestimated deployment of negative emissions may lead to an overestimation of energy use in the existing scenarios.

The first reason stems from the fact that BECCS is not only a negative emissions technology but also a significant electricity provider. Therefore, assuming a reduced deployment of BECCS means less energy will be generated from this technology. Second, large-scale reliance on BECCS allows the scenarios to reduce the speed at which they must cut their emissions and increase the energy generated from fossil fuels. On the contrary, fewer negative emissions from BECCS lead to a lower energy supply from fossil fuels and consequentially lower energy supply overall. Third, the alternative options to realise negative emissions options are expected to be highly energy intensive (Babacan et al., 2020) and may therefore reduce the energy available to other end-users.

While existing scenarios model the link between negative emissions and energy supply from BECCS, they do not represent the impacts on energy supply from other negative emissions options, as they do not specify how final energy is divided up between different end users and which energy services are provided to the society. If we take the final energy in mitigation scenarios at its face value, large-scale negative emissions deployment enables a higher energy use growth. However, this conclusion may be misleading, as much of the final energy could go to the negative emissions "industry" itself and, therefore, may not result in more energy being available to society.

To analyse the implications of negative emissions on the future energy availability, we assess the energy pathways from mitigation scenarios that do not overestimate the negative emissions potential from BECCS by estimating the energy required from the alternative negative emissions options. By reanalysing energy pathways from 153 scenarios used by the IPCC, we provide a range of possible energy futures that are compatible with stabilising global warming between 1.5°C and 2°C. Our study separates between final energy, which refers to the total energy for final consumption, and the energy for the society, defined as the difference between final energy and the energy requirements of negative emissions. Energy for society refers to the total energy available to perform valuable work for society.

Our analysis shows that a realistic range of future energy pathways is narrower and that the growth of energy use is more limited than suggested in the IPCC literature. Lower energy use must become the critical mitigation lever for a low-carbon energy transition to keep global warming within the goals of the Paris Agreement.

We start this chapter by describing our methodological approach for estimating the mitigation potential of negative emissions and reanalysing energy pathways in mitigation scenarios. Sections 3.1–3.3 presents the relationship between negative emissions deployment and energy use growth in existing mitigation scenarios. In sections 3.4 and 3.5, we calculate how much negative emissions could be realised by BECCS and how much would have to be provided by alternative negative emissions options. In sections 3.6–3.8 we analyse the impacts of negative emissions on energy for society. Finally, we conclude by deliberating on the long-term socioeconomic implications of large-scale use of negative emissions and compare these implications with the implications of an alternative scenario of lower energy use.

3.2 Methodological approach

3.2.1 IAM mitigation pathways

For this study, we selected 161 mitigation scenarios obtained from the *IAMC 1.5 °C Scenario Explorer* (Huppmann et al., 2019) that are consistent with stabilising global warming below 1.5 °C (RCP 1.9) or 2 °C (RCP 2.6) by 2100. These scenarios were used in preparing the *IPCC's Special Report on Global Warming of 1.5 °C* (IPCC, 2018b) and cover a wide range of possible socioeconomic and technological developments in a world that limits climate change with the temperature goals of the Paris Agreement. From 161 pathways, 153 passed the data quality and criteria checks and were used in the analysis. We provide the complete list of selected and analysed scenarios in Supplementary Table 3.1.

Mitigation scenarios report on energy and emissions starting from 2010 or 2020 (depending on the pathway) and diverge in their projections up to 2020. For the sake of consistency, we homogenised the data in the pathways up to 2020 – the starting point of our analysis – according to the historical data provided by IEA (IEA, 2021a) (energy) and the Global Carbon Budget project (Friedlingstein et al., 2020) (emissions).

Using the selected mitigation scenarios, we analyse the interdependence between growth in energy use on the use of negative emissions in different climate change outcomes. We divide scenarios into six different scenario groups, depending on their remaining carbon budgets, which are defined by the net cumulative emissions into the atmosphere from 2020 to 2100, and the quantity of total negative emissions in the scenarios.

The scenarios are divided into the scenarios with the remaining carbon budget below 500 $GtCO_2$, which represent the threshold for a 50% chance to limit global warming to 1.5 °C, and the scenarios with carbon budgets between 500 and 1150 $GtCO_2$, which conform with the threshold for a 66% chance to limit global warming to 2 °C (IPCC, 2022a). Scenarios that assume less than 500 $GtCO_2$ of negative emissions are called the 'NE-moderate'; scenarios ranging from 500 to 800 $GtCO_2$ of negative emissions are called 'NE-large'. Scenarios, where negative emissions exceed 800 $GtCO_2$ are called 'NE-extreme'. The numbers were chosen so that each scenario group consists of at least seven scenarios which I considered to be a minimum statistical sample in this study. Each scenario group is defined by a combination of the global warming threshold and the number of negative emissions assumed, e.g., 2 °C/NE-moderate (see Supplementary Table 3.2 for an overview of different scenario group categories).

3.2.2 Negative emissions in mitigation scenarios

Negative emissions assumed across the 153 scenarios analysed average 650 $GtCO_2$. 132 of these scenarios deploy BECCS, with average negative emissions from BECCS in these scenarios amounting to 545 $GtCO_2$. Negative emissions from land-based carbon sequestration, accounted for under the land use change and agricultural sector (AFOLU) (Vaughan et al., 2018), assume an average of 175 $GtCO_2$ across all scenarios analysed. Only five of the analysed scenarios assume negative emissions from DACCS, with an average deployment of 210 $GtCO_2$.

3.2.3 Negative emissions from BECCS

To estimate the mitigation potential of BECCS, we build on the global emission-supply curves approach from Hanssen et al., 2020. In their study, Hanssen et al. use the integrated assessment model IMAGE coupled with the dynamic global vegetation model LPJml, to estimate the emission factors of BECCS for all the global land that could, in theory, be converted into energy crop plantations, excluding land for agricultural production. Emission factors (EFs) describe how much net negative emissions can be produced per unit of bioenergy each year, starting from the year the plantations are established and up to 2100. EFs depend on the difference between the amount of carbon sequestered and the indirect emissions associated with BECCS. The lower the EFs, the bigger the net sequestration from BECCS on a particular area.

Carbon sequestration is proportional to the energy crop harvest on plantations. Indirect emissions from BECCS account for the emissions from land use change as land is converted into energy crop plantations, emissions from fertilisers used on plantations (N_2O emissions from fertilisers are reported in the values of CO_2 equivalent), emissions associated with carbon capture and storage (CCS), and upstream emissions of the biomass supply chain associated with harvesting, processing, transportation, and energy conversion of energy crops into final energy carriers. EFs tend to be the lowest if land conversion takes place earlier in the century, as this allows for more energy crops to be produced before 2100 and, therefore, more carbon to be sequestered (for a detailed description of the model, see Methods in Hanssen et al., 2020.

Cumulative net negative emissions (*N*) from any land area dedicated for energy crop plantation (marked by index *i*) are calculated as a product of energy crop production (PE) expressed in EJ per year. Then, the emissions factor of that plantation (EF) is multiplied by the time the plantation is to be exploited (τ), as shown in Equation 1.

$$N_{\mathrm{i}} = \tau \cdot \mathrm{PE} \cdot \mathrm{EF_i} \tag{1}$$

The global theoretical potential of negative emissions from BECCS is defined by the sum of cumulative net negative emissions over all of the land areas where conversion into energy crop plantations can contribute to negative emissions, i.e., where EFs are less than 0, as shown in Equation 2. To estimate the negative emissions potential from BECCS, we use the emission-supply curve ($\mathrm{PE}(\mathrm{EF},\tau)$), which specifies the distribution of global bioenergy potential for BECCS over the emission factors, starting from the plantations of the lowest emission factor ($\mathrm{EF_{min}}$) and includes all the plantations that can realise negative emissions ($\mathrm{EF} \leq 0$).

$$N_{\mathrm{max}}(\tau) = \tau \cdot \int_{\mathrm{EF_{min}}}^{0} \mathrm{PE}(\mathrm{EF},\tau) \cdot \mathrm{dEF} \tag{2}$$

In our calculations, we only consider the emission-supply curves for electricity generation, as the production of liquid fuels with BECCS was found to have a much lower potential to contribute to large-scale negative emissions (Hanssen et al., 2020). Therefore, we adjust the BECCS energy pathways in the IAM mitigation scenarios so that all of the biomass initially assumed to be used for liquid biofuels is shifted towards BECCS electricity generation.

3.2.4 Scenarios of land management

While theoretical global mitigation potential from BECCS is estimated at 40 $GtCO_2$ per year (Hanssen et al., 2020), this value is unrealistic, as it would require the conversion of almost all of the tropical and subtropical rainforests and savannahs into dedicated energy crops. Human appropriation of natural land is the biggest threat to biodiversity (Newbold et al., 2016) and was found to be the principal historical driver of the anthropogenic sixth mass extinction (IPBES, 2019). However, even if we limit BECCS to the lands humans have already appropriated, we cannot expect that all available lands will be dedicated to bioenergy because some of the rights-owners of communal lands and private landowners may not be interested in converting their lands into plantations. In addition, there are competing demands for land to consider, such as food production, energy crops, tourism, and urbanisation (Creutzig, 2017; Creutzig et al., 2019a; Powell and Lenton, 2012). Moreover, much of the land that appears to be available for plantations in the coarse spatial maps of global vegetation models may be inaccessible or too fragmented for commercial use (Calvin et al., 2021).

To address these constraints, we design a range of land management scenarios that differ in the assumption of how much of the theoretically available land can be converted into energy crop plantations. First, we simulate the constraints to land appropriation for BECCS by introducing a land management function (φ), which is defined by the share between the land dedicated to energy crop plantations for BECCS and the total land available, and that can range from 0 to 1. We assume the value of the management function depends on the potential EFs of the land, so the lower the emission factor higher the value of the management function, thereby assuming the lands that can realise most negative emissions are more likely to be converted into plantations. This is in line with the standard assumption in IAMs that mitigation efforts are first pursued in the most cost-optimal sectors to decarbonise (Klein et al., 2014; Popp et al., 2014).

Land management function takes the form of the exponential distribution over different EF values as shown in Equation 3, where C represents the share of the land dedicated to BECCS in lands that have the highest negative emissions potential (and the lowest EF) and α is the rate parameter describing how the share decreases with increasing EF.

$$\varphi(\mathrm{EF}) = C \cdot \exp^{-\alpha \cdot \mathrm{EF}} \tag{3}$$

In most of our land management scenarios, we limit the energy crop plantations to the historically "appropriated lands" which are currently abandoned or represented by managed and degraded forests, as dedicating these lands for BECCS would not notably contribute to a further decline of biodiversity, nor would it diminish agricultural land. Our study, therefore, applies a sustainability constraint, where natural lands consisting of tropical forests, temperate forests, boreal forests, grasslands, and savannahs are protected from being converted into energy crop plantations.

Our first "moderate management" scenario assumes that 50% of the appropriated land can be converted into energy crop plantations. The "good management" scenario assumes this share to be 75%, while the "optimum management" scenario assumes that all the appropriated land can be dedicated to BECCS. To cover a broader range of scenarios, we also explore the "weak sustainability and optimum management" scenario, where in addition to all the lands appropriated historically, up to 20% of the natural forests with the highest negative emissions potential can be appropriated. However, we strongly argue against considering this scenario a plausible or desirable mitigation strategy. We provide a detailed overview of all the scenarios and their land management function parameter values in the "Note on scenarios of land management", in the Supplementary Information.

3.2.5 Realistic mitigation potential of BECCS

To calculate cumulative net negative emissions from BECCS in each land management scenario, we multiply the emission-supply curve by the land management function and the time the plantation is exploited and calculate it over the range of appropriated lands with negative EFs, as shown in Equation 4.

$$N(\tau) = \tau \cdot \int_{\mathrm{EF_{min}}}^{0} \mathrm{PE}(\mathrm{EF}, \tau) \cdot \varphi(\mathrm{EF}) \cdot \mathrm{dEF} \qquad (4)$$

In addition to negative emissions from energy crop plantations, negative emissions can be realised by carbon sequestration from agricultural and forest biomass residues (Vaughan et al., 2018). Typically, IAMs project the availability of biomass residues to increase with the demand for bioenergy, as higher demand increases the prices for bioenergy and therefore diverts the residues from other economic uses to bioenergy (Hanssen et al., 2019). We model the availability of biomass residues as a function of total primary demand for biomass by calculating the median of residue availability estimates from eight different IAM models, with the data provided in (Hanssen et al., 2019). To calculate the indirect carbon emissions from residues, we sum the emissions from fertiliser, emissions associated with CCS and the upstream emissions associated with biomass supply. We assume that residues do not contribute to land use change. For a detailed description of how we calculate net negative emissions from biomass residues, see the "Note on biomass residues" in the Supplementary Information. The total negative emissions from BECCS account for the sum of negative emissions derived from energy crop plantations and biomass residues.

3.2.6 Reanalysis of BECCS in mitigation scenarios

To estimate the BECCS mitigation potential, we reanalyse how much energy crops can be produced and how much negative emissions can be realised from BECSS under different land-management scenarios and BECCS deployment rates assumed in the IAM scenarios. To do so, we first compare the mitigation potential of BECSS estimated in the IAMs with our calculations derived from the advanced global vegetation model, whereby we apply the sustainability constraint for the land that can be dedicated to energy crop plantations. Then, reanalysis is performed by comparing bioenergy deployment in the IAM scenarios with energy crop production and availability of residues from our land management scenarios, starting from the land with the highest net negative emissions potential (lowest EFs). If assumed bioenergy deployment in any IAM scenario exceeds the maximum bioenergy supply available in the specific land management scenario, we adjust the bioenergy demand in the respective scenario to the maximum bioenergy supply, which decreases the realised net negative emissions and the energy provided by BECCS.

3.2.7 Negative emissions from DACCS

DACCS are only a recent technological addition to the negative emissions options considered in IAMs, which is why most scenarios only assume BECCS. We consider DACCS and BECCS to be complementary negative emissions options and assume DACCS to be deployed when negative emissions estimated in the IAM scenarios exceed the realistic mitigation potential. We estimate the amount of negative emissions from DACCS as the difference between the BECCS assumed in each of the analysed mitigation scenarios and our scenario estimates of the realised negative emissions in the "good management" scenario.

3.2.8 Energy required for DACCS

Unlike BECCS, which generate energy in the carbon capture and storage process, DACCS are themselves consume substantial energy. Literature estimates of the energy requirements of DACCS range between 0.6 and 5.7 GJ of electricity (Chatterjee and Huang, 2020; Ishimoto et al., 2017; Realmonte et al., 2019) and from 3.4 to 10.7 GJ of heat (National Academies of Sciences, 2019) per tonne of CO_2 removed (see Supplementary Table 3.5 for a detailed overview of estimates in the literature). However, these estimates only refer to direct energy inputs for the operation of DACCS modules. Therefore, they do not capture the upstream energy requirements, including the energy for building and maintaining the DACCS modules, the energy for producing chemical sorbents, or the energy required to transport the captured CO_2 to geological deposits. Comprehensive boundary analysis that would include these indirect energy requirements would increase the expected energy requirements (Chatterjee and Huang, 2020). However, these requirements are also expected to decrease over time with the development of more efficient DACCS technologies (Realmonte et al., 2020).

In our calculations of energy requirements of DACCS, we use the calculations of energy requirements from the life-cycle assessment of energy and material flows for DACCS by Deutz and Bardow, 2021, estimated at 2.6 GJ of electricity ($\mathrm{FE_e}$) and 5.4 GJ of heat ($\mathrm{FE_{heat}}$) per tonne CO_2. To our knowledge, this is the only study that analyses energy requirements at an extended system boundary, including the energy required to produce chemical sorbents and transport the CO_2 from the DACCS module to the geological deposits. Still, the study by Deutz and Bardow does not provide the energy requirements associated with DACCS. For example, the study does not include the energy required for the construction of DACCS modules (i.e., the energy embedded in the materials of the module). However, a low material footprint of the technology suggests these energy requirements are much smaller compared to the energy required for operation.

We assume the heat for DACCS to be provided by a high-temperature heat pump with a coefficient of performance (COP) of 2.5 (2.5 GJ of heat obtained from 1 GJ of electricity), following the study by Terlouw et al., 2021. The total energy requirements of DACCS (FE_{DACCS}) in our model are estimated as described in Equation 5 and amount to 4.8 GJ per tonne CO_2.

The energy requirements of DACCS estimated by Deutz and Bardow compare closely to the mean value of the energy required for operating DACCS in the literature (Supplementary Table 3.5).

$$\mathrm{FE_{DACCS}} = \mathrm{FE_e} + \frac{\mathrm{FE_{heat}}}{\mathrm{COP}} \qquad (5)$$

We analyse the impact of DACCS on the energy system by estimating the total energy requirements of DACCS and deducting them from the final energy use in the mitigation scenarios. FE_{DACCS} represent the energy for "cleaning up the atmosphere", whereas the remaining final energy represents the energy that can be used for productive societal work.

3.3 Results

We begin the analysis by exploring the relationship between negative emissions and energy use across the IAM scenarios of ambitious mitigation.

3.3.1 Farewell to fossil fuels

The objective of stabilising global warming below 1.5 °C or 2 °C limits the future use of fossil fuels, thus breaking with the historical trend of growth in the use of fossil fuels. The constraint to using fossil fuels without carbon capture and storage follows directly from the diminishing carbon budget, which is defined by how much carbon can be emitted before we exceed a certain global warming threshold (Rogelj et al., 2019). Therefore, fossil fuels must be replaced with low-carbon alternatives to avoid dangerous climate change. However, the phasing out of fossil fuels differs amongst different scenario groups (Figure 3.1).

The speed required to phase out fossil fuels depends on the carbon budget and the number of negative emissions deployed. The bigger the carbon budget (the less ambitious the climate mitigation) and the higher the negative emissions, the larger, in theory, the emissions space for fossil fuels. The scenarios which assume only a moderate quantity of negative emissions (Figures 3.1a and 3.1d) must reduce the use of fossil fuels at the fastest rate, with an average decline of 5 % per year from 2020 to 2030 and must keep their residual use of fossil fuel at ~ 60 EJ per year, the lowest residual use of fossil fuels amongst different scenario groups. At the other end of the spectrum, the Extreme-NE scenarios (Figures 3.1c and 3.1f) keep their energy supply from fossil fuels constant for a prolonged period up to 2035, and decline at a slower pace of 4.2 % per year, in the decade afterwards.

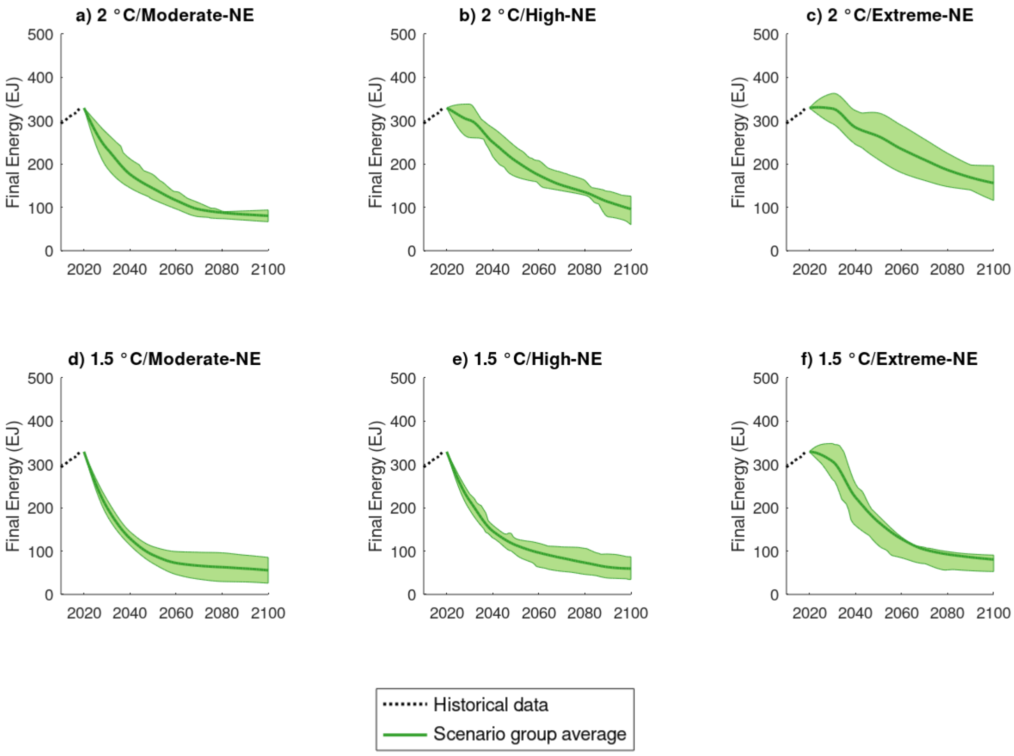


Figure 3.1: Final energy from fossil fuels in different mitigation scenarios. The envelope plots show the interquartile range of the global fossil fuel energy projections from the IPCC scenarios. From left to right, the scenarios are sorted into three groups according to the total amount of realised negative emissions. **Panels a-c** show the scenarios staying within the 2 °C carbon budget, while **panels d-f** include all the scenarios consistent with the 1.5 °C carbon budget.

3.3.2 The end to growth in energy use?

The initial phase of energy transition from 2020 to 2030 could mark an end to the historical trend of growth in energy use (Figure 3.2), as a decrease in energy use is required in all scenarios except the ones assuming high (Figures 3.2b and 3.2e) and extreme (Figures 3.2c and 3.2f) deployment of negative emissions. In other words, energy use must decline immediately to avoid catastrophic global warming unless negative emissions are successfully deployed at scale.

The most substantial decrease in energy use during the initial phase of the transition occurs in the 1.5 °C/Moderate-NE scenarios, with an average decrease in energy use of 120 EJ, representing 29% less energy in 2030 compared to 2020. Global energy use is also projected to decline for two other scenario groups. A decline of 60 EJ and 35 EJ is projected in the 1.5 °C/High-NE scenarios and 2 °C/Moderate-NE scenarios, respectively, representing a 14% and 9% decline in energy use. Only the 1.5 °C/Extreme-NE, 2°C/Extreme-NE and 2 °C/High-NE scenarios assume continued growth in energy use. However, even in these scenarios, the growth slows down substantially from the historical growth rate of 1.3% per year from the period from 2010 to 2020, averaging only: 0.4%,0.7%, and 0.5% per year during the initial phase of the transition in these respective scenarios.

Large-scale use of negative emissions has two potential implications, revealed by the close resemblance between the scenario envelopes of energy pathways between some of the scenario groups in Figure 3.2. First, negative emissions unlock the possibility of higher energy use, which is illustrated by an upward shift in the average energy pathways the more extensive the use of negative emissions, as illustrated if one moves from the envelope of Figure 3.2e to the envelope of Figure 3.2f. Alternatively, negative emissions make it possible to accomplish a more ambitious global warming goal of 1.5 °C without further decreasing energy use, as illustrated by the similarity between Figures 3.2a and 3.2e.

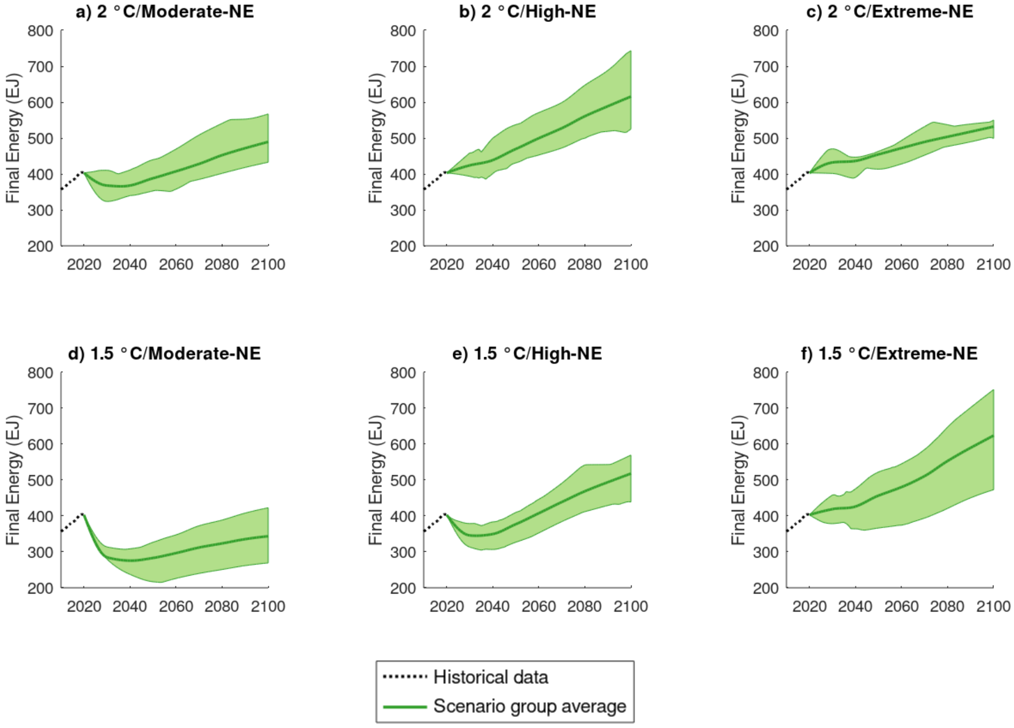


Figure 3.2: Final energy use in different mitigation scenarios. The envelope plots show the interquartile range of the final energy projections from the IPCC scenarios. From left to right, the scenarios are sorted into three groups according to the total amount of realised negative emissions. **Panels a-c** show the scenarios staying within the 2 °C carbon budget, while **panels d-f** include all the scenarios consistent with the 1.5 °C carbon budget.

3.3.3 Limits to low- and zero-carbon energy

IAM scenarios suggest that energy growth cannot be sustained during the initial push for the transition without assuming a large deployment of harmful emissions, but why is this the case? The main reason for a decline in energy use is that the build-up of low-carbon energy in mitigation scenarios does not match the necessary decline of fossil fuels (Figure 3.3). Across different scenario groups shown in Figure 3.4, the average deployment of low-carbon energy from 2020 to 2030 equals ~ 5 EJ per year. It does not exceed 10 EJ per year in any of the scenarios, whereas fossil fuels decline at an average rate of ~ 10 EJ per year unless we assume a high or extreme deployment of negative emissions (Figures 3.3b-3.3c and 3f).

The reason fossil fuels cannot be entirely replaced with low-carbon energy during the initial push for the transition is that such deployment of low-carbon energy would exceed the maximum growth rates assumed to be possible for these technologies in existing models (Krey et al., 2016). Indeed, the historical deployment of low-carbon energy infrastructure has been dismal compared to the deployment required to replace fossil fuels. For example, the average annual growth of low-carbon energy at the final energy stage from 2010 to 2020 equals 1.2 EJ/year. To increase the low-carbon energy deployment by up to 14 EJ/year, as required to replace fossil fuels and continue along the historic growth path, we would need a 10-times faster build-up of low-carbon energy infrastructure. While mitigation scenarios suggest the increase of up to 5 EJ per year (i.e., a 4-time faster build-up) to be feasible, the 10 EJ per year are beyond even the most optimistic assumptions concerning future low-carbon energy technologies. The transition that relies on low-carbon energy with moderate negative emissions is necessarily a transition to a pathway of lower energy use.

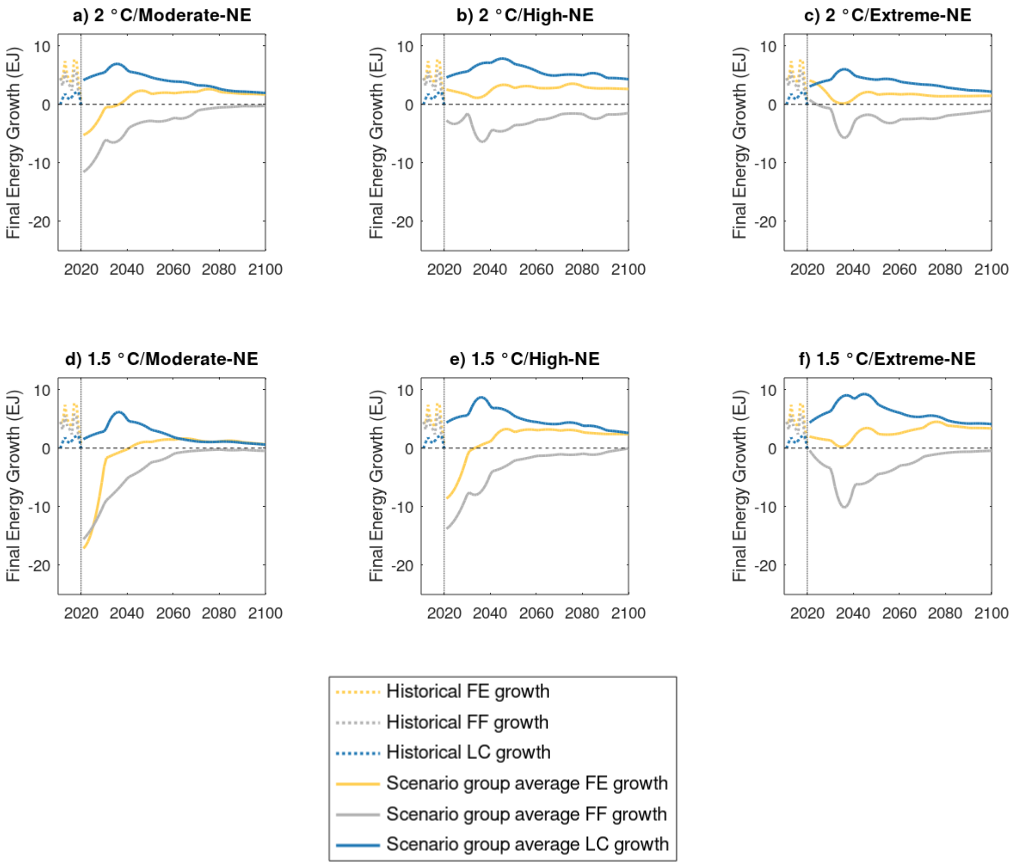


Figure 3.3: Change in final energy from fossil fuels and low-carbon technologies. From left to right, the scenarios are sorted into three groups according to the total amount of realised negative emissions. The dotted lines show the historical growth rates of final energy from fossil fuels (FF) and low-carbon technologies (LC), as well as the historical growth of final energy (FE). Solid lines show the average scenario projections for the three technology types across different scenario groups. **Panels a-c** show the scenarios staying within the 2 °C carbon budget, while **panels d-f** include all the scenarios consistent with the 1.5 °C carbon budget.

3.3.4 Theoretical potential of BECCS

Our analysis reveals that all the available abandoned, managed, and degraded lands cannot provide sufficient energy crops and carbon sequestration to realise the large-scale deployment of BECCS assumed in the IAMs (Figure 3.4a). The annual potential of energy crops and cumulative negative emissions is 190 EJ/year and 805 $GtCO_2$, assuming all these lands were converted into energy crop plantations in 2030, as shown by the energy-emissions curve for the year 2030 in Figure 3.4a, which is less than cumulative negative emissions assumed in the Extreme-NE scenarios.

Global potential of energy crops and negative emissions decreases to 140 EJ/year and 410 $GtCO_2$ in 2050 and to 60 EJ and 210 $GtCO_2$ in 2070, as shown in the energy-emissions curves for these respective years. Negative emissions potential from BECCS decreases over time, as shorter harvesting time on energy plantations between their first year and 2100 lower the harvest of energy crops and consequently decrease the amount of sequestered carbon. Moreover, some of the lands that can generate net negative emissions over the period from 2030 to 2100 cannot generate negative emissions over shorter periods, as the indirect emissions from land use change and upstream supply of biomass from these lands would exceed the carbon sequestered over the shorter period.

As a result of the decreasing potential over time, the median value of negative emissions from BECCS in the IAM scenarios of 495 $GtCO_2$ (pink dot in Figure 3.4a) can only be realised in case most of the abandoned, degraded, and managed lands are converted into energy crop plantations for BECCS before 2050. However, the speed at which these lands would have to be converted into plantations exceeds even the most ambitious scenarios currently available. This means that large-scale negative emissions from BECCS are realistically possible only if energy crop plantations are expanded into natural lands (Figure 3.4b). Expanding into natural lands increases the bioenergy potential beyond 300 EJ and increases the negative emissions potential up to 2300 $GtCO_2$. However, these are extreme cases where more than 95% of all global natural forests (including the tropical rainforest in the Amazon and Congo basin) would be converted into plantations for BECCS. Importantly, even such an extensive appropriation of natural lands would have to take place before 2070 to provide sufficient carbon sequestration, as the deployment of BECCS later in the century can only provide up to 310 $GtCO_2$ of negative emissions regardless of ignoring the adverse sustainability impacts of such a scenario.

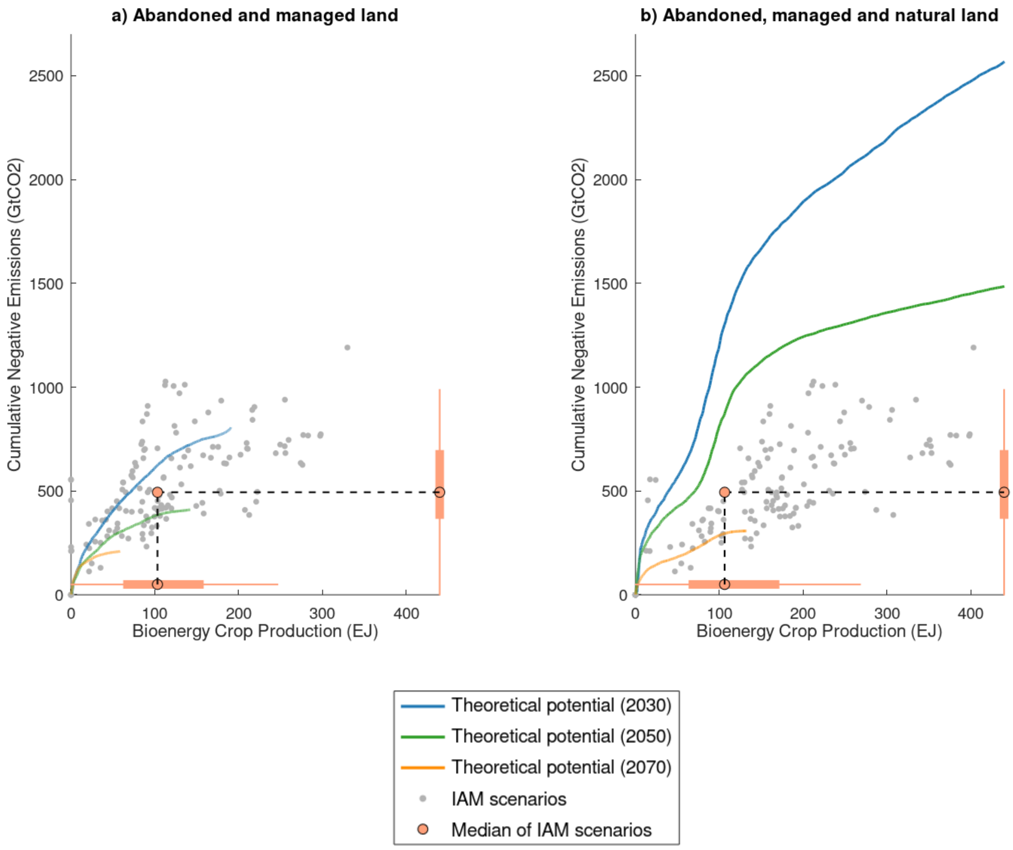


Figure 3.4: Energy-emissions curves for BECCS compared to the values assumed in the IAM scenarios. The curves show how much bioenergy is required to realise a certain amount of cumulative negative emissions from BECCS, assuming optimum land management for BECCS from the chosen start year up to 2100. Curves end at the point where all globally available land would be converted into energy crop plantations. **Panel a** shows the curves if the plantations are limited to abandoned, degraded, and managed land. **Panel b** shows the curves assuming that natural lands too can be used for plantations. Values of cumulative negative emissions from BECSS and maximum energy crop production in IAM scenarios are depicted as grey points. The probability distribution of values from IAMs is illustrated using boxplots, which show the median, the interquartile range and the whiskers depicting the distribution's upper/lower statistical boundaries. The upper/lower boundary is defined by the 1.5 times the interquartile range from the upper/lower quartile of the distribution. Both figures exclude the land currently used for agriculture.

3.3.5 Realistic potential of BECCS

We now move from the theoretical potential of BECCS under the assumption of optimal land management to analysing the realistically achievable mitigation potential of BECCS in the IAM mitigation pathways for different land management scenarios.

Our estimates of achievable negative emissions from BECCS are substantially lower than the estimates in mitigation pathways in all the land management scenarios (Figure 3.5a-b). In the moderate land management scenario, which limits the deployment of energy crop plantations to only half of the globally available abandoned, degraded, and managed lands, realised negative emissions range from 220 $GtCO_2$ to 340 $GtCO_2$ (interquartile range of 153 mitigation scenarios) in comparison to the 365–695 $GtCO_2$ range assumed in IAM scenarios. Even in the "optimum land management" scenario where 20% of the global natural forests with the most significant carbon sequestration potential are available for BECCS plantations additionally to all the globally available appropriated lands, BECCS only realise between 270 and 425 $GtCO_2$ of negative emissions. Moreover, between 160 $GtCO_2$ and 280 $GtCO_2$ of the negative emissions in our estimates originate from biomass residues and not from energy crops, which means the contribution of energy crop plantations to realising negative emissions is lower than suggested by the numbers above (see also Supplementary Figure 3.4).

The maximum value of negative emissions that can be realised based on the deployment of BECCS in IAM scenarios and our application of land-use constraints is 675 $GtCO_2$, compared to the maximum value of 1190 $GtCO_2$ in the scenarios. Overall, our estimates of realised negative emissions range from 54% to 67% of the negative emissions assumed in IAM scenarios (median values) across the four land management scenarios (Figure 3.4b).

In comparison to IAM scenarios, our calculations reveal a lower potential for energy crop production with our average estimates for the period from 2020 to 2100 in the range from 42 EJ to 66 EJ per year (median values), across the four land management scenarios, compared to 96 EJ per year in IAM pathways. Our calculations of possible bioenergy from energy crops for BECCS amount to 36%–64% of the energy assumed in IAM pathways (median estimates) across our land management scenarios (Figure 3.5d).

The reason for lower bioenergy crop production is that large-scale deployment of BECCS only happens after 2050 when less land with negative emissions factors is available for energy plantations compared to 2030, as demonstrated in Figure 3.4a-3.4b. However, the gap in bioenergy crop production between our estimates and those in IAM pathways is smaller than the gap in negative emissions, suggesting that the lower carbon sequestration potential of BECCS is not only due to a smaller bioenergy potential but also due to a lower net sequestration of BECCS if we compare our estimates with those in the IAM scenarios.

Given that our assumptions regarding carbon capture efficiency and carbon content of biomass from energy crops are derived from the parameters used in the IAM models, lower net negative emissions are likely to be a result of higher emissions from land-use change and energy supply estimated in the LPJml model, if compared to the estimates in the IAMs which confirms the hypothesis from previous studies that IAMs may underestimate emissions from land-use change associated with BECCS (Harper et al., 2018; Heck et al., 2018).

The realistically achievable mitigation potential of BECCS from energy crops and bioenergy residues is in the range of 220–425 $GtCO_2$ (interquartile range for all four land management scenarios). Increasing this potential would require an earlier deployment of BECCS alongside optimum land management and possibly expanding energy crop plantations into natural lands, which would adversely impact global biodiversity.

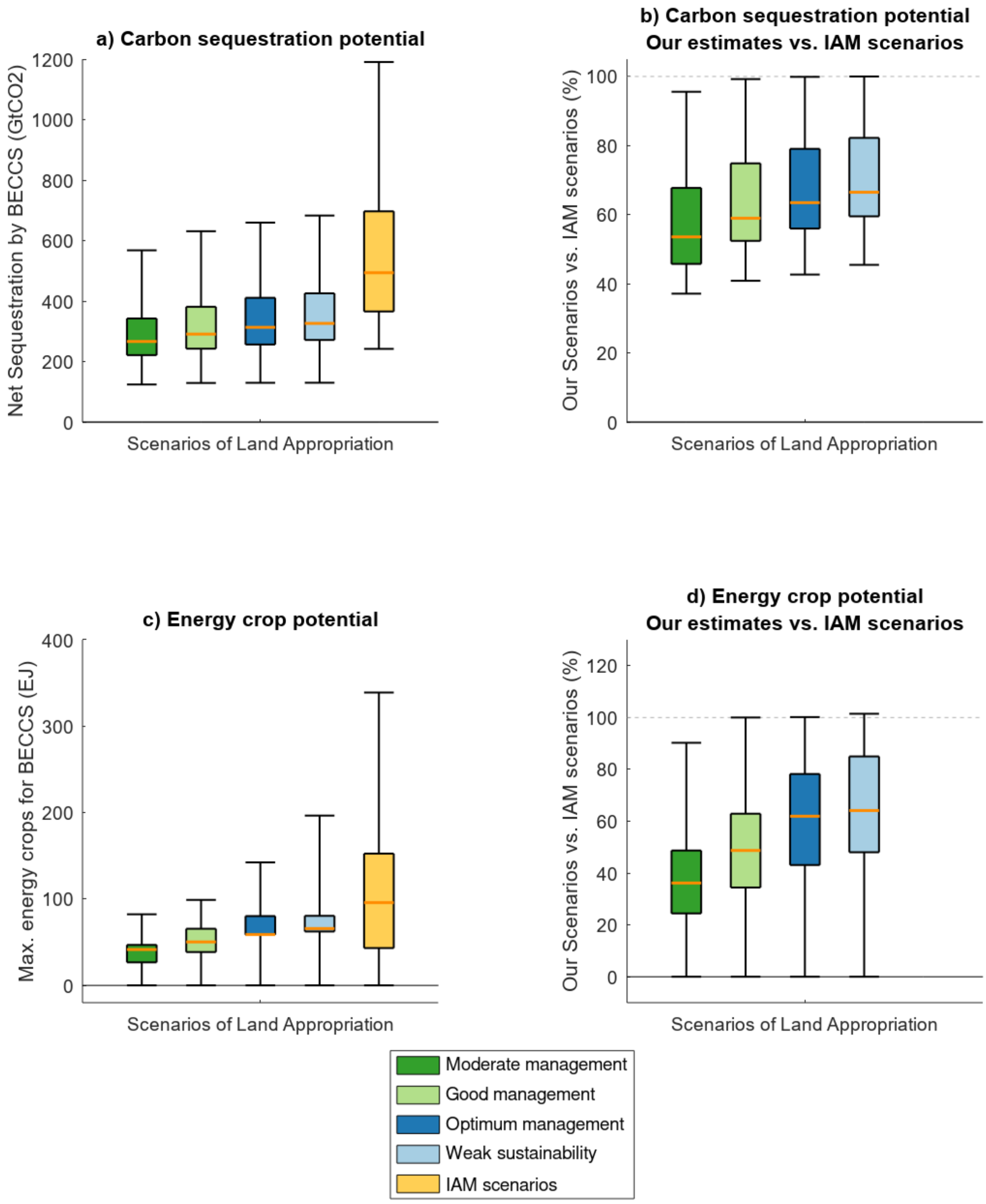


Figure 3.5: Boxplots showing the reanalysis of the negative emissions and bioenergy potentials for BECCS for four land management scenarios alongside the original estimates from IAM scenarios. Figures on the left show the range of absolute values of cumulative (net) negative emission, the maximum harvest of energy crops from our scenarios, and the original calculations from the analysed IAM scenarios. The figures on the right show the relative comparison of our estimates to the original IAM estimates.

3.3.6 Mitigation potential of DACCS

Here, we adjust the analysed IAM scenarios so that DACCS are used when BECCS alone are insufficient to provide the total amount of negative emissions assumed in these scenarios. We assess the impact of DACCS on energy use in the pathways by calculating how much of the total final energy would be used by DACCS. We base our modelling of DACCS on the technology developed by *Climeworks*, assuming their technology's lower range of estimated energy requirements. To estimate the energy requirements of DACCS, we multiply the negative emissions from DACCS by the estimates of energy requirements of this technology from the study by Deutz and Bartow, 2021 (see Methods).

We find DACCS to be necessary across all scenario groups. However, their deployment differs depending on the negative emissions assumed in different scenario groups (Figure 3.6). For example, in the low-NE pathways, the average use of DACCS never exceeds 3 $GtCO_2$ per year. In high-NE pathways, the average use of DACCS reaches 6 $GtCO_2$ per year by the end of the century, while in extreme-NE pathways, DACCS exceed 10 $GtCO_2$ per year.

The energy required for DACCS is proportional to the number of negative emissions realised by this technology. Therefore, DACCS take up a substantial amount of final energy in the High-NE and Extreme-NE scenarios but less in the Moderate-NE scenarios. DACCS make little difference to the energy pathways during the initial push for the transition from 2020 to 2050. However, afterwards, its impact on the energy system increases fast, as the energy required for DACCS can slow down or even completely halt the growth of energy available for society (Figure 3.7).

Extreme-NE pathways may use up to 60 EJ of energy per year by 2100 for DACC, which equals between 10% and 12% of the total final energy in the mitigation scenarios by the end of the century (scenario average). If we add to the energy required for DACCS the lower bioenergy potential from BECCS, the remaining energy left to society in the scenarios decreases by up to 120 EJ, as shown in Figure 3.7f, a decrease of up to 23% in relative terms. With energy requirements of this scale, the DACCS industry could become one of the biggest global energy consumers. As a result of the high energy requirements of DACCS in High-NE and Extreme-NE scenarios, the range of energy pathways across different scenario groups, shown in Figure 3.7, becomes narrower than suggested by the existing final energy pathways from IAMs.

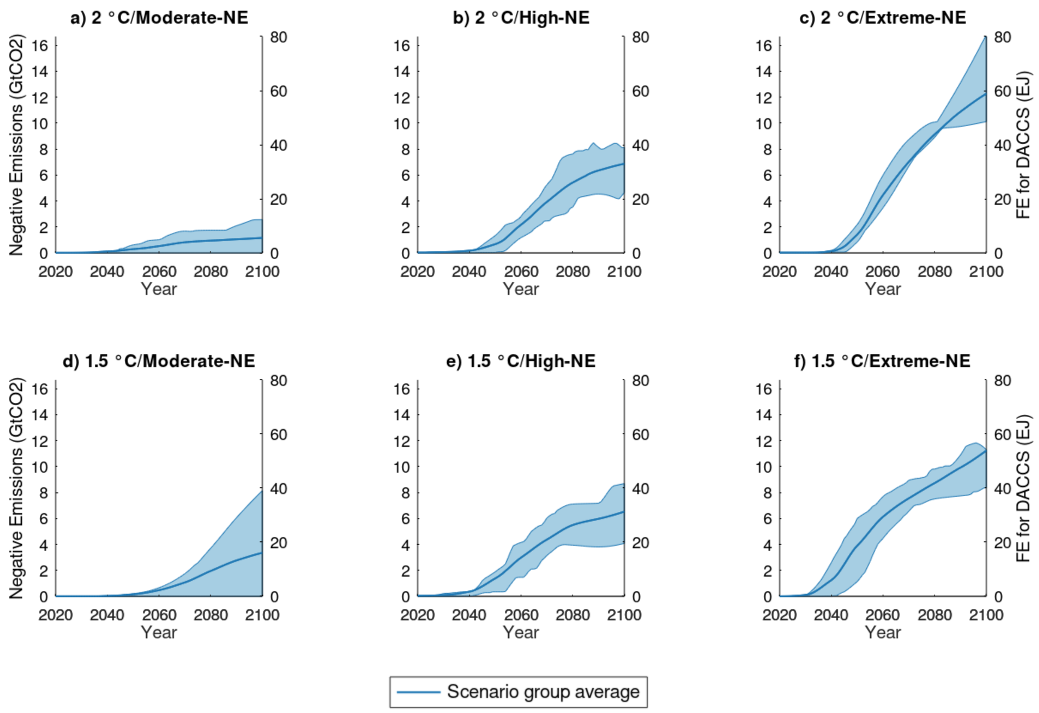


Figure 3.6: Negative emissions and energy required for DACCS. The envelope plots show the interquartile range of negative emissions from DACCS (left axis) and their energy requirements. DACCS are deployed according to the negative emissions assumed in the IAM scenarios, assuming that the maximum negative emissions that BECCS can realise are defined by our good land management scenario (see Figure 3,5). From left to right, the scenarios are sorted into three groups according to the total amount of realised negative emissions. **Panels a-c** show the scenarios staying within the 2 °C carbon budget, while **panels d-f** include all the scenarios consistent with the 1.5 °C carbon budget.

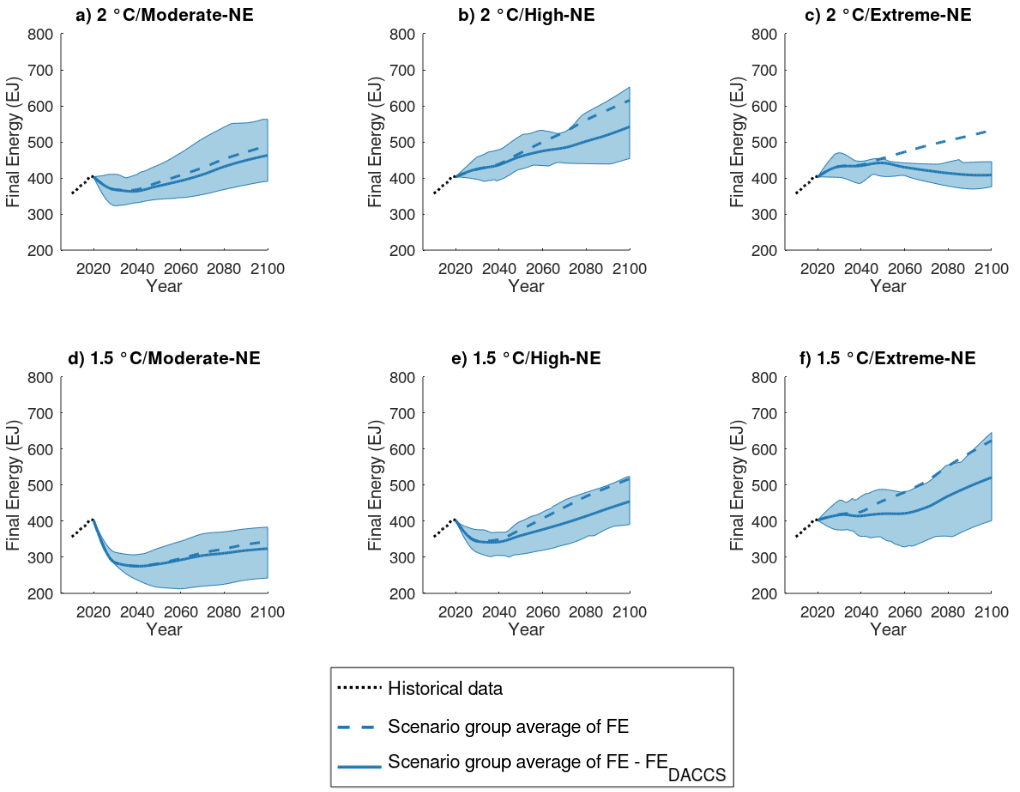


Figure 3.7: Adjusted final energy in different mitigation scenarios. The envelope plots show the interquartile range of the final energy projections from the IPCC scenarios after we deducted the energy required for DACCS. From left to right, the scenarios are sorted into three groups according to the total amount of realised negative emissions. **Panels a-c** show the scenarios staying within the 2 °C carbon budget, while **panels d-f** include all the scenarios consistent with the 1.5 °C carbon budget.

3.3.7 Mitigation potential of other NE options

In this chapter, we only analyse the negative emissions potential and impacts on the energy system for BECCS and DACCS, as these technologies have been studied most extensively in the mitigation scenario literature and because they are estimated to have the highest negative emissions potential among different options (Fuss et al., 2018; Minx et al., 2018). However, we must address the possibility that other negative emissions options, the most prominent examples being the enhanced weathering (EW) and land-based carbon sequestration options, could alter our conclusions based on the analysis of BECCS and DACCS.

The idea behind enhanced weathering is to expand the naturally occurring process, whereby mineral rocks dissolve by reacting with carbonic acid in the rainfall water, leading to a chemical transformation of CO_2 into bicarbonate ions (Beerling et al., 2018) by adding crushed mineral rock over agricultural soils. The upper range of negative emission potential for this option is estimated between 2 $GtCO_2$ (Beerling et al., 2020) and 3.6 $GtCO_2$ (Köhler et al., 2010) per year, equivalent to 140-250 $GtCO_2$ in total by 2100. However, this degree of EW would require 13 gigatonnes of crushed rock per year (Beerling et al., 2020), which is almost double the current amount of global coal extraction of 7.5 gigatonnes (IEA, 2022a). Such extensive mining operations could consume a substantial amount of energy. Energy requirements associated with mining, grinding, transporting, and spreading the mineral rock range from 1.8 to 3.9 GJ per tonne of realised negative emissions, which is comparable to or higher than the energy requirements of DACCS. Therefore, including EW in our analysis would not change our conclusions about the effect of negative emissions on the energy system. For a detailed calculation of the energy requirements of EW, see the "Note on enhanced weathering in the Supplementary Information.

Land-based carbon sequestration consists of nature conservation, restoration and improved land management actions that can increase carbon storage in soil and vegetation, including carbon sequestration by afforestation and reforestation, improved forest management, soil organic carbon sequestration and biochar (Roe et al., 2021). Afforestation, reforestation, and improved forest management are modelled by the IAM scenarios and are, therefore included in our analysis. However, the rest of the options are not considered. The latest IPCC report estimates the average carbon sequestration potential from afforestation and reforestation of 2.1 $GtCO_2$ per year by 2050, with additional 1.2 $GtCO_2$ per year for improved forest management and 3.4 $GtCO_2$ per year for soil organic carbon sequestration and biochar (Nabuurs et al., 2022). The achievable land-based carbon sequestration potential is estimated at 6.6 $GtCO_2$ per year (Roe et al., 2021). However, this potential is expected to decrease gradually as vegetation and soil become saturated the more carbon they absorb (Fuss et al., 2018; P. Smith, 2016). As a result of saturation, cumulative land-based sequestration potential is estimated at approximately 350 $GtCO_2$ (Hansen et al., 2013). In comparison, the IAM pathways estimate the cumulative potential of land-based carbon sequestration to be below 200 $GtCO_2$ (Roe et al., 2019), suggesting that IAMs probably underestimate the cumulative potential from land-based carbon sequestration by up to 150 $GtCO_2$. However, we must be careful when considering negative emissions from land-based carbon sequestration alongside BECCS, as both options compete for land and are, thus, are not additive if taken at the upper range of their respective negative emissions potentials (Lewis et al., 2019). Given that, on average, cumulative negative emissions in the mitigation scenarios amount to the substantially higher value of 650 $GtCO_2$, our conclusions would not change had we expanded the analysis of negative emissions options with biochar and soil organic carbon sequestration.

3.4 Discussion and conclusions

This article analyses the limits and trade-offs of negative emissions options used in mitigation scenarios. Our results show that the potential of a large-scale deployment of negative emissions is much more limited than suggested in most of the existing mitigation scenarios. Moreover, even if negative emissions were to be realised at a large scale, their deployment implies a trade-off with competing uses of energy, as the energy required by negative emissions options would use a substantial share of energy available for society.

We find the deployment of BECCS in mitigation scenarios to be considerably exaggerated, as the realistic potential of ~300 $GtCO_2$ is much lower than the scenario average of 650 $GtCO_2$ and well below the maximum value in the scenarios of 1190 $GtCO_2$. Values higher than 300 $GtCO_2$ are unrealistic, as they would require an extreme expansion of land for energy crop plantations with devastating consequences for natural ecosystems and would threaten the stability of the global food supply. In theory, higher negative emissions from BECCS could be achieved if BECCS was deployed earlier than currently estimated in the scenarios. However, an early push for a large-scale deployment of BECCS is unlikely to become an effective climate policy, as it would be more costly (Babacan et al., 2020) and may face greater technical and policy barriers compared to the conventional mitigation options (Fridahl and Lehtveer, 2018).

To realise more negative emissions, scenarios must look beyond BECCS. DACCS and EW are particularly appealing alternatives due to their considerable theoretical negative emissions potential. However, substituting BECCS for these negative emissions options would have far-reaching implications for energy pathways in scenarios, as it would change the role of the negative emissions industry from an energy producer to a substantial energy consumer. Our study shows that explicit modelling of biophysical and socio-ecological constraints of BECCS and accounting of energy requirements of DACCS could reduce the energy available for society in the mitigation scenarios by up to 20%. As a result of these changes, long-term growth in energy use may be inviable, even in the scenarios that assume extreme deployment of negative emissions.

Still, our conclusions may understate the impact of negative emissions on the energy system, as the total energy requirements of DACCS and EW are not fully understood, and their estimates are not transparently communicated in the existing literature. The current bottom-up estimates of these energy requirements typically limit their analysis to the most energy-intensive processes, such as the operation of DACCS modules (Babacan et al., 2020; Creutzig et al., 2019b; Terlouw et al., 2021) or the grinding of rock for EW (Beerling et al., 2020), but do not consider the energy requirements for the build-up of negative emissions infrastructure or upstream requirements of resource and energy supply. While it is difficult to guess the implications of these requirements given the limited literature about the supply chains of these alternative technologies alongside technological immaturity of these technologies, previous studies suggest that extended energy boundaries of analysis may lead to a substantial increase of the estimated energy requirements (Brockway et al., 2019; Castro and Capellán-Pérez, 2020). Therefore, our calculations are likely an underestimation of total energy requirements of EW and DACCS, implying that the actual impacts on energy use could be higher than suggested in this study.

3.4.1 Implications for climate policy and economy

Existing scenarios suggest that a large-scale deployment of negative emissions makes it possible to accomplish ambitious climate mitigation while increasing global energy use. This approach to mitigation is consistent with climate action plans of some of the major developed countries, such as the UK and the USA. Pledges of these countries to become carbon neutral by 2050 largely depend on the deployment of negative emissions and do not consider the reduction in energy use (Department for Business Energy & Industrial Strategy, 2021; United States Department of State and the United States Executive Office of the President, 2021). However, our study shows that continued growth in global energy use is incompatible with ambitious climate action regardless of negative emissions.

Our study reveals that ambitious mitigation scenarios face a fundamental constraint to energy growth. The most ambitious efforts of decarbonising the energy system and deploying negative emissions may fall short of stabilising global warming between 1.5 °C and 2.0 °C unless reduction in global energy complements these efforts.

Limits to energy use may raise concerns about possible negative impacts on the economy and human well-being due to the historical relationship between economic growth and growth in energy use (Brockway et al., 2021; Stjepanović, 2018). Recent scenarios, however, suggest that lower energy availability needs not to harm the economy (van Vuuren et al., 2017) and that decent living can be provided to everyone at much lower energy than currently used in the world's most affluent societies (Kikstra et al., 2021; Millward-Hopkins et al., 2020). While conceivable, the path to a flourishing lower energy economy would require unprecedented improvements in the efficiency of energy use and a reduction in unnecessary consumption (Creutzig et al., 2022; Grubler et al., 2018; Van Vuuren et al., 2018a).

The role that negative emissions play in mitigation scenarios, according to the existing literature, is to smooth out the dramatic breakaway from fossil fuels early in the transition and therefore make the transition possible with more modest energy efficiency improvements and lesser changes to human lifestyles (Fricke et al., 2017; Kriegler et al., 2017). Moreover, by slowing down the required speed of the transition, negative emissions reduce economic losses from stranded fossil fuel assets (Fuhrman et al., 2020) and reduce the short-term costs associated with the build-up of low-carbon infrastructure (Bistline and Blanford, 2021; Kriegler et al., 2014).

However, the problem with the IAM scenarios is that they only analyse the economic costs of negative emissions but do not estimate the energy and material requirements of these technologies (Pauliuk et al., 2017; Sgouridis et al., 2019). As shown by the share of the total energy that the negative emissions industry may take up, this is a critical research gap that may undermine the modelling of energy pathways in existing scenarios. Our research substantiates the importance of considering energy requirements in *Chapter 2*, where we show that the efficiency of the overall energy system, measured by the energy return on energy invested (EROI), decreases the higher the reliance on negative emissions from BECCS. The replacement of DACCS for BECCS would lead to a further decline in the overall EROI of the energy system, as the energy required for DACCS would decrease the (net) energy for society.

While lower net energy may not harm the economy, supposing the energy system becomes more efficient, negative emissions are likely to have the opposite effect, as they allow for extra energy from fossil fuels but do so at the cost of lower efficiency of the energy system. This may complicate the rationale for negative emissions, as empirical evidence shows that a decline in the EROI of the energy system leads to an increase in the expenditure of the gross domestic product (GDP) for the energy system, which may in turn decrease the expenditure for labour and capital (Fizaine and Court, 2016). This may have important implications for the economy, as periods of a lower EROI of the energy system have been empirically linked to higher energy prices and lower economic growth (Hall et al., 2009; Lambert et al., 2014).

Overall, our study suggests that future mitigation scenarios should improve our understanding of energy transitions by modelling the energy required for negative emissions and reporting on energy availability for society over time. Doing so may lead to a reframing of the perspective role of negative emissions in the transition. Negative emissions allow for a more gradual energy transition, which would allow current generations to maintain higher energy consumption and could limit financial losses from the fossil-fuel-dependent economic sectors. However, in exchange for these advantages in the short-term, future generations may have to dedicate a substantial share of their economic activity to cleaning up the atmosphere.

3.5 Supplementary Information

3.5.1 Note on mitigation scenarios used in our study

Mitigation scenarios considered in this analysis are a subset of the scenarios used in the *IPCC's Special Report on Global Warming of 1.5 °C* (IPCC, 2018b). They can be accessed at *IAMC 1.5 °C Scenario Explorer* (Huppmann et al., 2019) webpage*:* data.ene.iiasa.ac.at/iamc-1.5c-explorer. Mitigation scenarios in this database are categorised according to the expected global warming in 2100, and the maximum expected global temperature reached during the century. For our analysis, we use the 161 scenarios categorised as 'below 1.5 °C', '1.5 °C low overshoot', '1.5 °C high overshoot', and 'Lower 2 °C'. All of the scenarios used are characterised with a high probability (>66%) to stabilise global warming below 2 °C throughout the 21st century.

Scenarios from the models C-ROADS-5.005 and WITCH-GLOBIOM 4.4 that fall into these categories were excluded from our analysis due to a lack of data on the energy from different energy technologies, leaving 153 scenarios in our analysis (see Supplementary Table 3.1 for a complete list of scenarios and changes to the source data). Furthermore, we excluded the additional 53 scenarios from the analysis of final energy from fossil fuels (Figure 3.3), as they do not report on the oil and/or natural gas at the secondary energy stage. Moreover, 38 scenarios in our analysis do not report on the bioenergy for BECCS at the primary energy stage. For these scenarios, we calculated the primary energy from BECCS from the secondary energy data using the BECCS conversion factors used in the study by Hanssen et al., 2020.

Supplementary Table 3.1: List of scenarios used in this study and the quality control of their source data.

Model	Scenario	Included	Notes
AIM/CGE 2.0	ADVANCE_2020_1.5C-2100	Yes, but primary energy data for BECCS was calculated.	Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
AIM/CGE 2.0	ADVANCE_2020_WB2C		
AIM/CGE 2.0	ADVANCE_2030_Price1.5C		
AIM/CGE 2.0	ADVANCE_2030_WB2C		
AIM/CGE 2.0	SFCM_SSP2_Bio_1p5Degree	Yes	
AIM/CGE 2.0	SFCM_SSP2_EEEI_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_LifeStyle_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_Ref_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_ST_CCS_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_ST_bio_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_ST_nuclear_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_ST_solar_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_ST_wind_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_SupTech_1p5Degree		
AIM/CGE 2.0	SFCM_SSP2_combined_1p5Degree		
AIM/CGE 2.0	SSP1-19	Yes	
AIM/CGE 2.0	SSP1-26		
AIM/CGE 2.0	SSP2-19		
AIM/CGE 2.0	SSP2-26		
AIM/CGE 2.0	SSP4-26		
AIM/CGE 2.0	SSP5-26		
AIM/CGE 2.1	CD-LINKS_NPi2020_1000	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for oil and natural gas.

AIM/CGE 2.1	CD-LINKS_NPi2020_400		
AIM/CGE 2.1	EMF33_WB2C_cost100	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for oil and natural gas.
AIM/CGE 2.1	EMF33_WB2C_full		
AIM/CGE 2.1	TERL_15D_LowCarbonTransportPolicy	Yes, but primary energy data for BECCS was calculated.	Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
AIM/CGE 2.1	TERL_15D_NoTransportPolicy		
AIM/CGE 2.1	TERL_2D_LowCarbonTransportPolicy		
AIM/CGE 2.1	TERL_2D_NoTransportPolicy		
C-ROADS v 5.005	Ratchet-1.5-allCDR	No	Missing secondary energy for all energy generation technologies.
C-ROADS v 5.005	Ratchet-1.5-limCDR		
C-ROADS v 5.005	Ratchet-1.5-limCDR-noOS		
C-ROADS v 5.005	Ratchet-1.5-noCDR		
C-ROADS v 5.005	Ratchet-1.5-noCDR-noOS		
GCAM 4.2	SSP1-19	Yes	
GCAM 4.2	SSP1-26		
GCAM 4.2	SSP2-19		
GCAM 4.2	SSP5-19		
IMAGE 3.0.1	ADVANCE_2020_1.5C-2100	Yes, but primary energy data for BECCS was calculated.	Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
IMAGE 3.0.1	ADVANCE_2020_WB2C		
IMAGE 3.0.1	ADVANCE_2030_WB2C		
IMAGE 3.0.1	CD-LINKS_NPi2020_1000	Yes, except for analysing final energy from fossil fuels (Figure 3,2)	Missing secondary energy data for oil and natural gas.
IMAGE 3.0.1	CD-LINKS_NPi2020_400		
IMAGE 3.0.1	IMA15-AGInt	Yes	
IMAGE 3.0.1	IMA15-Def		

IMAGE 3.0.1	IMA15-Eff	Yes	
IMAGE 3.0.1	IMA15-LiStCh		
IMAGE 3.0.1	IMA15-LoNCO2		
IMAGE 3.0.1	IMA15-Pop		
IMAGE 3.0.1	IMA15-RenElec		
IMAGE 3.0.1	IMA15-TOT		
IMAGE 3.0.1	SSP1-19		
IMAGE 3.0.1	SSP1-26		
IMAGE 3.0.1	SSP2-26		
IMAGE 3.0.1	SSP4-26		
MERGE-ETL 6.0	DAC15_50	Yes	
MESSAGE V.3	GEA_Eff_1p5C	Yes, except for analysing final energy from fossil fuels (Figure 3.2). Primary energy data for BECCS was calculated.	Missing secondary energy data for oil. Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
MESSAGE V.3	GEA_Eff_1p5C_Delay2020		
MESSAGE V.3	GEA_Eff_AdvNCO2_1p5C		
MESSAGE V.3	GEA_Mix_1p5C_AdvNCO2_PartialDelay2020		
MESSAGE V.3	GEA_Mix_1p5C_AdvTrans_PartialDelay2020		
MESSAGE-GLOBIOM 1.0	ADVANCE_2020_1.5C-2100	Yes, but primary energy data for BECCS was calculated.	Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
MESSAGE-GLOBIOM 1.0	ADVANCE_2020_WB2C		
MESSAGE-GLOBIOM 1.0	ADVANCE_2030_Price1.5C		
MESSAGE-GLOBIOM 1.0	ADVANCE_2030_WB2C		
MESSAGE-GLOBIOM 1.0	EMF33_1.5C_cost100	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for natural gas.
MESSAGE-GLOBIOM 1.0	EMF33_1.5C_full		
MESSAGE-GLOBIOM 1.0	EMF33_Med2C_nobeccs		
MESSAGE-GLOBIOM 1.0	EMF33_Med2C_none		

MESSAGE-GLOBIOM 1.0	EMF33_WB2C_cost100		
MESSAGE-GLOBIOM 1.0	EMF33_WB2C_full		
MESSAGE-GLOBIOM 1.0	EMF33_WB2C_limbio		
MESSAGE-GLOBIOM 1.0	EMF33_WB2C_nofuel	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for natural gas.
MESSAGE-GLOBIOM 1.0	EMF33_tax_hi_full		
MESSAGE-GLOBIOM 1.0	SSP1-19	Yes	
MESSAGE-GLOBIOM 1.0	SSP2-19		
MESSAGEix-GLOBIOM 1.0	CD-LINKS_NPi2020_1000	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for oil and natural gas.
MESSAGEix-GLOBIOM 1.0	CD-LINKS_NPi2020_400		
MESSAGEix-GLOBIOM 1.0	LowEnergyDemand	Yes	
POLES ADVANCE	ADVANCE_2020_1.5C-2100		
POLES ADVANCE	ADVANCE_2020_Med2C		
POLES ADVANCE	ADVANCE_2020_WB2C		
POLES ADVANCE	ADVANCE_2030_1.5C-2100	Yes, but primary energy data for BECCS was calculated.	Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
POLES ADVANCE	ADVANCE_2030_Med2C		
POLES ADVANCE	ADVANCE_2030_Price1.5C		
POLES ADVANCE	ADVANCE_2030_WB2C		
POLES CD-LINKS	CD-LINKS_NPi2020_1000	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for natural gas.
POLES CD-LINKS	CD-LINKS_NPi2020_400		
POLES EMF33	EMF33_1.5C_cost100		
POLES EMF33	EMF33_1.5C_full		
POLES EMF33	EMF33_1.5C_limbio	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for natural gas.
POLES EMF33	EMF33_1.5C_nofuel		
POLES EMF33	EMF33_Med2C_cost100		

POLES EMF33	EMF33_Med2C_full		
POLES EMF33	EMF33_Med2C_limbio		
POLES EMF33	EMF33_Med2C_nobeccs		
POLES EMF33	EMF33_Med2C_nofuel		
POLES EMF33	EMF33_Med2C_none		
POLES EMF33	EMF33_WB2C_cost100		
POLES EMF33	EMF33_WB2C_full	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for natural gas.
POLES EMF33	EMF33_WB2C_limbio		
POLES EMF33	EMF33_WB2C_nobeccs		
POLES EMF33	EMF33_WB2C_nofuel		
POLES EMF33	EMF33_WB2C_none		
REMIND 1.5	EMC_Def_100$		Missing secondary energy data for oil.
REMIND 1.5	EMC_LimSW_100$	Yes, except for analysing final energy from fossil fuels (Figure 3.2). Primary energy data for BECCS was calculated.	Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
REMIND 1.5	EMC_NucPO_100$		
REMIND 1.5	EMC_lowEI_100$		
REMIND 1.7	ADVANCE_2020_1.5C-2100		Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
REMIND 1.7	ADVANCE_2020_WB2C	Yes, but primary energy data for BECCS was calculated.	
REMIND 1.7	ADVANCE_2030_1.5C-2100		
REMIND 1.7	CEMICS-1.5-CDR12		
REMIND 1.7	CEMICS-1.5-CDR20	Yes	
REMIND 1.7	CEMICS-1.5-CDR8		
REMIND 1.7	CEMICS-2.0-CDR12		

REMIND 1.7	CEMICS-2.0-CDR8		
REMIND-MAgPIE 1.5	SSP1-19	Yes	
REMIND-MAgPIE 1.5	SSP2-19		
REMIND-MAgPIE 1.5	SSP5-19		
REMIND-MAgPIE 1.7-3.0	CD-LINKS_NPi2020_1000	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for oil and natural gas.
REMIND-MAgPIE 1.7-3.0	CD-LINKS_NPi2020_400		
REMIND-MAgPIE 1.7-3.0	EMF33_1.5C_cost100	Yes, except for analysing final energy from fossil fuels (Figure 3.2)	Missing secondary energy data for natural gas.
REMIND-MAgPIE 1.7-3.0	EMF33_1.5C_full		
REMIND-MAgPIE 1.7-3.0	EMF33_1.5C_nofuel		
REMIND-MAgPIE 1.7-3.0	EMF33_WB2C_limbio		
REMIND-MAgPIE 1.7-3.0	EMF33_WB2C_nobeccs		
REMIND-MAgPIE 1.7-3.0	EMF33_WB2C_nofuel		
REMIND-MAgPIE 1.7-3.0	EMF33_WB2C_none		
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_NDC	Yes	
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_eff		
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_goodpractice		
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_netzero		
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_red_eff		
REMIND-MAgPIE 1.7-3.0	PEP_2C_full_eff		
REMIND-MAgPIE 1.7-3.0	PEP_2C_full_netzero		
REMIND-MAgPIE 1.7-3.0	PEP_2C_red_NDC		
REMIND-MAgPIE 1.7-3.0	PEP_2C_red_eff		
REMIND-MAgPIE 1.7-3.0	PEP_2C_red_goodpractice		
REMIND-MAgPIE 1.7-3.0	PEP_2C_red_netzero		

REMIND-MAgPIE 1.7-3.0	SMP_1p5C_Def	Yes	
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_Sust		
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_early		
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_lifesty		
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_regul		
REMIND-MAgPIE 1.7-3.0	SMP_2C_Def	Yes	
REMIND-MAgPIE 1.7-3.0	SMP_2C_Sust		
REMIND-MAgPIE 1.7-3.0	SMP_2C_early		
REMIND-MAgPIE 1.7-3.0	SMP_2C_lifesty		
REMIND-MAgPIE 1.7-3.0	SMP_2C_regul		
WITCH-GLOBIOM 3.1	SSP1-19	Yes	
WITCH-GLOBIOM 3.1	SSP1-26		
WITCH-GLOBIOM 3.1	SSP2-26		
WITCH-GLOBIOM 3.1	SSP4-19		
WITCH-GLOBIOM 3.1	SSP4-26		
WITCH-GLOBIOM 4.2	ADVANCE_2020_1.5C-2100	Yes, but primary energy data for BECCS was calculated.	Primary energy for BECCS was calculated from secondary energy data, using the conversion factors for secondary energy carriers from BECCS, as assumed in the model of (Hanssen et al., 2020)
WITCH-GLOBIOM 4.2	ADVANCE_2020_WB2C		
WITCH-GLOBIOM 4.2	ADVANCE_2030_Price1.5C		
WITCH-GLOBIOM 4.2	ADVANCE_2030_WB2C		
WITCH-GLOBIOM 4.4	CD-LINKS_NPi2020_1000	No	Missing secondary energy data for natural gas and oil. Erroneous historical final energy data.
WITCH-GLOBIOM 4.4	CD-LINKS_NPi2020_1600		
WITCH-GLOBIOM 4.4	CD-LINKS_NPi2020_400		

Supplementary Table 3.2: Categorisation of mitigation scenarios by the net cumulative CO_2 emissions and cumulative negative emissions.

Scenario Group	Net Cumulative CO_2 Emissions ($GtCO_2$)	Cumulative Negative Emissions ($GtCO_2$)	Number of Scenarios
1.5 °C & NE-Moderate	< 500	< 500	7
1.5 °C & NE-Large	< 500	500-800	33
1.5 °C & NE-Extreme	< 500	> 800	34
2 °C & NE-Moderate	500-1150	< 500	35
2 °C & NE-Large	500-1150	500-800	34
2 °C & NE-Extreme	500-1150	> 800	7

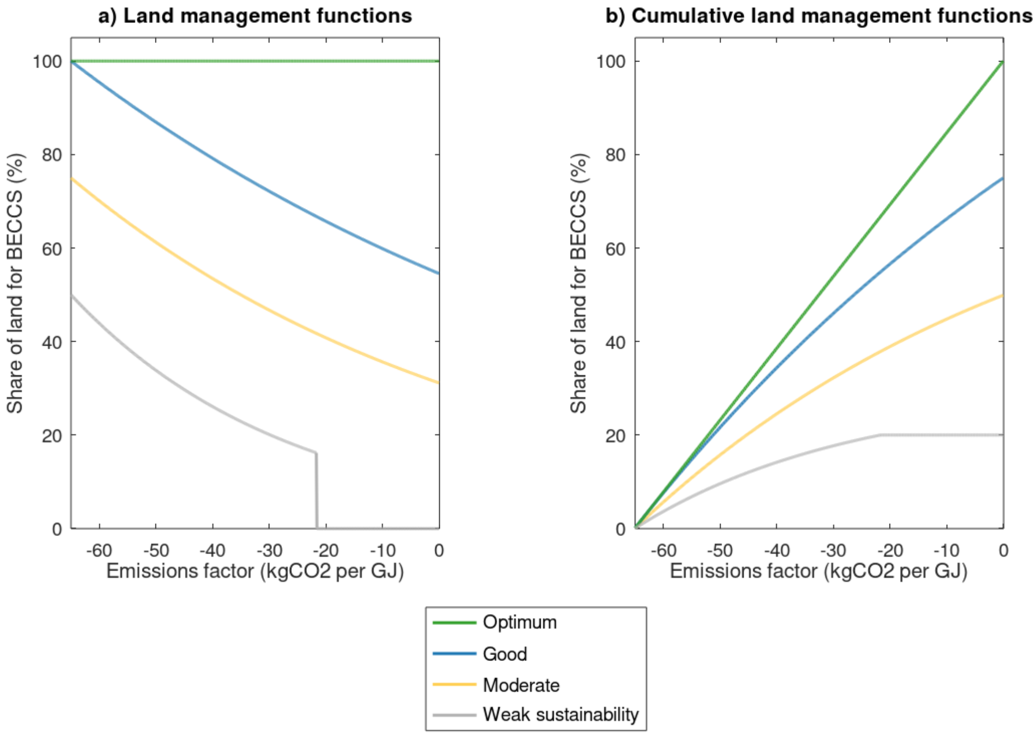
3.5.2 Note on scenarios of land management

Land management scenarios describe the share of globally available land that is assumed to be dedicated to energy crop plantations for BECCS. We consider all the lands that could realise net negative emissions with BECCS, so only areas with a negative emissions factor are considered. The land management function $\varphi(\mathrm{EF})$ relates the share of the land dedicated to BECCS to the total land available. For the land management function, we use the exponential distribution function, assuming that the higher the emissions factor (i.e., lower the negative emissions potential) lower the share of land dedicated to BECCS, as a lower potential for negative emissions decreases the economic benefits of BECCS on that area compared to other commercial uses of land, which makes it less likely that the land will be dedicated to bioenergy plantations for BECCS (see Supplementary Figure 3.1a).

The exceptions here are the optimum management scenarios, where we assume that all (100%) of the abandoned, degraded, and managed lands are dedicated to BECCS. These scenarios are used to estimate the maximum theoretical potential of these lands; therefore, calculated values of negative emissions and produced energy crops for BECCS in these scenarios' outcomes should not be interpreted as realistically achievable. In the "optimum management + weak sustainability scenario", we sum the two respective land management functions. The first function corresponds to the optimum management of abandoned, degraded and managed lands. In contrast, the second function corresponds to the management of natural lands, which are excluded in other scenarios. In the weak sustainability scenario, we assume that up to 20% of all available natural lands can be converted and that only lands with the lowest emissions factors can be converted into energy crop plantations (Lewis et al., 2019). Supplementary Table 3.3 provides an overview of the parameters from the land management function, described in Equation 3 of *Chapter 3*, for different land management scenarios.

Supplementary Table 3.3: Parameters for land management functions in different scenarios

<table>
<tr><th>Scenario</th><th colspan="2">Maximum share of land for BECCS (C)</th><th colspan="2">Exponential decay parameter (α)</th><th colspan="2">Range of emissions factors on converted lands ($kgCO_2$ per GJ)</th><th colspan="2">>Maximum cumulative share of land for BECCS (Figure 3.1b)</th></tr>
<tr><td>Moderate management</td><td colspan="2">0.75</td><td colspan="2">0.8784</td><td colspan="2">from -65 to 0</td><td colspan="2">50 %</td></tr>
<tr><td>Good management</td><td colspan="2">0.75</td><td colspan="2">0.6059</td><td colspan="2">from -65 to 0</td><td colspan="2">75 %</td></tr>
<tr><td>Optimum management</td><td colspan="2">1</td><td colspan="2">0</td><td colspan="2">from -65 to 0</td><td colspan="2">100 %</td></tr>
<tr><td>Optimum management (left) and weak sustainability (right)</td><td>1</td><td>0.5</td><td>0</td><td>1.6893</td><td>from -65 to 0</td><td>from -65 to -21.5</td><td>100 %</td><td>20 %</td></tr>
</table>

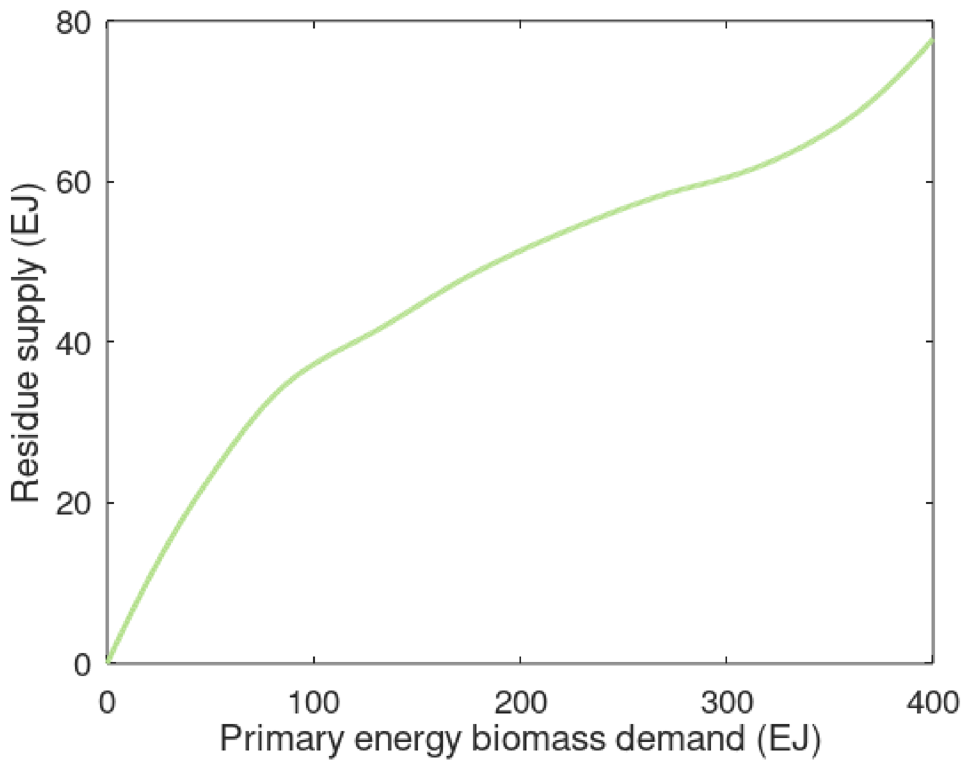


Supplementary Figure 3.1: Land management functions. Panel a shows the share of globally available land dedicated to BECCS, as a function of the land's emissions factor, for different land management scenarios. **Panel b** shows the cumulative share of all the available land dedicated to BECCS.

3.5.3 Note on biomass residues

IAMs model two pathways of biomass supply for BECCS: the biomass harvest from dedicated energy crop plantations and the “left-over” residues from non-energy uses of biomass, which include residues in agriculture and forestry. IAMs differ in their assumptions of how much biomass for BECCS can be provided from residues. However, IAM mitigation scenarios do not report on energy and negative emissions from the residues separately from the energy and negative emissions from dedicated energy crops. Therefore, we compare the aggregated IAM estimates from the residuals and dedicated energy crops to the sum of our calculations for both sources of biomass supply for BECCS.

We base our method for calculating the residue supply potential on the comparative analysis of biomass residues in IAM models by Hanssen et al., 2019. The authors of the study compared the representation of residues across eight different IAM models. The authors find that the supply of residues in these models increases with demand for bioenergy, increased biomass price and carbon price, as higher demand and higher prices lead to more residues being collected or diverted from other sectors towards bioenergy. To model residue supply, we analyse how residue supply depends on the primary energy supply of biomass across the IAM scenarios used in the abovementioned study. We obtain our function of residue energy supply by calculating the average of the model ensemble in the "400 EJ scenario with carbon pricing" after excluding the two models with the lowest and highest estimates of primary energy supply (see Supplementary Table 3.4 and Supplementary Figure 3.2).

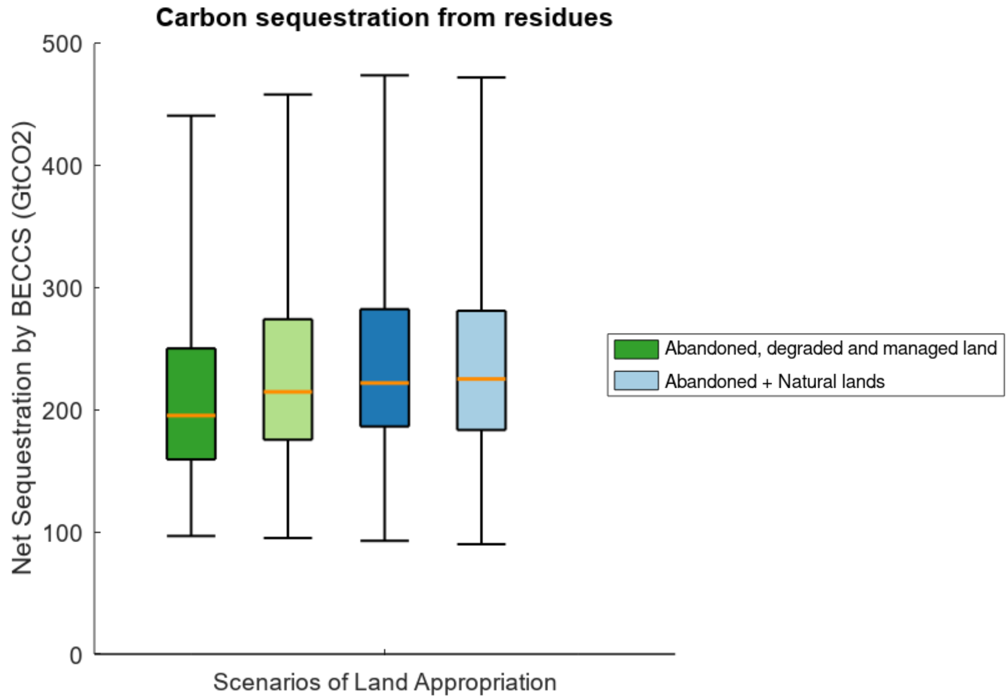


Supplementary Figure 3.2: Availability of biomass residues as a function of primary energy biomass supply in the mitigation scenarios.

Supplementary Table 3.4: Supply of biomass residuals as a function of primary energy supply of biomass in the "400 EJ scenario with carbon pricing" from (Hanssen et al., 2019) Values from the scenarios that were excluded from the analysis are coloured in yellow.

	Residual supply (EJ)	AIM	BET	DNE21+	GCAM	GLOBIOM	GRAPE	IMAGE	NLU	Scenario average
Biomass supply (EJ)										
44		7.3	34.6	8.4	35.1	15.2	35.6	16.2	12.0	20.1
89		3.7	49.2	8.4	45.5	26.2	64.9	24.6	15.2	27.4
133		8.9	62.3	9.4	52.4	35.1	82.7	34.6	20.4	35.6
178		15.7	73.3	9.4	59.2	44.0	97.9	43.5	25.1	43.5
222		24.1	78.5	8.4	65.4	52.9	110.5	46.1	26.2	48.9
267		33.5	83.8	6.8	72.8	60.7	117.3	48.7	26.2	54.3
311		41.9	104.7	7.3	80.1	65.4	147.1	50.3	26.2	61.4
356		54.5	121.5	7.3	90.6	59.2	151.3	51.8	25.7	67.2
400		65.4	157.6	7.3	104.7	59.2	151.3	54.5	25.1	77.7

We assume that biomass residues are used first before allocating any land to energy crop plantations for BECCS. Correspondingly, land-use change only occurs when the available biomass residues are insufficient to realise negative emissions assumed in the IAM scenarios. Negative emissions from BECCS realised from biomass residues range from 195 $GtCO_2$ to 225 $GtCO_2$ (median values), as shown in Supplementary Figure 3.3. Negative emissions from biomass residues do not differ substantially between different land management scenarios because most of the residues originate from other biomass uses like agriculture, forestry, etc.



Supplementary Figure 3.3: Boxplots showing the negative emissions potential for BECCS from biomass residues.

3.5.4 Enhanced weathering

An essential energy requirement for EW is the energy used to grind mineral rock into small gravel. The energy required for grinding is two magnitudes higher than the energy required for mining (Strefler et al., 2018). The other essential energy requirement is the energy used to transport gravel from the mine to the land where gravel is spread over. We base our estimates of energy required for grinding on Beerling et al., 2020, who estimate from 0.2 MJ to 0.6 MJ to be required for grinding 1 kg of basalt rock. The energy required for grinding depends on the gravel particle size; the smaller the particles, the larger the energy requirements. Beerling et al. assume that gravel will be transported using an electric-powered heavy truck with a payload capacity of 20 tonnes and energy use of 1.38 kWh per km, corresponding to 5 MJ per km. Assuming the average transportation distance of 300 km (Strefler et al., 2018), the energy for transportation amounts to 0.08 MJ per 1 kg of basalt. The total energy requirements for EW are the sum of energy required for grinding and transportation and range from 0.28 to 0.68 MJ per kg.

Beerling et al. estimate that 12.94 Gt of basalt is needed each year to realise net negative emissions of 2 $GtCO_2$. We divide the mass of basalt by the realised negative emissions to obtain the mass ratio of 6.47 tonne of basalt for 1 tonne of CO_2 sequestration. To estimate the energy requirements of negative emissions from EW, we multiply the mass ratio by the total energy requirements for grinding and transporting gravel, as shown in Supplementary Equation 5. We calculate that between 1.8 GJ and 3.9 GJ would be required to realise 1 $GtCO_2$ negative emissions from EW.

$$\mathrm{FE_{EW}} = \frac{M_{\mathrm{basalt}}}{M_{\mathrm{CO_2}}}\left(\mathrm{FE_{grinding}} + \mathrm{FE_{transport}}\right) \qquad (5)$$

Supplementary Table 3.5: Literature estimates of energy requirements for DACCS.

DACCS Technology (References)	Electricity Requirements (GJ/tCO_2)	Heat Requirements (GJ/tCO_2)	System Boundaries
Liquid sorbents			
IAM literature	1.3-1.8 (Fuhrman et al., 2020; Realmonte et al., 2019)	5.3-8.1 (Fuhrman et al., 2020; Realmonte et al., 2019)	Own-energy use by the DACCS modules.
Literature Review	0.7-1.7 (National Academies of Sciences, 2019)	7.7-10.7 (National Academies of Sciences, 2019)	Own-energy use by the DACCS modules.
Carbon Engineering	1.3 (Keith et al., 2018)	5.3 (Keith et al., 2018)	Own-energy use by the DACCS modules.
Carbon Engineering	1.6-2.4 (Madhu et al., 2021)	4.1-4.5 (Madhu et al., 2021)	Extended boundary including energy required for CCS compression and transportation.
IAM literature	3.6-5.7 (Chatterjee and Huang, 2020)	5.3-8.1 (Fuhrman et al., 2020; Realmonte et al., 2019)	Extented boundary including the energy required to produce the sorbent
Solid sorbents			
IAM literature	0.6-1.1 (Gebald et al., 2011; Ishimoto et al., 2017; Realmonte et al., 2019)	4.4-7.2 (Gebald et al., 2011; Ishimoto et al., 2017; Realmonte et al., 2019)	Own-energy use by the DACCS modules.
Literature Review	0.6-1.1 (National Academies of Sciences, 2019)	3.4-4.8 (National Academies of Sciences, 2019)	Own-energy use by the DACCS modules.
IAM literature	0.6-38.2 (Chatterjee and Huang, 2020)	7.1-37.5 (Chatterjee and Huang, 2020)	Own-energy use by the DACCS modules.
Literature Review	1.5 (McQueen et al., 2021)	(.0-6.0 (McQueen et al., 2021)	Own-energy use by the DACCS modules.
Climeworks[a]	1.8-2.5 (Creutzig et al., 2019b; Deutz and Bardow, 2021)	5.4-7.2 (Creutzig et al., 2019b)	Own-energy use by the DACCS modules.
Global Thermostat	0.5-0.9 (Creutzig et al., 2019b)	4.2-5.1 (Creutzig et al., 2019b)	Own-energy use by the DACCS modules.
Antecy	2.5 (Creutzig et al., 2019b)	7.5 (Creutzig et al., 2019b)	Own-energy use by the DACCS modules.
Climeworks[b]	2.2-4.6 (Terlouw et al., 2021)	0-5.4 (Terlouw et al., 2021)	Own-energy use by the DACCS modules.
Climeworks[c]	0.9-1.7	2.3-6.2	Own-energy use by the DACCS modules.
Climeworks[d]	2.6 (Deutz and Bardow, 2021)	5.4 (Deutz and Bardow, 2021)	Extended boundary including energy required for CCS compression and energy required to produce the sorbent
Our assumption	**2.6**	**5.4**	

[a] Lower range corresponds to energy requirements of existing systems, upper range corresponds to expected energy requirements of the future system.

[b] Energy requirements depend on the sources of electricity (grid, PV, PV + battery) and heat (waste heat or heat generated by a heat pump).

[d] The assessment of energy requirements assume that between 10% and 90% of heat requirements can be provided with waste heat. Limited availability of waste heat makes this set-up possible only for a small-scale deployment of DACCS.

[d] Corresponds to energy requirements of the future system.

3.5.5 Limitations to our approach

We framed our analysis around energy pathways in different IAM scenarios of ambitious mitigation. Our underlying assumption was that existing scenarios adequately represent possible energy futures. However, this approach could be questioned, as IAMs were not designed to assess the biophysical limits of energy generation from different energy technologies.

The range of possible energy pathways during the transition depends on the possibilities of developing and deploying low-carbon and negative emissions technologies. Energy consumption could be more limited than suggested by the Extreme-NE scenarios, not only if we fail to realise sufficient negative emissions but also if we fail to realise the dramatic upscaling of the renewables and nuclear energy assumed in the IAM scenarios (Keyßer and Lenzen, 2021). Although IAMs have underestimated the growth rates of renewable technologies in the past (Creutzig et al., 2017), they may still overestimate the long-term possibilities of upscaling the low-carbon infrastructure, as the supply of materials required for the production of components may not match the speed at which low carbon energy needs to replace fossil fuels in the pathways (Sprecher and Kleijn, 2021; Valero et al., 2018). In addition, supply-side constraints may be aggravated by public opposition to big energy projects triggered by the adverse impacts of mineral extraction and land-grabbing (Avila, 2018; Lèbre et al., 2020). On the contrary, technological innovation in new technologies, such as nuclear fusion, could boost the energy supply significantly. Even though the future of energy systems is unpredictable, our believe is that the urgency of avoiding dangerous climate change requires to approach the transition with the precautionary principle in mind, by relying on technologies currently available and therefore accepting the need to reduce global energy consumption.

Chapter 4
Existing climate mitigation scenarios perpetuate colonial inequalities[4]

Abstract

The challenge of climate mitigation is made more difficult by high rates of energy use in wealthy countries, mostly in the Global North, which far exceed what is required to meet human needs. In contrast, more than 3 billion people in poorer countries live in energy poverty. A just transition requires energy convergence—reducing energy use in wealthy countries to achieve rapid emissions reductions, and ensuring sufficient energy for development in the rest of the world. However, existing climate mitigation scenarios reviewed by The Intergovernmental Panel on Climate Change do not explore such a transition. On average, existing scenarios maintain the Global North's energy privilege at a per capita level 2·3 times higher than in the Global South. Even the more equitable scenarios perpetuate large energy inequalities for the rest of the century. To reconcile the Global North's high energy use with the Paris Agreement targets, most scenarios rely heavily on bioenergy-based negative emissions technologies. This approach is risky, but it is also unjust. These scenarios tend to appropriate land in the Global South to maintain, and further increase, the Global North's energy privilege. There is an urgent need to develop scenarios that represent convergence to levels of energy that are sufficient for human wellbeing and compatible with rapid decarbonisation.

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[4] This chapter corresponds to the article: Hickel, J., Slamersak, A. Existing climate mitigation scenarios perpetuate colonial inequalities. *Lancet. Planet. Heal*. **6**, e628–e631 (2022). https://doi.org/10.1016/S2542-5196(22)00092-4.

4.1 Introduction

The challenge of climate mitigation is made more difficult by the scale of energy use in wealthy countries. The core countries of the Organisation for Economic Cooperation and Development (OECD) and the rest of Europe (collectively referred to here as the Global North) use on average about 130 gigajoules of energy per capita each year, nearly ten times more than what low-income countries use (13·4 GJ/capita) (IEA, 2022b). The world's wealthiest 5% of individuals use more energy than the poorest half of the global population combined (Oswald et al., 2020). High rates of energy use pose a problem, because this makes it difficult to decarbonise the energy system fast enough to stay within the carbon budgets for 1·5 °C or 2·0 °C.

Energy use in wealthy countries far exceeds what is required to meet human needs at a decent standard of living (Millward-Hopkins et al., 2020). Much of this excess energy is consumed by forms of production that support corporate profits and elite accumulation, such as fast fashion, sports utility vehicles, industrial meat, and planned obsolescence, which have little relevance to wellbeing (Wiedmann et al., 2020). Furthermore, it is important to note that high rates of energy use in wealthy countries are sustained in large part through a net appropriation of energy from poorer countries through patterns of unequal exchange in international trade (Hickel et al., 2022).

More than 3 billion people in low-income countries do not have enough energy to achieve decent living standards (Kikstra et al., 2021). 38% of the world's population has access to less than 10 gigajoules of energy per capita per year, which is too little to meet even the most basic human needs (IEA, 2022b). 780 million people do not have access to electricity (The World Bank, 2021). Energy poverty is a reality even in countries with sufficient levels of aggregate energy use, because much of their energy—and their economic capacity—is diverted to production for consumption in wealthy countries, and is therefore unavailable to meet local human needs.

Effective climate action requires reducing the energy inequalities between the Global North and the Global South. The Paris Agreement calls for a just transition, to ensure that global emissions decline fast enough to keep global warming below 2.0 °C, and to pursue sustainable development and poverty reduction (United Nations, 2015). The agreement also enshrines the principle of common but differentiated responsibility, which acknowledges that wealthy countries have an obligation to decarbonise faster than other countries, given their disproportionate contributions to historical emissions. The Intergovernmental Panel on Climate Change (IPCC) recognises that the transition requires restricting the growth of global energy consumption and acknowledges that current patterns of consumption among the global rich are unsustainable (Intergovernmental Panel on Climate Change, 2015).

However, existing climate mitigation scenarios—which are assessed by the IPCC and form the basis for authoritative IPCC reports—fall foul of these principles. Instead of including scenarios which explore a fair and just transition, they reproduce colonial inequalities well into the future.

4.2 Research approach and methods

We analysed regional per-capita energy use in the 172 mitigation scenarios represented in the Integrated Assessment Modelling Consortium scenario explorer database that have a regional energy breakdown and that are consistent with the Paris Agreement targets of staying under 1·5 °C or 2·0 °C (i.e., RCP1.9 and RCP2.6 scenarios) (Huppmann et al., 2019). We found that these scenarios maintain substantial energy disparities between the Global North and the Global South for the rest of the 21st century (Figure 4.1a). Energy and population data in the integrated assessment models (IAMs) are reported at the level of regional and geopolitical country groups. In this chapter, the Global North refers to the IAM categories of OECD90+EU and REF, which encompass Europe, the USA, Canada, Australia, New Zealand, Japan, Turkey, and the former Soviet Union. The Global South refers to the rest of Asia, Africa, and Latin America.

4.3 Results

In the analysed scenarios, African and Middle Eastern countries tend to be limited to their existing rates of energy use for most of the century—i.e., less than 30 gigajoules per capita per year (Figure 4.1b). It is worth noting that these aggregate regional figures are skewed upward by the Persian Gulf nations—energy use for sub-Saharan Africa must therefore remain constrained to much less than 30 gigajoules in these scenarios. By contrast, the OECD countries and the rest of Europe are, on average, allocated energy well in excess of 100 gigajoules per capita per year for the rest of the century. Even in 2100, the allocation to OECD countries and the rest of Europe is 2.3 times more than the average energy consumed in the Global South (119 GJ per capita vs 52 GJ per capita). Latin America and Asia have rising energy use in these scenarios, but even by the end of the century their allocation amounts to barely half of what countries in the Global North consume.

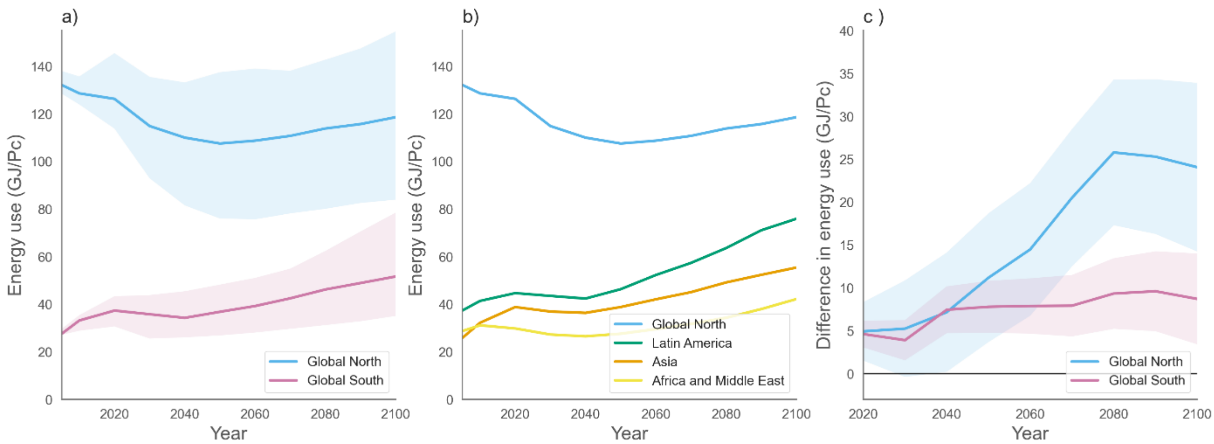

Figure 4.1: Unequal access to energy between the Global North and the Global South in climate mitigation scenarios. Panel a shows the 10–90% percentile range of per-capita energy use in the Global North and the Global South, corresponding to the 172 analysed scenarios that are compatible with keeping global warming below 1.5 °C or 2.0 °C. **Panel b** compares the median pathways of per-capita energy use in the Global North with energy use in the three regions of the Global South. (C) shows the difference in per-capita energy use for the Global North and the Global South, between scenarios that assume large-scale use of negative emissions (exceeding 700 GtCO2 in the period from 2020 to 2100) and scenarios that assume moderate or small-scale deployment of negative emissions (less than 400 GtCO2). **Panel c** shows how energy consumption in each of the two respective regions benefits from an increasing global deployment of negative emissions. In **panels a and c**, the range of scenario projections is illustrated with median values (solid line) and 90% confidence intervals of the analysed scenarios.

In addition to these average figures, we also assessed the scenario ranges. We found that although some scenarios are less unequal than others, none represent true convergence pathways. Only 11 of the 172 scenarios analysed have the Global North–Global South energy gap declining to less than 30 gigajoules per capita per year by the end of the century. Even these more equitable outliers still have substantial inequalities, with the Global North enjoying 40% more energy use than the Global South. Existing climate mitigation scenarios therefore tend to maintain the status quo, whereby wealthy countries continue to use disproportionately high amounts of energy, and energy consumption for much of the Global South is restrained in the decades to come.

To reconcile the high energy use in wealthy countries with the Paris Agreement targets, most of the mitigation scenarios rely on large-scale use of negative emissions technologies, especially bioenergy with carbon capture and storage (BECCS). These scenarios suggest that the Global North can continue to use high rates of energy, and emit additional carbon, so long as emissions can be pulled back out of the atmosphere in the future. But BECCS has been criticised by scientists as a risky and dangerous strategy. Scaling bioenergy monoculture would require large amounts of land—up to three times the size of India—with devastating effects on biodiversity, forests, water tables, and food systems (Creutzig et al., 2021). Furthermore, if carbon capture technology fails to work at scale, we will be locked into a high temperature trajectory from which it would be impossible to escape (Van Vuuren et al., 2017).

This reliance on negative emissions technologies is risky, but it is also unjust. We analysed the scenarios that assume large-scale deployment of negative emissions (more than 700 $GtCO_2$ from 2020 to 2100) and compared these with scenarios with lower reliance on negative emissions (less than 400 $GtCO_2$). We found that most of the additional energy that can be consumed in high-negative emissions scenarios is not allocated to the Global South, but rather to the Global North, thus maintaining or further widening global energy inequalities (Figure 4.1c). Moreover, these scenarios typically assume that the bulk of negative emissions will be realised by the biomass-rich countries of the Global South, with their cropland and natural ecosystems diverted to energy crop plantations (Popp et al., 2014; Roe et al., 2019). In other words, the scenarios appropriate land in the Global South to support, and further boost, the energy privilege of the Global North.

4.4 Discussion

The scenarios reviewed here are neither morally acceptable nor politically tenable. Why should countries in the Global South accept such an inequitable future? Why should these countries accept heightened risk of climate catastrophe—which already disproportionately harms them—so that wealthy countries can maintain an economic model based on overproduction and accumulation? Why should the Global South hand over their cropland and ecosystems to support excess in the Global North?

Climate mitigation scenarios are intended to represent a range of possible futures, to explore trade-offs, and to facilitate public debate about how best to approach the transition. This range is supposed to include undesirable or unjust futures, as well as better, alternative futures that show how the world could be arranged differently. The problem is that the existing range overwhelmingly represents futures of substantial Global North–Global South inequality, and does not explore futures of convergence and equity. A truly just transition is not represented—in marked contrast to the principles inscribed in the Paris Agreement and the Sustainable Development Goals—even though such a transition would make climate mitigation easier (and more politically acceptable to governments in the Global South), and would arguably improve the lives of most of the world's population.

What would such a transition look like? To decarbonise fast enough to keep global warming under 1.5°C (without gambling on negative emissions), wealthy countries must scale down excess production and consumption to enable a faster transition to low-carbon energy. Low-income countries should be granted access to the finance and technology necessary to deploy modern renewable energy systems sufficient to provide decent living for all, and they should have the freedom to organise energy use and economic capacity around meeting national needs (Hickel et al., 2021a). Global energy use should converge at a level that is sufficient for human wellbeing and compatible with keeping global warming to no more than 1.5°C, without gambling on dangerous technologies (Keyßer and Lenzen, 2021; Kuhnhenn et al., 2020). The planet is finite and it should be shared fairly. To stop climate breakdown and achieve human development for all, scenarios—and strategies—for radical convergence are needed.

4.5 Acknowledgments

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4.6 Contributors

JH: conceptualization, methodology, data analysis, writing-original draft, writing-review/editing. AS: data collection, methodology, data analysis, writing-review/editing, figures.

Chapter 5
Towards post-growth scenarios for climate mitigation[5]

Abstract

Existing climate mitigation scenarios assume future rates of economic growth that are significantly higher than what has been experienced in the recent past. In this article we explore how assuming lower rates of growth, in line with the hypothesis of secular stagnation, changes the range of mitigation possibilities. We compare scenarios with moderate and strong policy ambition under both high-growth and low-growth assumptions. The results show that low growth makes it easier to reduce emissions consistent with 1.5–2°C, reducing the need to rely on assumptions about unrealistically rapid buildout of low-carbon energy infrastructure and unprecedented rates of energy–GDP decoupling, which characterise existing scenarios. However, lower growth raises concerns about equity between and within countries, social stability, and ability to finance the low-carbon energy transition. With this in mind, we distinguish between inequitable low-growth scenarios and equitable 'post-growth' scenarios, identifying policies that could be used to achieve the latter.

[5] This chapter presents work that is currently under review: Slameršak, A., Kallis, G., O'Neill, D.W, & Hickel, J. Towards post-growth scenarios for climate mitigation. (2022). *Manuscript under review.*

5.1 Introduction

Measures to contain the coronavirus pandemic have caused the largest reduction in global carbon emissions since the Second World War ("Unexpected times," 2020), with emissions dropping by 6% in 2020 alone (Friedlingstein et al., 2020; IEA, 2021b). And yet the impact of this event on the global temperature trajectory will be very small unless a similar rate of decrease is sustained year after year for the next decade (Le Quéré et al., 2020). This challenge is heightened by the fact that recovery efforts are focused in large part on increasing the rate of economic growth.

Growth tends to increase energy use relative to what it otherwise might be, which in turn makes decarbonization more difficult to achieve. This problem is evident in existing climate mitigation scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) (Burgess et al., 2020). Existing scenarios tend to assume all countries pursue high growth, regardless of how wealthy they already are. To reconcile this assumption with the Paris Agreement targets, existing scenarios rely on an unprecedented decoupling of energy use from economic output (Brockway et al., 2021), alongside unproven negative emission technologies (Anderson, 2015; Larkin et al., 2018).

It is worth noting, however, that existing mitigation scenarios tend to over-project economic growth compared to recent trends, ignoring studies that suggest high-income economies may have entered into a prolonged period of secular stagnation (Gordon, 2017; Jackson, 2019). The possibility of secular stagnation is an important consideration, as lower growth rates may change the mitigation possibility space (Keyßer and Lenzen, 2021). Indeed, secular stagnation may already have kept emissions lower than they would otherwise have been. For example, Burgess et al. 2020 show that CO_2 emissions would probably exceed the upper range of the IPCC's projections if it were not for the low growth rates between 2005 and 2018 (Burgess et al., 2020). Likewise, a recent study found that the 11% decline in US emissions between 2007 and 2013 was 'largely a result of economic recession with changes in energy mix (substitution of natural gas for coal) playing a comparatively minor role (Feng et al., 2015).

In light of this work, there is an urgent need to consider climate mitigation scenarios that do not rely on high economic growth as the default assumption. The case for 'post-growth' scenarios has already been articulated in the literature (Hickel et al., 2021a; Keyßer and Lenzen, 2021), but such scenarios are not yet represented in existing climate mitigation scenarios, such as the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017; Rogelj et al., 2018), which have been used as the main point of reference in the IPCC scenario literature (IPCC, 2018c; Stocker et al., 2013).

The first question motivating this article is then: does slower growth make a difference to climate mitigation pathways, and if so, how important is this difference? We find that low growth does make a difference, but this finding raises additional questions. Low-growth scenarios without any other policy interventions tend to be characterised by rising inequality, both within and between countries (Milanovic, 2017; Piketty, 2014; Roser, 2021b), which may make it difficult to mobilise the investments needed for climate action (Chomsky and Pollin, 2020). We therefore seek to distinguish between low-growth scenarios and 'post-growth' scenarios, with the latter characterised by interventions intended to improve mitigation capacity, equity, and social outcomes (Jackson, 2009; Victor, 2008). Post-growth scenarios can build on recent empirical studies suggesting that high-income nations may not need more economic growth in order to achieve or maintain high levels of human well-being (Hickel, 2020; O'Neill et al., 2018). Regardless of where one stands on the debate over the desirability of a post-growth future, it is clearly important to explore the conditions under which low-growth economies can be stable and equitable (Burgess et al., 2021).

To assess the difference that lower growth might make when it comes to climate mitigation, we explore five scenarios that differ in terms of their assumptions regarding four factors that drive carbon emissions: population, per-capita GDP, the energy intensity of the economy, and the carbon intensity of energy. Unlike existing scenarios from the IPCC literature, which typically derive energy and emissions pathways by cost-optimising the deployment of energy efficient and low-carbon technologies, the mitigation pathways in our scenarios are derived in relation to existing plans of climate action. Our intention is not to develop state-of-the-art scenarios. Instead, we use a simple modelling analysis to illustrate the importance of considering slower growth trajectories. With this, we hope to start — and inform — a debate on the topic, hopefully leading to the development of more advanced post-growth scenarios.

Our first scenario assumes the continuation and realization of existing climate and energy policies pledged under the Nationally Determined Contributions (NDCs). We call this the 'High-Growth and Current Climate Ambition' scenario. Our second scenario assumes that the whole world adopts ambitious mitigation policies similar to those pledged by the European Union's (EU's) Green Deal program, in which government stimulus packages are invested in clean energy and efficient energy use. We call this the 'High-Growth and High Climate Ambition' scenario. A third scenario represents a more moderate progression of climate action compared to the High-Growth and High Climate Ambition scenario and is called the 'High-Growth and Moderate Climate Ambition' scenario. All these scenarios, in line with existing climate scenarios that are predicated on high growth rates into the future, assume a V-shaped high-growth recovery after the pandemic. For comparison, we present two low-growth scenarios, in which economic growth continues in line with the recent trend from 2007 to 2021. The low-growth scenarios are differentiated by the level of mitigation ambition: the 'Low-Growth and High Climate Ambition' scenario combines low growth with ambitious mitigation as in the High-Growth and High Climate Ambition scenario, while the 'Low-Growth and Moderate Climate Ambition' follows the mitigation assumptions of the High-Growth and Moderate Climate Ambition scenario. It should be emphasised that all of the scenarios, including the High-Growth and Current Climate Ambition scenario, assume mitigation rates that are historically unprecedented, so that all of our scenarios represent pathways of extraordinary ambition. In our analysis we focus on the 2021–2030 period, which is the last decade when decisive climate action can still prevent the overshooting of the Paris Agreement goals (IPCC, 2018c). To construct our scenarios we rely on informed choices for growth, energy use, and decarbonization based on policy reports and pledges as well as historical trends.

Our analysis reveals that the only scenario to achieve decarbonisation fast enough to prevent temperatures exceeding 1.5 °C is the one that combines ambitious climate mitigation with low growth. Scenarios of high growth are likely to overshoot this target even if the most ambitious current mitigation plans are implemented globally.

In the following sections, we first analyse how accurate the existing scenarios have been in their projections of emissions drivers by comparing the historical data with the past projections from thirty-three of the SSP scenarios (Gambhir et al., 2017; Grubler et al., 2018; Rogelj et al., 2018) that are consistent with the goal of stabilising global warming below 1.5–2°C, and that have been broadly used in the IPCC literature. This exercise reveals the challenges underlying a low-carbon transition with high economic growth. We then present our five illustrative scenarios and explore the possibility space of energy and emissions pathways under different trajectories of economic growth and climate action, over the next decade. Next, we discuss possible trade-offs between low growth and ambitious climate mitigation, and the equity challenges of low growth, distinguishing between an unplanned and inequitable 'low-growth' and a managed and equitable 'post-growth'. We conclude by discussing how our analysis might inform the development of a new set of equitable post-growth mitigation scenarios.

5.2 Challenges underlying a high-growth low-carbon transition

Over the past few years, an increasing number of scholars have raised doubts about the feasibility of some of the key assumptions that underpin existing climate mitigation scenarios. Here we review these concerns, focusing on four key issues.

5.2.1 GDP growth: the unquestioned norm

Existing IPCC scenarios of ambitious mitigation have over-projected annual per-capita GDP growth since 2010 (Figure 5.1a), with a projected GDP growth rate of 3.1–3.2%, exceeding the actual average growth rate from 2010 to 2020 by two percentage points. If we distinguish between high-income countries (OECD countries in 1990 and EU member states and candidates today) and middle-income plus low-income countries, thereafter 'lower-income countries', we find that the IPCC scenarios have over-projected rates of economic growth by 1.3 percentage points for high-income countries, and 2.1 percentage points for the lower-income countries (Figures 5.1b and 5.1c).

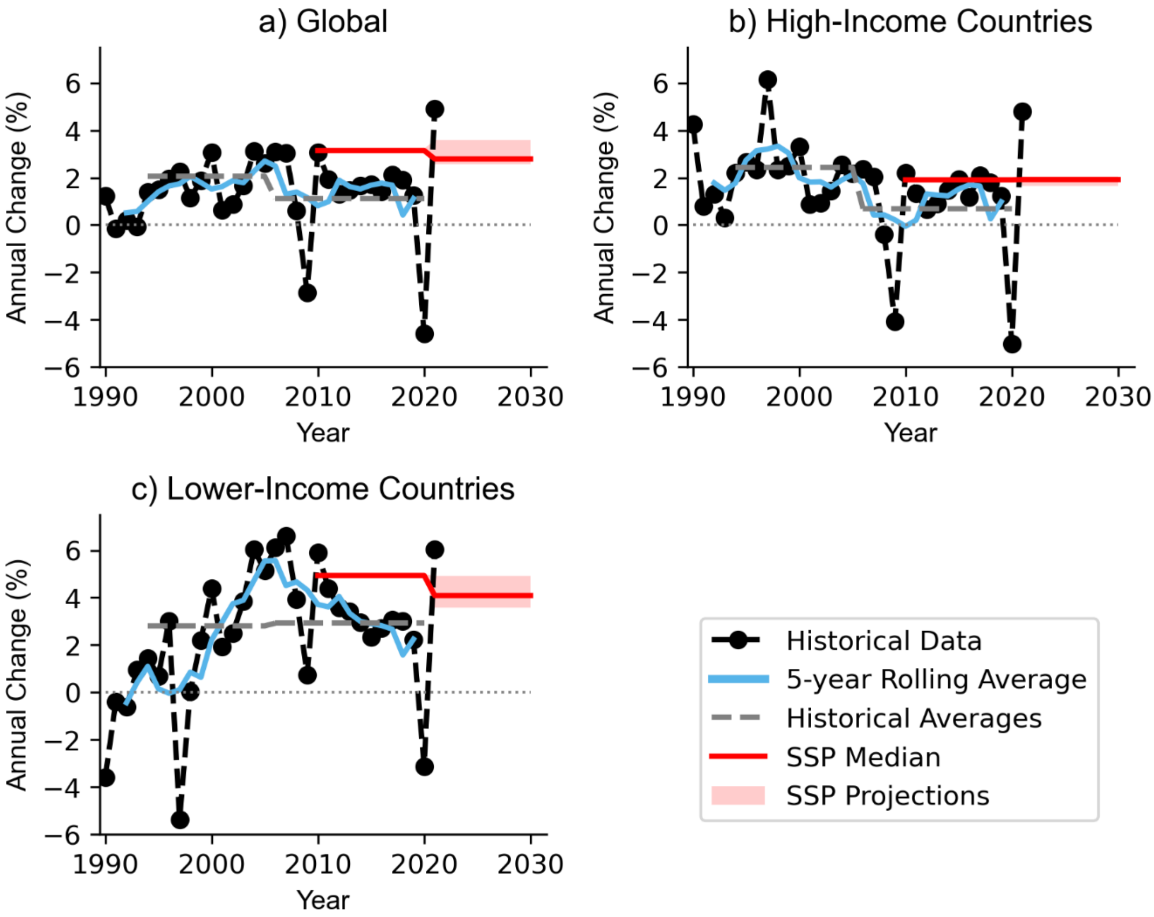


Figure 5.1: Historical trends and IPCC projections of per-capita GDP. This figure shows the historical timeline of per-capita GDP. The black line shows the annual values, whereas the blue line shows the 5-year rolling average of historical values. The grey dashed line shows the average rate of change for the period from 1994 to 2006 and from 2007 to 2021 The data was partitioned with regards to the financial crisis of 2007–2008, which represents a clear break in the trend of the global economic growth. The green envelopes show the interquartile range of the projections from the thirty-three IPCC scenarios, and the green line depicts the average rate of change in these scenarios.

In addition to over-projecting economic growth, none of the existing scenarios of ambitious mitigation compatible with 1.5 or 2 degrees of warming consider the possibility of lower GDP growth in the near future (Kuhnhenn, 2018; O'Neill et al., 2020). The global annual per-capita GDP growth rate for the thirty-three scenarios considered in our analysis is in the range of 2.6–3.6% per year (2020 to 2030), with five of these scenarios assuming growth rates that exceed 4.0%. As Figure 5.1a shows, these growth rates are unprecedented: in the decades since 1990, the period 2004–2007 was the only period when global per-capita GDP growth exceeded 2.0% per year for more than three consecutive years. In contrast to the high growth projections in existing scenarios, if we were to extrapolate the growth rates from the 2007–2021 period (as we do in our own scenarios), an average growth rate of 1.2% per year could be assumed for the period 2021–2030. This rate corresponds to an average growth rate of 0.7% per year in high-income countries and 2.6% in the lower-income countries.

The gap between the projections and data can only partly be explained by the economic downturn during the first phase of the Covid-19 pandemic, which could not have been anticipated by the pre-pandemic scenarios. However, the gap already existed before the recession and was due to overestimating growth rates for the recovery period after the crisis of 2007–2008 (Burgess et al., 2020). The period of low growth since 2008 may be an anomaly after which the global economy will eventually return to high growth, as the International Monetary Fund (IMF) suggests (IMF, 2021a). However, two recent studies claim that the uncertainty of long-term per-capita GDP projections is substantially larger than in the forecasts of the IMF and World Bank, upon which the economic growth projections in the SSPs are based (Christensen et al., 2018; Startz, 2020). These studies project that long-term global per-capita GDP growth could be as low as 1% per year. Moreover, the global supply-chain crisis and the war in Ukraine are likely to drive down the global economic growth in 2022 and the years to come. Indeed, some authors argue that high-income countries have entered a period of secular stagnation, whereby low growth is not confined to a temporary crisis but is likely to persist over the long term, given a slowdown in innovation and productivity (Gordon, 2012), a shift to services (Vollrath, 2020), changes in preferences (Vollrath, 2020), an ageing population (Piketty, 2014), high levels of debt (Reinhart et al., 2012), damages from climate change (Burke et al., 2015), and losses from stranded fossil capital (Semieniuk et al., 2021a). Recent research points to long-term low growth in the high-income economies of North America and Europe (Dorling and McClure, 2020; Gordon, 2017; Vollrath, 2020). Vollrath for example predicts a long-term per capita growth rate for the US economy of no more than 1% (Vollrath, 2020).

This shift may also be due to changes in global political economy. After the period of stagflation in the 1970s, growth rates in high-income economies were boosted by neoliberal globalization (Harvey, 2005). Structural adjustment programs imposed across much of the global South during the 1980s depressed the prices of labour and resources, removed capital controls, cut trade tariffs, and privatised public assets. The structural adjustment thereby opened new frontiers for foreign investment, and multinational firms shifted production to poorer countries to take advantage of cheaper inputs (Hickel et al., 2021b). But this process has now largely run its course. The prices of Southern labour and resources are increasing, the margins to further decrease tariffs and capital controls are small, and there are few territories remaining that have not been integrated into the international capitalist system. Several theorists argue that capitalism now faces the prospect of prolonged stagnation (Patnaik and Patnaik, 2021; J. Smith, 2016).

As for lower-income countries, structural adjustment has had several long-term negative effects. For one, these economies were largely reorganised around exports to high-income countries, which means that declining growth rates in the latter have led to slowdowns in the former. In addition, they have generally been prevented from using protective tariffs and subsidies to build up domestic industrial capacity, and have been prevented from using fiscal expansion to stimulate domestic demand (Hickel, 2018). A combination of economic reliance on high-income countries and the lack of sovereign industries may help explain the declining growth that the lower-income countries have experienced over the past decade (Figure 5.1c).

5.2.2 Population growth in existing scenarios

While mitigation scenarios tend to over-project economic growth, they underestimate global population growth rates (Figure 5.2). During the period 2010–2020, real population growth rates were higher than assumed in the IPCC mitigation scenarios. For the period 2020–2030, the mitigation scenarios assume that lower-income countries have lower population growth rates than UN projections suggest. However, the difference is only 0.2 percentage points globally (0.3 in lower-income countries and 0.1 in high-income countries), which is an order of magnitude less than the 2 percentage point difference in global GDP per-capita projections. Therefore, the inconsistency in population growth projections has much lower impact on emissions projections.

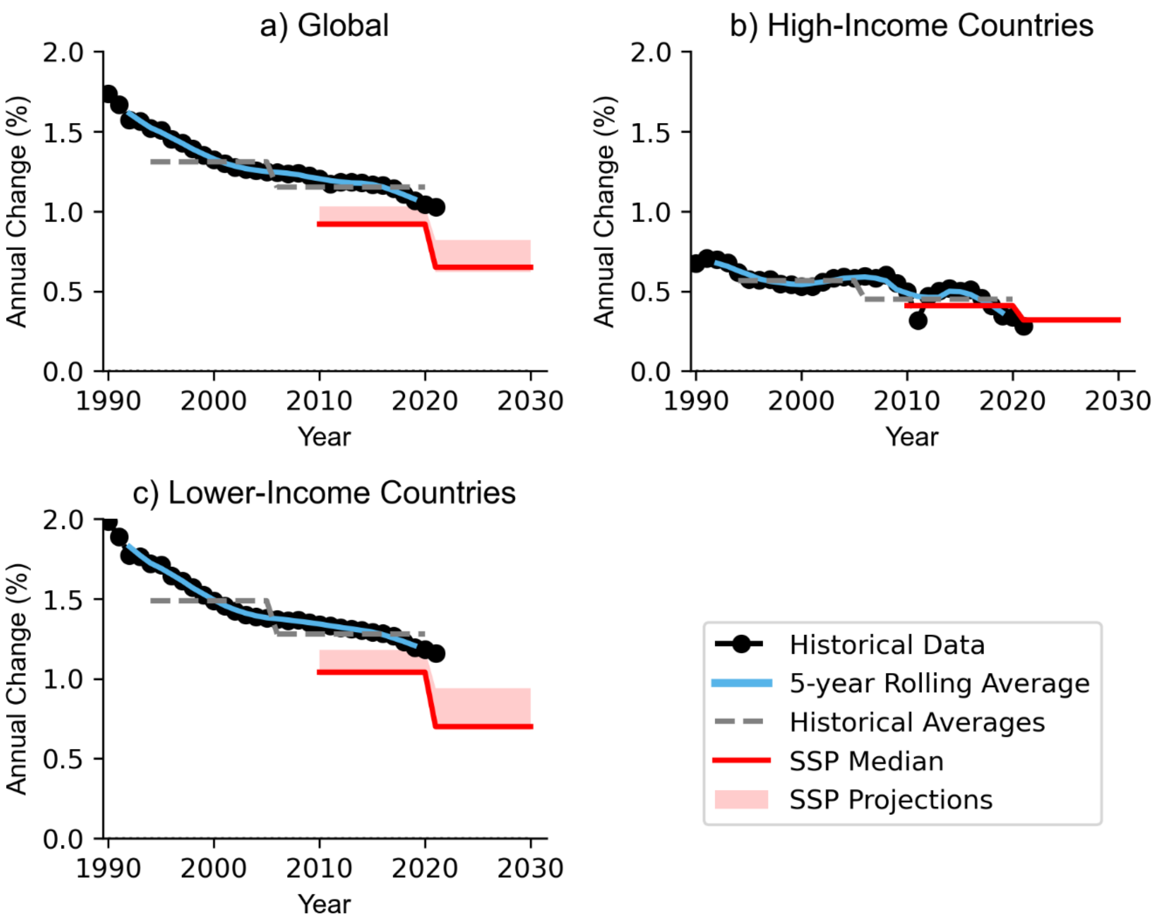


Figure 5.2: Historical trends and IPCC projections of population. The black line shows the 5-year moving average of historical values. The grey dashed line shows the average rate of change for the periods from 1994 to 2006 and from 2007 to 2021. The green envelopes show the interquartile range of the projections from the thirty-three IPCC scenarios, and the green line depicts the average rate of change in these scenarios.

5.2.3 Betting on energy efficiency

Existing scenarios of ambitious mitigation have also over-projected energy efficiency improvements for the period from 2010 to 2020 (Figure 5.3a). The average energy intensity improvement across the thirty-three SSPs is 2.5% per year, which substantially exceeds actual improvements (1.0% per year). In fact, long-term average energy intensity improvements have been stuck at approximately 1% since the 1990s.

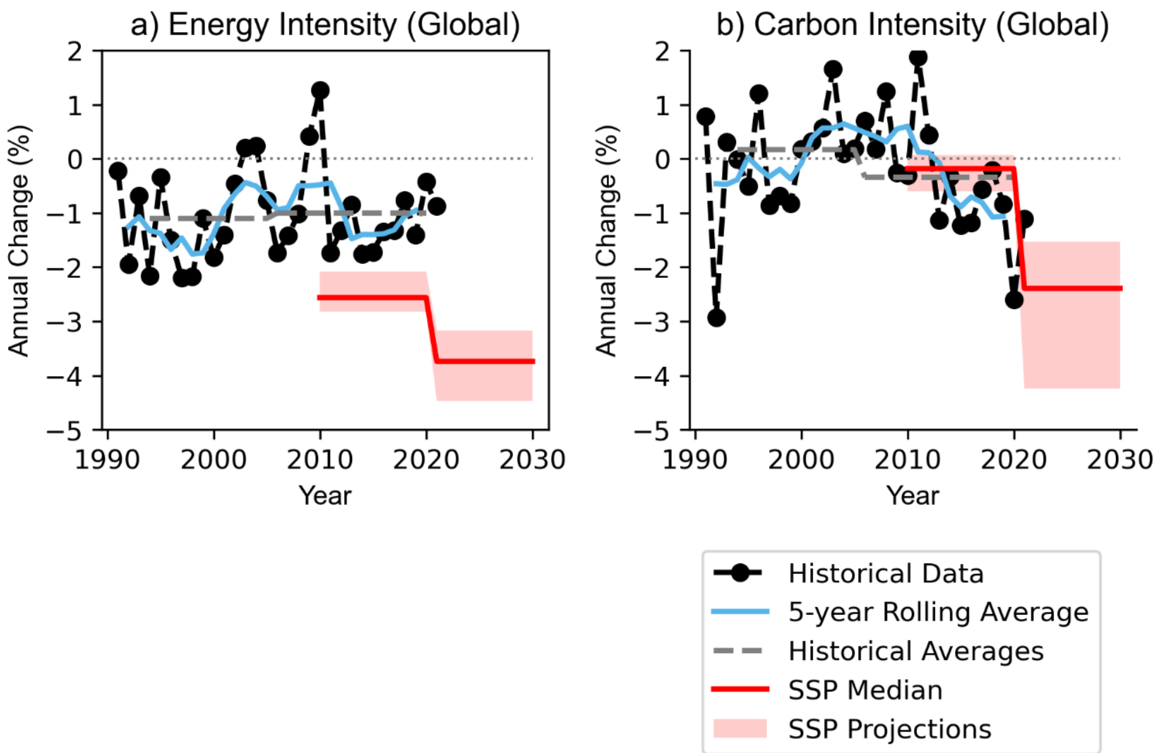


Figure 5.3: Historical trends and IPCC projections of energy and carbon intensity. The black line shows the annual values, whereas the blue line shows the 5-year rolling average of historical values. The grey dashed line shows the average rate of change for the period from 1994 to 2006 and from 2007 to 2021. The green envelopes show the interquartile range of the projections from the thirty-three IPCC scenarios, and the green line depicts the average rate of change in these scenarios.

For the 2020–2030 period, the scenarios assume even more dramatic energy intensity improvements. Over this period, average energy intensity improvements across the thirty-three scenarios are assumed to be 4.0% per year. At the upper-range of scenario assumptions, the Low Energy Demand scenario by (Grubler et al., 2018) assumes improvements of 6.7% per year. Modellers are assuming an absolute decoupling of GDP from energy, such that energy use declines as GDP grows. Assumptions about rapid efficiency improvements are defended on the grounds that existing conversions of primary to final energy are highly inefficient and can be feasibly improved. Indeed, bottom-up studies show that existing conversions are much less efficient than what can theoretically be achieved with existing best-available technology (Cullen et al., 2011; Gambhir et al., 2017; Guo et al., 2018).

However, a number of studies have questioned whether such ambitious efficiency improvements are feasible in practice, particularly at the global scale (Heun and Brockway, 2019; Stern, 2017). A recent systematic review of the evidence on decoupling shows no absolute decoupling of GDP from energy at the global level (Haberl et al., 2020), while a model-based analysis suggests that absolute decoupling is unlikely to be achieved globally in the future (Ward et al., 2016). Whereas several studies find evidence of decoupling as a result of growing energy efficiency in high-income countries (Csereklyei et al., 2016; Jakob et al., 2012), these have been linked to the offshoring of energy-intensive activities (Akizu-Gardoki et al., 2021; Moreau et al., 2019). Moreover, existing scenarios do not account for macro-economic rebound effects, whereby savings from efficiency improvements induce additional consumption, thus driving up total energy demand, or at least eroding a significant proportion of the gains (Exadaktylos and Van Den Bergh, 2021; Stern, 2020).

Achieving global energy efficiency improvements may be further complicated by the socio-economic context of low-income countries. To resolve the trade-off between economic growth and emissions from increased energy use, existing scenarios assume industrialisation in low-income countries, but without growth in energy use (Steckel et al., 2013). This is a strong assumption, considering that low-income economies mainly depend on agriculture, which tends to be less energy intensive compared to industrial production (Smil, 2017). To accomplish industrial development without energy growth, low-income countries would have to achieve equal or even faster energy efficiency improvements than high-income countries (Semieniuk et al., 2021b). Such dramatic improvements would require low-income countries to industrialise by importing the most efficient and costly ‘frontier technologies’. Unless high-income countries initiate extensive programmes of technology transfer and financial assistance for industrial development, the envisaged energy efficiency improvements seem implausible.

The difficulty of achieving the energy efficiency projections of the ambitious mitigation scenarios is reflected by the modest global energy intensity improvements estimated from existing national energy plans (Figure 5.3a). Even the most ambitious target to improve energy intensity, the EU’s target of 3.0% per year, falls short of the average efficiency improvements of 4.0% assumed in mitigation scenarios.

5.2.4 Betting on low-carbon energy

Existing scenarios of ambitious mitigation have accurately projected a small decline in the carbon intensity of energy, averaging 0.3% per year from 2007 to 2021 (Figure 5.3b). The scenarios assume that the decarbonisation rate of the energy system will dramatically accelerate to 1.5–4.2% per year (median 2.4%), from 2020 to 2030. To hit this target, an immediate global implementation of policies driving rapid decarbonisation is needed.

Historical growth rates of renewables — solar energy in particular — indicate that it is possible to achieve a rapid build-up of renewable energy capacity, as the figures exceed even the most ambitious projections documented in past IPCC reports (Creutzig et al., 2017). However, gains in renewable capacity in the period from 2010 to 2020 have been outstripped by increased fossil fuel use by a factor of three (IEA, 2021c). In other words, renewable energy is being added on top of fossil fuel energy, rather than replacing it. What is more, projections based on extrapolated historical trends may overestimate the possible build-up of low-carbon infrastructure, as the supply of material resources required and the production of necessary components may not match the speed at which low-carbon energy needs to replace fossil fuels in existing scenarios (Capellán-Pérez et al., 2019; Sprecher and Kleijn, 2021; Valero et al., 2018). Furthermore, studies warn that a fast low-carbon transition may lead to major disruptions to the economy, as construction of low-carbon infrastructure will direct investments away from more productive sectors of the economy (Sers and Victor, 2018), and reduce the resources available for other economic activities (King and Van Den Bergh, 2018; Pauliuk et al., 2017) due to the significant demand of materials and energy required to scale up a low-carbon energy system. Supply-side constraints may be aggravated by public opposition to big energy projects, triggered by the adverse social and environmental impacts of mineral extraction and land-grabbing (Avila, 2018; Lèbre et al., 2020).

Here, the problem is not only the faster decarbonisation rate expected from 2020 to 2030 compared to pre-pandemic times, but also the difficulty of catching up if projected decarbonisation rates do not come to pass. Missing decarbonisation targets in one year means that the targets must be set even higher in subsequent years. Each additional year of missed targets makes the task more difficult.

An additional obstacle to fast decarbonisation is carbon lock-in in response to the Covid-19 pandemic. Implemented recovery packages have invested heavily in carbon-intensive sectors of the economy, which will not only lead to short-term increases in emissions, but continue ties to a fossil-fuel-based economy (Tong et al., 2019). Fiscal stimuli to carbon-intensive sectors of the economy run contrary to necessary divestments from the fossil fuel economy, which are estimated at $280 billion each year (Andrijevic et al., 2020). According to the Energy Policy Tracker, 41% of current recovery packages across the twenty major global economies are being invested in carbon-intensive sectors, which may result in even faster growth in emissions than in the years preceding the crisis (Shan et al., 2020).

5.2.5 Towards alternative mitigation scenarios

Our analysis suggests that existing mitigation scenarios tend to over-project economic growth and energy efficiency improvements. And while decarbonisation rates in these scenarios are consistent with historical trends, rapid decarbonisation also depends on policies to actively phase-out fossil fuels. Large uncertainties regarding the drivers of mitigation lead us to the conclusion that existing scenarios over-represent optimistic mitigation outcomes but do not adequately consider the possibility that one or more of the mitigation levers may fail to perform (Hickel et al., 2021a).

We illustrate this gap by examining a series of mitigation pathways that represent still ambitious, but somewhat more realistic (in the sense that nations are pledging to meet them) mitigation outcomes over the 2021–2030 period. We estimate carbon emissions using projections of final energy intensity, per-capita GDP, population, the share of low-carbon energy in final energy consumption, and the use of different fossil fuels (see Experimental Procedures). We compare emissions in each of our five scenarios with the thirty-three IPCC scenarios. These include a range of fourteen Shared Socioeconomic Pathways (SSPs) compatible with 1.5 °C (SSP-1.9) and nineteen SSPs compatible with 2 °C of warming (SSP-2.6). The SSPs are obtained from the *IAMC 1.5 °C Scenario Explorer* (Huppmann et al., 2019).

5.3 Five futures after the pandemic

In our 'High-Growth and Current Climate Ambition' scenario (HG-Current), policies to support fossil fuel technologies and infrastructure lead to a rebound in energy use and emissions similar to those that followed the 2008–2009 recession (Peters et al., 2012; UNEP, 2021). Large government stimulus packages aid a quick economic recovery and increase the rate of per-capita GDP growth. Energy intensity and carbon intensity improvements in this scenario are broadly compatible with existing climate and energy plans from Nationally Determined Contributions (NDCs), as estimated by the International Renewable Energy Agency (IRENA, 2020). Even though HG-Current is the least ambitious of our five scenarios, the assumed improvements in energy efficiency and carbon intensity are much more ambitious than what has been achieved historically.

In our 'High-Growth and High Climate Ambition' scenario (HG-High), we assume that the whole world rolls out ambitious decarbonisation and energy efficiency improvements similar to those pledged by the European Green Deal (European Commission, 2020). We assume a boosting of investment in clean energies, which shows up in our calculations as an increased share of low-carbon energy in final energy consumption, and faster improvements in energy intensity achieved by a gradual shift to less-energy-intensive lifestyles and investments in energy efficiency. We also model a 'High-Growth and Moderate Climate Ambition' scenario (HG-Moderate), representing a middle-of-the-road trajectory between current policy commitments and the HG-High scenario. In terms of per-capita GDP, the assumptions in these scenarios remain the same as in the HG-Current scenario: a V-shaped recovery in line with the IMF's predictions (IMF, 2021b).

For comparison, we present two low-growth scenarios: 'Low-Growth and High Climate Ambition' (LG-High) and 'Low-Growth and Moderate Climate Ambition' (LG-Moderate), which incorporate the decarbonisation and energy efficiency improvement aspects of the European Green Deal, but also assume economic growth to be lower (in line with what it has been from 2007 to 2021). In the LG-Moderate scenario we explore whether a lower rate of economic growth can make up for the less ambitious middle-of-the-road efficiency and decarbonisation improvements. The LG-High scenario reflects what can be achieved if ambitious mitigation policies take place in the context of lower economic growth (Mastini et al., 2021). We assume the same trajectories of population growth across all five scenarios, given the small differences in population projections across the scenarios from 2020 to 2030. We take our projections of population growth from the medium fertility scenario of the United Nations World Population Prospects from 2019. For a detailed description of scenario assumptions see Table 5.1, Figure 5.4, and Scenario Assumptions in Experimental Procedures.

Table 5.1: Five post-recovery scenarios.

<table>
<tr><th>Historical data and scenarios</th><th>Annual global per-capita GDP growth</th><th>Annual population growth</th><th>Annual change in final energy intensity</th><th>Annual change in carbon intensity</th><th>Annual change in carbon intensity due to fuel-switching between fossil fuels</th></tr>
<tr><td>Historical trends</td><td>• 2007–2021: +1.1%</td><td>• 2007–2021: 1.2%</td><td>• 2007–2021: -1.0%</td><td>• 2007–2021: -0.3%</td><td>• 2007–2021: -0.2%</td></tr>
<tr><td>HG-Current</td><td rowspan="3">• 2022: +3.4%
• 2023–2030: +2.4% (IMF baseline)</td><td rowspan="3">• 2022–2030: 0.9% (UN World Population Prospects)</td><td>• 2022: -1.3% (2009 crisis)
• From -1.9% in 2023 to -2.5% in 2030 (NDC estimate)</td><td>• From -0.4% in 2022 to -1.2% in 2030 (IRENA current strategies)</td><td>• 2022–2030: -0.2% (IRENA current strategies)</td></tr>
<tr><td>HG-Moderate</td><td>• 2022–2030: -2.5% (Middle-of-the-road)</td><td>• From -1.1% in 2022 to -2.1% in 2030 (Middle-of-the-road)</td><td rowspan="2">• 2022–2030: -0.3% (IRENA transformative energy scenario)</td></tr>
<tr><td>HG-High</td><td>• 2022–2030: -3.0% (EU Green Deal)</td><td>• From -1.8% in 2022 to -4.6% in 2030 (EU Green Deal)</td></tr>
<tr><td>LG-Moderate</td><td rowspan="2">• 2022–2030: +1.2% (Continuation of 2007-2021 trend)</td><td rowspan="2">• 2022–2030: 0.9% (UN World Population Prospects)</td><td>• 2022–2030: -2.5% (Middle-of-the-road)</td><td>From -1.1% in 2022 to -2.1% in 2030 (Middle-of-the-road)</td><td rowspan="2">• 2022–2030: -0.3% (IRENA transformative energy scenario)</td></tr>
<tr><td>LG-High</td><td>• 2022–2030: -3.0% (EU Green Deal)</td><td>• From -1.8% in 2022 to -4.6% in 2030 (EU Green Deal)</td></tr>
</table>

Note on acronym. IMF – International Monetary Fund, UN – United Nations, NDC - Nationally Determined Contributions, IRENA - International Renewable Energy Agency.

Note on the economic growth assumptions in low-growth scenarios. The annual global historical per-capita GDP growth from 2007 to 2021 of 1.1% per year can be broken down into an average growth rate in high-income countries of 0.7% per year, and an average growth rate in lower-income countries of 2.9% per year. For the period from 2022 to 2030, we extrapolate the recent trends in both regions which leads to a higher average global economic growth of 1.2%, due to an increasing share of global GDP that is produced in the lower-income countries.

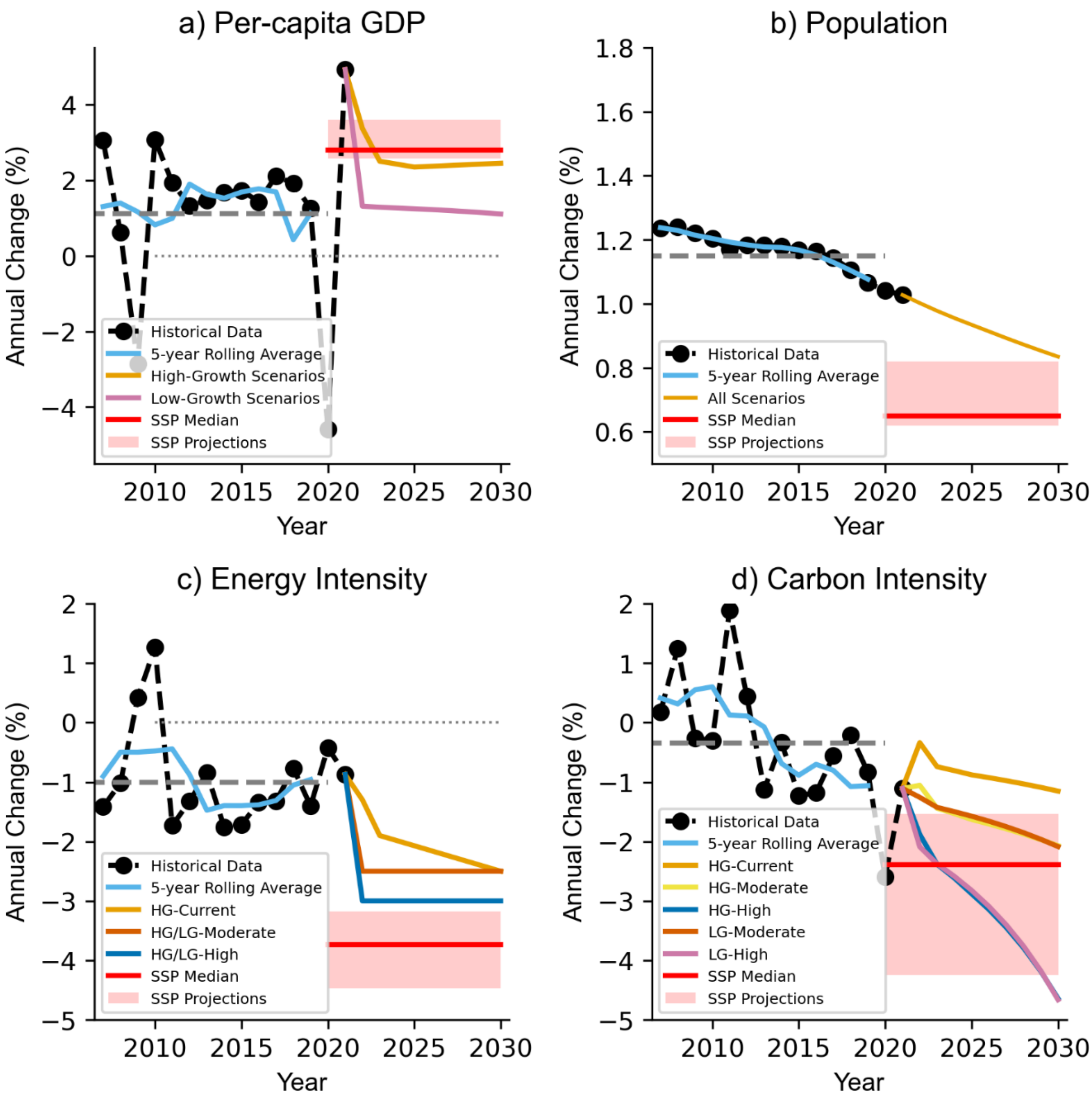
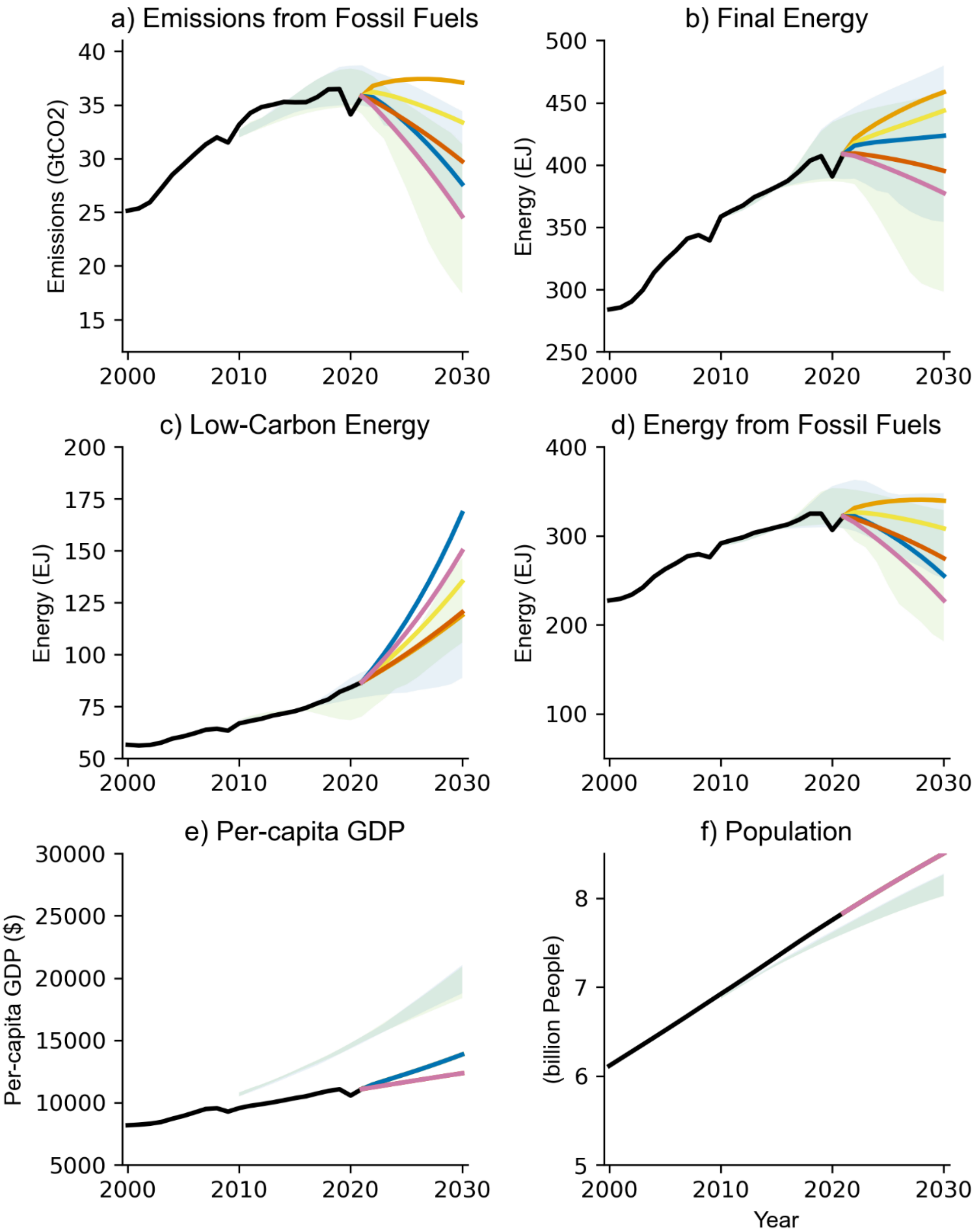


Figure 5.4: Recent historical trend and future projections underlying our five post-recovery scenarios and the IPCC scenarios. This figure corresponds to Table 5.1, showing the timeline of historical trends since 2007 and future trajectories for key parameters in our scenarios. The black line shows the 5-year rolling average of historical values. The grey dashed line shows the average rate of change for the period from 2007 to 2021. The green envelopes show the interquartile range of the projections from the thirty-three IPCC scenarios, and the green line depicts the average rate of change in these scenarios. The orange, red, yellow, dark blue, brown, and purple lines show the future projections for our five scenarios. Note that the brown line in panel a represents all of the scenarios that assume high growth, while the blue line in this panel represents both of the low-growth scenarios.

5.4 Results

The most ambitious low-growth scenario (LG-High) is the only one that is fully consistent with the emissions pathways that are necessary to limit global warming to 1.5 °C (Figure 5a). The LG-Moderate scenario and the HG-High scenario overlap with the upper range of the 1.5 °C pathways. The upper range encompasses pathways that substantially rely on negative emissions in the second half of the 21st century (see the illustrative pathways in the IPCC's *Special Report on Global Warming of 1.5 °C* (IPCC, 2018c)).

The HG-Moderate scenario falls short of the emissions reductions necessary to comply with the 1.5 °C goal, although it comes close to the upper range of the 2 °C emissions pathways. The HG-Current scenario, with total emissions of 405 $GtCO_2$ from 2020 to 2030, uses all of the remaining carbon budget for 1.5 °C within the decade (estimated at 320±250 $GtCO_2$ in 2018, (Rogelj et al., 2019)). In other words, current climate pledges, unprecedented as they are and with questions regarding the ability of nations to achieve them, are not sufficient if the rate of economic growth turns out to be high. Increasing emissions in this scenario also put it out of reach of the less ambitious 2 °C global warming pathway. (It is also worth noting that in the majority of the SSPs that we use as a reference in the envelopes, the projected emissions from 2020 to 2030 are higher than they otherwise would be because the scenarios assume significant amounts of carbon removal later in the century).



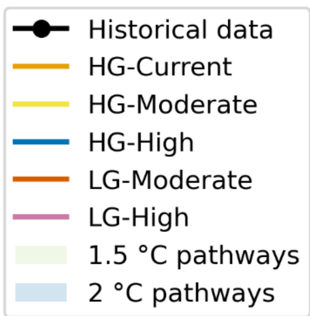


Figure 5.5: Five post-pandemic scenarios compared with a range of IPCC 1.5 °C and 2 °C pathways. The brown, yellow, blue, red, and purple lines show projections for our high-growth and low-growth scenarios. The envelopes show the interquartile range of the SSP scenarios that are consistent with 1.5 °C (light green) and 2 °C (light blue) of global warming by 2100. In panel e, the blue line shows the GDP trajectories for all of the high-growth scenarios, whereas the purple line shows GDP in both of the low-growth scenarios. Panel f shows the population trajectory based on the median scenario of the UN World Population Prospects that we use in all of our scenarios.

Both the HG-Current and the HG-Moderate scenario use an increasing amount of energy, thus overlapping with the upper ranges of the 1.5 °C and 2 °C pathway envelopes (Figure 5.5b). Scenarios with higher energy efficiency improvements and/or lower GDP growth (HG-High and both low-growth scenarios) succeed in stabilising or decreasing energy use after the pandemic, and thus conform to the envelope of 1.5 °C energy pathways.

The HG-High scenario and the LG-High scenario roll out low-carbon energy much faster than the most ambitious emissions pathways in the 1.5 °C range (Figure 5.5c). The growth of low-carbon energy in the LG-Moderate and HG-Current scenarios is slower and consistent with the recent trend. All of the scenarios except for the HG-Current scenario reduce the overall energy from fossil fuels (Figure 5.5d).

Per capita GDP projections in our five post-pandemic scenarios diverge substantially from the SSP scenarios, with the divergence starting in the aftermath of the 2007–2008 crisis (Figure 5.5e). The gap between the projections and our scenarios remains relatively constant in the high-growth scenarios, whereas in the two low-growth scenarios the gap continues to grow. The scenarios also differ, albeit less so, with respect to population growth (Figure 5.5f). Population growth in our scenarios is slightly faster than projected in the SSPs. Here too, the divergence between SSPs and our scenarios starts around 2010, as the SSPs have historically underestimated population growth.

Our scenarios reveal the challenging path to stabilising global warming at 1.5–2 °C if we fail to reduce energy use. Achieving the necessary emissions reductions without reducing energy use requires much faster growth in low-carbon energy than projected by existing scenarios, as illustrated by our HG-High scenario (Figure 5.5c). However, energy use can be reduced by lower global economic growth, even if potential energy efficiency improvements are much lower than assumed in existing high-growth mitigation scenarios. Moreover, as shown by the LG-Moderate scenario, lower energy use means that much less low-carbon energy needs to be generated to sufficiently decarbonise the energy system. A low-growth trajectory allows for the achievement of dramatic emissions reductions with lower improvements in energy efficiency and less low-carbon infrastructure. Lower growth, other factors being equal, makes the transition easier. But of course, other factors may not be equal, and it is to this issue that we now turn.

5.5 From low-growth to post-growth

Our scenarios show that projecting lower rates of economic growth, in line with recent trends, makes climate mitigation easier in several key respects. Lower growth would make it possible to achieve the necessary emissions reductions despite slower rollout of low-carbon energy and less ambitious energy efficiency improvements compared to existing mitigation scenarios. But the prospect of lower growth raises two additional concerns that need to be addressed. First, could low growth impede national attempts to achieve ambitious mitigation? And second, could low growth lead to undesirable social outcomes?

Here we find it useful to distinguish between baseline 'low-growth' scenarios (i.e. without any additional policy intervention), and 'post-growth' scenarios. We see a 'low-growth' scenario as a continuation of the period from 2007 to 2021, with involuntary stagnation and rising inequalities. Under 'post-growth', however, governments would move beyond the pursuit of increasing GDP, and actively prepare to manage lower rates of growth by introducing policies designed to counteract potential negative social outcomes. In addition, they might adopt progressive social and environmental policies that further reduced GDP growth.

Scholarship in ecological economics indicates that with the right policy mix, economies can manage low-growth scenarios, maintaining economic stability and even improving social outcomes (Jackson, 2009; Victor, 2008). In a recent article, Burgess et al. argue that developed economies should prepare for long-term economic slowdowns (Burgess et al., 2021). Here we explore possible interventions that could address issues related to climate mitigation and social outcomes in low-growth scenarios. In doing so, we start identifying the constitutive elements of post-growth scenarios and differentiate them from low-growth scenarios.

5.5.1 Climate mitigation

The mitigation rates in the low-growth scenarios presented above are still much more ambitious than what has been achieved historically. It is important to ask whether lower growth could make it difficult for governments to achieve this mitigation (e.g. by reducing investment).

In recent years, major economies have been investing around 1% of their GDP towards renewable energy infrastructure and energy efficiency (Birol, 2020; McCollum et al., 2018). Recent studies estimate that under a 'Green Deal' scenario, these investments would have to double to approximately 2% each year (Andrijevic et al., 2020; McCollum et al., 2018). The additional 1% of GDP required for a low-carbon energy transition is substantial, but feasible if compared to the fiscal stimuli injected into the economy during the pandemic, which cost major economies between 5 and 25% of GDP in 2020 alone (Andrijevic et al., 2020; BBC, 2020; McCarthy, 2020).

Existing scenarios assume a direct relationship between growth and mitigation capacity, on the grounds that growth is associated with technological development and efficiency improvements (Dellink et al., 2017; Leimbach et al., 2017; O'Neill et al., 2017). These scenarios assume that high-growth scenarios can achieve rapid emissions reductions, since growth can foster the development of advanced low-carbon and negative emissions technologies that can offset rising energy and resource use from economic growth (Calvin et al., 2017; Kriegler et al., 2017). High growth also makes it possible to pay for more costly mitigation, indicated by higher carbon prices in such scenarios (Riahi et al., 2017). But in reality the relationship between growth and mitigation may not be so straightforward. There are countervailing forces to consider. As Figures 5.5a and 5.5c show, high growth scenarios entail higher energy demand, and therefore require substantially more low-carbon energy and greater energy efficiency improvements to achieve the emission reductions, compared to low-growth scenarios. To draw conclusions about the link between economic growth and mitigation, we need a more comprehensive understanding of how these trade-offs might play out.

Moreover, existing scenarios generally assume that growth in low-carbon technology sectors mirrors growth in the economy at large. But here too the relationship is not so simple. Aggregate growth may not necessarily entail growth in low-carbon sectors if investments are directed elsewhere (as post-pandemic recovery plans demonstrate). Likewise, a push for a ‘green industrial revolution’ may enable low-carbon sectors to grow at much faster rate than the rest of the economy, similar to the digital sector (Bureau of Economic Analysis, 2021).

Importantly, mitigation in the IPCC scenarios depends not only on investments in low-carbon solutions, but also on lifestyles and consumption behaviour (Riahi et al., 2017). A shift to sustainable lifestyles could be facilitated by redesigning infrastructure, expanding sustainable consumption choices, and regulating high-emission social practices — changes that could greatly reduce emissions and that are largely independent of economic growth (Creutzig et al., 2022).

Lower growth scenarios were likely excluded from existing modelling studies of ambitious mitigation (Grubler et al., 2018; Riahi et al., 2017; Rogelj et al., 2018) because the modellers at the time considered them to be politically unfeasible, not because such scenarios are theoretically impossible. The lack of interest in low-growth scenarios was explicitly acknowledged by the authors of the SSPs framework who state that their choice of scenarios omits the ‘low-growth/high sustainability’ scenario, which would assume a dramatic shift to lower consumption lifestyles (O’Neill et al., 2017). In sum, we argue that there is a need to consider and develop scenarios where strong mitigation is achieved in low-growth scenarios, for example by government policy that incentivises and prioritises investments in necessary low-carbon sectors, and encourages societal shifts that reduce demand for energy and other resources.

5.5.2 Social outcomes

One of the problems our two low-growth projections face is that they perpetuate inequalities between high-income countries and the lower-income countries. As Figure 5.6 shows, when we project growth in line with recent trends, there is no noticeable convergence in per-capita GDP between high-income countries and the lower-income countries, and relatively slow convergence in per-capita energy use. Such a scenario is clearly unjust, and raises questions about the ability of lower-income countries to end poverty and achieve human development goals.

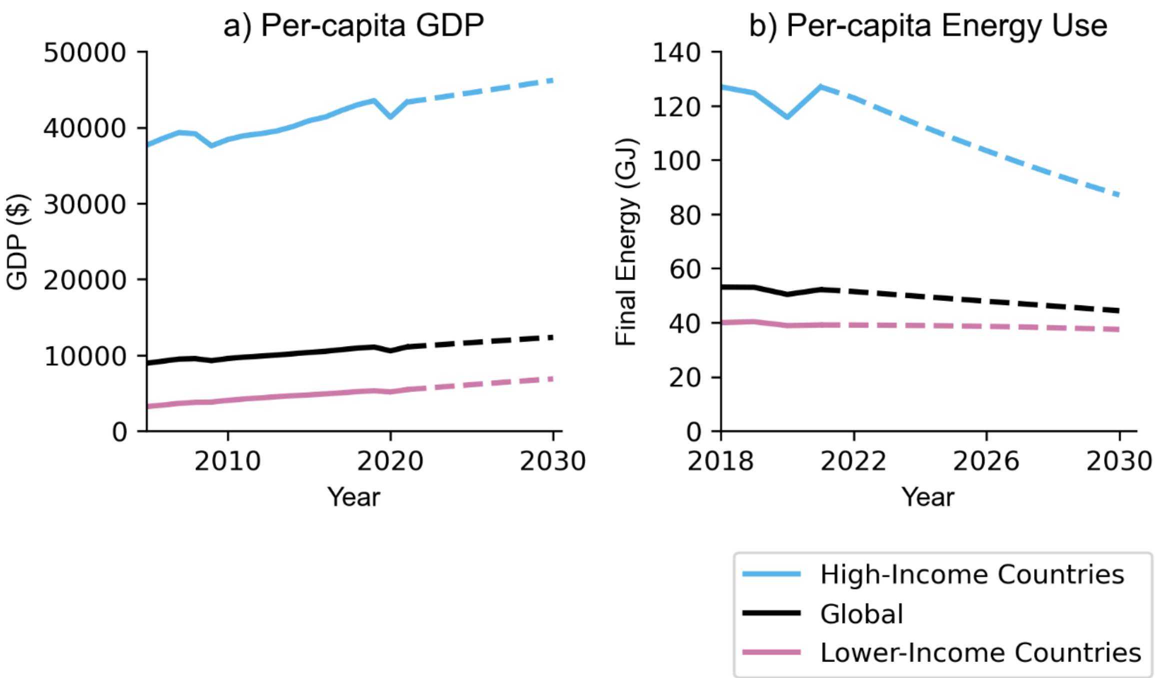


Figure 5.6: Convergence in GDP and energy use between high-income countries and the lower-income countries under projected low-growth conditions. The solid lines show the historical data, and the dashed lines show future projections under the low-growth scenario without the addition of equity-focused policies. The blue line shows the trajectories for high-income countries, the purple line shows the trajectories for lower-income countries, and the black line shows the global average.

It would be sensible, therefore, to aim for and develop more equitable scenarios. Recent research demonstrates that economic growth in high-income countries relies on a large net appropriation of resources and energy from the lower-income countries, through unequal exchange in international trade induced in large part by structural adjustment programs (Dorninger et al., 2021; Hickel et al., 2022). If policies were introduced to ensure fairer trade relations (e.g. ensuring that lower-income countries have the right to use tariffs and subsidies to develop their economic capacity, and ensuring living wages and fair resource prices throughout global supply chains), it would allow lower-income countries to capture a fairer share of global income and energy. Policies for fairer trade would yield a faster rate of convergence, while allowing governments to end poverty, provision for human needs, and achieve human development goals despite lower growth at the global scale.

Equity-focused scenarios along these lines are likely to entail a lower rate of GDP growth and a declining rate of energy use in high-income countries. Under existing conditions, lower GDP and energy use might lead to undesirable social outcomes within high-income countries, such as unemployment and inequality. Piketty, for instance, argues that worsening inequalities in the OECD countries are a direct result of declining economic growth and suggests that, in the absence of policy interventions, inequality is likely to worsen (Piketty, 2014).

But research in post-growth economics indicates that this need not be the case. Jackson and Victor, for example, demonstrate that inequalities can be reduced in low-growth scenarios with redistributive policy interventions (Jackson and Victor, 2016). Others show that inequalities can be stabilised if growth rates decline at the same pace as savings and/or capital gains (Jackson, 2019; Stiglitz, 2015). Policies to limit inequality include progressive taxation on capital gains or carbon emissions (Hartley et al., 2020) and legislation to protect wages (such as a universal basic income (Jackson, 2019) or a public job guarantee (Lawn, 2011)). Moreover, inequality could be reduced with a structural shift towards services such as care, culture, and education, where substituting labour with capital is difficult (Jackson, 2016). Burgess et al. review how countries like Japan and Italy have responded to low-growth realities and call for a 'guided civic revival', 'including government and civic efforts aimed at reducing inequality, socially integrating diverse populations and building shared identities, increasing economic opportunity for youth, improving return on investment in taxation and public spending, strengthening formal democratic institutions and investing to improve non-economic drivers of subjective well-being' (Burgess et al., 2021).

It is also helpful to think about social outcomes in terms of energy use. High-income countries presently use on average 140 GJ per capita, which is significantly higher than what empirical studies show is required for decent living (Millward-Hopkins et al., 2020). The problem is that much of this energy is expended on elite consumption, wasteful inefficiencies, and socially unnecessary forms of production, as exemplified by the fact that the world's richest 5% use more energy than the world's poorest 50% combined (Oswald et al., 2020). By reducing elite consumption, improving efficiencies, and prioritising forms of production that are essential for human welfare, high-income countries should be able to improve social outcomes for the majority of their citizens with lower aggregate energy use (Wiedmann et al., 2020).

In sum, post-growth scenarios should build on plausible hypotheses for how countries can improve social equity, reduce poverty, and reduce unemployment even under conditions of low or negative economic growth (D'Alessandro et al., 2020; Kallis et al., 2020; Victor, 2012). In a post-growth scenario, social outcomes would be progressively decoupled from GDP growth (Dietz and O'Neill, 2013; Victor, 2010).

5.6 Conclusions: Towards post-growth scenarios

Regardless of what one thinks about the desirability of lower growth, it appears to be a reality. Existing climate mitigation scenarios tend to over-project economic growth, making the transition appear more difficult than it may be in reality. Our analysis has illustrated the difference that low growth makes when it comes to achieving climate mitigation consistent with 1.5–2 °C. Low growth may make it possible to achieve necessary emissions reductions without relying on large-scale negative emissions and unrealistically high rates of energy–GDP decoupling. That said, low growth within a system that is dependent on growth for its stability is problematic, both in terms of paying for a clean energy transition and reducing inequalities both within and between countries. Therefore, we have sought to distinguish between unmanaged low-growth scenarios, which may result in undesirable outcomes, and managed 'post-growth' scenarios that improve mitigation, equity, and social stability.

We identify two major tasks for a post-growth scenario research agenda. First, advanced modelling studies should explore the conditions and limits of ambitious mitigation in the context of declining economic growth. In theory, declining growth rates could be a direct result of the downscaling of the carbon-intensive 'brown sectors' of the economy, while the 'green economic sectors' driving the low-carbon transition could still grow substantially. Major emissions reductions could be achieved by a societal shift towards sustainable lifestyles and reduced consumption (Creutzig et al., 2018). These mitigation actions do not require high rates of economic growth and are therefore compatible with a post-growth narrative.

Second, post-growth scenarios should construct more complete narratives that allow low- and middle-income countries to capture a fairer share of global output and energy in order to achieve human development goals, while high-income economies develop frameworks for ensuring strong social outcomes despite low growth. There is nothing inevitable about the existing dependency on growth for social and political stability, and for public investment. A flourishing literature in heterodox and ecological economics demonstrates that policy interventions can reduce growth dependence and allow economies to manage well without growth (Dorling and McClure, 2020; Jackson, 2016; Raworth, 2017).

Future research should craft post-growth narratives based on the policy proposals that have emerged from the post-growth literature, and model their effects on the economy and emissions using existing or new Integrated Assessment Models (IAMs). Working-time reduction, for example, has the potential to reduce carbon emissions, while increasing employment at a given level of output (Kallis et al., 2013; Knight et al., 2013). Shifting financial resources to decarbonise energy systems, or shifting from products to services, may lower labour productivity growth and reduce the carbon/energy intensity of the economy, while increasing employment (Van Den Bergh, 2017). Finally, if one wants to be more ambitious, social changes could be modelled and their effects projected — from the growth of social movements that succeed in blockading new fossil fuel projects to the spread of new ethics that may lead to radically downscaled energy use (Millward-Hopkins et al., 2020). Given that existing IAMs rely extensively on speculative negative emissions technologies, and contentiously ambitious levels of decoupling between GDP and energy use, there is no reason they should not also include visionary social and economic trajectories, to explore the full range of possible mitigation pathways (McCollum et al., 2020).

5.7 Supplementary Information

5.7.1 Decomposition of emissions drivers

To estimate carbon emissions in our five post-pandemic scenarios, we adapt a simple decomposition formula, known as the Kaya identity (Kaya, 1990), which is widely used to study the drivers of emissions from the energy sector (Nakicenovic et al., 2000; Raupach et al., 2007). We derive the extended decomposition, starting from a formula that relates emissions to the product of the primary energy intensity of the economy (EI_{PE}), carbon intensity of primary energy (CI_{PE}), population (P), and economic activity per capita (GDP_{pc}) (Equations 1–3).

$$CO_2 = EI_{PE} \times CI_{PE} \times P \times GDP_{pc} \tag{1}$$

$$EI_{PE} = \frac{PE_{tot}}{P \times GDP_{pc}} \tag{2}$$

$$CI_{PE} = \frac{CO_2}{PE_{tot}} \tag{3}$$

We further expand the equation by disaggregating primary energy intensity into final energy intensity (EI_{FE}) and the ratio of final energy to primary energy ($\frac{PE_{tot}}{FE_{tot}}$) (Equations 4–6), following the approach described by (Koomey et al., 2019) This expansion allows us to distinguish between the efficiency improvements in the economy that lead to higher economic output at lower energy use (Equation 5), and the improvements in energy conversion efficiency (η_{sys}) from primary energy to final energy (Equation 6), accomplished by the reduction in energy losses along the energy supply chain from the point of extraction to the point where energy enters the economy (Brockway et al., 2019).

$$CO_2 = \frac{FE_{tot}}{P \times GDP_{pc}} \times \frac{PE_{tot}}{FE_{tot}} \times CI_{PE} \times P \times GDP_{pc} \tag{4}$$

$$EI_{FE} = \frac{FE_{tot}}{P \times GDP_{pc}} \tag{5}$$

$$\eta_{sys} = \frac{FE_{tot}}{PE_{tot}} \tag{6}$$

Final energy intensity can be decreased either via end-use efficiency improvements in the conversion of energy to goods and services or through structural changes in the economy (i.e. by undertaking a transition from a high-intensity industrialised economy to a lower-intensity service economy). The final-to-primary energy ratio changes when one energy carrier replaces another (e.g. electricity replaces gasoline) and by improving energy conversion efficiencies from primary to final energy. The ratio will increase if power generation from fossil fuels is replaced by more efficient energy sources, typically renewables, or if obsolete power generation facilities are replaced by modern facilities with a higher energy conversion efficiency.

We arrive at the final decomposition formula by decomposing the carbon intensity of primary energy into the factors of low-carbon energy share ($\mathrm{LC_{share}}$) (Equation 7) and the total carbon intensity of fossil fuels ($\mathrm{CI_{FF}}$) (Equation 8), following the approach of (Peters et al., 2017) Here, we define the low-carbon energy share as the share of low-carbon energy in final energy consumption, which includes energy from renewables, biomass, and nuclear power. We obtain the expanded equation for carbon intensity (Equation 9) by first expressing total primary energy as total final energy divided by the final-to-primary energy conversion ratio (Equation 6); and, in the next step, by describing total final energy as a function of low-carbon energy share (Equation 7).

$$(1-\mathrm{LC_{share}}) = \frac{\mathrm{FE_{FF}}}{\mathrm{FE_{tot}}} = \frac{\mathrm{FE_{FF}}}{\mathrm{FE_{LC}}+\mathrm{FE_{FF}}} \tag{7}$$

$$\mathrm{CI_{FF}} = \frac{\mathrm{CO_2}}{\mathrm{FE_{tot}}} \tag{8}$$

$$\mathrm{CI_{PE}} = \frac{\mathrm{CO_2}}{\mathrm{PE_{tot}}} = \frac{\mathrm{FE_{tot}}}{\mathrm{PE_{tot}}}\frac{\mathrm{CO_2}}{\mathrm{FE_{tot}}} = \frac{\mathrm{FE_{tot}}}{\mathrm{PE_{tot}}}(1-\mathrm{LC_{share}}) \times \frac{\mathrm{CO_2}}{\mathrm{FE_{FF}}} \tag{9}$$

Finally, we obtain an expression that allows us to distinguish the effects of changes in energy efficiency from both the mitigation efforts to decarbonise the energy system (which depend on the share of low-carbon energy alongside changes in the carbon intensity of final energy from fossil fuels) and the effects of economic growth (Equation 10). This formula is used alongside the underlying scenario assumptions from Table 5.1 to estimate the emissions in our five scenarios.

$$\mathrm{CO_2} = \frac{\mathrm{FE_{tot}}}{P \times \mathrm{GDP_{pc}}} \times (1-\mathrm{LC_{share}}) \times \frac{\mathrm{CO_2}}{\mathrm{FE_{FF}}} \times P \times \mathrm{GDP_{pc}} \tag{10}$$

5.7.2 Calculating Energy and Emissions

To calculate energy and emissions pathways for each of the five post-pandemic scenarios shown in Figure 5.5, we use the scenario assumptions for the annual changes in energy–emissions factors (presented in Table 5.1 and Figure 5.4). Values of energy–emissions factors in a particular year are calculated by multiplying their values in the preceding year by their respective annual changes, as shown in Equation 11.

$$y_{t+1} = y_t \times (1 + \Delta y_{\%}) \tag{11}$$

To calculate the annual growth rates of factors from the post-pandemic scenarios and the SSPs that are portrayed in Figure 5.5, we use the compound annual growth formula, shown in Equation 12.

$$\Delta y_{\%} = \left(\frac{y_{t+\Delta t}}{y_t}\right)^{\frac{1}{\Delta t}} - 1 \tag{12}$$

5.7.3 Scenario Narratives and Assumptions

5.7.3.1 High-Growth Scenarios

In the High-Growth and Current Climate Ambition (HG-Current) scenario, we assume that the rate of final energy intensity changes from an average of -1.0% per annum (p.a.) for the period 2007 to 2020 to -0.9% for 2021, which we estimate from the IEA energy (IEA, 2021b) and IMF GDP projections for 2021 (the 2007–2021 average is then -1.0% p.a.) (IMF, 2021c).

Final energy intensity gradually improves to -2.5% p.a. by 2030. The value of -2.5% p.a. is the global final energy intensity improvement that we estimate from the International Renewable Energy Agency (IRENA) assessment of the existing energy policies and countries' Nationally Determined Contributions (NDCs) to the Paris Agreement in 2030 (IRENA, 2020). Whereas IRENA estimates the energy efficiency improvements on the basis of primary energy intensity, our method applies the changes to the final energy intensity. To convert the IRENA estimates of primary energy intensity into final energy intensity, we assume the energy conversion efficiency from primary to final energy will continue in line with the reported historical trend from 2005 to 2018. According to the IEA, the conversion efficiency improved by around +0.1% each year. As a result, the IRENA estimate of change in primary energy intensity of -2.4% p.a. equals the -2.5% p.a. change in final energy intensity as assumed in our HG-Current scenario.

Achieving an annual decrease in final energy intensity of -2.5% by 2030 is an improvement compared to the pre-pandemic average of -1.9% (from 2009 to 2019), but is lower than the improvement in the High-Growth and High Climate Ambition (HG-High) scenario of -3.0% p.a.

For GDP, we follow the IMF baseline projections of a V-shaped recovery, with 6.0% global growth in 2021, 4.4% growth in 2022, and 3.5% growth in 2023, followed by 3.3% growth p.a. until 2030 (IMF, 2021c). This is a business-as-usual scenario whereby pre-pandemic trends return, following a swift recovery. For our population assumptions, we follow the median scenario of the UN World Population Prospects (United Nations Department of Economic and Social Affairs Population Division, 2019). We decided to only use the median fertility scenario after conducting a preliminary sensitivity analysis which showed the low fertility and high fertility variants of the UN projections make very little difference to the final energy and emissions trajectories by 2030.

To estimate final energy, we combine the assumed changes in final energy intensity and GDP growth. This results in an average final energy growth of 1.3% p.a. from 2021 to 2030. We assume that low-carbon final energy continues to grow at a rate of 3.6% p.a., bringing the share of low-carbon energy from 19.4% in 2018, to 25.9% in 2030, as assumed in the assessment of current energy policies by IRENA.

To calculate the annual change in the carbon intensity of final energy, we combine the low-carbon share equation (Equation 8) with the annual growth rate equation (Equation 12). We estimate a +0.3% increase in carbon intensity in 2021, followed by a gradual return to a slow decarbonisation starting at -0.1% p.a. in 2022, to -0.5% by 2030. We assume the share of coal and oil in total final energy from fossil fuels decreases by -0.3% p.a. from 2021 to 2030, while the share of gas increases by 0.6% p.a. Our assumptions on fuel-switching correspond to the dynamics of the primary energy shares of different fossil fuels, from 2018 to 2030, according to the assessment of existing energy policies by IRENA.

We see the HG-Current scenario happening if countries invest in existing fossil fuel infrastructure and polluting industries, and reject energy and carbon taxation. This scenario could occur if countries maintained a supply of energy from fossil fuels and removed incentives for structural changes in energy consumption and improvements in energy efficiency. However, within the HG-Current scenario, countries implement current renewable energy strategies and commitments. The latest emissions-energy data from the IEA (IEA, 2021d) suggest a strong rebound in energy use and emissions taking place in 2021, meaning the return to a business-as-usual, carbon-intensive economy.

We design two high-growth scenarios that both include a major boost in investment in low-carbon energy and substantial improvements in energy efficiency. We design the High-Growth and High Climate Ambition (HG-High) scenario to represent the high-end of foreseeable mitigation efforts over the next decade, assuming global implementation of the decarbonisation and energy efficiency targets from the European Green Deal (Commission, 2020). In the High-Growth and Moderate Climate Ambition (HG-Moderate) scenario, we assume that global policy goes halfway towards meeting the decarbonisation and efficiency targets of the European Green Deal.

In the HG-High scenario, final energy intensity decreases by -3.0% p.a. by 2030 (compared to -1.0% p.a. before the pandemic). We estimate this rate of efficiency improvement by referring to the policy goal of the EU's energy efficiency directive (Official

Journal of the European Union, 2018), which aims to reduce final energy consumption from 2018 to 2030 by 17% (Eurostat, 2020), alongside the projected economic growth in the EU of +1.8% of GDP p.a. over the same period (IMF, 2021b).

Final energy intensity in the HG-Moderate scenario decreases by -2.5% p.a. each year from 2022 to 2030, which roughly corresponds to the improvements that would be needed if Goal 7 of the UN Sustainable Development Goals were to be met (UN, 2015b). The improved energy efficiency in our scenarios can be thought of as the result of intentional policies to increase the price of fossil fuels (e.g. energy and carbon taxes in the highest-emitting countries), and an organised shift towards less carbon-intensive activities (e.g. by making bailouts and government loans conditional on compliance with climate targets, and accelerating the retirement of older, inefficient energy infrastructure) (IEA, 2020). Energy efficiency also improves when there is a higher share of renewable energy, as this reduces the energy transformation losses from primary to final energy (Guo et al., 2018).

The decarbonisation in the HG-High scenario increases the share of low-carbon energy by 18.5% from 2021 to 2030. We calculate this could be accomplished by an average growth rate of low-carbon energy of 7.6% each year. We calculate the resulting rates of carbon intensity improvements starting from -1.1% p.a. in 2021, and improving to -4.6% in 2030. In the HG-Moderate scenario, we increase the share of low-carbon energy by 9.3% from 2021 to 2030. As a result, carbon intensity decreases from -1.1% p.a. in 2021 to -2.1% in 2030. Although less ambitious than the HG-High scenario, the decarbonisation in the HG-Moderate scenario is still two times faster than the trend in the HG-Current scenario.

To estimate the effects of fuel-switching between different fossil fuels, we follow IRENA's Transforming Energy Scenario, an energy transition scenario that emphasises a fast mitigation through renewable energy. We apply the same fuel-switching assumptions in both the HG-Moderate and HG-High scenarios. We estimate that fuel-switching can decrease the carbon intensity of fossil fuels by -0.3% p.a. Thus, fuel-switching has a much lower potential to decarbonise the economy in comparison to the share of low-carbon energy. This is because: (a) switching between fossil fuels decreases emissions but does not eliminate them completely, unlike when fossil fuels are replaced by low-carbon alternatives; (b) carbon intensity improvements through fuel-switching are constrained by the inflexibility of the fossil fuel infrastructure and the inability of end-use appliances to change between different fuels (e.g. natural gas is not a good substitute for petroleum in the transportation sector, especially when considering the existing fleet of petroleum-powered vehicles).

The HG-Moderate and HG-High scenarios would be most likely to occur if countries linked fiscal recovery policies to compliance with climate objectives, which would accelerate the retirement of older, less-efficient energy infrastructure. Introducing carbon taxation would also suppress rebound in both energy demand and carbon emissions in the immediate aftermath of the pandemic. Faster deployment of renewable energy together with additional investment in energy efficiency would speed up decarbonisation of the energy system.

5.7.3.2 Low-Growth Scenarios

In the low-growth scenarios, countries boost green investments, and low-carbon energy increases by the same share as in the HG-Moderate and HG-High scenarios. We also assume the same decline in final energy intensity as in the HG-Moderate and HG-High scenarios. In addition to a shift to a more-efficient energy system with a higher share of low-carbon energy, we assume the GDP growth rate continues to decline in line with the trend from 2007 to 2021. Assuming the same energy intensity improvements as in the HG-Moderate and HG-High scenarios, this leads to a decline in the growth of final energy by -0.4% p.a in the Low-Growth and Moderate Climate Ambition (LG-Moderate) scenario, and -0.9% p.a. in the Low-Growth and High Climate Ambition (LG-High) scenario. We assume the same fuel switching from coal and oil to gas as in the HG-Moderate and HG-High scenarios.

In our per-capita GDP projections for the low-growth scenarios, we divide the global economy into high-income economies and the lower-income countries (the latter includes both low- and medium-income economies). The high-income countries refer to the OECD members as of 1990 alongside the EU members and candidate states, the United States, Canada, Australia, New Zealand, Japan, and Turkey. This definition of high-income states is based on the OECD90+EU country group in the SSP scenarios, and was used to ensure consistency when comparing our scenarios with the SSP projections (Huppmann et al., 2019).

The partitioning of GDP and energy between country groups is based on World Bank GDP data (World Bank, 2021) and final energy data from the IEA (IEA, 2021a). The World Bank attributes 59.2% of global GDP in the year 2019 to high-income economies. For 2021, the IMF estimated GDP growth of 5.1% in high-income countries and 7.3% growth in the lower-income countries. These growth rates correspond to per-capita GDP growth of 4.8% in high income countries and 6.0% in the lower-income countries, if we adjust GDP for the UN projections of population growth. After 2022, we assume that per-capita GDP growth continues in line with the trend from 2007 to 2021, which results in a constant per-capita growth rate for high-income economies of 0.7%, and a gradually deaccelerating growth rate from the value of 2.6% in 2023 for the lower-income countries (decelerating by 0.1% each year). For high-income countries, the LG-High scenario roughly represents a scenario that has been referred to in the literature as a 'Green New Deal without growth' (Mastini et al., 2021).

According to the IEA, high-income countries consumed 37% of final energy in 2018, and the lower-income countries consumed the remaining 63%. For the sake of simplicity, we assume the same final energy intensity improvements for both regions. A sensitivity analysis, where we assume higher energy intensity improvements (-1%) in high-income countries, allows energy use in the lower-income countries to increase by 0.3%, yet implies a -1% faster reduction of energy use in high-income countries. This suggests that the degree of energy intensity improvements in high-income countries only weakly affects the required energy intensity improvements in the lower-income countries, if we assume the same global energy intensity improvements.

5.8 Data

Energy and emissions data for the SSP energy transition pathways were obtained from the IAMC Scenario Explorer repository: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/.

Historical emissions were obtained from the Global Carbon Budget Project repository of 'Fossil fuel emissions and Industry' data, accessible at: https://www.globalcarbonproject.org/carbonbudget/20/data.htm.

Historical data for final energy, gross/primary energy, and the share of low-carbon energy in final energy consumption were taken from the online IEA Data and Statistics database, accessible at: https://www.iea.org/data-and-statistics.

Historical data for per-capita GDP at constant 2010 US$ prices were taken from the online World Bank database, available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.

The high-growth projections for per-capita GDP were taken from the online IMF Datamapper tool, available at: https://www.imf.org/external/datamapper.

The workbooks containing the historical data and our five post-pandemic scenarios are available in an online data repository, accessible at: https://osf.io/efv89/?view_only=283f2994a68d4d87b7133ac419e230c6

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5.10 Author contributions

All authors contributed to designing the project and writing up the results. A.S. led the project, developed the method, collected and analysed the data, and produced the results, under the supervision of G.K., D.W.O., and J.H.

Chapter 6
Conclusions

In this thesis, I analysed a range of mitigation scenarios that are consistent with the goal of the Paris Agreement to stabilise global warming well below 2 °C. My research aimed to investigate the challenges posed by a low-carbon energy transition from the perspective of energy and emissions that are available to society under different mitigation scenarios.

Overall, the thesis findings suggest that energy use reduction may be unavoidable during the transition regardless of the successful development of negative emissions. Moreover, emissions associated with the transition mean that the emissions for the provision of goods and services for society may be lower than commonly believed. These energy use and emissions constraints make it possible that the transition may occur in conditions of lower economic growth. However, scenarios of low growth are critically underrepresented in existing mitigation literature. To address this research gap, I deliberate on the critical characteristics of an equitable low-growth transition that could accomplish ambitious mitigation while enabling a decent life for all.

6.1 Key findings and discussion

6.1.1 How much energy will be available during the transition?

During the initial push for a low-carbon energy transition, net energy available for society is expected to decrease considerably, which would have been historically unprecedented since the industrial revolution. Two contributing factors steer the transition towards lower energy availability. The first one is the urgency of reducing fossil fuel use which is well understood in the literature. The second factor concerns the much-debated question about which low-carbon alternatives could lead the transition and how much energy they could provide for society. As shown in *Chapters 2 and 3*, a rapid transition to low-carbon energy makes it difficult to fully substitute the reduced energy from fossil fuels.

The transition may be further complicated by high upfront energy investments for a low-carbon energy infrastructure, which mostly come from electricity. High requirements for electricity could become the principal obstacle to the transition, as they could slow down the ambitions of electrifying energy services across the economy. The intuitive response to deal with lower energy availability by building more energy infrastructure cannot solve this problem. However, it can, in fact, make it worse, as the energy required for additional infrastructure can temporarily exceed the energy generated by the new infrastructure. The apparent contradiction between upscaling of the energy system and the decrease in energy available for society has been largely overlooked in the literature. However, there is a well-understood analogy to it in macroeconomics. Just as investments for capital formation can decrease the economic expenditure for consumption, so can energy requirements for an overhaul of energy infrastructure provoke a decrease in the energy available for society.

Growth in low-carbon energy generation needs not to result in increased availability of energy for society. On contrary, growth can increase the challenge of the transition, as the bigger the energy system, the higher the costs, and the bigger the industrial production needed for new energy infrastructure, and the higher the demand for rare-earth minerals and locations for harnessing of renewable energy sources. The importance of considering limits to scalability during the transition is demonstrated by the ongoing supply chain crisis, whereby increased demand for low-carbon energy technologies has led to rising prices but only marginal increases in the supply of these technologies (PWC, 2019; Wallace, 2022).

The good news is that the net energy for society could increase after the initial push for the transition, as energy requirements of renewables become insignificant and their energy return on energy invested (EROI) high once the energy infrastructure has been established. Moreover, the high-EROI of the renewables in the aftermath of the initial push could accelerate the shift from liquid fuels to electricity and hydrogen, therefore decreasing the economic rationale for a transition to biofuels and fossil fuels with carbon capture and storage.

6.1.2 What does lower energy use mean for the economy?

Overall, *Chapters 2 and 3* suggest that ambitious mitigation entails a major constraint to energy use, as net energy is expected to decrease from 10% to 34% during the initial push for the transition. Moreover, the availability of electricity is expected to remain approximately constant during this period, which could complicate the substitution of oil for electricity. However, while these findings lay out the broader picture of necessary adjustments in society and economy to come to terms with the lower availability of energy and electricity, they provide little detail about the implications in different economic sectors. Here, I briefly outline the possible impacts of lower energy availability during the transition across three major economic sectors and discuss the necessary adjustments in the provisioning of energy services for society.

The industrial sector currently consumes 30% of global energy generation and has historically been the sector with the highest growth in energy use (IEA, 2022c). The transition could be particularly difficult for this sector, which must substantially increase the manufacture of low-carbon technologies while having little to no possibility of increasing energy consumption. When comparing the energy requirements of building up a low-carbon energy system to the energy use in the industrial sector, it becomes clear that the transition itself could require from 9 to 30% of the current energy use in the sector. Due to the limitations of energy use in the sector, such an increase in the production of low-carbon technologies may need to be accompanied by a reduction in the manufacturing of other products.

To accomplish a transition to lower energy use, existing studies emphasise the need for dematerialisation in affluent societies across the economy (Creutzig et al., 2022; Kuhnhenn et al., 2020). This could be supported by the sharing economy model that aims to move away from the ownership of products towards providing services in a sharing economy, thereby achieving more optimum utilisation of products during their lifespan (Grubler et al., 2018). Furthermore, the demand for industrial production could be reduced by targeting planned obsolescence and marketisation of superfluous products that do not contribute to social well-being and by mandating longer lifespans of the products and making them easily reparable and upgradable (Hickel et al., 2021a).

In the transportation sector, the combined aim of decarbonisation and energy use reduction is even more challenging. Electricity currently represents only 1.4 EJ of energy used in the transportation sector each year, as oil, with 119 EJ per year, is still the dominant fuel used (IEA, 2022b, 2022c). Even though substituting petrol-powered vehicles with more efficient electric vehicles may save up to 50% of energy use per km (Guo et al., 2018) and reduce the total energy used for transportation, the problem lies in the supply of electricity for this sector. Even according to studies that assume lower energy use in transportation, electrifying the bulk of passenger and freight transport would require at least 30 EJ of electricity per year (Grubler et al., 2018), which corresponds to 33% of total current electricity production. Such an increase in electricity demand may be difficult to realise, given the competing demands of the industrial sector and the limited availability of electricity overall. In light of these concerns, society may need to travel less and differently (de Blas et al., 2020; Kuhnhenn et al., 2020). Replacing cars with lighter electric vehicles, such as e-bikes and e-scooters, along with faster and more affordable public transportation, to substantially reduce the energy use per kilometre travelled could be part of the solution (de Blas et al., 2020). Meanwhile, complementary measures, such as compact city design, making public services accessible at short distances via safe infrastructures for pedestrians and cyclists (Ahmad et al., 2020), and incentives for teleworking would reduce the demand for mobility. Finally, significant potential savings per kilometre travelled may come from reducing the highly energy-intensive means of travelling, especially flying, which could be disincentivised, for example, by imposing a frequent flyer levy (Devlin and Bernick, 2015).

In the commercial sector and private buildings, energy use can be reduced by improving the efficiency in the provision of energy services, such as thermal comfort and lighting, and by reducing the size of buildings, as bigger buildings require more energy for construction and the provision of services. Thermal comfort can be provided more efficiently by retrofitting old buildings with insulation and heat pumps and mandating passive-house energy standards in new constructions (Creutzig et al., 2022). The efficiency of cooking and lightning can be improved by deploying high-efficiency appliances, and in the case of the latter, by designing the floor-space distribution in accordance with the availability of natural light. Another way to reduce energy use in buildings is by reducing superfluous floor space, which has been estimated to waste up to 50% of the energy used (Creutzig et al., 2022). The energy wasted could be decreased by incentivising the sharing of spaces for housing and commercial services and by taxing the ownership of housing proportionally to the floor space per inhabitant, thereby disincentivising the construction of large mansions and underutilised "summer houses".

6.1.3 How to best move away from fossil fuels?

Chapter 2, which calculates the emissions associated with a low-carbon energy transition, shows that the bigger the energy system and slower the phase-out of fossil fuels, the bigger the energy system emissions, as more of the remaining carbon budget is taken up by the energy system itself. In contrast, transitions that combine rapid decarbonisation with lower energy use and a high share of renewables in the energy system tie up less of the remaining carbon budget to the energy system. This points to an important conclusion: that a low-carbon energy transition to lower energy demand allows a bigger share of the remaining fossil fuels to be used by society.

Chapter 3 demonstrates that large-scale use of negative emissions offers few advantages but comes with risks and drawbacks. In terms of advantages, negative emissions expand the carbon budget and thus allow for a slower reduction of energy from fossil fuels during the initial push for the transition. However, I find the mitigation potential of negative emissions to be exaggerated in current scenarios by 40–50%, which means the available energy from fossil fuels may be much smaller than currently believed. Moreover, higher energy availability due to negative emissions is limited to the supply of liquid fuels (oil), but does not meaningfully increase the availability of electricity, which is set to become the primary energy carrier in a low-carbon energy system. Higher availability of oil implies that negative emissions may allow people to travel more, continue using oil for heating, and consume more plastic. However, higher oil consumption does not contribute to higher availability of electricity, which is crucial for industrial production and many energy services performed by electronic devices. Also, negative emissions do not reduce the need to deploy low-carbon energy technologies but only extend the time in which low-carbon infrastructure needs to be built. Furthermore, while negative emissions unlock the additional energy from fossil fuels, they also consume much of this energy, decreasing the overall EROI of the energy system.

6.1.4 Is low-carbon energy transition compatible with high economic growth?

Existing scenarios assume no trade-offs between economic growth and climate mitigation and suggest that ambitious mitigation may increase economic growth (O'Neill et al., 2017; Rogelj et al., 2018). However, the modelling of mechanisms that affect economic growth during the transition is somewhat limited, raising questions if scenarios of high economic growth are, in fact, an accurate representation of possible futures. In the modelling of economic growth, existing mitigation scenarios start from the assumption of high growth rates (Dellink et al., 2017) and typically only calculate how these growth rates may change as a result of investments in climate mitigation (Riahi et al., 2021). Thereby, the models do not account for possible impacts on growth from the reorganisation of industrial production and lifestyle changes during the transition. An incomplete representation of mechanisms determining economic growth rate is further underlined by omitting economic damages from climate change in the scenarios (Rogelj et al., 2015a).

While this thesis does not quantify the impacts of a low-carbon energy transition on economic growth and, as a result, cannot provide a definite answer if high rates of economic growth are unfeasible, the findings reveal additional constraints that make returning to high growth during the transition difficult. In addition to the persistence of low growth rates since the global financial crisis of 2008 and the headwinds to growth already identified by (Burgess et al., 2021), I identify three reasons that will make returning to high economic growth during the transition difficult.

First, a decrease in net energy and a lower EROI during the transition that I address in *Chapters 2 and 3* suggest that existing scenarios assume an even bigger historical break in the decoupling between economic growth and energy use than currently estimated. Previous studies have analysed decoupling in the existing mitigation scenarios by comparing the link between final energy and GDP growth (Heun and Brockway, 2019; Parrique et al., 2019). However, what matters for the growth of the productive economy is the availability of net energy to perform work for society and not the total energy generated (Brockway et al., 2019). Decreasing the EROI of the energy system means the difference between final energy and net energy will increase, which may result in a higher rate of decoupling at the point of net energy of up to 1.2 % per year, if compared to the decoupling rates at the point of final energy. This additional decoupling is significant, given that the average decoupling rate from 2007 to 2021 was only 1.0% per year. To realise sufficient decoupling at high economic growth would then require a transition where value added in the economy is growing faster than recently while the energy used to support such an economic system declines rapidly, which is a highly dubious proposition (Brockway et al., 2021; Hickel and Kallis, 2020).

Second, a decrease in the EROI associated with the transition means that higher expenditure of GDP will have to go for the energy system. This is an additional concern for economic growth, as periods of high GDP expenditure for energy have been empirically linked with lower growth rates (Fizaine and Court, 2016; Hall et al., 2009; Lambert et al., 2014).

Finally, our studies suggest the need for a rapid phase-out of fossil fuels and the dematerialisation of the economy, which will depreciate the value of capital in fossil fuel industries and high energy-intensive industries. Previous studies find that capital depreciation of fossil fuel industries alone may cause substantial losses in global GDP (Semieniuk et al., 2021a). However, there is a broader concern about the spill-over effects of these losses onto other sectors of the economy and the destabilising effects they may have on financial markets (Semieniuk et al., 2022). We conclude that a profound transformation of the industrial sector makes a period of lower growth during the initial push for the transition more likely than a period of high growth assumed in the mitigation scenarios.

In light of these issues, I argue in *Chapter 5* that anticipating lower economic growth is likely to be more conducive to designing possible mitigation scenarios and policies. Lower economic growth can make ambitious mitigation outcomes possible with smaller improvements in energy efficiency, slower deployment of renewable energy and reduced reliance on negative emissions. For example, suppose per-capita GDP growth remains at a present-day low value of 2% per year. In that case, the most ambitious climate policy plans could reduce emissions in line with the objective of stabilising global warming to 1.5–2 °C. On the contrary, in conditions where the economy grows at rates above 3.4%, as projected by the IMF and existing mitigation scenarios, even the most ambitious of current climate action plans would be insufficient to comply with the goals of the Paris Agreement.

I leave it up to deliberation of the reader whether a high growth low-carbon energy transition may or may not happen. A more crucial insight may be that regardless of the economic growth rate, the resulting economic system would hardly resemble the current economy based on energy-intensive industrial production and excessive consumption.

6.1.5 Are equitable outcomes possible in conditions of low growth?

Our analysis of a low-carbon energy transition outlines profound changes needed in the economy's organisation to conform to the reduction of available energy and lower economic growth. However, the notion of limits to growth raises concerns that it could undermine efforts to eradicate poverty and perpetuate the great divide in wealth between high-income countries and the rest of the world (Milanovic, 2017; Roser, 2021a). Equity considerations are essential in this context, given that 8.6% of the global population still lives below the $1.90-a-day extreme poverty line (UN, 2020), and 11% still lacks electricity. (UN, 2015b)

While these concerns are relevant, there is a broader question here: if growth is the crucial mechanism for reducing poverty and inequality? Empirical analyses of subjective well-being show that positive growth is not conducive to improving well-being over time (Easterlin et al., 2010; Fanning and Neill, 2019; Ward et al., 2016), which has led some economists to the conclusion that income growth should not be used as a measure of well-being and prosperity (Costanza et al., 2014; Wiedmann et al., 2020).

Analysis of global energy inequalities in *Chapter 4* shows that equitable outcomes are not represented regardless of the energy use and economic growth rate assumed in existing mitigation scenarios. The perpetuation of inequalities in these scenarios is not because of low growth, but is a result of the modellers' design of developmental pathways, which have disregarded the possibility of convergence towards equal energy use and incomes between the Global North and the Global South. Therefore, my contribution demonstrates that the focus on economic growth oversimplifies the path to improvements in well-being as it overemphasises the production side of the economy to the detriment of changes in distribution.

Although growth may have been necessary to reduce poverty and inequality in the past when economies have generated insufficient energy and wealth to provide decent living conditions, today's global economy arguably generates more than enough. In fact, instead of using their respective growth rates, today's economy is better characterised by striking inequalities in the distribution of wealth and energy. For example, the average global energy use exceeds the decent living energy threshold estimated at ~20 gigajoules per capita by factor three (Kikstra et al., 2021; Millward-Hopkins et al., 2020). However, because the consumption of the wealthiest 5% exceeds the decent living threshold by a factor of ten, their total energy use amounts to more than that of the poorest 55% of the world's population combined (Oswald et al., 2020).

The astounding inequality gap in today's economies makes it possible to imagine equitable scenarios of post-growth. *Chapter 5* outlines the fundamental characteristics of such a scenario, whereby energy and income currently going to excessive consumption and wealth accumulation by the privileged minority would be redistributed towards the universal provision of basic needs, working-time reduction and job guarantees. A post-growth scenario would entail a radical convergence in energy use and income between the Global North and the Global South and the convergence across social classes within both respective regions. In that sense, post-growth is not a negative outcome but rather a sign of economic maturity and high living standards, which have led to a shift from consumerist lifestyles to sufficiency (Dietz and O'Neill, 2013). Moreover, the redistribution in a post-growth scenario would not jeopardise the living standards of the majority in the Global North, as it could be primarily achieved by curbing affluent lifestyles and wealth accumulation of the wealthy minority (Millward-Hopkins, 2022).

6.2 Future research

Methodological contributions and findings of this thesis open several possible avenues for future research.

6.2.1 Net energy and emissions associated with scenarios of higher global warming

Overall, this thesis shows that existing mitigation scenarios lack representation of futures of low energy demand and low economic growth, although these may be the most achievable pathways to meet the goals of the Paris Agreement. However, such a transition is in stark contrast with current climate policies that typically pursue a strategy of green growth and which rarely consider the measures of reducing energy use. Moreover, the insufficiency of current climate policies makes it increasingly likely that the climate targets will be breached and that global warming will reach between 2.5 °C and 3 °C by the end of the century (Hausfather and Peters, 2020; Ya et al., 2021). Therefore, a gloomy political reality may soon compel us to extend the scope of research beyond aspirational futures and to consider scenarios where the goals of the Paris Agreement are overshot.

The framework presented in *Chapters 2 and 3* offers a straightforward approach to model net energy pathways and energy system emissions in scenarios where global warming exceeds 1.5 °C. Based on the analysis performed on scenarios consistent with the 1.5 °C of global warming, we can expect the emissions in scenarios of higher global warming to increase due to bigger energy use and slower decarbonisation. Moreover, previous results suggest that a more gradual replacement of fossil fuels for renewables may lead to a smaller drop in net energy during the initial push for the transition. However, despite higher energy system emissions expected in the scenarios where global warming exceeds 1.5 °C, it remains unclear what share of the remaining emissions in these scenarios would be tied to the transition, as their carbon budgets substantially exceed the value of the 1.5 °C carbon budget. Moreover, contrary to the 1.5 °C scenarios, where the EROI of the energy system declines during the initial push for the transition and increases afterwards, in scenarios of higher global warming the EROI is initially expected to decline by less, but the decline could continue over an extended period, due to the remaining reliance on fossil fuels.

The framework developed in this thesis aimed to estimate the biophysical requirements underlying society's efforts in addressing climate change. While the focus on the mitigation part of climate change may be adequate for scenarios that manage to keep global warming close to today's temperature, scenarios of higher climate impacts need some further considerations. In scenarios of higher climate impacts, climate adaptation becomes the dominant response to climate change, as adaptation costs are estimated to exceed those of mitigation (Chapagain et al., 2020). Likewise, studies estimate the adaptation to higher global temperatures to considerably increase the global demand for energy (Colelli et al., 2022; Yalew et al., 2020).

Therefore, it would be crucial to extend our framework by calculating energy and emissions associated with climate adaptation and the losses from climate change to capture broader biophysical requirements associated with climate change. Such an update of the framework is, in fact, essential for an adequate intercomparison between the scenarios of different global warming temperatures in terms of total energy requirements and emissions associated with climate action. The energy and emissions associated with adaptation would include the energy required and emissions associated with the construction of infrastructure to protect against adverse impacts of climate change, such as dykes, the increased energy demand for space cooling and refrigeration, and the energy required, and emissions associated with improved climate resilience in economic sectors that are most exposed to climate change, such as agriculture. The energy and emissions associated with losses would encompass the requirements to rebuild the infrastructures destroyed in extreme weather events and re-establish the affected economic activities. In the context of climate adaptation, "energy requirements for climate action" could be defined as a sum of the energy requirements of the energy system and the energy requirements for adaptation and losses. Net energy could then be reinterpreted in the context of climate change as a difference between total energy generated and the energy requirements for climate action. Likewise, the “emissions associated with climate action” could combine the energy system emissions with a separate emissions category of “indirect emissions from adaptation and climate losses”.

6.2.2 Towards a general biophysical model of a low-carbon energy transition

As shown throughout the thesis, the energy and emissions associated with a low-carbon energy system are both critical constraining factors of the transition. However, there are other factors to consider, including the availability of minerals, land, labour, and capital, which remain largely unknown in existing scenarios, even though they may further constrain the possibility space of the transition. Further research could extend the model presented in this thesis by quantifying the requirements for these additional factors in different scenarios of a low-carbon energy transition. For example, estimates of mineral requirements could be used to quantify the necessary scale of mineral extraction, which could then be compared with the current flows of extraction and known mineral reserves. Land requirements would inform us about the space dedicated to the low-carbon energy infrastructure and allow us to anticipate possible conflicts due to competing land uses. Labour requirements would give us insight into the size of the working force that needs to be trained to implement the transition on the ground. Finally, capital requirements would improve our understanding of the transformation that needs to take place in the industrial sector. Previous attempts in this direction have been made by MEDEAS (de Blas et al., 2020; Nieto et al., 2020) and EUROGREEN (D'Alessandro et al., 2020) models, which could be used as a starting point for future model development.

By extending the framework to capture a broader range of biophysical and economic requirements for a low-carbon energy transition, one could improve the modelling of necessary changes in the economy's structure and further scrutinise which mitigation scenarios are realistically achievable. In the next step, the framework could be extended by modelling social outcomes by linking the provisioning of goods and services for society with the associated biophysical and economic stocks and flows. Economic systems of provisioning could then be analysed in terms of equality in the distribution of produced goods and services (Kikstra et al., 2021) and by calculating the share of the population that lives above the threshold of material and energy requirements for a decent life (Millward-Hopkins et al., 2020; O'Neill et al., 2018). Furthermore, a series of lifestyle options could be represented with different baskets of goods and services to analyse which lifestyles can be sustained with the provisioning systems in each scenario investigated.

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