FACULTEIT ECONOMIE
EN BEDRIJFSKUNDE

ECOLOGICAL MACROECONOMICS

USING ECOLOGICAL MACROECONOMIC MODELS TO SIMULATE CARBON POLICY SCENARIOS. ARE ALTERNATIVES TO GREEN GROWTH BENEFICIAL TO THE FEASIBILITY OF REACHING CURRENT CLIMATE GOALS?

Aantal woorden/ Word count: 39 169

ir. Alexander Van Overmeiren
Stamnummer/ student number : 01003845

Promotor/ Supervisor: Prof. dr. Brent Bleys

Masterproef voorgedragen tot het bekomen van de graad van:
Master's Dissertation submitted to obtain the degree of:

Master of Science in Economics

Academiejaar/ Academic year: 2022-2023

UNIVERSITEIT
GENT

Contents

Abstract

Governments have expanded their ambitions to tackle climate change. The EU has declared that it wants to reach net zero carbon emissions in 2050, while maintaining continuous growth in the economy. This strategy is also called 'green growth'. These goals will necessitate unprecedented investments in renewable energy capacity, electrification, negative emission technologies and more. It would imply absolute decoupling of the economy from emissions through technological improvements. However, absolute decoupling has been called unattainable or utopian by several authors. In order to stay within ecological planetary boundaries, these authors usually suggest a reduction in material and energy throughput in the economy by stepping away from continuous growth. This is called 'post-growth', as an alternative to green growth. This study provides an answer to the following question: is degrowth, as a form of post-growth, a useful policy instrument in accomplishing current climate goals? The ecological economic model MEDEAS was used to simulate different policy scenarios. In the end, two net zero scenarios were found that include degrowth as policy instruments. In accordance with previous studies, these showed that higher rates of degrowth will lower the needed environmental investments to reach net zero. However, it was found that reaching net zero requires a broad set of policies. Degrowth alone is not enough. While the challenge is daunting, reaching climate goals remains possible and appears to becomes more feasible if economic output is lowered.

Acknowledgements

I would like to thank prof. Bleys for his many suggestions, literature recommendations and frequent feedback while I was writing this dissertation. His suggestions and feedback have helped me to delve deep into the topic of ecological economic modelling. I would also like to thank him for helping me set up an interview with a research group in Barcelona headed by prof. Solé that works on the MEDEAS model. The extensive interview was very helpful in understanding interesting and unexpected outcomes from scenarios that I had simulated.

I am grateful for the support I got from Amber, Ruben, Linde, Xavier, Marco, Anneleen and Laura. Thank you Amber for your detailed review of this dissertation. Many of your suggestions found their way into the final version and without a doubt improved the overall reading experience. Thank you Ruben for reviewing the introductory sections and using your customary eye for detail to highlight some points of improvement. I would like to thank Luc, Tine and Ann for their support at work and for their faith that I could bring this endeavour to a succesful end. Thank you all for supporting me through this period in which I was balancing a full-time job and part-time studying. It was a challenge, but you guys made it exciting and fun.

1 Introduction

In February 2022 the Intergovernmental Panel on Climate Change (IPCC) published their sixth assessment report (AR6) on climate change (CC). Owais (2022) has written an overview summing up the main conclusions found in AR6. The report examines global emissions, progress towards mitigating these emissions and analyses the effects of national policies on reaching their stated emission goals. At this time, global emissions are increasing, albeit at a slower pace than during previous decades. If a business as usual (BAU) approach is followed with regard to current abatement strategies during the coming years, then global warming will definitely exceed the Paris goal of 1.5 degrees Celsius (°C) global warming. Even though the economic costs of mitigation will be large, the IPCC has written that keeping global warming below 2°C can outweigh the costs of carbon reduction. Managing the effects of global warming, reduction of carbon emissions and creating a sustainable economy are important policy objectives in present times.

The European Comission (EC) has taken legislative action in order to handle imminent ecological challenges and to prevent the worst effects of climate change. The European Commission (2022) details a set of climate strategies and targets describing how the EC wants to achieve climate neutrality by 2050. The EC defines climate neutrality as having net zero greenhouse gas (GHG) emissions by 2050. An intermediate goal is a 55% net reduction in GHG emissions (GHGE) by 2030 compared to 1990 GHGE levels. At the time of writing, this goal will have to be reached in seven years. The Council of European Union (2022) sums up the EU policies in the following five facts:

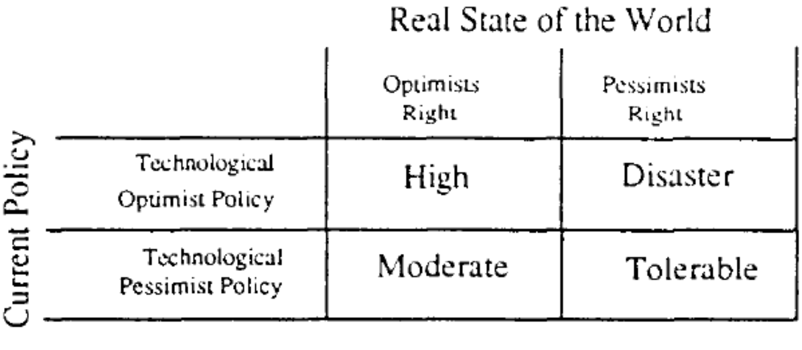
1. Climate neutrality is about emitting less and absorbing more. This encompasses using greener fuels, becoming more efficient and expanding forest and soil capabilities of absorbing CO_2 from the atmosphere.
2. EU climate action is not new, but the Green Deal is. The Green Deal is an investment package to help the union deal with the challenge of climate change while maintaining economic growth. Two examples of investments would be making buildings more energy efficient and decarbonization of the energy sector.
3. Climate strategy is not only about environmental policy, but it will require changes in all aspects of life. People will have to change their methods of transportation, food consumption and more.
4. Climate strategy will have to be just. Different regions in the union rely on fossil fuels in varying degrees. The just transition policies will support the regions with high fossil fuel dependency in their transition.
5. The EU's position impacts the rest of the world, since the climate goals will have global effects. The EU can influence third countries by including environmental components in bilateral trade deals, exchange of technology and expertise. The

> development of the carbon border adjustment mechanism will be designed to support the competitiveness of European companies while creating financial incentives to reduce environmental impacts abroad.

To reach the EU goals, policy makers can find some insights in ecological economics (ECE). Ecologial economics and environmental economics (ENVE) are subdisciplines of economics that find their origin in the 1960s and 1970s. Their development was sparked by social and environmental crises caused by a growth-obsessed world, and also by severel significant publications that stressed the importance of connection between human society and the natural world (for example *Silent Spring* by Carson and Wilson (2002), *Limits to growth* by Meadows, Randers, and Meadows (2004) and *Our Common Future* by World Commission on Environment and Development (1987)). In these publications and in ECE, the connection between economic activities and nature takes centre stage.

There are several paths society can folow to reach net zero in 2050. Among other things, there is discussion about the view on economic growth. One view is called 'green growth' (GG), which keeps the conventional economic vision of continuous growth. The other is called 'post-growth' (PG). Proponents of PG suggest that society should be designed in such a way that it will not exceed the ecological limits of the earth. These proponents do not inherently say economic growth is a bad thing, Hardt and O'Neill (2017) write, as long as it happens within these ecological limits. PG economists usually see zero-growth (ZG) or degrowth (DG) as possible policy tools to reduce the environmental impact.

So far, policy makers have mostly followed the GG strategy, Parrique et al. (2019) say, which implies absolute decoupling of the economy from emissions through technological improvements. Ecological economists have criticized this strategy, for a number of reasons. For example, Jackson (2016, p. 43) points out that higher growth does not necessarily lead to increased well-being. Furthermore, ECE is usually rather technologically pessimistic, or as Costanza (1989) calls this: "prudent pessimism". The motivation for taking this stance can be understood by looking at the image below. If technological innovation does not come through, yet society followed GG policies, it will lead to climate disaster according the matrix. If technological innovation does come through, but society followed DG policies, it will lead to missed out growth, which is labelled as moderate.



		Real State of the World	
		Optimists Right	Pessimists Right
Current Policy	Technological Optimist Policy	High	Disaster
	Technological Pessimist Policy	Moderate	Tolerable

Figure 1: Payoff matrix technological optimism versus pessimism by Costanza (1989)

Thus, if GG with its dependence on technological innovation and absolute decoupling is not a viable solution to the challenges posed by climate changes, that leads to the main questions of this dissertation: is DG, as a form of PG, a useful policy instrument in accomplishing current climate goals? If so, what level of DG would lead to the best possible outcomes? How can DG be combined with environmental policies to reach net zero scenarios? How feasible are those scenarios?

Models allow policy makers to simulate different policy scenarios and their outcomes, helping them compare different paths towards net zero in 2050. This dissertation will also answer the research questions by simulating DG scenarios using an ecological economic model (ECEM) which is a type of integrated assessment models (IAM). IAMs combine economic, ecological and social functions, or any combination thereof. These types of models are complex and aim to connect different fields of science into one overlapping model. That is why this dissertation will also analyse how ECEMs are constructed, to deeply understand how models may help settle on/choose an economic strategy to reach climate goals.

To answer the research questions mentioned above, this dissertation will begin with a literature review, specifically: a historical overview of the development of ECE (chapter 2), an overview of relevant economic theories (chapter 3), important concepts that connect the economy and the environment (chapter 4) and a discussion of ECEMs, including an updated overview of current models (chapter 5). Chapter 6 will explain the methodology: candidate models, criteria for choosing MEDEAS and scenario simulation. Chapter 7 contains the results, followed by the discussion in chapter 8 and finally the conclusion in chapter 9.

The conclusion consists of four sections. The first section will discuss points of improvement for MEDEAS. The second section will compare MEDEAS to other ECEMs and give suggestions for future research. The third section will place ECEMs within the broader field of economics. The last section will elaborate in what way ECEMs can be useful for broader society and policy makers, with general remarks on a possible path forward for society in these challenging times.

2 History of ecological economics

In this first part of the literature study, the history of ecological economics will be built up, starting from the first economists in the 19th century who developed the school of political economics up to modern ECE theories. This part will show how the views of macroeconomists regarding nature has evolved since the early beginning of the science of economics. Historical building blocks will be described that lead up to the creation of the modern field of ecological economics in 1988.

2.1 Precursors of ecological economics (19th century - World War 2)

Theories involving the interaction between economies and the environment can first be observed in the late 18th and 19th century. De Steiguer (1995) wrote a paper on these theories that accounted for environmental effects in one way or the other. Some of these models were developed by famous economists: Thomas Robert Malthus, John Stuart Mill and Alfred Marshall.

De Steiguer (1995) describes the societal effects of the Industrial Revolution (IR) as the context in which the first economists operated. In the late 18th century the IR spread from England to Europe. Three important developments paved the way for industrial manufacturing. These are coal as an energy source, the steam engine and gas lighting. Rising demand for labour in these industries caused migration from the countryside to cities. This lead to rapid urbanisation in Europe. During the IR the mortality rate of people started decreasing, which was one of the causes of fast population growth. Economic hardships caused the poor to live in (near) destitution. As academics observed these hardships, a new school of thought came into existence that researched how to deal with scarcity, allocation and human well-being. This school of thought was political economics.

The following quote by Adam Smith demonstrates this school's focus on well-being:

"The principle object of this science is to secure a certain fund of subsistence for all the inhabitants, to obviate every circumstance which may render it precarious; to provide every thing necessary for supplying the wants of the society, and to employ the inhabitants (supposing them to be free-men) in such a manner as naturally to create reciprocal relations and dependencies between them, so as to make their several interests lead them to supply one another with their reciprocal wants." (Adam Smith, as cited by Raworth (2017, p. 33))

2.1.1 Malthus and the Classical Economists

The classical economists attempted to find rules that govern society by using reason. These scholars used the philosophy of natural law as their research method. Murphy (2019) explains the concept of natural law extensively. The concept was first argued for in the work of Thomas Aquinas. Aquinas distinguishes between the role of the giver and the receiver of natural law. Aquinas considered God to be the giver, as a part of divine providence. The receiver is humanity. Natural law consists of the principles by which actions can be judged as reasonable or unreasonable. These principles should be universally binding and comprehensible by every human. Natural law as such is an important part of practical rationality. The classical economists wanted to find these natural laws that governed society.

The model that is usually associated with Malthus is the model in which agricultural output grows arithmetically and the human population grows at a geometric rate. This would lead to famines and other tragedies as population growth would outpace the growth of agricultural output. This is a very simplified view on Malthus's theory. The Malthusian model uses more factors than the aforementioned land and population. De Steiguer (1995) discusses Malthus's theory of scarcity in more detail. Malthus saw land as one production factor, next to labour and tools. If all land is used for agriculture, there would still be room for increases in productivity. Malthus argued further that each new addition of labour will be less productive than the last one. Malthus used the concept of diminishing marginal rates of return on labour. In the end, famines and other tragedies will keep happening periodically. In Malthusian economics continuous growth is not a possible outcome. Loschky and Lee (1987) have developed and estimated a Malthusian model on historical data. This model finds oscillations due to the presence of biological and social lags. They find that real wages influence birth rates directly and indirectly by its influence on marriages. Loschky and Lee (1987) write how models that contain these oscillations can enrich the understanding of economic-demographic interaction in societies that existed before the IR.

2.1.2 Mill's Equilibrium theory

De Steiguer (1995) describes the following contributions of John Stuart Mill to classical economics. Mill theorized that growing human populations and wealth will reach a limit. This would be a stationary state where population and consumption are in equilibrium. As there are limits to the aggregate consumption by humanity, a growing population could lead to a low pro capita welfare. As such, Mill argued, policy makers should stabilize the size of the human population immediately, consumption should be reduced and wealth distributed more equitably. This would lead to a desired steady state with high welfare for the most people.

Another interesting view of Mill was how he looked beyond material consumption as an important factor in human welfare: moral, social and cultural progress will keep contributing to further improving the human condition. Mill argues that increasing development of land for agriculture and mining will lower the quality of the human environment. Mill's view on living in balance with the environment sound quite modern. Raworth (2017, p. 43-45) reveals similar views when she describes her concept of the Doughnut.

Spash (1999) adds to Mill's insights, by saying how Mill envisioned that non-renewable resources could put a strain on economic growth, independently of demographic growth. Technological development could postpone the limits to growth caused by resource scarcity. Spash (1999) mentions William Stanley Jevons as another economist who proposed limits to growth on the 19th century English economy due to coal depletion. This prediction did not come true due to the discovery of oil and helped establish the argument of resource depletion not being problematic in modern economics, Spash writes.

2.1.3 Neoclassical economics

In the late 19th century, the neoclassical school emerged and greatly influenced economic thinking. While the previously discussed economists used natural law to understand the rules in society, this school started using mathematics and methods associated with engineering to analyse the mechanisms at work in markets. De Steiguer (1995) discusses how neoclassical economists saw equilibria reached in efficiently working markets as the means to maximise welfare.

Alfred Marschall is a key economist of this school, De Steiguer (1995) writes. Looking at Marschall's original work, one can see how he leaves behind the concept of natural law. The alternative Marschall proposes is looking at the behaviour, wants and needs of people. Marschall (1920, p. 14-15) keeps an ethical component in his view of economic behaviour. The desires of the individual that prevail, Marschall writes, should help in building a strong and righteous character. With regards to modelling, Marschall (1920, p. 64) has developed mathematical and graphical ways to represent economic processes. For examples, he designed a graph containing the budget line and what would become an indifference curve. These kinds of models still appear in economic textbooks to this day.

Using the mathematical and graphical representations of markets, meant a new way to measure social welfare was found. The neoclassical economists measured welfare using consumer and producer surpluses in the market. Later on Pigou also added the concept of externalities. Tietenberg and Lewys (2018, p. 25) define externalities as the impact of one agent's choices on the welfare of another. Externalities can have positive and negative effects on people's welfare. By adding externalities to models, it became possible to calculate the effects on human welfare that changes in the environment have. These neoclassical models opened a door towards policies that regulate compensation for negative externalities. Taxes on polluters and restitutions towards those suffering from pollution would be an example of such a policy, De Steiguer (1995) writes. Edenhofer, Franks, and Kalkuhl (2021) have written a paper on the 100th anniversary of the publication of Pigou's most famous book *The Economics of Welfare.* The Pigouvian tax is a tax rate imposed on agents that cause negative externalities on other agents, that leads to an optimal total welfare.

This way of approaching environmental issues is typical of environmental economics. This school of economics uses methods that are associated more with microeconomics. Microeconomics, Heylen (2020, p. 6) writes, studies behaviour of individual agents and their interactions on a single market. This in contrast to previously mentioned economists who discuss ecological issues on the scale of a country or society, on the macroeconomics scale. Using neoclassical methods to solve environmental issues will be an important difference between environmental economics and ecological economics. The latter will not use neoclassical methodology as a foundation, as the assumptions used do not represent reality as seen by ecological economists. This will be elaborated upon later.

2.1.4 Economies of resource extraction

As relevant 19th century theories are discussed, the 20th century dawns. Spash (1999) describes precursors to ecological economic thinking developed in the early 20th century. There was little regard given to environmental issues by mainstream economists at the time. The general view on the economy was that it could function independently from resource constraints and the environment's capacity to process pollution. Some work has been done that is relevant to this day: optimal resource extraction of non-renewables, intergenerational resource use, energy-economy interactions, developments in agricultural economics on soil preservations and more. The work by Gray (1914) is one example economic theory of this time period. Gray studied the economies of resource extraction and discusses the effects of policies on extraction behaviour of mining companies. Different policies take the form of possible tax schemes. One example he studies is the effect of an annual tax on operating a mine. This would increase the extraction rate, as faster extraction would lead to less taxes paid overall.

2.2 Precursors of ecological economics (World War 2 - 1970s)

In the second half of the 20th century, ENVE and ECE develop into formal subdisciplines in economics. These decades saw the publication of multiple influential works that reached mainstream audiences and influenced policy makers to take protective measures for the environment. *Limits to Growth* and *Silent Spring* are some well known examples. Environmental Protection Agency (2022) writes how it was established by president Richard Nixon in 1970 due to increased public concerns with regards to the environment.

2.2.1 Safe minimum standard

The concept of 'safe minimum standard' was developed by Ciriacy-Wantrup in 1952 and further elaborated upon by Bishop in 1978, Spash (1999) writes. Bishop (1978) used the work of Ciriacy-Wantrup as the basis for his research on the economics of the safe minimum standard with regards to endangered species. The safe minimum standard (SMS) is developed for a specific category of renewable resources. The resource is renewable, but within limits. There is a critical zone of exploitation of this resource which would damage the resource's capacity to recover from extraction. Because of this characteristic, there must exist a safe minimum standard of the resource base that will not endanger its capacity to replenish. An example of this is sustainable fishery: fishermen will not catch all the fish they can. This ensures the fish population remains healthy in the next years.

Important ideas that arise from SMS for further modelling are carrying capacity and overshoot that damages the renewable resource. Bishop (1978) adds social and natural uncertainty and 'intolerable costs' to the SMS approach, Farmer and Randall (1998) add the importance of a universal moral theory to develop SMS policies, as different societies might put different values on sacrifices made to preserve natural capital. This concept of SMS can be found in the more recent work by Steffen et al. (2015) on the seven planetary boundaries.

2.2.2 Kapp's criticism of neoclassical (environmental) economics

Spash (1999) mentions the work of Karl William Kapp and his 1950 and 1970 papers. Kapp criticized the neoclassical approach to answer environmental questions. Kapp called externalities pervasive social costs resulting from the context within which markets operate. He discarded market prices of environmental externalities, because markets in reality do not function in perfect competition. This leads to the observation tat effects of environmental damage or improvements cannot be quantitatively compared due to their heterogeneity.

Gerber (2016) studied the work of Kapp. Central to the work of Kapp was the integration of economics, social sciences and natural sciences in decision making. This can be observed in his views on social costs, which can be economical, ecological, cultural and psychological in nature. In his work, Kapp steps away from economic growth as the main indicator. He suggests social and ecological standards as a way to examine the status of a socio-ecological system. This way of thinking can be seen in the social development goals put forward by United Nations Development Programme (2022) or in the doughnut by Raworth (2017).

2.3 Developments in early ecological economics (1970s - 1988)

Røpke (2004) has compiled an overview of early EE related developments. EE has at its foundation a heterogenous group of scientific fields: system ecology, socio-economics, system dynamics, environmental economics, biophysical economics, energy flows based on engineering and physics. In a recent publication Batker (2020) lists general points that ecological economists usually agree on. Firstly there are physical limits to the size economy, secondly this leads to questions about just distribution of these finite resources and thirdly questions about allocation of these resources within limited sources, sinks and throughput.

In a publication in the late 1960's Daly (1968) describes economics as a life science. The economy as a whole will behave in a way comparable to an organism. The economy needs energy and resource inputs and will develop waste and dissipated energy. The economy consumes low entropy inputs and produces high entropy waste. Daly argues that the economy can't be seen as separate from the natural world, but as a subdivision of this natural world. One way to make these connections between the natural world and the economy tangible is through ecosystem services. Kreager (2022) writes that ecosystem services were developed in the 1970's, as a way to increase the interest of the public for conservation efforts. Tietenberg and Lewys (2018, p. 307) describe ecosystem services as functions and services provided by the ecosystem, usually for free, that benefit at least one person. Examples of these services are carbon sequestration by forests, pollination by insects, nitrogen fixation and many other services. Costanza et al. (2014) estimate the total value of ecosystem service to be much larger than the global GDP (roughly $> 66\%$ larger in 2011). The authors mention that one of the challenges in managing these valuable services is that they do not have the characteristics of private property. Ecosystem services behave like common pool resources or public goods. This implies that using free market instruments to manage them will not be optimal. It is well known that the health of the ecosystems has deteriorated over the last decades, Tietenberg and Lewys (2018, p. 308) write, due to increasing demand on the earth resources and services. Some changes will be irreversible and make it harder to reach Millennium Development Goals.

Daly makes an argument for a steady state economy. Røpke (2004) states that using biophysical perspectives when looking at the economy has caused several authors to question the mainstream views of continuous economic growth in politics and economic thought. To illustrate important developments for the field of ECE, two contributions will be explained in more detail: *Limits to Growth* by Meadows, Randers, and Meadows (2004) and *The Entropy Law and the Economic Process* by Georgescu-Roegen (1974).

2.3.1 Limits to Growth

In 1965 Italian industrialist Aurelio Peccei and Head of Science at the Organisation for Economic Co-operation and Development (OECD) Alexander King both were concerned for the future of human society and it's interaction with the planet. They gathered a group of researchers to study the effects of continuous exponential growth. In this research they simulated the evolution of demographic growth, agricultural output, resource use, industrial production and pollution, as written by Club of Rome (2022) on their history. The Club of Rome is well known for writing *Limits to Growth* (LTG) in 1972, Meadows, Randers, and Meadows (2004) is an updated version of the original 1972 publication after 30 years have passed.

The simulations were done by running computer models that used system dynamics (SD), which allows for richer interactions between variables compared to linear models. System dynamics will be explained in more detail later in the part on modelling techniques for ECE models. The Club of Rome used the World 3 model they designed to simulate the evolution of aforementioned variables in different scenarios. Meadows, Randers, and Meadows (2004, p. 158) found four types of behaviours and their underlying structural causes:

- Continuous growth would happen if physical limits are very far off or the limits grow exponentially.
- Sigmoid growth towards the limit of a variable if signals from this variable are immediate and the economy responds immediately or society limits itself without needing signals from their limits.
- Overshoot and oscillations if signals or responses are delayed and limits can recover from overshoots.
- Overshoot and collapse if signals or responses are delayed and limits cannot recover from overshoots.

Meadows, Randers, and Meadows (2004, p. 167) write that the fourth behaviour will be the most likely to happen: population growth will only stop when people are very rich, economic growth only stops when confronted by its limits, there are delays in the feedback (FB) loops within these systems and the processes governing the global ecosystems have a lot of inertia. In the final chapters of LTG, Meadows, Randers, and Meadows (2004, p. 259-260) have laid out guidelines for policy makers to follow in the transition towards a sustainable system.

Turner (2008) writes in his comparison of LTG to 30 years of reality how policy makers did not heed the warnings and applied the suggestions formulated in LTG. He continues discussing the methodological approach used in LTG. It brought system dynamics and quantitative scenario analysis into environmental school, it created an integrated global model by linking the economy and the environment. Turner used data gathered from 1970-2000 and compared it to the simulations made in the original LTG. He found that the data most closely followed the 'standard run' in LTG, which is simulation run using 'BAU' inputs. He concludes by saying that, unless the models in LTG are invalidated by other research, that the world is on an unsustainable trajectory. Turner (2014) repeated his research with another decade of data and came to the same conclusions. The primary cause of collapse, according to him, is the increasing costs of resource extraction, while in general the public would assume GHG emissions would be the main cause of collapse. The critical state of reserves with regards to natural resources has been published by BBC (2012), which shows that known rare earth metal reserves will be depleted long before the effects of climate change come into effect, according to the estimates at the time.

2.3.2 The entropy law and the economic process

During the 1970's economist Georgescu-Roegen used the physical concepts of entropy, energy transformations and their interactions in energy flows in economics to understand evolutionary processes in economics as he termed them. The following definition of entropy will be useful to understand the reasoning of Georgescu-Roegen:

"a measure of the unavailable energy in a closed thermodynamic system that is also usually considered to be a measure of the system's disorder, that is a property of the system's state, and that varies directly with any reversible change in heat in the system and inversely with the temperature of the system" (Merriam-Webster 2022)

Georgescu-Roegen (1974, p. 302-304) develops an example of his way of thinking and the economic process of mechanization in agriculture. In the distant past the energy necessary for agricultural production only came from the sun, which supplies low entropy energy to the crops. Humanity used draft-animals to lower the amount of labour that each person should supply on the fields, this decision increased their enjoyment of life. Draft animals turned solar energy into draft energy by eating plants. As human and animal populations grew, competition between food and feed crops increased. Mechanization offered a way out by supplying draft power and not needing feed to function. Oil is the new energy source with low entropy to power mechanization. Draft animals produce manure, which helps preserve the soil quality. Mechanization reduced the need for draft animals and the supply of manure. So a substitution for manure was found by using chemical fertilizers, the production of which depends on new low entropy sources like oil. Georgescu-Roegen continues by saying that technological progress has continued the shift towards the use of these new entropy sources. He expects that, due to non-renewables being finite, humanity will be forced to return to relying on solar energy.

2.4 Modern ecological economics (1988 - 2000s)

Røpke (2005) has written a follow up paper to the paper discussed in the previous section. ECE as a discipline in its modern form took shape in 1988. In 1988 the international society of ecological economics (ISEE) was established. In the following year the first issue of the Ecological Economics journal was published. In this edition, Costanza (1989) explains what ECE is as a scientific field. ECE, he writes, will describe the relationships between the ecosystems and economies present in these ecosystems in the broadest way. These connections are where many current challenges for humanity are located: global warming, sustainability, species extinction and more. A more detailed description of ECE will follow later in the text. Røpke (2005) writes that the development of ECE was necessary, as none of the existing disciplines were able to take this perspective of the embeddedness of the economies in ecosystems. In the 1990s different controversial issues emerged when ECE was confronted by mainstream economic views, which are still currently relevant:

- How substitutable is natural capital by man-made capital?
- Does economic growth cause deterioration or improvement of the environment?
- Does trade lead to deterioration or improvement of the environment?
- Can technological change solve environmental issues?
- How strong is the relationship between quality of life and economic growth?
- Does nature have intrinsic value?

Røpke (2005) describes how the views of ENVE and ECE can be opposite when looking at these questions. The former will usually be more technologically optimistic, while the latter is more sceptical. This is the aforementioned "prudent pessimism" with regards to technological developments. These decades saw new theoretical developments. Three paths will be discussed: firstly the views on the scale of the economy, secondly valuation strategies and thirdly energy theories of value.

In ECE, the economy is embedded in the ecosystem. This leads to the concept of the scale of the economy. The economy uses resources and produces wastes, which are dependent on economic output. The scale is the space humans use in the closed system that is planet earth. An important question is to find the scale at which the economy can operate sustainably. Different approaches to express the size of the economy have been developed by ECE: energy, exergy (the amount of work a system can provide before reaching thermodynamic equilibrium, as explained by Jørgensen (2008)), land area, product of photosynthesis and materials. If land area is chosen as an approach to determine the size of the economy the size becomes the ecological footprint of the economy. Some researchers found that these approaches focus to narrowly on the economy and propose jointly determined ecological-economic systems. Development of these systems is path dependent and changes can be irreversible. Resilience becomes an important characteristic of the ecological-economic system. This is a measure of the intensity of a shock that can be absorbed without the system being pushed towards a different equilibrium state. Resilience is higher if a larger biodiversity is present. An example given by Røpke (2005) is how a keystone species that supports the organization of the ecosystem can be replaced by another species if they would go extinct, provided the biodiversity level is high enough. She continues by explaining the importance of ecosystems for humans: providing resources for society, assimilating pollution and in providing ecosystem services.

A second path of theoretical developments focus on the valuation strategy applied in ECE. If policy makers need to choose between a set of action they could take, they will need a way to value the different options against one another. Røpke (2005) explains that alternatives for cost-benefit analysis need to be developed, because many valuable aspects of the environment cannot be expressed in monetary terms. Different languages of valuation exist: justness, emotional value, intrinsic value of nature, rights of individuals. When making value judgements, multicriterea analysis can be applied in ECE.

A third path relates partially to the valuation strategies that can be applied: energy theories of value. Røpke (2005) writes that not much development has happened with regards to energy theories, but they are important in describing the scale of the economy, the scale of economic processes for different variables and the efficiency of these processes.

2.5 Conclusion

Describing connections between the natural world and the economy are as old as the science of economics itself. Thomas Malthus and Adam Smith were contemporaries and communicated with each other on economic matters, Kreager (2022) writes. The importance of these connections was sidelined as limits to growth seemed non-existent due to the discovery of new energy sources, like coal and oil. Mainstream economics kept pursuing continuous growth and keeps pursuing it to this day. The development of ECE regained traction due to increased interest in the environment after the publication of influential books. The field of ECE aims to describe the relationships between ecosystems and economies in the broadest sense possible, for which it will use concepts stemming from a variety of scientific disciplines. As said before, it is in these relationships that many of the most pressing challenges of humanity exist: climate change, biodiversity loss, dealing with a finite resource base and more. The next part of this text will describe relevant economic theories that will return in the rest of this work repeatedly. After that additional important concepts will be discussed in detail that are used frequently in ECEMs. The final part of this literature review will discuss contemporary ECEMs, how they can be set up and in the end an overview of current ECEMs.

3 Overview of relevant economic theories

Different theoretical economic models are used in designing ECEMs. The choice of model will impact the behaviour of the ECEM. An overview of relevant economic theories will help the understanding of contemporary ECEMs and their behaviours.

3.1 Macroeconomics

Macroeconomics is a branch of economics that studies the functioning and evolution of economies as a whole, in contrast to microeconomics, which studies the behaviour of single agents within the economy. Macroeconomics studies relationships between aggregated variables, Heylen (2020, p. 5) writes. Examples of these variables are: savings (S), investment (I), inflation, growth, interest rates, inequality, consumption (C) and government spending (G). Two important schools within macroeconomics will be discussed: neoclassical economics (NCE) and post-Keynesian economics (PKE). The framework of the former is used by ENVE, Spash (1999) writes, and the framework of the latter is more often used by ECE, Hardt and O'Neill (2017) say.

3.2 Neoclassical economics

The NCE school arose in the first years of the 1970s, Heylen (2020, p. 71-74) writes, as a response to the Keynesian view on governmental actions in the economy. They criticized the lack of microeconomic foundations, weak ways in which agents developed expectations and lacking dynamics. The NCE school suggested the real business cycle (RBC) approach as a better way to understand the macroeconomic processes in the economy. In this approach the economy is perfectly competitive with flexible wages and prices. The agents in these economies are perfectly rational and have access to all relevant information. The agents will be able to form rational expectations and have a perfect understanding of how the economy works. Households will behave in a way that maximises their lifetime utility. Firms will behave in a way that maximises their profits. The NCE point of view will lead to fundamentally different outcomes of policies and interpretations of behaviours of the economy compared to Keynesian views. The following list shows examples of NCE outcomes that differ significantly from Keynesian views:

- Monetary policy will not have a real effect on the economy.
- Budgetary policies by the government will not have real effects on the economy anymore, as agents can predict the actions of the government.
- Business cycles are optimal responses by agents to shocks.
- Unemployment is a rational choice and response to negative technology or demand shocks.

King and Rebelo (1989, p. 5-9) have written a paper that discusses NCE growth theory and transitional dynamics. The production function in a basic form will be represented by a Cobb-Douglas production function, which allows substitutability between production factors. This substitutability will be a major point of criticism by ECE scholars. These production factors usually are labour and capital. The neoclassical growth function will be supply driven. The savings function can be a fraction of income or an outcome of optimal consumption choices by households. The savings rate will drive the rate of investment. This rate of investment will determine the rate of capital accumulations. As long as the amount of capital accumulation is larger than the fraction of capital that is discounted each period, the capital present will grow in size, just as the economy. In this basic form, the economy uses the Solow model and will be able to reach a steady state growth rate if continuous technological development is present.

3.3 Environmental economics

ENVE is a school of economics that developed in the 1960s and 1970s due to increased interest in the environment, as mentioned before. ENVE utilizes NCE methods to find solutions for environmental issues. According to Tietenberg and Lewys (2018) and Pearce (2002), examples of ENVE assumptions are: utility maximization of agents, the possibility of continuous growth, substitutability between human, natural and physical capital and rationality of agents. ENVE will use economic incentives to guide economic agents towards less damaging behaviour. Typical problems handled in ENVE are discussions about externalities and compensation thereof to find economically efficient solutions. The presence of negative externalities will produce suboptimal levels of human well-being. Examples of this are water and air pollution. (Environmental) externalities are seen as effects stemming from market imperfections. This will lead to inefficient allocation of resources and/or pollution. Tietenberg and Lewys (2018, p. 23) write that these can be caused by property rights systems that are not exclusive, transferable and enforceable. Environmental issues frequently do not have this efficient property rights system. One possible solution to this has been mentioned before as the Pigouvian tax rate to correct externalities.

3.4 Post-Keynesian economics

Stockhammer (2022) writes that PKE is a school of economic theory that differs from NCE in how it approaches the economy. PKE follows Keynes's insights that the world evolves in fundamentally uncertain ways. This will have consequences for investment decisions. These will not be made in fully rational ways. In PKE terms, Holt, Pressman, and Spash (2009, p. 119) write that economic agents have bounded rationality. Gathering information can be costly in time and/or money. Agents will rely on information that is available in the surroundings where they operate. This way, the bounded-rational individuals will have to depend on the collective experience of their surroundings. These irrational behaviours cause markets to lack a self-adjusting mechanism towards equilibrium and guaranteed full employment. Cyclical dynamics can be a consistent property of the economy in PKE. King (2015) discusses important building blocks of post-Keynesian economics (PKE). He discusses the following six core propositions of PKE:

1. Employment and unemployment are determined in the product market, not in the labour market. This is analogous to saying that employment will be determined by the aggregate demand.

2. Involuntary unemployment exists and is caused by a deficit in effective demand. PKE allows frictional and structural unemployment to exists next to each other. The former is caused by the lack in effective demand, while the latter is non-demand-deficient unemployment. A demand-deficient economy is one in which full employment is not reached. This kind of unemployment will not be eliminated by labour-market policies which fix the labour market imperfections.

3. The relationship between aggregate investment and aggregate savings is fundamental to macroeconomic theory. Causation runs from investment to savings. Investment will be the driving force of the capitalistic economy; as such the determinants of investment should be the first step in the analysis of this economy. Investment decisions will be part of the aggregate demand. This in contrast to life-time utility maximization by consumers. Investment will determine individual's incomes through its effects on aggregate demand. Individuals will save part of this extra income and consume or invest the rest.

4. A monetary economy will be different from a barter economy. Money is not neutral and theory cannot be divided in a monetary and a real part. Finance is important in macroeconomics as expenditures for the aforementioned investments need to be paid in advance. Debt is important and behaviour of creditors and debtors as well. The latter can be forced to decrease their expenses, while the former cannot be demanded to increase their expenses.

5. The quantity theory of money is rejected, as money is not neutral. In PKE money is generated endogenously, rather than exogenously. In more practical terms, the supply of money is demand driven. When an agent needs a loan, banks create a deposit and an advance. This change in causation leads to the observation that changes in money supply will follow from changes in economic activity. Monetary policy will be determined by a given rate of interest, not a given amount of money supply. Increases in money supply will not cause inflation, but will be caused by inflation. In other words, cost-push shocks, like wage or input-price increases, will cause inflation. Thus PKE suggests policies that influence those shocks will be necessary to let inflation evolve to a desirable rate.

6. Capitalist economies are driven by the 'animal spirits' of investors. Investors will not make their decisions based on precise calculations of future incomes, but will utilise rules of thumb to deal with uncertainty. Akerlof (2003) observes that the stock market is more volatile than one would expect if stock prices were truly a representation of the predicted value of future returns. Stock prices are too responsive to news as well. Two points that show how the stock market is not an efficient market.

In short, PKE will describe the economy as demand driven, where agents with bounded rationality make decisions based on incomplete or asymmetrical information using heuristics. The financial sector and monetary authority will have real effects on the economy.

The assumption of the existence of a natural rate of unemployment and intrest rate is discarded, Post-Keynesian Economics Society (2022) writes. Bachner et al. (2020) summarizes important characteristics of PKE. PKE uses heterogeneous agents as the consumption or investment behaviour varies between income groups. PKE allows economies to not function at full capacity and agents to make short-term and long-term decisions.

3.5 Ecological economics

As said in the previous part, ECE developed into a full-fledged field of science in 1988. Some previously written parts will be restated here to bring the most important elements of ECE together. This way it will be easier for the reader to find the relevant information of what ECE is. Røpke (2004) wrote that EE has at its foundation a heterogenous group of scientific fields: system ecology, socio-economics, system dynamics, environmental economics, biophysical economics, energy flows based on engineering and physics. Costanza (1989) said that ECE will describe the relationships between the ecosystems and economies present in these ecosystems in the broadest way. Batker (2020) explains some general points that ecological economists usually agree on:

- Physical limits exist to the size economy.
- These finite resources need to be distributed justly.
- These resources need to be allocated efficiently.

These points will need the economy and society to behave differently from a world with infinite physical growth. Spash (2017) writes that ECE places the economy within its biophysical boundaries, while it focusses on the needs of those in the present and the future, expanding these views even to non-human life. Tietenberg and Lewys (2018, p. 7) write that ECE has a pluralist methodology. Hardt and O'Neill (2017) expand on this by stating that ECE rejects orthodox ways to describe the interactions between the environment and the economic world. As alternatives to the orthodox views, the authors suggest taking ideas from neo-Ricardian, Marxist or evolutionary economics. ECE proponents argue that assumptions made in neoclassical models (which is the economic foundation of ENVE) do not represent reality.

General themes on which the views of ecological economists deviate from the neoclassical economists have been summed up by Daly (2019). ECE does not do away with the models as used by conventional economics, but builds upon them with new variables and explicit connections between the economy and the natural world. ECE will not accept the assumption of substitutability which is a part of ENVE. Production functions will not have the smoothness as modelled in neoclassical economics due to possible discontinuities in ecological systems. These discontinuities could be caused by irreversible damage to the ecosystem. ECE prefers low discount rates. High discount rates will lower the importance of future generations and will lead to less sustainability.

Pearce (2002) writes how ECE advocates probably see environmental issues as much more threatening than ENVE advocates. He argues that ECE contains contradictions and ambiguities, as it accepts a broad set of viewpoints on the functioning of society. Methodological pluralism and multidisciplinarity still form a central part of ECE, which can lead to significant discussions on how to approach problems. Recurring themes in ECE are questions about the connection between GDP and welfare, between GDP and physical resource use in the concept of decoupling, substitutability of natural capital, physical capital and human capital and more. Farley and Kish (2021) explains that reaching the goals of ECE will require changes in moral values, institutions and behaviours, supplemented with technological change and simple behavioural nudges. According to Farley and Kish (2021), the latter two will not suffice in reaching a sustainable and just society. Svartzman, Dron, and Espagne (2019) formulate comparables a criticism of models based on NCE or PKE as insufficient in how they describe nature. This insufficiency might be a consequence of theory formation during the post-WW2 golden age. In this period, access to biophysical production factors as resources and pollution sinks were abundant. This neutralized the connection between the economy and nature. In more recent theory, nature is seen as an additional form of capital that can be preserved using green investment. Modelling the greening of the economy this way will overlook institutional, technical and ethical aspects of socio-ecological changes. This does not reflect environmental values and the human relationships with nature.

To conclude: ECE says that the economy functions in a world that is finite. This lead some researchers to question the feasibility of continuous growth as it is incorporated in mainstream economic theory. In the following part continuous growth alternatives will be discussed that are central to the question that this work will answer: ”Is degrowth a viable policy instrument to work towards a carbon neutral society in 2050?”

3.6 Post-Growth economics

In conventional economic theory, growth can go on indefinitely. In ecological macroeconomics, different growth strategies are being studied, which will be discussed. As decoupling is a central point of argument between proponents of these different growth strategies, this will be discussed as well, following a short overview of the growth strategies.

- Green growth (GG), which keeps the continuous growth model of conventional economics and depends on reaching absolute decoupling of the economy from the environment.
- Zero growth (ZG), where the growth of economic production is halted at a certain level of gross domestic product (GDP) or GDP per capita (GDPpc).

- Degrowth (DG), where GDP or GDPpc is consciously lowered to decrease the impact of the economy on the natural world. Less economic output will lead to lower resource and energy needs on the one hand and less pollution and emissions on the other hand.

3.6.1 Decoupling

Decoupling CO_2-emissions from the GDP is defined as a lowering of the amount of GHGE per dollar of GDP. Two cases can be distinguished:

- Relative decoupling, where this ratio is decreasing, but the total GHG-emissions keep increasing.
- Absolute decoupling, where the ratio is decreasing at a sufficient pace to lower the total GHG-emissions, even if GDP is growing.

This last situation has rarely been observed in practice Spash (2017, p. 114-115) writes. Distelkamp and Meyer (2019) and Giampietro (2019) came to similar conclusions. Lenaerts, Tagliapietra, and Wolff (2021) write that if the climate targets of a maximum $1.5°C$ increase in temperature are to be reached, the rate of decoupling should be much faster than it is now. Globally, the authors write, the economy is experiencing relative decoupling at a rate of -1.8% annually. To reach net zero emissions in 2050, this rate of decline should be -8.7% annually. Hickel and Kallis (2020) question the feasibility of absolute decoupling of resource use due to efficiency gains being governed by physical limits. Absolute decoupling of emissions due to energy production could in theory be possible by using renewable energy sources (RES) and negative carbon emissions technology and using carbon sinks.

3.6.2 Green growth

Spash (2017, p. 477-479) critiques GG, because it is not a tenable way towards sustainable development. Spash argues that GG depends on absolute decoupling of the economy and the environment. This has never been observed, Hickel and Kallis (2020) write. Hickel and Kallis (2020) write that proponents of green growth assume technological progress and advances in the substitutability of production factors will happen that make it possible to decouple economic growth from resource use and carbon emissions. Hickel and Kallis (2020), Jackson and Victor (2019), Heikkinen (2020), Jackson (2016), and Parrique et al. (2019) argue that green growth will be impossible to reach, at least within the time that humanity has left to reach its climate goals. Even though GG can be seen as outside of ECE, because of its technological optimism with regards to decoupling and not having limits to the size of the economy, it is included here, because it completes the possible paths that the economy can take towards a sustainable society. Despite these criticisms, it is the leading point of view for policy makers at this time, for example the IMF and OECD, Heikkinen (2020) writes.

3.6.3 Post-growth, zero growth and degrowth

Hardt et al. (2021) group ZG and DG together as post-growth (PG). Post-growth economies are economies that reduce their carbon emissions and resource use, Hardt et al. (2021) write, while allowing human well-being to grow. The authors argue that this is difficult, but not impossible. Usually alternative well-being indicators are argued for, as GDP is not a good well-being indicator. ZG and DG can be taken together, as both assert that continuous growth will lead to inevitable increases in resource use. These views object to the concept of absolute decoupling. A well known proponent of PG is Tim Jackson. In a book on post-growth, Jackson (2016, p. 39) quotes Kenneth Boulding, from a speech Boulding gave at US congress in 1973: "Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist."

Jackson further describes his motivations behind PG and how this could be a model for future economies. A first argument made by Jackson (2016, p. 42) is that the definition of prosperity in our current age is lacking. Because prosperity is difficult to define, one can respond to this complexity by trying to define prosperity through economic terms. If GDPpc grows, people will have more to spend, more options to choose from and their lives will improve. However, Jackson formulated arguments to question the continued focus on growth in high-income nations. He states that during the last decades inequality has increased, a social recession has happening and that the planet is ultimately finite. In the present, Jackson (2016, p. 62) writes, continuous and exponential economic growth forms the prevailing economic model. As an alternative to prosperity through growth, the following passage is written by Jackson:

[...] a different kind of vision for prosperity; one in which it is possible for human beings to flourish, to achieve greater social cohesion, to find higher levels of wellbeing and yet still to reduce their material impact on the environment. To live well, and yet to consume less. To have more fun – but with less stuff. - Jackson (2016, p. 90).

This PG economy will have a different structure than the current one. The economy will shift from being product-based to being service-based. Investments will try to improve the different aspects that help people to flourish. It is possible that investments that build environmental resilience will not show easily calculated returns on investment. Investments in services usually do not increase the productivity by a magnitude similar to the productivity increases in manufacturing. Jackson calls these 'slow capital' investments. As these slow capital investments would take up a larger share of total investments, they will slow down economic growth.

The employment rate in a PG economy does not have to fall, due to aggregated demand decreasing. The shift towards services would entail a decrease in labour productivity growth and increase in labour intensity. Another policy could be a shortening of the work week, which would be a kind of labour-sharing. According to simulations by Jackson, Victor, and Naqvi (2016), these two changes could support a full employment in a PG economy.

Another problem that could be faced in a PG society is an increase in inequality. Jackson (2016, p. 232-234) argues that as we move towards a service base economy, the elasticity of substitution between capital and labour decreases. This would prevent the increase in inequality Thomas Pickety predicted when an economy would enter a recession. The government would maintain its role as a stabilizing agent in the economy, similar to its role in conventional economics. In Jackson's view, these points show that having a PG economy which supports the flourishing of humans is possible.

The idea of using PG (specifically DG) to tackle climate change is subject to criticism. Materially disadvantages groups will have difficulty accepting degrowth, both in developing and developed societies. Multiple building blocks of the welfare state are built on the assumption of continuous growth. Lenaerts, Tagliapietra, and Wolff (2021) argue that DG will not be pursued by developing and developed countries. Growth is central to increase welfare and the management of pensions, social security and public debt. Büchs and Koch (2019) write that the capitalist society has produced a growth lock-in. The growth mindset is present in the economic dimension of peoples lives, but in culture, welfare, legal and financial systems as well. All these systems will have to co-evolve in a PG/DG society. This would lead to fundamental changes in society. Muradian (2019) write that DG will not be accepted by the disadvantages groups in society and that it will remain a Eurocentric, middle class concept as it does not resonate with the values and goals of these disadvantaged groups.

An important challenge to address in PG are negative social outcomes that could result from a negative growth rate if DG would happen in an badly thought out way. This would resemble a recession. Looking at the effects of recessions is useful. Negative social effects in recessions could be: higher unemployment, fewer goods and services being available to the population, Fitzpatrick (2020) writes. Older individuals can leave the workforce early and receive social security during the recession, they would receive lower retirement benefits later, according to Coile and Levine (2011). Hone et al. (2019) lists increased mortality in poor regions that lack social security and healthcare systems as effects of recessions in poor regions. Tackling social challenges will be an important dimension for PG to support the vision of human flourishing that Jackson formulated.

3.6.4 Post-growth and planetary boundaries

Hardt and O'Neill (2017) describe the characteristics and challenges of PG economies. In PG economies, the goal is to stabilize resource and energy use within ecosystem limits. This does not imply DG necessarily, but these kinds of economies should be able to handle DG. Steffen et al. (2015) have suggested explicit definitions of planetary boundaries. The figure presented below shows that humanity has crossed some of these boundaries:

- Losses in genetic diversity
- Phosphorous use
- Nitrogen use

Phosphorous and nitrogen are two active ingredients in agricultural fertilizers. If these flow into the environment, they can destabilize ecosystems in a process called eutrophication, Steffen et al. (2015) write. National Oceanic and Atmospheric Administration (2022) explains the effects of eutrophication: a higher than normal release of fertilizers in (freshwater) ecosystems will lead to excess plant and algae growth. These organisms will die and the excess biomass will decompose. The process of decomposition will use oxygen present in water. As oxygen levels decrease, dead zones can develop where fish and other aquatic animals cannot survive any longer.

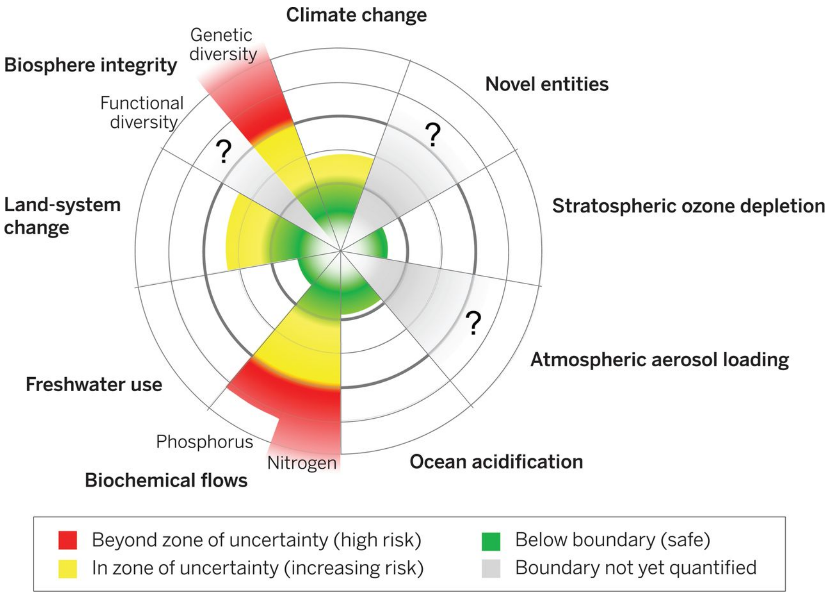


Figure 2: Overview planetary boundaries, by Steffen et al. (2015)

4 Connections between the environment and the economy

This chapter will describe a couple of concepts which come from both ENVE and ECE. These concepts are important to understanding the ECE models discussed later.

4.1 Sustainability criterion

When economists look for optimal allocation of goods and services through time, they will discuss the effects of choices made today on the utility of future generations. In other words: goods that are consumed today will not be available for consumption tomorrow. People's actions in the present will impact the well-being of people in the future. Tietenberg and Lewys (2018, p. 112) define a sustainability criterion, which protects the interest of future generations as follows: "The sustainability criterion suggests that, at a minimum, future generations should be left no worse off than current generations. Allocations that impoverish future generations in order to enrich current generations are, according to this criterion, patently unfair." Tietenberg and Lewys (2018, p. 116) define allocations within the economy as strongly sustainable if this allocation maintains the value of the natural capital. Weak sustainability is defined as maintaining total capital, which is the sum of physical and natural capital. If scenarios need to meet strong-sustainability constraints, this implies that there is little to no substitutability between physical and natural capital.

4.2 Energy return on energy invested

Roman and Thiry (2017, p. 382) define energy return on energy invested (EROI) as: "the ratio between the energy obtained and the energy spent in the process geared to supplying energy to the economy". If an energy source has a high EROI this means that energy is easily obtained from this energy source. Kerschner and Capellán-Pérez (2017, p. 429) write that the EROI of oil was 30 in the 1995 and has declined to 18 in 2006. Oil produced in unconventional methods have lower EROI values that range from 1-5. Lower EROI values are to be expected for NRES, as the easily accessible sources were the first to be extracted and these will be depleted first. These harder to reach sources can in turn lead to more pronounced environmental impacts. Jackson and Jackson (2021) write that low EROI values will likely lead to higher energy costs and less net energy available to society. EROI values for RES are expected to be lower than those of non-renewable energy sources (NRES). The authors explain that there are no standardized EROI values for RES at this time. Some authors put the EROI values at comparable levels to those of NRES, but those estimates usually do not take into account the energy investment needed to increase storage capacities and develop surplus generation capacity to compensate for the intermittent generation behaviour of RES.

4.3 Environmental damages and social cost of carbon

Discussing environmental damages is a central part of ENVE and ECE. A common way to describe damages in ENVE is through the use of externalities. Tietenberg and Lewys (2018, p. 54) introduce a way to represent the externalities caused by GHGE using the social cost of carbon (SCC). This is an aggregate variable that represents the different impacts climate change will have on society. It encompasses issues such as sea level rise, lower agricultural productivity, altered ecosystem services and more. Nordhaus (2017) described SCC as the most important concept in the economics of climate change. The authors have constructed the DICE model, which allows for the simulation of SCC in different policy environments. This is not an ECE model, as DICE uses NKE to represent the economy and it does not have physical limits built into its equations. Nevertheless it is an important model four our research, as it is actively used by policy makers. Simulating different scenarios leads to different SCC values, as one can observe in the following table:

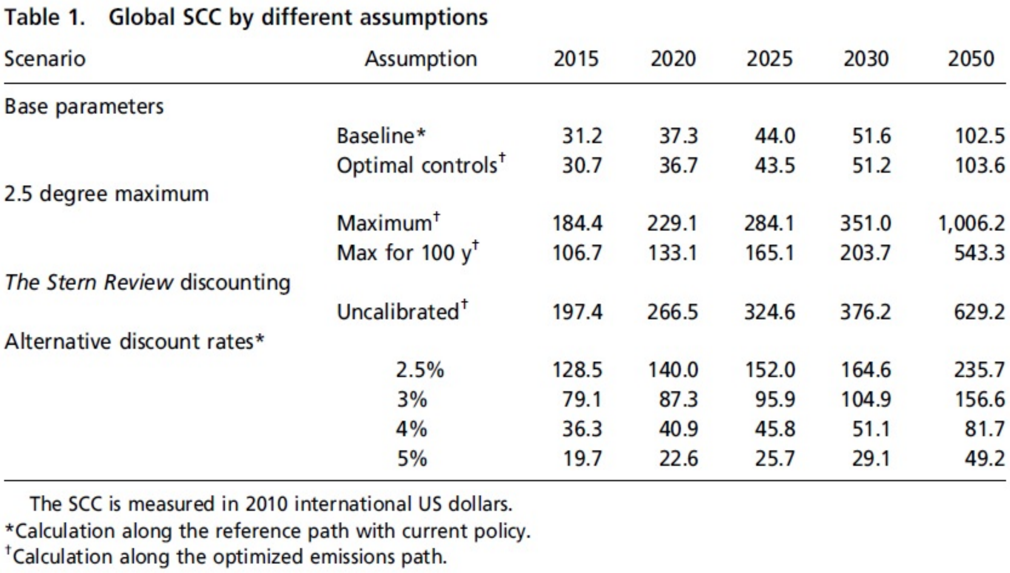


Table 1. Global SCC by different assumptions

Scenario	Assumption	2015	2020	2025	2030	2050
Base parameters						
	Baseline*	31.2	37.3	44.0	51.6	102.5
	Optimal controls†	30.7	36.7	43.5	51.2	103.6
2.5 degree maximum						
	Maximum†	184.4	229.1	284.1	351.0	1,006.2
	Max for 100 y†	106.7	133.1	165.1	203.7	543.3
The Stern Review discounting						
	Uncalibrated†	197.4	266.5	324.6	376.2	629.2
Alternative discount rates*						
	2.5%	128.5	140.0	152.0	164.6	235.7
	3%	79.1	87.3	95.9	104.9	156.6
	4%	36.3	40.9	45.8	51.1	81.7
	5%	19.7	22.6	25.7	29.1	49.2

The SCC is measured in 2010 international US dollars.
*Calculation along the reference path with current policy.
†Calculation along the optimized emissions path.

Figure 3: SCC simulations in different policy environments, by Nordhaus (2017)

An interesting figure in this table is the large difference between the two possible values of the 2.5 degree maximum. This is caused by the first simulation putting a hard cap on this temperature upper bound and the second simulation only demanding an average increase of 2.5 degrees over a 100 year period. In the latter the temperature can overshoot the 2.5 degree target for a limited amount of time. In the updated DICE version, the SCC has increased substantially since DICE2013R due to changes in the way the carbon cycle is modelled and in the estimated economic production. The DICE model is a model that is being used by researchers and policy makers to estimate the SCC, Nordhaus (2017) writes. The SCC approach used by the authors calculates the damage caused by CC by linking the temperature increase to economic damage.

Ackerman and Stanton (2012) criticise the United States's calculation of the SCC, because it underplays the impact of current emissions on future generations and does not take into account ecological uncertainties. The authors found values for SCC that are an order of magnitude larger or more. An alternative approach is used by Samsó and Ollé (2019, p. 228) in the MEDEAS model. They link the effects of CC to the energy production function. This damage function is written as an Energy Loss Function (ELF); climate change affects the net available energy for society. This will negatively impact the growth rate of GDP.

4.4 Carbon budget and remaining ultimately recoverable resources

Kawamiya et al. (2020) have written a paper on earth system modelling (ESM) that describes the carbon cycle. This cycle describe the flows of carbon in the biosphere. A well-known example of a carbon flow is the flow from atmosphere into organic matter due to photosynthesis. The authors describe the strong, roughly linear relationship between carbon present in the atmosphere as CO_2 and global temperature increase. It is feasible to make an estimate of the total amount of carbon that is allowed to be present if the policy goal is to keep the temperature increase under a certain level. From this maximally allowed carbon one can calculate the remaining carbon budget available to achieve the policy goal. Forster et al. (2022) explain that a carbon budget represent an amount of CO_2 in the atmosphere that will cause global warming by a certain amount with a chance of 50%. Kawamiya et al. (2020) write that limiting global warming to 1.5°C will be difficult, even though recent ESM estimate the carbon budget to be larger than estimated in AR5. Tokarska and Gillett (2018) have come to the same conclusion on the difficulty but not impossibility of reaching the 1.5°C-target.

A concept closely related to the carbon budget are discussions on the remaining ultimately recoverable resources (RURR). In the chapter on peak oil, Kerschner and Capellán-Pérez (2017, p. 431) report that in a situation where policy makers aim at limiting global warming to 1.5°C, not all remaining discovered fossil fuel reserves can be extracted and utilised. The author mentions that at least a third of all oil reserves should not be burned and that development of unconventional oil and other fuels cannot be rationalized when aiming for this climate goal. Welsby et al. (2021) have researched the different fossil fuels and the fractions that can be extracted. They report the following values for the fractions: 58% for oil, 56% for fossil methane gas and 89% of coal, based on the 2018 resource base. To find the RURR-fraction for oil, one subtracts the percentages of Welsby et al. (2021) from 100%. For example, this means the RURR-fraction for oil will be 42%.

4.5 Representative concentration pathway

The concept of the representative concentration pathway (RCP) is explained by Moss et al. (2010). The authors describe RCPs as possible pathways of radiative forcing. Radiative forcing is defined by Moss et al. (2010) as: "the change in the balance between incoming and outgoing radiation to the atmosphere caused by changes in atmospheric constituents, such as carbon dioxide". These different possible pathways are based on changes in land-use, GHG-emissions (CO_2 and other gases) and aerosols. These pathways lead to a certain level of radiative forcing in 2100. Many paths can lead to a certain level of forcing. Moss et al. (2010) write that these different levels of forcing are to be used by modellers to simulate different climate outcomes. Using different RCPs when modelling a policy set will create an interval of outcomes related to this policy set. There are four standard scenarios of radiative forcing. Each represents a possible set of socio-economic, technical, land use, air pollution,... changes, Vuuren et al. (2011b) writes. These four scenarios range from successful climate mitigation to keep global warming under $2°C$ (RCP2.6), two stabilizing scenarios (RCP4.5 and RCP6.0) and the last one is a scenario with high GHG-emissions and little mitigation (RCP8.5). In the report of IPCC (2014, p. 57), the current trend of radiative forcing is predicted to be between RCP6 and RCP8.5.

4.6 IPAT equation

The IPAT equation is an equation that explains the environmental impact of society in broad terms, Chertow (2000) writes. It is calculated by multiplying population with affluence and technology. This equation was developed by Ehrlich and Holdren, she writes. It shows that environmental impact of all factors together will be higher than the three factors taken separately. If all three factors would increase by 20%, the total effect on environmental impact would be 73% and not 60%, as one would expect if all variables increased independently. The Ehrlich and Holdren write that the impact of population is frequently underestimated when studying environmental impact.

$I = P.A.T$

One can observe in this equation that technological progress in efficiency should develop at a rate that is high enough to compensate the growth in affluence and population, if the aim is to keep the environmental impact constant. This would be absolute decoupling, as it was discussed earlier. Different authors question the feasibility of absolute decoupling. If impact needs to be reduced, without lowering population growth, affluence and technology together can cause a reduction of environmental impact. Chertow (2000) shows that not all environmental impacts behave the same way. Pollutants that have a local and short term impact like SO_2 will increase at first with affluence. Later their impact will decrease with increasing affluence. This is what the Kuznet's curve predicts. Tietenberg and Lewys (2018, p. 483-484) explain this as: at low levels of development pollution increases with GDPpc, later it decreases with increasing GDPpc. Chertow (2000) shows that long-term and global pollutants will not follow this evolution. The most obvious example is GHGE, which keeps increasing with GDPpc.

5 Ecological economic modelling

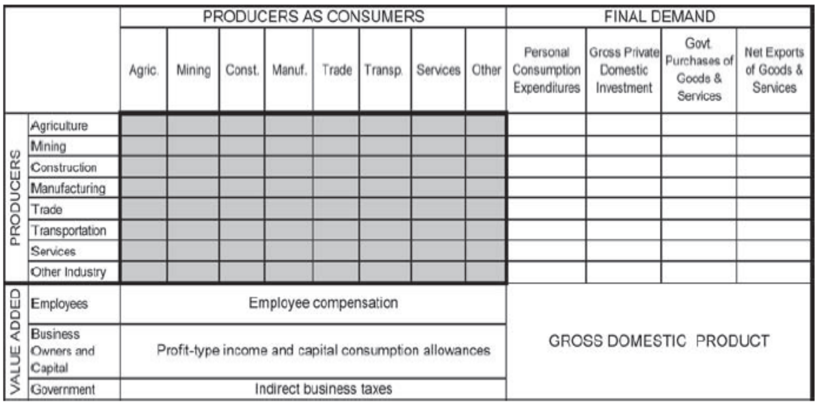
Hardt and O'Neill (2017) have found three important themes within ECE literature: the need to manage an economy without growth, finding ways to incorporate the dependence on the natural world in macroeconomic models and to combine PKE and ECE approaches. Hardt and O'Neill (2017) argue that macroeconomic frameworks need to be designed that can simulate PG policies. Ecogical economic models (ECEMs) incorporate these themes or some of these themes. ECEMs can be classified as integrated assessment models (IAMs). IAMs are models that integrate economical, social, environmental factors that are, usually, relevant to climate change and environmental policies. IAMs aim to provide insights into the effectiveness of these policies, Vuuren et al. (2011a) explains. These characteristics makes ECEMs useful tools in finding answers to the research questions. In the following part the building blocks of ECEMs will be presented. This section concludes with an overview of contemporary ECEMs. Hardt and O'Neill (2017) categorized ECEMs based on the growth theory these models use. Another categorization by Hardt and O'Neill (2017) is based on the modelling techniques used in the ECEMs. The modelling technique simulates the evolution of the model through time. Hardt and O'Neill (2017) list four categories of growth theories and four modelling techniques. Both categorizations will be discussed in this section. ECEMs will use one growth theory and one or more modelling techniques.

5.1 Modelling techniques

The modelling techniques that Hardt and O'Neill (2017) mention are physical or monetary input-output analyses (IOA), system dynamic models (SDM) and stock-flow consistent modelling. The general idea behind IOA will be explained using a book written by Miller and Blair (2009), a more detailed look at the differences between monetary and physical IOA will be based on a publication by Weisz and Duchin (2006), a SD handbook by Pruyt (2013) has been chosen to explain system dynamics and for stock-flow consistent (SFC) modelling a set of papers by Godley (2012) will be used.

5.1.1 Monetary and physical input-output analysis

Miller and Blair (2009) describe how IOA tries to represent the flow of goods and services from productive sectors as producers to different consumers in the economy. The consuming sectors consists of productive sectors that utilize other products as inputs, residential consumers, investment, exports, government consumption,... The mathematical representation of an IOA consists of n linear equations in n unknown variables, which lends itself to matrix representation. Rows represent how production of a sector is distributed across different consumers. The columns are the set of inputs required by a certain industry. Final demand columns show the sales of each sector to the final market. Value added rows register the inputs that sectors use in their production which are not intermediate goods from other sectors. Labour would be an example of this input type. The following table shows this matrix representation:



		PRODUCERS AS CONSUMERS								FINAL DEMAND			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Govt. Purchases of Goods & Services	Net Exports of Goods & Services
PRODUCERS	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other Industry												
VALUE ADDED	Employees	Employee compensation								GROSS DOMESTIC PRODUCT			
	Business Owners and Capital	Profit-type income and capital consumption allowances											
	Government	Indirect business taxes											

Figure 4: Input-output transactions table, by Miller and Blair (2009, p. 3)

Each cell in the table represents a transaction between sectors. Miller and Blair (2009) give the example of tons of steel bought by automotive producers. These transactions can be represented by their physical values as x tons of steel per year or as the monetary value of x tons of steel. The monetary representation can be a better choice if a producer produces many different kinds of comparable goods. These could be aggregated in one transaction value. Cells are usually represented by z_{ij}, which is the sale of sector i to sector j. This is an interindustry sale. If all sectors present in the economy are accounted for in the IOA table, it is possible to calculate macroeconomic variables: total output of sector i, C, I, government spending (G), export (X) and GDP, by aggregating the columns.

The technical coefficient can be calculated from the IOA table. This is the value of input z_{ij} over the output of x_j. If €100 steel is used to produce €1000 of car parts, the technical coefficient would amount to 0,1. In IOA these coefficients are assumed to be stable, independently of the amount produced. This last point is an effect of the assumption of constant returns to scale. Stable technical coefficients lead to Leontief production functions, as no firm would buy excess inputs to produce a certain amount of x. In a Leontief production function the total production is determined by the input that is the most scarce. This makes it possible to write the interdependency of industry in simple linear equations. If final demand is known, the necessary production of each sector can be calculated using matrix algebra to find solutions of the n unknown variables, Miller and Blair (2009, p. 17-21) explain.

IOA can be used to solve energy and environmental problems. As explained by Miller and Blair (2009, p. 399-445), adding an energy dimension to the IOA can be achieved by adding linear equations that express the energy input per dollar of output. This is the most basic form of energy IOA. An improved methodology to exeute an IOA is the hybrid method, where energy-flows and dollar-flows are intertwined. The total energy requirements matrix translates the final demand of a good to the total energy requirement to produce this good. This will be expressed in BTU/$. Final demand of energy is translated to the total energy requirement to produce this unit of energy. This value will be dimensionless.

Environmental problems can be a part of IOA, Miller and Blair (2009, p. 446-498) write. A pollution dimension can be added in a similar way to an energy dimension: new linear equations that describe pollution generated by the different sectors of the production chain. These can be transformed into total pollution generated per unit of final consumption. This new type of environmental IOA can be set up in three ways:

- Generalized IO-models, which add rows containing pollution and abatement efforts.
- Ecological-economical IO-models, where flows between economic and ecosystem sectors are recorded.
- Eommodity-by-industry models, that use environmental factors as commodities would be used in standard IOA.

Weisz and Duchin (2006) write on the differences between physical and monetary IOA. They mentions that, under the right assumptions, both types of IOA will be equivalent. However, in other literature differing results were found when studying the same problems with physical IOA or monetary IOA. Weisz and Duchin (2006) discuss two causes of these discrepancies. The first is a poorly specified treatment of waste, which caused the mass balance condition to not be met. This condition states that inflows need to be equal to outflows. This was argued as being a frequent issue in physical IOA by Suh (2004). The second is an unwarranted aggregation of prices across sectors, which is the main point of Weisz and Duchin (2006). In reality the price for an intermediate good will not be equal for all sectors, this necessitates the construction of a price matrix instead of a price vector. The conclusions is that under the right assumptions physical and monetary IOA should be equivalent.

5.1.2 System dynamics

System dynamic modelling has been mentioned in the literature study earlier. The World3 model developed for LtG is an example of an SD model. This section discusses the constituent parts of SD, based on a handbook by Pruyt (2013, p. 85-87). A system consists of all its constituent parts and their interactions. A classic example of a dynamic system is the rabbit-fox ecosystem. Both populations influence each other's evolution through time. A small population of foxes will allow a large number of rabbits to survive to adulthood. This leads to an increase in rabbit population in the next period. If there are lots of rabbits, the foxes can eat a lot and their population will increase in the following period. The population of foxes can expand and will eat a bigger group of rabbits. This will lead to sinusoidal evolution of the respective populations. This kind of SD model is called a predator-prey model or a Volterra model. Mimmo and Pugliese

(2014, p. 145-153) have mathematically derived this model.

This paragraph will explain stocks, flows, auxiliary variables. A stock in SD is a state variable. The value of this variable at the end of the current period will be equal to the value of the last period with added or substracted flows from the current period. These variables need to have an initial value when a simulation starts. Examples of stock variables are: amount of water in a water tub or the amount of CO_2 in the atmosphere. A flow variable originates from or arrives in a stock variable. It will regulate the change in the stock variable in each period. They can increase or decrease the value of a stock variable. Flows do not have to be constant, the size of the flow can change over time, which will impact the behaviour of the stock variable. This can impact the behaviour of the flow variable. An example of a constant flow variable is the amount of water that runs through the tap each second. An example of a changing flow variable would be the amount of water that passes through the drain each second if the drain is opened. The flow rate through the drain depends on the level of water in the tub. Auxiliary variables are variables that are not stocks or flows in the system, which can be used to keep the model simple and understandable. If the relationships between these variables and the stocks and flows are determined, they are called hard variables, otherwise they are called soft variables. TU Wien (2022) mentions interest rate as an example of an auxiliary variable.

This paragraph explains constants and parameters. Universal constants can be used in SDM, an example of which is the universal constant of gravitation. Model specific parameters can be added as well. These would be variables in the model that can be assumed to remain constant during the runtime of the simulation. An example of a parameter in SD could be the rabbit birth rate. In a dynamic system, FB loops will be central to guiding the evolution of the system, Pruyt (2013, p. 36) writes. FB loops can be positive or negative. Rabbit growth is dependent on the rabbit population in the previous time period. If the birth rate of rabbits is > 1, it will be a positive FB loop. This kind of loop will lead to exponential growth without some way to stabilize the population. A larger rabbit population will experience more deaths than a small rabbit population, which could guide the system to an equilibrium rabbit population. Or the presence of a carnivore that hunts rabbits could cause a population equilibrium.

Impacts of changes in SD do not have to be instantaneous, delays are important properties of processes. There are two kinds of delays that can be modelled. A first kind is explained by Pruyt (2013, p. 121). In this delay function the inflow will be perfectly mixed with the present stock variable. The outflow will be the total value of the stock variable divided by the delay time. Another way to model delays can be found in the Time Delay function in the Xcos software as a package of SciLab, by Scilab Enterprises (2015). In this case the delay function holds the inflow variable at current time and will make it flow out when an amount of periods has passed equal to the specified delay. This function sends a delayed signal without mixing happening in the stock variable.

5.1.3 Stock-flow consistent modelling

Godley (2012) has written a collection of papers on the development of stock-flow consistent (SFC) modelling. An important criticism by Godley on macroeconomic theory was how it was based on flow variables, without taking the effects of stocks into account. Budget constraints of companies and other stock variables were not consistently represented in relation to each other and the flow variables. Godley criticises the "neoclassical paradigm" (NCP), as he calls it. NCP is defined as follows by Godley (2012, p. 40): "market-clearing, full-employment macroeconomic equilibrium... the intersection of an aggregate demand curve with a vertical aggregate supply curve." . This model lacks dynamics, according to Godley. It only describes the end state after a shock has happened. If dynamics are introduced in a model, the presence of stocks will be necessary. These could be retained production or profits. The model Godley developed is named "real stock-flow monetary model" (RSFM). In this style of modelling, budgeting constraints will play out as changes in asset stocks due to the net flows of factor incomes, expenses and transfers. Full stationarity will still be possible in this model, but will be formulated in real stock equilibria that are functions of the flows connected to this stock. In RSFM, commercial banks will play an important role. One of the roles will be channelling finance for stock formation and destruction. Godley (2012, p. 15) explains one of the critical deviations he developed from more standard macroeconomic modelling. RSFM is not based on microeconomic foundations of rational expectations, but on tight national accounting (which are ways to represent stocks and flows in the economy). An example of a stock-flow consistent model is LOWGROW, which was developed by Jackson and Victor (2020) for the Canadian economy.

5.2 Underlying growth theories

Hardt and O'Neill (2017) have categorized ECEMs both in their modelling approach and their growth models. Four types of growth theories are discussed: Post-Keynesian growth models, other demand driven growth models, supply driven growth models and models without growth.

5.2.1 Post-Keynesian growth models

PKE has been discussed earlier in the text. To repeat the main points of PKE: heterogenous agents are present in the economy who do not use rational expectations. PKE is a demand driven growth model.

Sawyer and Fontana (2016) have designed an ECEM model that uses PKE growth theory. PKM assumptions the authors use are the economy functioning as a monetary production economy where money is necessary and can lead to instability, presence of fundamental uncertainty, path dependence of choices made by agents and the interdependence of aggregate supply and demand in the evolution of output and employment in the long term. A core assumption added by Sawyer and Fontana (2016) is the inability to substitute the production factors. This will imply strong sustainability. The production function used in the model has three production factors, which are interconnected in their evolution. These production factors are: physical capital, labour and natural capital. The depletion rate of this the natural capital in this model will depend both on the level of output, the growth rate of output and technological progress, which can lower the depletion rate of natural capital.

Sawyer and Fontana (2016) find that the growth rate of output depends on the sum of the growth rates of capital, effective labour and depletion of natural capital. Due to the non-substitutability of these factors, imbalances in the growth rates can happen. For example: the growth rates of labour and capital are higher than the sustainable depletion rate of natural capital. This will cause environmental problems to arise. In the long run the sustainable depletion rate will be a limit for the sustainable economic growth rate. To conclude, Sawyer and Fontana (2016) argue that using these interconnections between the production factors implies lower growth rates, lower profits, lower labour usage. To evolve towards a low, but sustainable growth rate, governments will need to guide the volume and types of investments made by agents. The final remark is that these changes will probably need to come from governmental policies and social norms, not the free market system.

5.2.2 Other demand-driven growth models

A demand-driven growth model that does not use PKE has been developed by Victor and Rosenbluth (2007). The authors have constructed a demand-driven SD model that is called LOWGROW. The aggregate demand is made up of C, I, G, import (M) and export (X). It is demand driven as the supply will adapt to meet demand by increasing employment and capital utilization in periods of demand surplus. The model has no explicit monetary sector, it utilizes linear regressions on earlier data to estimate its equations, making estimations on data or projections in the period 2000-2020. The model does not use concepts of behavioural economics in its equations. GHGE reduction policies are modelled as pure costs, without possible positive impacts on aggregate demand. The authors admit that this last point is a conservative assumption.

The model allows for the simulation of different policies and their effects on indexes of GHG emissions, unemployment, debt to GDP ratio and poverty. The final conclusion made, is that low growth with high employment, decreased poverty, reduced GHG emissions and decreased debt to GDP ratio is possible. This would necessitate a substantial growth in the public sector to facilitate increased redistribution and increased development of public goods relative to private goods. All of this within a context of lower GDP growth, as the BAU simulation would have an increase of GDP of 88% while to low growth simulation would have an increase close to 40%.

5.2.3 Supply-driven growth models

In Hardt and O'Neill (2017), the main difference of supply-driven models compared to demand-driven models can be found in the determination of the economy's output. In supply-driven models a production function is used and the growth path of the economy is determined by the production factors that are defined as exogenous or found in another part of the model. An example of a supply-driven growth model is the DICE model of Nordhaus and Sztorc (2013). The demand side of the economy will play a passive role in these models. The production function used by Nordhaus and Sztorc (2013, p. 10) is given below. $Q(t)$ is net output, $A(t)$ is total factor productivity, $K(t)$ is capital stock, $L(t)$ is labour, $\Omega(t)$ is the damage function due to CC and $\Lambda(t)$ is fraction of total output that goes towards abatement of climate effects.

$$Q(t) = \frac{[1-\Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}}{1+\Omega(t)}$$

The DICE model fits ENVE better than ECE. Nevertheless, it is a useful model to discuss due to its importance for policy makers. The first edition of this model was developed by Nordhaus (1992). DICE is an acronym that stands for: Dynamic Integrated model of Climate and the Economy. The aim of DICE is to use economic tools to determine an efficient strategy to handle CC. Dynamic models like DICE are useful in studying these issues, because of the long lags in economic processes and climate change. A central assumption in this model is: societies should apply environmental policies (abatement policies) up to the point where the benefits of these policies are equal to the costs. An easy strategy to formulate, Nordhaus says, but difficult to execute when tackling CC. This is an approach typical to ENVE. Tietenberg and Lewys (2018, p. 49) explain in their work on ENVE that an economy reaches a state of efficiency if the marginal abatement cost will be equal to the marginal benefit caused by the abatement of emissions. This method of looking for efficient solutions is typical of NCE. As such it will not be ECE. Nordhaus (1992) says that GHGE could cause modest damages to the environment, which warrants policies to slow down climate change. Harsh cuts in GHG emissions at levels of 50 percent or more were not warranted at the time, based on available scientific literature.

5.2.4 Other models without growth

The last category of models in Hardt and O'Neill (2017) are models without growth. The authors describe that these types of models see the economy as static. The paper by Kemp-Benedict (2014) examines the 'inverted pyramid' view, which argues that the economy rests fully on the extractive sector, even though this sector by itself can in many cases represent a small part of the economy. This builds on the work of Herman Daly.

The model the writer designed is a linear model consisting of three sectors, which represents the economy in a similar way to earlier discussed IOA: the extractive sector, the bulk materials sector and the circulating goods sector. The goods and services produced in this last sector are both the inputs for all three sectors and final goods. Price-setting in this model happens by applying a mark-up on costs during normal levels of output. Using mark-ups allows the concept of economy-wide mark-ups to be determined. This follows from the vertical integration of this three-sector economy. The linear structure allows the writer to determine an expression of the nominal GDP as a function of natural resources and labour multiplied by a factor. These factors will represent the economy-wide mark-up on a unit of natural resources or labour.

To make a connection with the biophysical world, Kemp-Benedict (2014) uses conversion factors that link the resource sector to the bulk goods sector. In the paper the writer relates this concept to EROI. As time progresses, this ratio will come down, as easily accessed deposits will be depleted. The paper suggests that a minimum value of 3.6 would be necessary to support civilization. An interesting point found in this paper is the observation that resource productivity rises with increased complexity of the economy, as each layer adds it's own mark-up. This leads to a larger GDP based on the same resource base. The aim of this paper was to build a functional model that can be build upon by subsequent developers.

The more recent paper by Scalia et al. (2020) builds on the ideas of Daly. They work towards a steady-state economy as well. The authors use a LVM to describe a broader concept of 'steady state'. In their work a steady-state takes the shape of a torus, along which variables travel through time around en equilibrium value. The authors suggest this as an alternative, as an enrichment of the concept of steady state. In most steady-state models the equilibrium is a point. This new point of view allows for periodical evolution.

5.3 Applied ecological macroeconomics

Developing ecological macroeconomic models is interesting from a theoretical point of view. At the same time policy makers are looking for tools to help them make effective decisions to reduce GHG emissions and mitigate the effects of climate change. An application of ECEMs could be to test the feasibility of environmental policies. An example if this can be found in the work of Nieto et al. (2020). They have used MEDEAS, an ECEM, to find out how the Energy Roadmap 2050 targets can be reached. MEDEAS will return later in the practical part of this work as well. The conclusion in this paper is that the emission reduction goals can only be reached in a PG scenario, while maintaining employment levels and shifting towards renewables. In this PG economy, the economy is steered towards more labour-intensive sectors. The results of these simulations question the policy strategies to reach net zero by 2050. Nieto et al. (2020) agree with Jackson's PG ideas.

Bachner et al. (2020) formulate a warning towards policy makers and researchers. They have studied different kinds of uncertainties in ECEM. Technological uncertainty is a first kind, which encompasses the uncertainty caused by different technologies that can be used. This reflects the differences in efficiency between technologies. A second kind of uncertainty is socio-economic uncertainty. Bachner et al. (2020) use shared socioeconomic pathways (SSPs) as developed by O'Neill et al. (2017). These pathways are different scenarios that societies can follow. A subset of variables contained in these SSPs are demographic evolution, lifestyle changes, resources, technological change. A third kind of uncertainty can be found in climate policy. Policies on national or regional levels can be ambitious or reluctant, which creates variance in the size of total climate policy on a global level. The fourth and final kind of uncertainty is macroeconomic uncertainty.

The results of ECEMs are dependent on the model structure. At the extreme ends of possibilities the authors position computable general equilibrium models and PKE models. The former is supply driven, where the economy functions at full capacity. The latter models allow economies to function below full capacity and to contain rigidities. These are demand driven. Between these types there is a spectrum of possible models that reflect reality. Bachner et al. (2020) conclude that the choice of model structure used, can lead to different sizes and signs with regards to estimated parameters. This can lead to different policy recommendations depending on the used model. More cooperation and model validation is necessary the authors say. On a more positive note, Bachner et al. (2020) mention that in their analysis the cost of carbon mitigation on welfare in the worst case scenario is moderate, at a loss of <2% GDP. This could be an acceptable price to avert the worst of climate change.

5.4 Overview current ecological economic models

The work of Hardt and O'Neill (2017) has been mentioned multiple times in this text as a valuable reference to explore the field of ECEM. At the time of writing, in (2022-2023), it has been five years since the publication of this paper. Developments in the field of ECE have not stopped. New models have been designed. Lundgren (2022) writes that ECE is a young field with continuous discussion on fundamentals. Ecological economists have a wide variety of backgrounds and frameworks, which can be contradictory. Lundgren (2022) continues by saying this cross pollination of backgrounds is conductive to innovation within the field. An updated overview might help to show the evolution ECEM went through these last five years. This overview will use the four main categories of Hardt and O'Neill (2017).

Model ID	Model Source	Model Name
Post-Keynesian models		
1	D'Alessandro et al. (2018)	Eurogreen
2	Capellán-Pérez et al. (2020b)	MEDEAS

3	Jackson and Victor (2020)	LOWGROW
4	Bachner et al. (2020)	
5	Distelkamp and Meyer (2019)	GINFORS
6	Safarzyńska and Bergh (2022)	ABM-IAM
7	Hafner, Jones, and Anger-Kraavi (2021)	GIBM
Other demand-driven growth models		
8	Althouse, Guarini, and Gabriel Porcile (2020)	
9	Dávila-Fernández and Sordi (2020)	
10	Jackson and Jackson (2021)	TranSim
Supply-driven growth models		
11	Nordhaus (2017)	DICE
12	Bercegol and Benisty (2022)	
13	Kennedy (2022)	
14	Blampied (2021)	
15	King (2020)	HARMONEY
16	Keen, Ayres, and Standish (2019)	energy-based CPDF
Other models without growth		
17	Monserand (2019)	
18	Heikkinen (2020)	
19	Espinoza et al. (2022)	EEDEC

Table 1: Overview of recent EME models, own work

6 Materials and methods

The main goal of this dissertation is to find out if ZG or DG can help society reach its climate goals, specifically with regards to GHGE, while maintaining a sufficient level of material wealth. To find the answer to this question, an ECEM will be chosen and simulations will be run. In the first part of the practical work a list of candidate models will be described. One of these models will be chosen. The research question focusses on GHGE, GDP-evolution and energy economics. A well developed energy dimension in model will be preferred, as GHGE and energy production are closely linked. The International Energy Agency (2021a) writes that two thirds of GHGE are due to energy production. Models that have integrated these variables in more detail will be preferred in our final model choice. This chosen model will be used to produce a BAU simulation and subsequent simulations with adapted scenario parameters. to climate policy Optimally a scenario can be found that leads to a zero-carbon society in 2050, this scenario would meet the EU climate goals.

Once the model is chosen, the next part of the research will investigate policy options present in the model. These will form the other possible ingredients for a net zero scenario. The impact of each of these policies will be measured to distinguish which are the most effective in reducing GHGE. After that a method will need to be developed to represent ZG and DG in different scenarios. Once methods to add ZG/DG have been found, the next step will be developing a process to choose an optimal model. If ZG/DG by themselves will not be enough to reach the net zero emissions target in 2050, the optimal ZG/DG model will be supplemented with other possible policies found earlier. Finally the feasibility of this net zero scenario will be discussed, if one is found.

6.1 Candidate models

During the literature study several candidate models came up. The following part will provide an overview of these models. The building blocks will be discussed: their underlying growth theory, modelling techniques they use and how they account for environmental impacts. If possible some of their results will be shown as well.

6.1.1 DEFINE

The following model is developed by Dafermos, Galanis and Nikolaidi. DEFINE is an acronym of Dynamic Ecosystem-FINance-Economy. DEFINE describes a SFC economy for physical and monetary flows. The model uses the work of Godley and Lavoie in creating a SFC approach with the flow-fund model of Georgescu-Roegen Dafermos, Galanis, and Nikolaidi (2022) say. Dafermos, Galanis, and Nikolaidi (2016) motivate this model structure by listing three coinciding crises: the financial crisis of 2008, slow to no growth which has become the norm in developed economies and the environmental crisis. ECEMs that came before, they argue, lack connections with the financial system and the macroeconomy, while green financial investments will play an important role in the transition towards a sustainable economy.

The following paragraph will describe how Dafermos, Nikolaidi, and Galanis (2017) constructed DEFINE. The SFC aspect of this model represents the real and financial economies and the links between them through accounting. The flow-fund aspect of this model represents the links between the biophysical sphere and the macroeconomy. Material inflows and outflows are specified. The model separates resources into two categories: stock-flow resources (i.e. materials) and flow-fund resources (i.e. labour, Ricardian land and capital). As both resource types are necessary for production, production will take the shape of a Leontief production function. In most literature NCE production functions are used. In DEFINE environmental effects affect both types of resources differently. The stock-flow resources will be influenced by depletion. The flow-fund resources will be influenced by degradation effects. In the DEFINE economy one kind of good will be produced. This good needs matter and energy. Matter can be sourced from sources through extraction or it can be sourced from recycled matter. Energy can be either renewable or non-renewable. Capital used in production can be green or conventional. The former uses renewable energy and the latter uses non-renewables. Capital will form the connection between the energy source and the energy used by the process. The following parameters will be influenced by the capital used: energy intensity, material intensity and recycling rate. Firms can invest in capital using loans or profits. Due to the need for loans, there has to be a banking system. As banks can ration the credit they make available, banks will be able to play a role in company investment patterns. Households provide labour and receive the profits of the financial sector. Prices are assumed constant and unit costs of products for consumption and investment are one dollar. The production process has the following end products: goods, carbon emissions and energy dissipation.

The ecological equations are based on the first and second laws of thermodynamics. The first law states that matter and energy can neither be created nor destroyed, only transformed. The second law states that energy will transform from low entropy to high entropy energy when used. A well-known example of this process is the transformation of petroleum to work, CO_2 and water. A fraction of capital and consumption goods will be discarded at the end of each period. A part can be recycled, a part will be waste and a small portion will consist of hazardous waste. This last type of waste will negatively affect the production process.

Dafermos and Nikolaidi (2022) have used DEFINE to study climate policies. In their conclusion, the authors write that socio-ecological transformation of the economy is urgently needed. To reach ecological and socio-economic stability, a set of policies will be needed. They argue that single policies can have positive effects on ecological variables but negative effects on socio-economic ones. Combinations of policies can lead to positive evolution towards ecological and socio-economic stability. The authors warn that ecological instability is unlikely to be prevented, unless humanity changes its destructive consumption patterns.

6.1.2 Eurogreen

The Eurogreen model is based on PKE and ECE. Eurogreen studies transition towards a low-carbon economy within the constraints of social equity. This way of thinking reflects the developments in ECE to include both ecological and social limits and how these interact with growth. D'Alessandro et al. (2018) explain Eurogreen model is in detail. The authors write that connections of environmental damages, resource exploitation and macroeconomic variables like inflation and employment have rarely been worked out in ECEMs.

Eurogreen uses multiple modelling techniques. SD is used to model the connections between socio-economic and environmental components. Within the economic model, ten sectors are represented, dynamically connected through their inputs and outputs. Agents in the economy use different sources of energy. These are modelled separately. Coal, oil, gas, nuclear, renewables all have a specific amount of carbon emissions per unit of energy. Households in the Eurogreen model are heterogeneous. They can be employed, unemployed, inactive, retired or capitalists. Employees are split in three skill levels based on their educational achievements. A welfare state is present with tax and benefit systems. This welfare state allows modelling of social policies like basic income.

Innovation happens in a partially endogenous way that impacts energy efficiency, labour productivity and the technological mix used by producers. This model provides an environment to test different policies and policy mixes and their effects on economic and environmental variables.

Policies and policy mixes

The first policy type in this model is called "New Productivity Revolution" (NPR). This represents higher odds for new innovations to happen. Producers can choose from four types of technology:

- Current technology
- Technology that improves labour-productivity but at constant or lower energy efficiency
- Technology that increases energy efficiency but at lower or constant labour-productivity
- Technology that increases both labour-productivity and energy efficiency

Mechanically innovation happens if a certain new technology, like an energy efficiency innovation, has a positive impact that goes above an adoption-threshold. This threshold is dynamic and depends on a level value, which represents how fast technology evolves and it depends on relative costs of production factors. In an economy with high labour costs, the threshold for labour-saving innovation adoption will decrease and the threshold of energy-efficiency technology adoption will go up. If this policy is enacted, the level-value will be lowered to represent an increase in technological development.

The second policy instrument is the development of basic income (BI), which will replace all other types of redistribution through the welfare system. A third policy instrument is job guarantee (JG), where the government will make sure all active individuals have a job. This system substitutes unemployment benefits. These employees will provide care-services that can substitute private sector services or they will help in constructing ecological infrastructure. The next policy instrument is work-time reduction (WTR), which reduces the amount of hours that encompasses a full-time job. The penultimate single policy is the energy mix policy (EnM). This consists of both a transition towards renewable energy production and electrification of the economy. The last policy is a carbon-tax and border carbon adjustment (BCA), which will be levied both on internal production and on imported goods. The tax's size will increase as time progresses.

Different policy mixes were simulated in the Eurogreen project:

- Green Growth (GG), which combines NPR, EnM, BCA.
- Policies for social equity (PSE), which combines JG, WTR, EnM, BCA, with an increase in energy efficiency innovation.

- Degrowth (DG), consisting of JG, WTR, EnM, BCA, high energy efficiency, consumption reduction and de-growth wealth tax.

Simulation results

D'Alessandro et al. (2018) simulated the different policy mixes and evaluated the results with regard to important macroeconomic variables. In GDP growth and GDP growth per capita, the results are as one could expect: negative only for the DG mix. GHG emission reduction happens in all mixes. The DG mix has the strongest reduction. The underlying factors that cause these reductions are very different. This shows that, on the one hand it is possible to reach similar targets through different policy mixes. On the other hand, environmentally-friendly technological progress on its own will not suffice. In a mix that uses accelerated innovation, an important part of GHG emission reduction is caused by the trickle down effect of increases in labour productivity, which lower employment rate, which lowers aggregate demand en production.

Energy intensity evolution is fairly similar in all energy mixes. In some European countries nuclear energy makes up an important part of the energy mix. D'Alessandro et al. (2018) have studied what the effects on transition towards a low carbon energy production would be if an additional 'zero nuclear energy' policy was implemented. This would lead to the transition being even more challenging and disruptive to the economy. This additional policy would, the authors explain, lead to a situation comparable to the degrowth mix.

The less apparent results of the policy simulations can be found in the evolution of social variables like unemployment under each mix. Unemployment rates are highest in the GG mix, at a rate comparable to the BAU simulation. The DG mix leads to lower unemployment. PSE leads to an even lower rate of unemployment. This is caused by the fact that the economy can keep growing while applying the employment policies (JG, WTR). This leads to an increase in aggregated demand, which leads to more employment. In the DG mix, consumption and exports are lowered, which weakens the realised effects of the employment policies. Different policy mixes also had different results on the evolution of inequality. BAU and GG increased the Gini coefficient, while DG and PSE reduced it. This pattern follows the evolution of unemployment described earlier. The final social variable is the evolution of governmental deficits. The evolution of deficits shows the same pairing of policy mixes: BAU and GG lead to lower deficits, while DG and PSE lead to higher yearly deficits, but these rates stabilize.

6.1.3 MEDEAS

Capellán-Pérez et al. (2020b) describe the MEDEAS framework. MEDEAS is an acronym that stands for Modelling the Energy Development under Environmental And Socioeconomic constraints. The authors criticize many IAMs for lacking crucial parts in their design. Four key points of criticism with regards to model design are listed. On top of this, Capellán-Pérez et al. (2020b) criticize the lack of openness of researchers with regards to their ECEMs:

- A lack of FB links between modules from different fields of science.
- The use of conventional general equilibrium models to find optimal solutions. These models do not capture socioeconomic dynamics and the impact of environmental policies on these dynamics.
- The different resource bases are frequently assumed to be sufficient not to have supply-side impacts. Energy transition in this situation would be demand-driven. Capellán-Pérez et al. (2020b) mention that this is questioned in literature, as the ease of resource extraction will diminish in the coming decades.
- The concept of EROI is seen as critical in MEDEAS, which is not the case in all IAMs.

Capellán-Pérez et al. (2020b) describe the MEDEAS model as one that builds bridges between PKE and ECE. The former provides a framework of a demand-led economy, as has been discussed earlier in this text. The latter places the socioeconomic system within the boundaries of the environment. The model contains several submodules: economy, energy demand, energy availability, energy infrastructure, transportation, land-use, water-use and climate. The MEDEAS economy contains different sectors, connected using IOA. IOA is done for economic factors and for energy, making it a hybrid IOA as discussed earlier. The MEDEAS model distinguishes 25 energy sources. This extensive breakdown is motivated by varying GHG emissions amongst extraction technologies. In the model conventional and unconventional oil make up different categories, because of the differences in GHG emissions during extraction. EROI of energy sources is assumed to be constant across the simulation, except for renewables used for electricity generation. These EROIs will change endogenously during the simulation. The climate model of MEDEAS is based on the C-ROADS model. Fiddaman et al. (2022) have developed a guide to the most recent version of this model C-roads uses SD to model interactions of GHGE from fossil fuels, land-use change and non-carbon GHGE.

Two novel damage functions were developed for MEDEAS, based on climate change damage assessments by natural scientists. Both functions are non linear, to reflect the non-linear nature of the relationship between climate change and the impact it has on other variables. One function is a logistic function and affects the economy through losses in the available energy for production. The other function is parabolic and represents monetary damages. Damages will have an effect on the GDPpc. In MEDEAS the GDP function behaves like a Leontief function. The energy demand is calculated based on GDP level in a certain year. This demand is compared to RES energy supply. If RES do not supply enough electricity, MEDEAS will use NRES to generate the necessary electricity. If limits on NRES cause a supply shortage, the GDP will drop in that year until supply and demand are equal.

The authors reflect on the lack of a social dimension in this model. MEDEAS in this form is built using monetary and biophysical variables. Adding social variables like employment, inequality, interactions with institutions and the effects of political power are not elements of this model at the current time. Capellán-Pérez et al. (2020b) write in their conclusion that MEDEAS, due to limits on resource extraction and climate change, will not have a continuous growth path. Due to the lack of a continuous growth path, the BAU in 2100 will not have an economy that is 4-8 times larger than it is now, together with an increase in global temperature in the range of 3,5-4,5 °C, which is what MEDEAS predicts if limits on resource extraction are absent. The BAU scenario in MEDEAS will experience persistent recession in the coming scenario, due to limits on inputs for the economy and due to climate damages. This BAU scenario will have a large penetration of renewables (60-80%). These results are comparable to other IAMs, the authors conclude. MEDEAS forecasts a global socioeconomic and environmental crisis if governments do not implement drastic policies towards sustainability on a global scale.

6.1.4 LOWGROW

LOWGROW is a model developed by Victor and Rosenbluth (2007). It aims to explore the effects of low or ZG scenarios for Canada. The supply side in this model is represented by a Cobb-Douglas production function using aggregate capital and labour. The demand side is made up of household consumption, government expenditures, import, export and investments. The aggregate demand and supply evolve independently from each other. If they do not reach equilibrium in a certain time period, this will be solved by changes in employment. For example: if demand exceeds supply, unemployment will decrease and capital utilization will increase. LOWGROW has a significant social dimension. To represent poverty, the authors devised the low-income cut-off (LICO) metric. A family reaches LICO if it spends more on food, shelter and clothing than the average family by a significant amount. This is calculated by taking the mean expenditures on these goods (43,6%) + 20% as a fraction of income. The ecological dimension of LOWGROW models the GHGE, Kyoto compliance and forestry activity. Users of LOWGROW can use sliders in the model to exogenously override variables to generate new scenarios.

Results from simulations show initially that a ZG scenario without additional policies will lead to demand deficits. These deficits initiate a downward economic spiral. This ZG scenario cannot reach Kyoto targets. A better outcome is achieved if the government takes an active role by deeper redistribution, which means supporting people to get at a LICO level of income, implementing the plan to reach Kyoto targets and applying the stabilization program in which the government raises expenditures in times of demand deficit and vice versa.

LOWGROW2020 is a reworked model by Jackson and Victor (2020). This is an update of its 2007 version. It is a PKE and SFC model. LOWGROW2020 has an expanded ecological dimension compared to its predecessor. In this model economic growth is endogenous just like improvements in labour productivity. Growth depends on the latter. To model the ecological side, LOWGROW2020 has green investment equations able model productive or non-productive green investments. Jackson and Victor (2020) write that early, 'low hanging fruit' green investment will probably be productive green investment, while later green investment will be dominated by non-productive investments. This could be seen as efforts to mitigate the impact of climate change. The authors use the Sustainable Prosperity Index (SPI) to judge the effectiveness of different scenarios for Canada. The SPI was developed in earlier work of the authors and is a composite index which aggregates economic, social and environmental variables into one value.

Three scenarios were developed for Canada by Jackson and Victor (2020) and compared using SPI and GDP as target variables. If SPI is used, than the BAU scenario will lead to a reduction in SPI, while a sustainable prosperity scenario will lead to increases in SPI. The authors wonder if scenarios that lead to the best SPI outcome still describe a capitalist economy, due to the extensive ecological and redistributive policies of the government.

6.1.5 Observations taken from preliminary model study

Even though the models are built differently, there are similarities between some of their conclusions. Continuous growth as is practised now, with added technological change will likely not suffice to reach climate goals. Degrowth strategies are important in reaching climate goals. Redistributive policies and strong governmental action is needed to guide society towards an ecologically and socio-economically stable situation. Environmental policies can lead to worse socio-economic outcomes. The policy set should have policies tackling both the ecological and socio-economic challenges. On a positive note, these policies do not necessarily lead to poverty and increased inequality.

6.2 Model of choice

This dissertation's research question focusses on GHGE and (energy) economics. Therefore, MEDEAS has been chosen as the preferred model for running DG-related simulations. These factors are developed in most detail in MEDEAS for energy supply, energy demand and GHGE.

The code that runs the model is publicly available. MEDEAS is programmed in Python and runs in the open source program PyCharm. MEDEAS uses a data-sheet with initial conditions and trends of certain variables as inputs in the simulations. This data-sheet can be edited by the user to simulate different scenarios. Samsó and Ollé (2019) have designed two base scenarios:a BAU scenario and one mid-level transition (MLT) scenario. The source code for MEDEAS can be freely edited by the user. This allows the user to edit variables which are not present in the standard inputs data-sheet. The BAU scenario will be used as the reference scenario in the first part; later both BAU and MLT will be updated as some assumptions in BAU and MLT can be improved upon. These will be scenarios MLT2 and BAU2. All simulations will be done on a global scale. This is important when calculating global carbon budgets, global average GDPpc and other relevant variables.

6.3 Model decomposition

MEDEAS is an ECEM rich in parameters. The two base scenarios (BAU and MLT) contain a set of policy decisions that together lead to their respective outcomes. Not every decision made in these policy sets will have the same impact on the simulation's end result. It will be useful in the discussion of the two scenarios to know in detail what policy decisions have been made and the impact of each separate decision on the final outcomes. This way it will be possible to distinguish the most influential policy decisions. These decomposed elements will be used in designing a scenario able to reach net zero in 2050. To keep tables easy to interpret, a letter code will be assigned, which is similar to the method that D'Alessandro et al. (2018) use for Eurogreen scenarios.

6.4 Simulating scenarios that implement zero-growth and degrowth

Earlier in the text it was discussed how the connection between increases in GDP growth and GHG-emissions is positive. This showed that absolute decoupling is not observed in the present and many authors doubt the viability of absolute decoupling in the near future. The DG movement argued that reduced growth or DG can be a useful policy measure to decrease the GHG emissions and help in reaching climate goals.

The MLT scenario in MEDEAS will not reach the net zero goal in 2050. This dissertation will use ZG and DG policies to find the least costly set of policies to supplement MLT in reaching net zero. Samsó and Ollé (2019) use constant GDP-growth figures. This does not represent the dynamics of real economies. GDP predictions from the OECD will be used to add more dynamics to the GDP evolution. If DG is to be used as a policy instrument, this will have to be modelled in the GDP evolution as well. One way of modelling this could be a constant negative growth rate, analogous to the constant positive GDP-growth rate found in the two standard MEDEAS scenarios. Constant degrowth rates will not be strong representations of the economy, as sudden changes of this magnitude do not happen overnight. The optimization scheme will use a two factor way of modelling the DG rate. The first factor will represent a kind of 'societal learning' to live without growth. This is mathematically represented by a logistic function that evolves from 0 to 1 over a period of 20 years (2021-2040). This is the fraction of growth prevented from happening in the economy in each year. Without a DG factor added to this, growth per person would be zero from 2041-2050. Logistic functions start with slow growth, which can be interpreted as a learning period. In the next period living with less growth is better understood and can the growth rate can decrease at a faster rate. In the final part the absolute value of the growth rate decreases again as it closes in on its maximum value of 1. This could be interpreted as having more difficulties in finding parts of the economy to reduce growth in. The first factor will over time dampen the growth forecast by OECD (2022). It will by definition end in a zero growth rate (zgr) situation in 2040.

The logistic function used is shown below. The value 0.4 was chosen as the logistic growth rate. This logistic growth rate makes the year on year reduction of the economic growth rate happen gradually. These repeated shocks will not be bigger than shocks during crises like the great recession or the corona crisis (The World Bank (2020) forecast a 5.2% GDPpc decline for 2020). At most the logistic function will cause to a 1.89% reduction in economic growth rate per year. .

$\Delta GDP_{zgr,t} = \Delta GDP_{gr,OECD,t} * \frac{1}{1+e^{-0.4*(t-10)}}$

The second factor of the degrowth rate (dgr) will use a logistic function that represents DG efforts. This logistic curve will evolve from 0 to 1 in a 30 year period (2021-2050). It represents additional learning on how to live in a DG society. Different magnitudes of DG can be modelled by multiplying the values of this logistic function by the amount of DG desired. The constant by which this function is multiplied will be the amount of GDP prevented due to DG policies. To determine the system's behaviour at different levels of DG, a standard amount of DG needs to be chosen that can be increased stepwise. This will be based on fractions of the GDP in 2021. One step will be 10% of 2021 GDP as reported by the OECD. Simulations will happen that start at ZG to a DG amount that is 100% of 2021 GDP reduction. The variable 'a' is the number of 10% steps that are taken out of GDP in that scenario.

$\Delta GDP_{dgr,t} = a * 0.1 * \Delta GDP_{2021} * \frac{1}{1+e^{-0.4*(t-15)}}$

Once the first and second factors have been established, the final growth path for each year can be easily calculated by:

$\Delta GDP_{pc,t} = \Delta GDP_{gr,OECD,t} - \Delta GDP_{zgr,t} - \Delta GDP_{dgr,t}$

6.5 Choosing an optimal policy

Once all necessary simulations have been performed, the next step is choosing an amount of DG that balances economic productivity and environmental impact. Different variables will be compared and a procedure that uses threshold values will be used to choose an optimal scenario.

6.5.1 RURR policies

Initially the aim was to use a combination of RURR and DG policies to find an optimum. This would have been achieved using an optimization algorithm of steepest descent, based on the Powell method as described by Nopens (2013, p. 86-87). The optimal solution would be bound by the condition that net carbon emission had to be zero and in the optimal solution the GDPpc will be maximised. After trying to execute this process, it was found that using RURR was not useful as a policy instrument within the MEDEAS framework. If the economy would hit the barrier imposed by RURR, it would suddenly crash. During an interview with developers of MEDEAS this observation was discussed. MEDEAS will compare the available energy production and the economic output. If energy demand is bigger than energy supply, it wil decrease the GDP in one step until the energy demand matches the energy supply. This caused abrupt contractions of the economy. One of the results of this process is shown in appendix A.3. This behaviour of the scenario due to RURR policies will be one of the points of criticism on MEDEAS that will be discussed later.

6.5.2 Choosing the optimal degrowth path

If the simulations of ZG and DG scenarios mentioned above are executed, a choice has to be made out of the twelve scenarios: updated BAU (BAU2), updated MLT (MLT2), MLT2 with ZG (MLT2ZG) and the different amounts of DG (example: MLT2D1, for a DG amount of 10% of 2021 GDP). To make a decision, different variables will be collected from all scenarios. These will be direct variables: GDP, GDPpc, GHGE per year, temperature increase, fraction of RES, final energy consumption in 2050, cumulative GHGE (CGHGE) in 2050, EROI in 2050. A second set of variables are the complementary variables. These will be calculated to help while choosing an optimal solution. Carbon intensity of the economies in the different scenarios is calculated by dividing GDPpc by GHGE. Surplus in GDPpc in a first form is calculated by taking the difference between the global average GDPpc in 2050 and substracting a threshold value. Variables could form a threshold, that exclude scenarios. For example overshooting all carbon budgets. A variable could be one to maximise or minimize. GDPpc is an example of the former, carbon intensity of the latter.

During an interview with MEDEAS developers, they confirmed the lack of an explicit value in literature of a minimal GDPpc level for a decent life. To solve this, the simulation will use two different GDPpc threshold values. The first based on a text by Hickel (2020). He states that reaching a GDPpc level of $7000 corresponds to a Human Development Index (HDI) of 0,8. The HDI is a composite index that uses life expectancy, GDPpc and average years of schooling to calculate a value between 0 and 1. The second GDPpc threshold is the global average 2009 GDPpc which is $6086. The former will be a higher GDPpc threshold, the latter a lower GDPpc threshold. It is to be expected that values will lead to different net zero scenarios. It has been mentioned earlier that multiple paths exist to reach net zero. Having two scenarios would make it possible to compare how additional investment in environmental policies is needed to allow for a higher level of output.

Energy surplus is calculated by subtracting the minimum necessary energy for decent living as it was developed by Millward-Hopkins et al. (2020) from the produced net energy. Millward-Hopkins et al. (2020) write that a global energy production of 149 EJ/year is sufficient for leading a decent life.

$$E_{surplus} = E_{prod,net} - E_{min}$$

Carbon budget calculations are taken into account for four different budgets: a stringent one for 1.5°C developed by Forster et al. (2022) and budgets for 1.5, 1.7, 2°C developed by European Space Agency (2022). A carbon budget is an amount of CO_2 that can be present in the atmosphere to have a 50% chance of causing a certain amount of global warming. MEDEAS reports tow values related to GHGE: GHGE for CO_2 and GHGE for all GHG in CO_2-equivalents. The expression for equivalent emissions adds methane in a first step to the total GHGE of CO_2. In a second step this is multiplied by a conversion factor that is assumed to convert CO_2-equivalents for CO_2 and methane to GHGE for all GHG. In MEDEAS the rate of global warming is calculated based on a function that uses CGHGE in equivalents for all GHG. This correction factor is not explicitly explained in the MEDEAS user manual and it was not possible to find standardized correction factors in literature. In the literature carbon budgets are expressed in CO_2 emissions. This issue with correction factors will be discussed later in the dissertation. While choosing an optimal policy, the CGHGE for CO_2 will be used. This will lead to higher than expected rates of global warming in MEDEAS, as other GHG are not accounted for. Even though this is not optimal, these are the units in which carbon budgets are usually expressed.

Threshold values for the minimum EROI needed for societies to function is debated in the literature. An EROI of at least 3 as a bare minimum is proposed by Hall and Hart (2010). Brandt (2017) suggests an EROI of 5, as lower EROI values will burden society with excessive expenses on the energy sector. Fizaine and Court (2016) have found an EROI value of 11 to be necessary to support a growing society. The simulation's EROI values will be compared to these three thresholds.

If possible, a DG path will be chosen that produces enough energy, has a GDPpc that is sufficient, does not exceed carbon budgets, has sufficient EROI and minimizes GHGE. If not possible, a second best option will be chosen that meets the highest amount of these criteria.

6.6 Building upon the chosen degrowth path

If a ZG/DG path can be found that meets the constraints and lowers GHGE to a lower level than MLT2 or BAU2, then this path will be chosen to continue putting together a new scenario. This scenario will try to lower the GHGE to zero in 2050. The additional policies which will be used in this final scenario cannot be predetermined exactly at this time. The amount of possible variables that can be adapted in MEDEAS is large, and with each extra variable the number of possible scenarios grows quickly. Finding this net zero scenario will be done by trial-and-error. It will mostly consist of increasing the size of MLT2 policies.

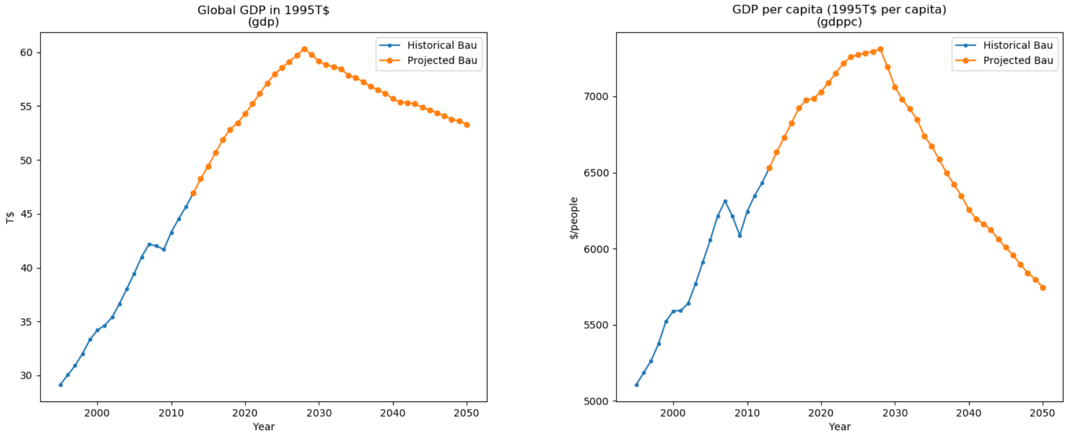
7 Results

7.1 MEDEAS base simulations

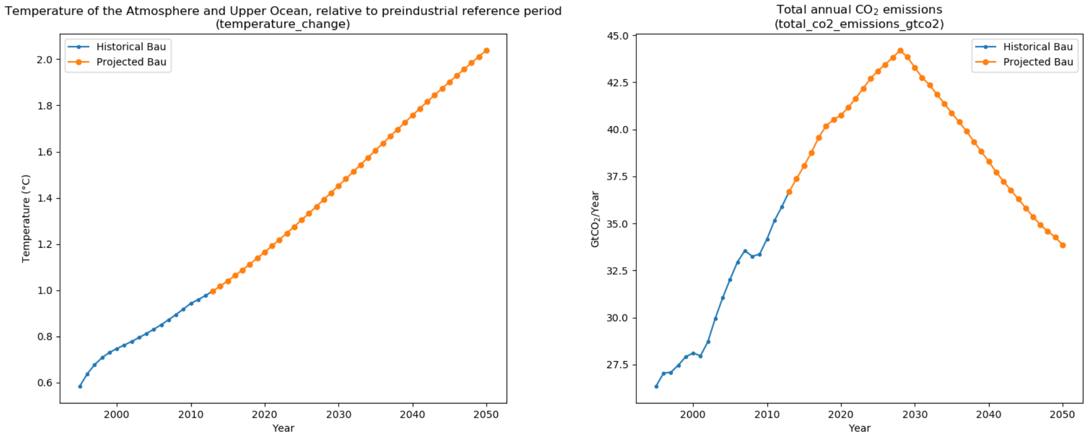
Two simulations are included in the MEDEAS base package set up by Capellán-Pérez et al. (2022). As mentioned earlier, these are the BAU scenario and a MLT scenario. The results of these simulations will be shown in the following part, together with a short explanation of the important characteristics of these scenarios.

7.1.1 BAU

The first scenario describes possible BAU outcomes. Capellán-Pérez et al. (2020b) describe four possibilities. They differ in their inclusion of climate damages and/or restrictions in energy availability. These BAU scenarios represent different assumptions about the world that other IAMs frequently use. The most common assumptions according to the authors are the lack of climate damages and lack of energy restrictions. MEDEAS's standard reference scenario uses both climate damages and energy restrictions. Capellán-Pérez et al. (2020b) justify this choice by referring to uncertainty about the accessibility of unconventional NRES and issues with implementing RES to replace NRES. An example of such an issue is competition for land with other sectors. The different assumptions lead to different BAU-behaviour. These simulations can be found in A.1. In this dissertation the standard MEDEAS scenario will be used that implements climate damages and energy restrictions. The following graphs show simulation results for four variables of interest: GDP, GDPpc, global temperature increase and CO_2 emissions. These graphs show a drop in GDP starting from 2028, which is caused by reaching peak oil.



(a) Global GDP (b) GDP per capita



(c) Global temperature increase (d) CO_2 emissions

Figure 5: Results BAU scenario

Peak oil in BAU scenario

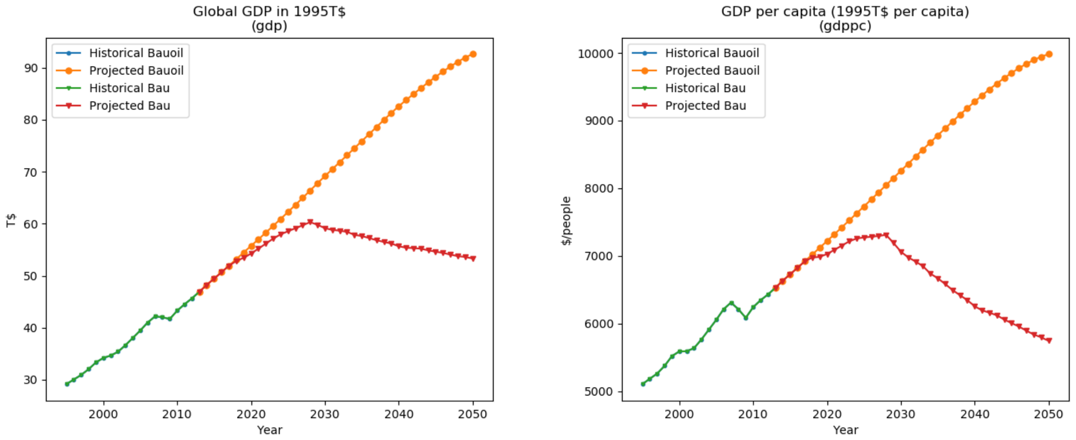
In the BAU scenario the GDP and GDPpc evolution shifts downwards starting from 2028. In the MLT scenario this shift does not happen. Solé et al. (2020) have also done simulations using the MEDEAS model. Their explanation is that the system reaches maximum fossil fuel production in 2028, which they call ’peak oil’ and ’Hubbert peak’. To examine this cause of the GDP shift in the BAU scenario, a simulation has been done which allows infinite use of NRES: oil, natural gas, coal and uranium. If the GDP and GDPpc shift is caused by limits on NRES, the hypothesis is that the downwards shift should not happen if NRES are infinitely available. The new scenario is named

BAUOIL. The following table shows the changed parameters.

Variable	**BAU**	**BAUOIL**
Unlimited NRE? (1=Y;0=N)	0	1
Unlimited oil? (1=Y;0=N)	0	1
Unlimited gas? (1=Y;0=N)	0	1
Unlimited coal? (1=Y;0=N)	0	1
Unlimited uranium? (1=Y;0=N)	0	1

Table 2: BAUOIL changes

The results of the simulation support the view of Solé et al. (2020). GDP and GDPpc growth keep increasing at a roughly constant rate. This can be observed in the figure below.



(a) Global GDP

(b) GDP per capita

Figure 6: Results BAU and BAUOIL-scenarios, own simulation

7.1.2 MLT

Capellán-Pérez et al. (2020a) have designed two possible pathways for the RES transition: optimal level transition (OLT) and MLT. These are scenarios that should reach the COP21 goal, also known as the Paris Agreement formulated by the United Nations Framework Convention on Climate Change (2022). OLT and MLT can both start in 2020 or 2030, which reflects the moment at which policy makers change behaviour and leave the BAU scenario. Unlike OLT, the MLT scenario is not optimal as a transition scenario. This model's outcome will be between BAU and OLT. In the modelling package the MLT scenario starting in 2020 is included, OLT scenario is not. The authors have run both MLT2020 and MLT2030. They observe that starting the reduction of GHGE in 2030 will necessitate a steeper decline to keep within the allocated carbon budget to reach the COP21 goal in 2050. In MLT2020 the decline in GHGE is less steep while it can still reach the 2050 goal. Results of these simulations by Capellán-Pérez et al. (2020a) can be found in appendix A.2.

In this dissertation MLT starting in 2020 will be used as a first alternative policy scenario to BAU. This is the scenario provided by the authors. The simulation results of BAU and MLT are shown in the following graphs. The policy set applied in the MLT scenario consists of: faster deployment of renewable energy sources, electrification and energy storage facilities. These changes will help the road-transport sector to electrify. At this time, the transport sector is one that mainly uses fossil fuels as its energy source. The following table shows the changed parameters by Capellán-Pérez et al. (2022), in BAU and MLT.

Scenario Parameter	**BAU Value**	**MLT Value**
Population growth (example year: 2015)	0.0105	0.009488
Labour share 2050	0.52	0.6
Electric RES		
Nuclear power	Constant	1.5%
Hydro growth	2.8%	5.6%
Geothermal growth	2.4%	4.8%
Solid BioE-Electricity growth	7.2%	14.4%
Oceanic growth	4.8%	20%
Onshore wind	25.1%	30%
Bio-energy		
Additional land biofuels	100 Mha	200 Mha
Evolution Biogases (vs past trends)	1	2
RES for heat		
Solar growth	12.7%	30%
Geothermal growth	7.6%	20%
Solid Bio-energy	11.5 %	20%
Afforestation		
Afforestation program	No	Yes
Resources		
Coal to Liquid (CTL) growth	15%	0%
Gas to Liquid (GTL) growth	20%	0%

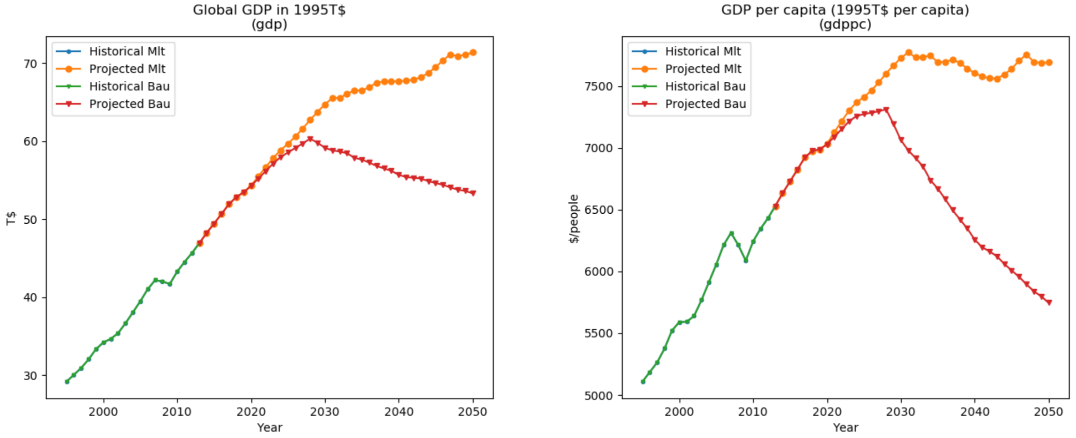
Climate		
Exogenous other GHG emissions: selection of RCP	RCP8.5	RCP2.6
Household transport policies, shares at final time		
Policy electric household 4wheeler vehicle	0.0064	0.3
Policy hybrid household 4wheeler vehicle	0.0108	0.25
Policy gas household vehicle 4w	0.1489	0.4
Policy electric 2wheeler h.	0.9254	0.9
Policy change to 2wheeler h.	0.3325	0.6
Inland transport sector policies, shares at final time		
Policy hybrid HV	0.00045	0.7
Policy gas HV	0.00045	0.3
Policy electric LV	0.00074	0.3
Policy hybrid LV	0.00036	0.5
Policy gas LV	0.01597	0.2
Policy electric bus	0	0.45
Policy hybrid bus	0	0.45
Policy gas bus	0	0.1
Policy electric train	0.2	0.8
Common annual variation for all minerals		
P recycling minerals rest of economy	0%	5%
P recycling minerals alternative technologies	0%	5%

Table 3: Changes in MLT scenario compared to BAU scenario[1]

These parameters represent most of the policies mentioned above. Energy storage facilities are not modelled explicitly. Additionally, reforestation policies, recycling, expansion of nuclear energy, halting the growth of coal-to-liquid (CTL) and gas-to-liquid (GTL) fossil fuels are policies applied in MLT that were not mentioned before. The climate parameter that was changed in MLT is the RCP. In the MLT scenario the level op GDPpc growth remains identical to the BAU scenario. This at a constant rate of 1.4%.

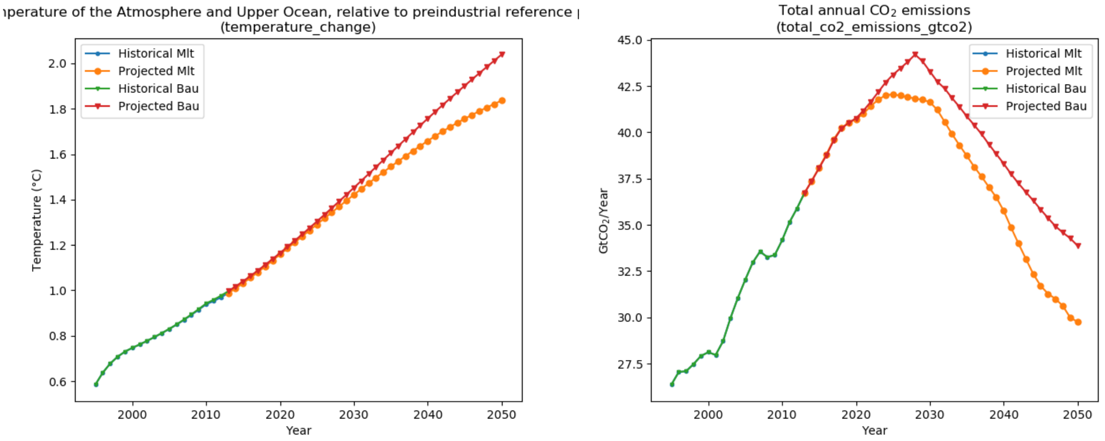
---

[1] h. = households, HV = heavy vehicles, LV = light vehicles



(a) Global GDP

(b) GDP per capita



(c) Global temperature increase

(d) CO_2 emissions

Figure 7: Results MLT scenario, own simulation

7.1.3 Nomenclature of MLT decomposition

Due to the mix of policies in MLT, it is useful to decompose the effects of these policy decisions. The following list shows the nomenclature of the decomposed simulations:

MLT policies

- RES - Contains electric, bio-energy, and heat RES policies.
- ELEC - Contains policies which govern electrification of over-land transportation.

- N - Expansion of nuclear energy
- A - Afforestation program activated
- RCP - Representative concentration pathway 1 is activated.
- C - CTL and GTL growth blocked
- M - Improved recycling policies activated.
- LAB - Higher labour share

Addictional scenario options

- OIL - Infinite use of NRES
- ND - Climate damage function disabled.
- ZERO - Yearly GDPpc growth = 0%
- DEG1 - Yearly GDPpc growth = -1.4%
- NORCP - Representative concentration pathway 4 is activated in MLT.
- OECD - OECD growth projections by OECD (2022) are used.
- NELF - Climate change module turned off.

7.1.4 Results of MLT decomposition

The MLT scenario has changed many parameters compared to BAU. The table below shows the outcomes with regard to the most important variables for each policy change: GDP, GHGE and global warming. The effects of these changes are expressed as deviations from BAU at the end of the simulation in 2050. Some policies will have significant effects on variables different from GDP, GHGE and temperature change. Change in labour share will for example have effects on growth of the capital share and cumulative capital present. After discussing LAB, different policies will be combined to find out if synergies are present.

Scenario	GDP (%)	GHGE (%)	ΔT (°C)
LAB	-0.6	-0.3	+0.002
N	+0.7	-0.18	0
RES	+14.98	-16.61	-0.038
A	+0.056	-9.24	-0.019
C	0	0	0
RCP	0.038	0.030	-0.19
ELEC	+5.33	+0.44	+0.007

M	+0.19	-0.03	0

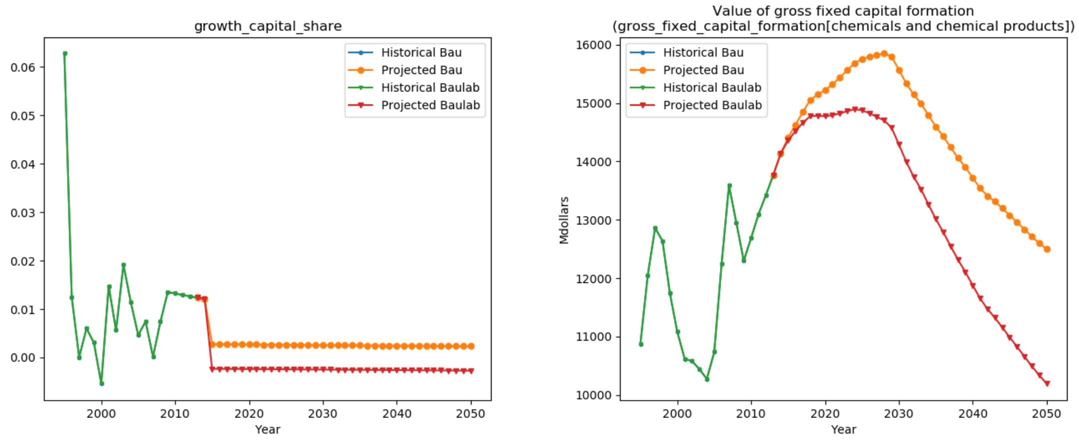
Table 4: Single policy simulations

BAU and BAULAB

In the MLT scenario, the labour share is increased from 0.52 to 0.60. The significant effect of an increase in labour share can be found in the evolution of capital growth and labour share. If the share is increased, the growth rate of the capital share will be negative. When the evolution of fixed capital is simulated, the LAB simulation shows a reduced peak amount of total capital and comparable behaviour once peak oil production kicks in. The evolution is comparable across all simulated sectors. The chemical industry has been chosen here.

Variable	**BAU**	**BAULAB**
Growth Capital Share	>0%	<0%
Value fixed capital	$12.7 * 10^{12}\$$	Peak $10.2 * 10^{12}\$$

Table 5: Results BAU - BAULAB



(a) Growth Capital Share

(b) Gross fixed capital formation

Figure 8: Results BAU and LAB-scenarios

BAURES and BAURESELEC

The following two scenarios have unexpected results. If policy makers only use RES in their mix and no ELEC, then GDPpc evolution does not seem to stabilize. Global temperature does not seem to be affected significantly in either scenarios. If policy makers only use RES in their mix, the total annual CO_2-emissions are lower than the MLT scenario. In the RESELEC scenario GDPpc seems to stabilize. It is at a lower level than MLT, but stable. The atmospheric temperature does not lower in these simulations, even when adopting RESELEC policies.

Variable	**BAU**	**...RES**	**...ELEC**
Global GDP	55 T$	61 T$	68 T$
GDPpc	5750$	6600$	7500$
Temperature increase	2°C	2°C	1.9°C
Annual CO_2-emissions	33.5 Gt/year	28.5 Gt/year	32.5 Gt/year

Table 6: BAURES and BAURESELEC scenarios

RESELEC and RESELECRCP

Simulating RESELEC and RESELECRCP shows that RCP choice has the biggest impact on temperature change in the model. Total annual CO_2 emissions did not reduce much due to these policies. Samsó and Ollé (2019, p. 248) explain that the lower RCP use is motivated by a deployment of carbon capture and sequestration policies (CCS). RCP does also lower emissions of GHG different from CO_2, Samsó and Ollé (2019, p. 407-411) write. Different RCP predict different emission patterns of these other GHGs. Earlier in the text it was argued that using different RCPs was intended to show a policy set's effect on different climate outcomes. One could wonder if changing RCP between the BAU and MLT scenarios is warranted in this case. This singular change explains most of the prevention of atmospheric temperature increase. This can be seen in the following table.

Variable	**BAU**	**BAURESELECRCP**	**MLT**
Global GDP	55 T$	70 T$	71 T$
GDPpc	5750$	7700$	7800$
Temperature increase	2°C	1.85°C	1.83°C
Annual CO_2-emissions	33.5 Gt/year	32.5 Gt/year	30 Gt/year

Table 7: Scenarios RESELECRCP and MLT

Does this mean that RESELEC policies barely impact on temperature change? If RCP changed to its BAU level, the same effects can be observed. The following table compares MLT and MLTNORCP simulations with regards to atmospheric temperature change.

RESELECRCPA and RESELECRCPNA

The following two simulations used afforestation policies and expansion of the nuclear production. The economic variables are not significantly affected. The following graphs show that the afforestation policy is the significant one in lowering the CO_2 emissions. The added prevention in temperature increase will be about 0.2°C. Expansion of nuclear

Variable	**MLT**	**...NORCP**
Temperature increase	1.8°C	2°C

Table 8: Scenarios MLT and MLTNORCP

energy generation does not seem to have significant impact on GDP, GDPpc, temperature change or GHG-emissions at the levels modelled in MLT.

Variable	**RESELECRCP**	**...A**	**...NA**
Temperature increase	1.85°C	1.83°C	1.83°C
Annual CO_2-emissions	32.5 Gt/year	28.5 Gt/year	28.5 Gt/year

Table 9: Scenarios RESELECRCP(N)(A)

7.1.5 BAU, MLTNORCP and MLT that use different growth paths

The previous simulations have given an overview of the effects of single policies from MLT. These can later be used when developing a net zero scenario. The main aim of this dissertation is to find out what the effects are of ZG or DG on climate outcomes. The first set of simulations that change the growth path will follow. These will study the effect of the growth path on the evolution of environmentally interesting variables.

These simulations will take the BAU scenario and both apply policies of ZG at the start of the simulations and a constant DG path of -1.4%. This value is chosen as a mirror of the standard growth rate in BAU and MLT. The ZERO simulation has comparable behaviours across the variables of interest. The GDP grows until it hits peak oil. This DG scenario does not contain a plateau followed by a decrease. The decline in GDP is dominated by the imposed negative growth rate and not peak oil. In this DG scenario the EU-target of net zero by 2050 is not reached. The DG causes GHGE to almost halve by 2050. The simulations show that this DG path would lead to a reduction of the atmospheric temperature levels comparable to the MLT scenario. It is important to keep in mind that these simulations use the RCP of the BAU scenario, while MLT uses lower RCP levels.

Variable	**BAU**	**...ZERO**	**...DEG1**
Global GDP	53 T$	51 T$	37 T$
Annual CO_2-emissions	33.5 Gt/year	32.5 Gt/year	19.5 Gt/year
Primary energy RES	29%	30.5%	43%
Temperature Change	2.04°C	2.02°C	1.84°C

Table 10: Results alternative growth scenarios using BAU

Total GDP in the BAUDEG1 scenario would keep the global GDP level above what it was in 2000. This GDP will have to be shared with more people, due to population growth. An interesting observation is that in the DG scenario, using BAU parameters, a bigger fraction of the primary energy will be produces by RES. The simulations suggests this would happen while investments in RES remain the same as the BAU scenario. It was explained before that in MEDEAS the growth rate of RES is modelled independently of the GDP. As a lower GDP level will lower energy demand, a larger fraction of this can be supplied by RES.

The following simulations use NORCP as the reference scenario. If the MLTNORCP and DEG1 policies are combined, the GHG emissions reaches 10 Gt/year in 2050. This closes in on net zero, but falls short of reaching the EU 2050. The DEG1 policy has significant effects on the fraction of primary energy from RES (increase of more than 20%) and on global warming reduction (almost 0.3°C) compared to the MLTNORCP evolution. These simulations indicate that DG has effects on GHGE. Later in this section an optimal rate of DG will be chosen.

Variable	**MLTNORCP**	**...ZERO**	**...DEG1**
Global GDP	71.5 T$	59.7 T$	37.3 T$
Annual CO_2-emissions	29.6 Gt/year	21.1 Gt/year	10.4 Gt/year
Primary energy RES	41.2%	47.8%	63%
Temperature Change	2.02°C	1.89°C	1.76°C

Table 11: Results alternative growth scenarios using MLTNORCP

The table below show the results of these scenarios with RCP2.6 enabled. In these scenarios the temperature change is reduced. The other outcomes are similar. This is to be expected, as a lower RCP encompasses a pathway with extensive environmentally beneficial developments in society with regards to efficiency, behaviour in the population, etc. The atmospheric temperature evolution is close to stabilising when using MLT and DEG1 together.

Variable	**MLT**	**...ZERO**	**...DEG1**
Global GDP	71.5 T$	59.7 T$	37.3 T$
Annual CO_2-emissions	29.6 Gt/year	21.1 Gt/year	10.2 Gt/year
Primary energy RES	41%	47.5%	63%
Temperature Change	1.83°C	1.71°C	1.56°C

Table 12: Results alternative growth scenarios using MLT

7.2 Updated MLT and BAU

It could be argued that some choices in the MLT and BAU scenarios can be improved upon. A first choice is the GDP growth path, which is a constant rate in BAU and MLT instead a more dynamics rate by using OECD forecasts. Secondly, the RCP choice in BAU and MLT scenarios are pessimistic in the former and optimistic in the latter. These will be changed to less pessimistic for BAU and less optimistic for MLT, which is more in line with prudent pessimism with regards to technological innovation. And finally, electrification of the transport fleet has been updated to more recent policy goals.

7.2.1 Growth path based on OECD

In MLT and BAU scenarios the growth rate is a constant GDP growth rate of 1.4% for the period 2015-2050 (and beyond, up to 2100). The updated scenarios will focus on the period 2015-2050, as these are the time periods that have been used in the previous simulatios for BAU, MLT and the other variants. 2050 is also relevant as it is when the EU intends to reach net zero.

The MLT and BAU growth paths are underestimations of the growth path estimated by OECD (2022). The impact of using OECD-data and not the basic MEDEAS growth path is relatively modest on final outcomes, as long as oil demands become the limiting factor on economic growth. If these limits are taken away, the OECD growth path impact becomes more noticeable. The OECD growth path will be used in BAU2 and MLT2. The growth path according to OECD has been calculated as follows from absolute GDP values:

$$Growth = \frac{GDP_t - GDP_{t-1}}{GDP_{t-1}}$$

The following table shows the results of these calculations for the first five years compared to the MLT growth path. The MLT growth path underestimates the OECD predictions up to 2050, which will have a growth rate of 1.49%.

YEAR	**MLT**	**MLT2**
2015	0.014	0.035
2016	0.014	0.031
2017	0.014	0.038
2018	0.014	0.037
2019	0.014	0.029

Table 13: GDP-growth rates forecasts by OECD (2022)

7.2.2 Choice of RCP

The RCP pathways have been discussed before. MLT and MLTNORCP have shown that global warming reduction is mostly caused by the RCP assumption, not by explicit policies used in MLT. Using a higher RCP for BAU and lower RCP for MLT implies substantial policy and technological changes not explicitly accounted for. This goes against the ideas of prudent pessimism. Samsó and Ollé (2019, p. 248) explain that this RCP2.6 world needs new bioenergy and CCS technology. If a modeller is cautious with regard to technology not yet developed, he or she could use RCP4.5 for MLT and RCP6.0

for BAU scenarios. Doing this will force a bigger part of climate change prevention to be caused by the explicit policies in the scenario. Therefore, MLT2 will use RCP4.5 instead of RCP2.6 and BAU2 will use RCP6.0 instead of RCP8.5.

7.2.3 Electrification in MLT

Electrification is one of the main policies in MLT. Electrification of the transport sector in particular is developed in detail: household transportation, freight road-vehicles, trains and public transportation. The figures used by Samsó and Ollé (2019) have been updated as closely as possible to the policy targets formulated by International Energy Agency (2021, p. 72). The table below shows the changes. International Energy Agency (2021) does not use a subdivision for hybrid vehicles. Because of this all vehicles that are not purely electric are classified as internal combustion engine (ICE) vehicles in MLT2. MEDEAS does not have an electric heavy vehicle (HV) classification. The electric HV goal set by International Energy Agency (2021) will be added in the hybrid HV cell.

Household transport policies, shares at final time

Variable	**MLT**	**MLT2**
Policy electric household 4wheeler vehicle	0.3	0.86
Policy hybrid household 4wheeler vehicle	0.25	0
Policy gas household vehicle 4w	0.4	0.14
Policy electric 2wheeler h.	0.9	1
Policy change to 2wheeler h.	0.6	0.6

Inland transport sector policies, shares at final time

Variable	**MLT**	**MLT2**
Policy hybrid HV	0.7	0.59
Policy gas HV	0.3	0.41
Policy electric LV	0.3	0.84
Policy hybrid LV	0.5	0
Policy gas LV	0.2	0.16
Policy electric bus	0.45	0.79
Policy hybrid bus	0.45	0
Policy gas bus	0.1	0.21
Policy electric train	0.8	0.8

Table 14: Transport electrification targets of International Energy Agency (2021), compared to standard MLT

7.2.4 Comparing updated scenarios

The new scenarios behave very similarly to the original MLT and BAU scenarios. They do differ in the level of temperature change by 2050. These flip in BAU2 and MLT2. This will partially be caused by the RCP choice. Another factor which could be at play are the GHGE. BAU2 experiences peak oil and subsequent contraction of the economy. Its CGHGE are higher than those of MLT2 though. CGHGE will this not be the cause of the lower temperature increase in BAU2. It was found that other GHG have a higher rate of forcing in MLT2 than in BAU2. The relative difference in level of forcing is larger than the relative difference in CGHGE. This could explain the higher rate of warming while CGHGE of CO_2 is lower in MLT2. The environmental outcomes in BAU, MLT, BAU2 and MLT2 can be seen in the following table.

Variable	**BAU**	**BAU2**	**MLT**	**MLT2**
CGHGE (Gt)	3413	3443	3345	3382
T increase (°C)	2.04	1.86	1.84	1.92
Forcing (W/m^2)	3.92	3.47	3.37	3.59

Table 15: Environmental outcomes BAU2, MLT and MLT2

7.3 MLT2 scenarios with ZG/DG component

Previously it was determined that the growth paths have a significant impact on GHGE and climate outcomes. After that reference scenarios BAU and MLT have been updated to BAU2 and MLT2. The next part will add ZG and DG scenarios to MLT2. The purpose will be to find the optimal rate of ZG or DG which maximises desirable climate outcomes while minimizing undesirable economic impacts. Frequent references will happen to simulation results. These can be found in tables at the end of the results section.

7.3.1 Simulation results

Different levels of DG have been simulated to test the effects of ZG/DG on GHG emissions and other environmentally and economically relevant variables. The methodology used when simulating ZG and DG has been discussed in chapter 6. All values use the BAU2 scenario as a reference. These are mostly shown as fractions. In the case of temperature increases and CGHGE the values are shown in degrees Celsius and Gton of CO_2. These simulation results are shown in the first table.

There are unexpected results. The MLT2 scenario, even though it is a GG scenario, will lead to a higher level of global warming than BAU2. This could be caused by a number of factors. Firstly, the use of a more lenient RCP for BAU2 and a stricter RCP for MLT2 will push the temperature change of the former down and of the latter up. Secondly, the increased electrification causes an increase in global warming, as shown in the decomposition of MLT earlier in the text. RES policies used in MLT are able to mostly stabilize GDP, while the electrification together with RES will make most of the economic growth possible. Peak oil effects are still present in BAU2, which causes a strong negative evolution of GDP in that scenario. Increasing the amount of DG will lower GHGE further. EROI results are what was expected: as the fraction of RES increases, the EROI will decrease.

7.3.2 Complementary variables and choice of optimal model

As mentioned earlier in the text, a strategy to decide an optimal amount of DG depends on direct and complementary variables from the simulations. The first is carbon productivity. The second variable is energy surplus. The third variable is GDPpc surplus. The final set of additional variables looks at the CGHGE of the different scenarios and compares them to different carbon budgets. Carbon budget calculations are made for four different budgets: a stringent one for 1.5°C as reported by Forster et al. (2022) and budgets for 1.5, 1.7, 2°C determined by European Space Agency (2022). These simulation results can be found in the second table.

7.3.3 Choosing an optimal degrowth scenario

When analysing both the direct outcomes and complementary variables, there is not one scenario that is optimal for all the different variables. If the goal is to reduce environmental impacts as much as possible, it is obvious that the harshest level of DG will have the beset effects. The carbon-productivity keeps increasing with the level of DG. If policy makers aim to maximise this, the harshest level of DG should be applied to the economy. However, these harsh scenarios will have a strongly negative effect on GDPpc, which is to be expected. Lenaerts, Tagliapietra, and Wolff (2021) have argued that it will be difficult for any DG to be accepted.

The next variable looks at the energy output. All scenarios will produce enough energy to provide decent living conditions. All scenarios have an EROI level that is above 3 and 5 in 2050, but none reach the minimum of 11 as proposed by Fizaine and Court (2016).

None of the scenarios adhere to the limits on CGHGE set by the most stringent 1.5°C carbon budget by Forster et al. (2022) and the less stringent 1.5°C carbon budget by European Space Agency (2022). One scenario complies with the 1.7°C carbon budget, MTL2D10. All scenarios comply with the 2.0°C goals, at least by 2050. As said before, the CGHGE only calculates CO_2 emissions, which might lead to an underestimation when compared to CGHGE in equivalents.

The final complementary variable shows the number of years at 2050 GHGE left before reaching the 2°C budget. Scenario MLT2D5 has decent results if GDPpc2009 is used as a minimal necessary output for a decent life. Its GDPpc is slightly under the GDPpc2009 level and it reaches 2050 with more than 17 years of GHGE left according to the 2°C budget. This will be used to build upon to find a net zero scenario. If a minimal GDPpc is used based on Hickel (2020), MLT2D2 is the highest amount of DG that does not cross this threshold. MLT2D2 complies with the 2°C budget with eight years to spare. The GHGE of MLT2D2 is 24.74 Gt in 2050, which implies that a lot of work still needs to be done to reach net zero. MLT2D2 and MLT2D5 will both be used to find net zero scenarios.

7.4 Further development of the degrowth scenarios

The following part will describe how net zero were found, starting from the two DG scenarios that were chosen above. These were MLT2D5 for the lower GDPpc2009 threshold and MLT2D2 for the higher GDPpc$7000 threshold. The results of the development of these scenarios can be found in the third table at the end of the results section.
MLT2D5 does not reach net zero GHGE in 2050. After looking for a net zero scenario based on MLT2D5 using trial-and-error, a scenario was found that will reduce GHGE to near zero. The first policy change in MLT2D5 was the expansion of RES. MLT2 has roughly doubled the growth of RES compared to BAU2. The MLT2D5RES2 scenario has multiplied all RES growth factors of MLT2 by 1.5. Simulations using these growth rates showed that the economy reaches its peak RES capacities before 2050. It was necessary to increase the peak global capacities to go continue. The peak capacities were multiplied by 1.5. This increased development of RES lead to increased economic growth. This allowed for a cut in GDP without losses in the final GDPpc.

The next step in building the net zero scenario is MLT2D6RES2. Until now efficiency improvements were not included in the different scenarios, both in BAU(2) and MLT(2). In the next scenario energy efficiency improvement are included that evolve at medium speed. This is MLT2D6RES2EF2.

The last policy change is afforestation. Afforestation is a part of MLT(2). In our final scenario the rate of afforestation will be fourfold of the rate in MLT2. All these policies combined show a possible pathway towards net zero GHGE in 2050, which includes a DG factor as one of its core policy instruments. This final scenario is MLT2D6RES2EF2A4.

The impact of each policy is shown in the third table. The reported variables are GDP, GDPpc, the fraction of RES, the level of global warming, yearly GHG-emissions, fraction of GHGE due to a certain policy in the final scenario, CGHGE, carbon budget remaining and the amount of time remaining before crossing the carbon budget.

These different simulations bring a lot of insights with regard to the effects of DG in reaching a net zero society in 2050. This scenario uses four building blocks on top of MLT2: faster deployment of RES, DG, improvements in energy efficiency and negative emission strategies. Earlier it was concluded that a D5 scenario was the best possible amount of DG within the formulated constraints on GDPpc and the carbon budget. After increasing the RES policies and the peak capacities of RES, GDPpc could grow enough to allow for a D6 amount of DG without violating the GDPpc constraint significantly. This scenario comes short $27 per person. In total the DG policies will be responsible for a 46% reduction in GHGE.

Going from D5 to D6 without loss of GDPpc can be explained as follows: the higher fraction of RES causes a higher rate of relative decoupling, which will increase the production of the economy at constant GHGE. But if the GDPpc is kept constant, this will lead to lower total GHGE for the same amount of output. Improving the efficiency of the economy significantly impacts GHGE. The final part of this scenario is afforestation, which at this rate will cause 30% of the reduction in GHGE. This shows the need for negative GHGE to be part of a net zero policy strategy.

The second scenario, MLT2D2, was based on the GDPpc threshold of $7000. The results are shown in the third table. In this scenario a higher rate of decoupling will be needed, because the economy is bigger. To achieve this an even more elaborate rollout of RES has been applied. This policy, RES3, doubles both the maximal capacities and the growth rates compared to MLT2, leading to MLT2D2RES3. The previous scenario used a 50% increase of RES rollout compared to MLT2. As explained before, more RES will cause more economic growth. This will make it possible to increase the DG amount to D4, without crossing the threshold. The resulting scenario is MLT2D4RES3. This model is not net zero yet. The next step is adding efficiency improvements to the model. In this scenario the fast rate of efficiency improvement has been chosen, which leads to MLT2D4RES3E3. The last step is adding afforestation as a way to capture CO_2 emissions. MLT2D4RES3E3A5 is the final form of this second scenario. This scenario will reach net zero in 2050.

7.5 Conclusion

The research consisted of four main parts:

1. Discussion of the BAU and MLT scenarios. The decomposition of MLT has shown that three policies are key in explaining its improved environmental outcomes: electrification, faster rollout of RES and the RCP choice.
2. It was argued that certain assumptions in BAU and MLT could be improved. The RCP choice for both was changed, the BAU scenario went from RCP8.5 to RCP6.0 and MLT went from RCP2.6 to RCP4.5. The growth path was updated in both to the growth rate based on OECD forecasts. Electrification rates of MLT2 were updated as well, these figures will be higher than MLT.
3. The choice of an initial DG scenario was based on two threshold GDPpc values, one was GDPpc2009 and the other was a GDPpc of 7000$ which would correspond to a HDI of 0.8 according to Hickel (2020). MLT2D5 was found for the former and MLT2D2 for the latter.
4. Developing net zero scenarios was done by expanding environmental policies. It was necessary to increase the peak global capacities of RES to reach the necessary capacities for a net zero scenario. Increased RES allowed for increased levels of DG without diminishing the final GDPpc. Energy efficiency policies were used that were not included in MLT2. Afforestation was used as a negative emissions policy.

These simulations show that MLT2 is not sufficient to reach net zero in 2050. When the less favourable RCP4.5 is used, the environmental outcomes with regard to global warming are worse than those in BAU2. This can be explained with MLT2 being a GG scenario and BAU2 going through uncontrolled DG due to the effects of peak oil. The final scenarios need a multitude of policies to reach net zero, which demonstrates that CC will most probably not be solved by one 'silver bullet' technology. It has been shown that multiple paths exist towards reaching net zero. Acceptable paths towards net zero will depend on the constraints that are used. One could say that a 'menu of options' exist. This is comparable to the interpretation of the Phillips curve as a menu of policy trade-offs, as said by Samuelson and Solow, Hall and Hart (2010) write.

7.6 Results MLT2, BAU2 and DG policies

Variable	MLT2	BAU2	MLT2ZG	MLT2D1	MLT2D2	MLT2D3	MLT2D4
GDP (T$)	70	-24.00%	-2.00%	-4.00%	-7.00%	-11.00%	-16.00%
GDPpc ($)	7561	-25.00%	-2.00%	-4.00%	-7.00%	-11.00%	-16.00%
RES fraction	0.416	-30.00%	5.00%	7.00%	9.00%	13.00%	17.00%
Temp change	1.91	-0.06	-0.01	-0.02	-0.03	-0.05	-0.07
GHGE (Gt CO2 per year)	29.97	13.00%	-11.00%	-14.00%	-17.00%	-24.00%	-30.00%
GHGCum (GT CO2)	3383	60	-31	-50	-73	-108	-147
Final E consumption 2050	406.9	-22.00%	-2.00%	-4.00%	-7.00%	-11.00%	-15.00%
EROI	7.31	8.57	7.07	7	6.9	6.78	6.63

Variable	MLT2	MLT2D5	MLT2D6	MLT2D7	MLT2D8	MLT2D9	MLT2D10
GDP (T$)	70	-21.00%	-26.00%	-31.00%	-36.00%	-41.00%	-47.00%
GDPpc ($)	7561	-21.00%	-26.00%	-31.00%	-36.00%	-41.00%	-47.00%
RES (%)	0.416	22.00%	28.00%	35.00%	41.00%	48.00%	54.00%
Temp change	1.91	-0.09	-0.11	-0.13	-0.15	-0.17	-0.19
GHGE (Gt CO2 per year)	29.97	-37.00%	-45.00%	-51.00%	-58.00%	-63.00%	-68.00%
GHGCum (GT CO2)	3383	-183	-224	-263	-300	-338	-372
Final E consumption 2050	406.9	-20.00%	-25.00%	-30.00%	-35.00%	-40.00%	-45.00%
EROI	7.31	6.47	6.31	6.18	6	5.91	5.7

Table 16: Results MLT2 with additional DG policies

7.7 Complementary variables calculated for MLT2 with DG policies

Variable	MLT2	BAU2	MLT2ZG	MLT2D1	MLT2D2	MLT2D3	MLT2D4
GDP/GHGE	2.34	1.56	2.57	2.61	2.65	2.72	2.83
Energy Surplus	257.9	168.3	248.9	241.8	230.8	214	195.4
GDPpc Surplus GDPpc2009	1475	-386	1335	1192	966	638	274
GDPpc Surplus Hickel 0.8	561	-1300	421	278	52	-276	-640
Low C-budget reserves 1.5 degrees (Gt)	-823	-883	-792	-773	-750	-715	-676
C-budget reserves for 1.5 degrees (Gt)	-704	-764	-673	-654	-631	-596	-557
C-budget reserves for 1.7 degrees (Gt)	-354	-414	-323	-304	-281	-246	-207
C-budget reserves for 2 degrees (Gt)	146	86	177	196	219	254	293
Years left of GHGe (2050, 2 degrees)	4.87	2.53	6.61	7.56	8.85	11.1	14.07

	MLT2	MLT2D5	MLT2D6	MLT2D7	MLT2D8	MLT2D9	MLT2D10
GDP/GHGE	2.34	2.96	3.13	3.33	3.55	3.74	3.85
Energy Surplus	257.9	176	156.33	136.2	115.9	95.85	74.6
GDPpc Surplus GDPpc2009	1475	-99	-482	-876	-1259	-1656	-2057
GDPpc Surplus Hickel 0.8	561	-1013	-1396	-1790	-2173	-2570	-2971
Low C-budget reserves 1.5 degrees (Gt)	-823	-640	-599	-560	-523	-485	-451
C-budget reserves for 1.5 degrees (Gt)	-704	-521	-480	-441	-404	-366	-332
C-budget reserves for 1.7 degrees (Gt)	-354	-171	-130	-91	-54	-16	18
C-budget reserves for 2 degrees (Gt)	146	329	370	409	446	484	518
Years left of GHGe (2050, 2 degrees)	4.87	17.55	22.32	28.13	35.34	44.08	53.46

Table 17: Complementary variables based on DG scenarios

7.8 Final scenarios, using GDPpc2009 and GDPpc7000$ thresholds in 2050

Variable	BAU2	MLT2	MLT2D5	MLT2D5RES2	MLT2D6RES2	MLT2D6RES2EF2	MLT2D6RES2EF2A4
GDP (T$)	53.02	70.25	55.54	60.24	56.28	56.87	57.23
GDPpc ($)	5710	7562	5985	6497	6066	6131	6174
RES (%)	29.2	41.6	51	64.12	65.55	72.41	72.15
Temp. Change	1.86	1.92	1.82	1.78	1.76	1.74	1.69
GHGE (Gt CO2/year)	34.01	30.06	18.81	15.52	14.18	10.18	0.78
Cum. GHGE (Gt CO2)	3443	3383	3198	3129	3095	3046	2903
GHGE prevented (fraction)	/	/	0.39	0.14	0.07	0.1	0.3
CB remaining (1.7 degrees)	-414	-354	-169	-100	-66	-17	126
CB years (1.7 degrees)	/	/	/	/	/	/	161.54
CB remaining (2 degrees)	86	146	331	400	434	483	626
CB years (2 degrees)	2.53	4.86	17.6	25.77	30.61	47.45	802.56

Table 18: Scenario GDPpc2009 overview

Variable	BAU2	MLT2	MLT2D2	MLT2D2RES3	MLT2D4RES3	MLT2D4RES3EF3	MLT2D4RES3EF3A5
GDP (T$)	53.02	70.25	65.4	73.3	65.55	65.77	66.33
GDPpc ($)	5710	7562	7050	7900	7066	7090	7150
RES (%)	29.2	41.6	45.34	67.53	70.7	74.13	74.13
Temp. Change	1.86	1.92	1.88	1.79	1.76	1.74	1.67
GHGE (Gt CO2/year)	34.01	30.06	24.74	17.82	15.27	12.03	-0.4
Cum. GHGE (Gt CO2)	3443	3383	3308	3151	3091	3063	2870
GHGE prevented (fraction)	/	/	0.15	0.31	0.12	0.05	0.38
CB remaining (1.7 degrees)	-414	-354	-279	-122	-62	-34	159
CB years (1.7 degrees)	/	/	/	/	/	/	GHGE <0
CB remaining (2 degrees)	86	146	221	378	438	466	659
CB years (2 degrees)	2.53	4.86	8.93	21.21	28.68	38.74	GHGE <0

Table 19: Scenario GDPpc7000$ overview

8 Discussion

The main purpose of this research was to find out if DG policies can be a meaningful part of a policy set that works towards net zero emissions in 2050. To answer this question environmental impacts of single policies in MLT were studied by decomposing MLT in its constituent parts. The three central policies in MLT are: faster RES deployment, electrification and choice of RCP. MLT and BAU were updated to MLT2 and BAU2. It was found that without the most optimistic RCP, the MLT2 scenario will have worse environmental outcomes than BAU2 with regard to global warming. This shows the importance of choosing climate parameters that fit the model's aim. Even though MLT featured elaborate environmental polices that fit GG, it was found that the lion's share of the reduction in temperature change was caused by the RCP choice.

After that an array of DG scenarios were simulated to find different policy outcomes. It was found that none of the scenarios turned out to be optimal in all outcome variables. In the end the GDPpc threshold was the variable that determined the level of DG. It was found that higher economic output necessitated higher investment in RES, efficiency and negative emission policies. Keyßer and Lenzen (2021) came to a similar conclusion when they compared different scenarios and their characteristics. If the growth rate increases, higher rates of RES and decoupling are needed. This is predicted by the IPAT equation as well: higher affluence necessitates a decrease in the technological variable if the impact needs to remain constant. Keyßer and Lenzen (2021) argue that DG lowers the reliance on negative carbon technologies and uncertain technological innovation to reach net zero.

Once DG rates had been determined, it became possible to further design the final scenarios. Increased RES lead to further relative decoupling and allowed for higher levels of DG in both scenarios. However, DG was found not to be a silver bullet with the power to solve CC. DG used in combination with extensive environmental policies is necessary to reach net zero in 2050. Lower amounts of DG needed more extensive environmental policies to reach the net zero goal. Reaching a 1.5°C will not be achievable using these scenarios. The two final scenarios are able to stabilize at close to a 1.7°C increase in global temperature, based on the limits imposed by the different carbon budgets. Both scenarios needed extensive negative emission strategies to reach their goal. This was achieved by afforestation. Other negative GHGE technologies are not explicitly modelled in MEDEAS. Efficiency improvement is an important part of the policy set, but far from the dominant one. It accounts for 10% of GHGE prevention in the GDPpc2009 scenario and 5% in the GDPpc7000$ scenario.

The discussion will consist of three main parts. The first section will examine specific modelling decisions in MEDEAS. The next section will discuss the feasibility of the scenarios that were found. The final part will compare these scenarios to Eurogreen's DG scenarios. This comparison will show deficiencies that one model has that the other can account for. For example, Eurogreen has a better developed social dimension, while

MEDEAS has more elaborate energy-economy connections. The discussion will end with suggestions for future research, both for MEDEAS as for ECEMs in general.

8.1 MEDEAS scenarios

Two issues in the MEDEAS model will be discussed in more detail. Firstly, the low impact of the damage function in MEDEAS on simulation outcomes. The effects of environmental problems in MEDEAS take the form of supply side issues with regard to energy. Reaching peak oil output will cause DG in the BAU scenarios. It will be explained that environmental damages are underestimated in MEDEAS. The second part will discuss peak oil, RURR and the carbon budget. Different types of peak oil exist. The way MEDEAS simulations react to supply-side peak oil is not ideal. The variety in carbon budgets will be called into question.

8.1.1 Damage function

The CC impacts in MEDEAS are modelled from a strong-sustainability point of view. Samsó and Ollé (2019, p. 228) list following assumptions from using the strong sustainability constraint:

- Use climate change planetary boundary as a proxy for environmental degradation.
- Apply precautionary principle, as the uncertainty of climate change effects are large.
- Mathematically, the damage function is written as an Energy Loss Function (ELF), climate change affects the net available energy for society. This will impact the growth rate.
- The drivers of climate change used in MEDEAS are the CO_2-equivalent concentrations and the total radiative forcing, rather than temperature increase.
- No discounting of impacts, which maintains equity across generations.

ELF is a logistic function. The damages due to CC are modelled as having an impact on net energy availability to society. This function has an upper bound CO_2-concentration level after which CC has progressed so far as to be incompatible with human society. The authors mention that these damages could be seen as the cost of mitigation efforts that make sure society can keep functioning. The upper bound in MEDEAS model is 1000ppm CO_2.

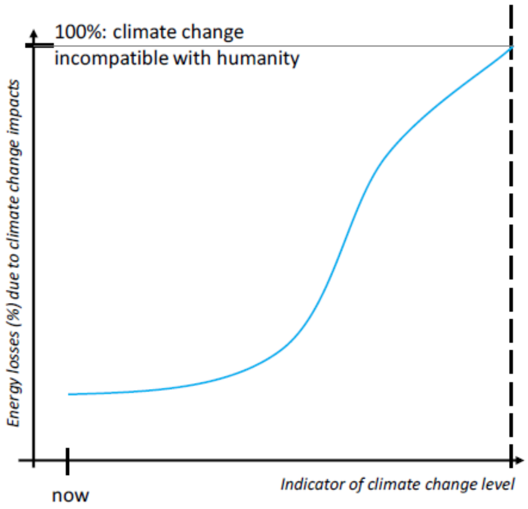


Figure 9: Logistic function, Samsó and Ollé (2019, p. 231)

The damage function implemented in the standard MEDEAS models has a small impact in the year 2050. As an example of this the BAU and BAUNELF scenarios will be compared in the following table. This table shows that the impact of climate damages in the BAU scenario will amount to 1% of GDP/GDPpc in 2050. This damage level is substantially lower than damage levels reported by WEF (2022). The World Economic Forum (WEF) reports that in a RCP4.5 scenario the global impact on GDP would be 4%. As BAU uses RCP8.5, the damage levels are underestimated even more than this comparison to the WEF results show. International Renewable Energy Agency (2019) have modelled climate damages in 2050 and predict a loss in GDP of 15.5%.

Variable	**BAU**	**BAUNELF**	**%Change**
GDP	53.3 T$	53.8 T$	0.95
GDPpc	5747 $	5804 $	0.99

Table 20: Results BAU and BAUNELF

An alternative way is to model damages using a SCC. These would have direct impacts on GDP, rather than indirectly through energy availability. As mentioned before, CC can induce higher sea levels, lower agricultural productivity and changed ecosystem services. If ELF is used, a technology that improves energy efficiency would decrease the impacts of CC. In the world of MEDEAS, energy efficiency improvements could counteract the losses in agricultural productivity and changed ecosystem services. However, if SCC would be used, improvements in energy efficiency would not have these effects. This leads to a new problem: how to determine the SCC? There is a lot of discussion in literature on the social cost of carbon. Howard and Sterner (2017) use a quadratic equation to determine the SCC, similar to the DICE damage function. They find an SCC value that is three to four times larger than one found by Nordhaus and Sztorc (2013). To go even further, the SCC could be split by region or sector. Neumann et al. (2020) and Zhao et al. (2020) use sectoral or regional damage functions to determine climate damages. MEDEAS is designed to be used by policy makers to simulate the effects of their environmental policies. Adding sectoral or regional climate damage functions could help policy makers forecast which parts of society will need the most support with regard to climate change.

8.1.2 Peak oil, RURR and carbon budget

It has been shown earlier in the text that unmet oil demands, caused by limits on oil extraction are the main driver of negative GDP growth in the post-2028 part of the BAU scenario. The BAUOIL scenario, which allowed for unlimited extraction of fossil fuels, showed that the BAU scenario growth rate could continue unimpeded. In the MLT scenario this peak oil effect was averted by high level of electrification and expansion of RES capacity.

The discussion concerning the impact of peak oil is ongoing. Different viewpoints have been formulated. A first one concerns peak oil due to peak-demand. Halttunen, Slade, and Staffell (2022) argue that the future world will not experience a moment of peak oil as is presented in the BAU model, as oil-demands would diminish before limits to oil exploitation would be reached. A second one is the better known type of peak oil, which is caused by supply-constraints. This model was formulated by Marion King Hubbert in the 1950s. Bardi (2019) is a proponent of this kind of peak oil. Bardi argues that, even though Hubbert's predictions were wrong, the assumptions were correct and a supply-side peak oil moment will happen. Decreasing EROI will cause production prices and oil prices to rise. EROI issues in oil energy extraction are proposed by Delannoy et al. (2021) as well. The authors describe that contemporary oil extraction uses 15.5% of the extracted energy in its production. This will increase to 50% in 2050. As discussed before, the BAU scenario in MEDEAS follows this second view on peak oil. MLT follows the first view on peak oil, as RES deployment and electrification happen at a rate that prevents a supply deficiency from happening.

A third point of view regarding oil production is that currently discovered reserves are higher than our allotted carbon budget to keep global warming below 1.5°C or 2°C. McGlade and Ekins (2015) conclude that burning all fossil fuel reserves as they were known in 2015 would lead to CGHGE about three times the CGHGE allowed in the period 2011-2050 to keep global warming below 2°C with a probability of 50%. The remaining carbon budget is 1100 Gton CO_2. Welsby et al. (2021) have repeated this exercise for a 1.5°C scenario. They found a budget of 580 Gton cumulative CO_2 emissions between 2018-2100. To not exceed this budget, 58% of oil, 56% of fossil fuel methane gas and 89% of coal of the reserves known in 2018 should not be extracted. Tokarska and Gillett (2018) write that reaching the 1.5°C goal will be difficult and that the latter half of the 21st century should have negative carbon emissions. Issues with carbon budget depletion are mentioned by Samsó and Ollé (2019, p. 485-486). The authors admit that this depletion is problematic and write that comprehensive measures will have to be taken in all demand and supply sectors. According to them this could be achieved by serious efficiency improvements and an abrupt fuel switch towards less emission-heavy fuels. A scenario that reaches net zero in 2050 and does not exceed the carbon budget for 1.5°C by too much would be preferable to the MLT scenario. This hypothetical scenario would reach the goals of the Paris climate agreement as defined by United Nations Framework Convention on Climate Change (2022), which states that the goal is to limit global warming to well below the 2°C limit, preferably under 1.5°C.

It was necessary to use carbon budgets to determine optimal DG scenarios and final scenarios. Using carbon budgets can be challenging as many different budgets exist, depending on the literature that is consulted. Matthews et al. (2020) have compiled a list of assumptions that can influence the way in which carbon budgets are calculated. Two examples of such assumptions: what odds to exceed a particular level of warming are chosen and the effects of aerosols on forcing levels. The existence of a variety of budgets suggests the need of a standardized way to calculating the carbon budget. This would make it easier to compare studies and simulations. A first step could be to determine a yearly conversion factor to express emissions in CO_2-equivalents which incorporates other GHG as well. This method is based on what Samsó and Ollé (2019) use in MEDEAS.

8.2 Feasibility of planned policies

The scenarios that have been designed could reach net zero in 2050 according to MEDEAS. They consist of four main parts in addition to the original MLT2: faster deployment of RES, DG, efficiency improvement and afforestation. Afforestation fills the space of negative carbon policies. To develop this scenario, it was necessary to increase the peak capacity of different RES. The The International Energy Agency (2021b) writes that deployment of RES is going faster than expected. When these results are compared to the scenario's growth rates, it is apparent that the deployment is not fast enough. In a more recent publication, the The International Energy Agency (2022b) reports that 90% of the increased capacity of electricity generation between 2022-2027 will come from RES. This forecast is 30% higher than the forecast made in the year before. The International Energy Agency (2021b) reports a solar energy growth rate of 17% in 2021. In the scenario with a higher level of DG the growth rate of solar energy is 52,5%, in the scenario with a lower level of DG this growth rate is 70%. At the current rate the necessary RES capacities will not be reached.

Many will dislike using DG as a policy instrument. Growth will still need to happen in the poorest regions of our planet to improve material well, Fitzpatrick (2020) write, and DG will not be accepted in those regions, Muradian (2019) say. People still expect ever increasing health and well-being according to Büchs and Koch (2019). Fitzpatrick (2020) argues that DG should not target uniform cuts in GDP, but should instead target sectors that have high environmental impacts. These are valid arguments and will necessitate further development of models.

One of the arguments against MLT and some GG scenarios was their reliance on technologies that were not present in the market yet, nor ready for mass mobilization. To represent this in the scenario, a lower RCP was chosen for BAU2 and a higher RCP was chosen for MLT2. This did not influence GHGE, but had substantial effects on the outcome of global warming. One of the core elements in these scenarios is efficiency improvement. In MEDEAS three different deployment rates can be chosen: slow, medium and fast. Medium was chosen, to represent present policies of innovation with regard to for example improved insulation of buildings. In the second scenario, it was necessary to use the faster rate of improved efficiency to reach net zero. The last part of the scenarios encompass negative carbon policies through afforestation. One can wonder if this amount of land is available? Samsó and Ollé (2019, p. 227) use an afforestation program in MLT that covers 345 Mha. If this is quadrupled, the area to be afforested becomes 1.380 Gha. According to Ritchie (2021) this is smaller than the area which would become available if the food system changed to a vegetarian agricultural system, i.e. 1.92 Gha. In the second scenario an area five times that of MLT2 was used, which is 1.725 Gha. An area of this size would be available as well. Unfortunately, working towards a vegetarian agricultural system goes against current developments. Ritchie, Rosado, and Roser (2019) show that meat consumption tends to increase as income increases. A strong push towards eating less meat and more plant-based will be necessary. This would allow for a higher rate of afforestation and would in itself prevent GHGE. The Food and Agriculture Organization (2013) reports that GHGE due to the livestock supply chain account for 14.5% of global GHGE.

Two policy instruments that were tried during the trial-and-error simulations after finding the optimal DG-rate were RURR and increase rate of substitution between energy sources. It was discussed earlier that the former would lead to economic collapse, as can be seen in appendix A.3. This is to be expected if the rates of substitution are 0, as they are in standard MEDEAS. This should be interpreted as follows: if a sector uses gas as an energy source, it can only use gas and will not function if not enough gas is available. A car analogy can make this easier to understand. In MEDEAS all sectors function as cars. Cars that run on diesel have to use diesel. Cars that use gasoline have to use gasoline. MEDEAS allows agents to change their energy source as time moves forward. Once the energy source is determined for that year, these agents are bound to their fuel source. It could be expected that if MEDEAS does not allow any substitution between energy sources, that RURR policies would lead to collapse. However, this is not realistic, as some substitution should be possible between energy sources. This is present in MEDEAS, but does not seem to work as one would expect. Professor Solé provided a scenario his team used that incorporated substitution of this kind. This was used in a follow up GDPpc$7000 scenario, but was found to have no effect. Alternative negative GHGE technologies like carbon capture and utilization (CCU) and CCS are assumed to be included in the RCP choice in MEDEAS, these are not explicitly modelled. This could be an area for MEDEAS to expand in.

8.3 MEDEAS scenarios compared to Eurogreen

The main characteristics of the Eurogreen model developed by D'Alessandro et al. (2018) have been discussed in the part on candidate models before. Here, the results of the Eurogreen simulations are going to be put next to the scenarios developed earlier. In Eurogreen, the DG scenario consists of job guarantees, work time reduction, increased RES in the energy mix, border carbon adjustment tax, high energy efficiency, consumption reduction and DG wealth tax. The MEDEAS scenarios developed here do not have detailed social policies, which means job guarantees and work-time reduction will not be included in this discussion. Taxes levied by the government are not implemented in MEDEAS either. DG wealth tax and border carbon adjustment tax can not be compared. Again: MEDEAS lacks this social component. Eurogreen focusses on the EU and does not calculate their GDPpc, D'Alessandro et al. (2018) do share relative changes in GDPpc, which is useful for this comparison. Changes in GDPpc are expressed as changes from the BAU scenarios used. GHGE are expressed as relative changes from 1990 in Eurogreen. To compare this to the absolute GHGE reported in MEDEAS, information on global emissions in 1990 is taken from The International Energy Agency (2022a). The IEA reports 20.5 Gt of CO_2 emissions in 1990. Energy intensities are calculated relative to the 2014 value of energy intensity, which is 7.12 EJ/T$ in MEDEAS. The RES policy in Eurogreen uses nuclear energy as a significant low GHGE source of energy. In the MEDEAS scenarios, the role of nuclear energy is negligible in 2050.

	Eurogreen DG	**GDPpc2009**	**GDPpc7000**
GDPpc	-28%	+7.96%	+25%
GHGE 2050	-80%	-95%	GHGE<0
Energy intensity	-56%	-31.1%	-27.7%
Fraction of RES	74.74%	72.11%	74.1%
Fraction of nuclear energy	24.21%	0%	0.05%

Table 21: Comparison of MEDEAS scenarios to Eurogreen DG scenario

The following paragraph will go more in depth to possible explanations of these differences between Eurogreen and MEDEAS. Differences in GDPpc levels can be explained by the lack of a peak oil moment in Eurogreen's scenario. The BAU scenario of Eurogreen can grow unimpeded. By contrast, in MEDEAS, the BAU scenario will experience uncontrolled DG up to the point that its final GDPpc will go below the GDPpc2007 scenario. Energy intensity is significantly lower in Eurogreen. Eurogreen uses a different way to model efficiency and technological evolution. These are based on stochastic variables. The MEDEAS scenarios were developed with a low dependence on technological innovation in mind. The results of both scenarios are similar in the fraction of RES that are deployed in 2050. The fraction of nuclear energy in the MEDEAS simulations are (close to) zero, while Eurogreen has a significant fraction of nuclear energy for electricity generation. The scenarios which are currently designed in MEDEAS have no need for nuclear capacity any longer. Saidi and Omri (2020) write that nuclear and RES are complementary energy sources. It could be interesting to expand the nuclear sector in follow up simulations to find out what the effects are on RES deployment. One of the effects could be a lower need for negative carbon emissions, which would lead to a lower need for afforestation in these scenarios.

8.4 Conclusion

First it was shown how these scenarios simulated in MEDEAS broadly come to similar results as previous studies. Higher levels of DG reduce the extent of environmental policies needed to reach net zero outcomes. Because of this, it can be said that DG policies can be used to increase the feasibility of reaching climate goals. Secondly points of improvement for MEDEAS were discussed. The environmental damage function and implementation of RURR and substitution of energy sources can be improved upon. MEDEAS could also use a social dimension, comparable to the implementation in Eurogreen. This would allow modellers to see the impact of their scenarios on social variables like inequality and rate of unemployment.

Thirdly, it was found that the final net zero scenarios are possible in theory. In practice it will be challenging to bring these policies into practice. The scenarios require extensive investments in RES, efficiency improvements, and afforestation, all of which would lead to an overhaul of the agricultural and energy systems and electrification in society. All of this will need to happen at rates that are currently far from being achieved, while the economy contracts to lower its resource and energy use. It is possible, but challenging.

Finally the MEDEAS scenarios were compared to Eurogreen scenarios. Both had comparable RES fractions in 2050. MEDEAS scenarios did not rely on nuclear energy, which constituted about a quarter of the energy generation in Eurogreen. It was argued that nuclear and RES could work in tandem. This could be an improvement to the current scenarios. Eurogreen lacks the peak oil moment, which causes important behavioural changes in the MEDEAS simulations. This is an aspect of energy economics that needs to be studied further and implemented in ECEMs, as it has significant effects on outcomes.

There were some challenges while running the simulations. During the modelling phase it was difficult to find values that represent an income level representative for decent living, analogous to the energy demand for decent living as developed by Millward-Hopkins et al. (2020). Another issue were the many different carbon budgets, all leading to different conclusions, depending on the budget used. It might be beneficial for researchers and policy makers to standardize the way carbon budgets are calculated. A method of using standard conversion factors was suggested. These could be determined by a central authority. Once the conversion factors are determined, it is possible to express carbon budgets in CO_2-equivalents. This would make scenarios easier to compare.

It may also be problematic that ECEMs can have very different outcomes, depending on the model used. This might reduce the utility of ECEMs for policy makers who have to design environmental policies. After all, how can policy makers make an informed decision if models differ on crucial points? The peak oil effect that does not exist in Eurogreen is a clear example of this. On the other hand, models do agree on several points: RES is a necessary part of net zero policy, DG will lower the necessary extent of environmental policies in the policy mix, efficiency improvements are significant and negative emission strategies will play a role. Negative emissions could be achieved through afforestation, land-use changes and negative emission technologies. The relative sizes of all these policies will depend on each other, as was shown in the two net zero scenarios. GG scenarios will depend on high levels of RES and/or negative emission technologies. In some cases Keyßer and Lenzen (2021) calls these utopian. MEDEAS sadly lacked a social dimension. Other ECEMs exist that have a social dimension. These show that increased redistribution will be needed to make sure people maintain a decent standard of living. This is one of the conclusions found in the LOWGROW model by Jackson and Victor (2020). They show that improved social and environmental outcomes can occur concurrently. This social dimension is missing in the net zero scenarios that were found, due to the lack of a social dimension in MEDEAS.

9 Conclusion

This dissertation aimed to study alternatives to green growth and how these could be included in the toolbox of policy makers who aspire to reach their climate goals. The conclusion will be divided into four parts. The first part will look at the most important results from the MEDEAS ecological economic model. Some suggestions are made for future versions of the model. The second part will discuss ecological economic models in a more general way and how MEDEAS fits in. This section will also contain some ideas for further research. The third part will place the ecological economic models within economics as a whole. There are important differences in assumptions and model outcomes when these ecological economic models are compared to conventional macroeconomic models. The final part will discuss the significance of ECEMs for policy makers and society in general.

9.1 Suggestions for MEDEAS and an overview of net zero scenarios

The MEDEAS model was used to simulate degrowth scenarios and to find optimal rates of degrowth to use in designing net zero scenarios. These scenarios were built on a foundation of a green growth scenario called MLT. This scenario received three updates. First, MLT2 uses GDP growth rates as forecast by the OECD instead of constant rates of growth. A next update was the use of less optimistic RCP, since the model's decomposition revealed that most of the global warming prevention of its GG scenario was a consequence of RCP choice rather than the policies found in MLT. When the BAU scenario used a less pessimistic RCP and updated OECD growth rates, simulations showed that MLT had a higher level of global warming than updated BAU. It is important to note that the BAU scenario suffered from uncontrolled degrowth due to a supply-side peak oil event happening in the late 2020s. This was one of the explanations as to why BAU ended up with a lower level of global warming: peak oil causes energy shortages and persistent recessions in the economy. Another reasen was that forcing levels of other GHGs was higher in MLT2 compared to BAU2. A third update was done in the electrification policies, as MLT underestimates current electrification targets formulated by International Energy Agency (2021).

These updates are not the only opportunities for improvement. It was discussed that MEDEAS could also be improved upon by using a more impactful damage function, more options to simulate negative emissions, improved substitutability between energy sources, fewer abrupt changes of the economy due to RURR policies and an added social component.

Several scenarios were built upon the updated MLT2 scenario mentioned above. Some were found which could reach net zero emissions in 2050. These scenarios needed a multitude of policies to achieve that goal. These consisted of: electrification, increased rollout of RES, improved efficiency, negative emission policies and degrowth. It was found that degrowth could represent a significant part (46% in a low GDPpc scenario and 27% a high GDPpc scenario) of GHGE reduction while maintaining a minimal level of material output for a decent life. Lower GDPpc thresholds lower the needed RES and negative emissions to reach net zero in 2050. This was expected: a bigger economy needs more resources and energy. Even if the low GDPpc DG path is chosen, the speed at which RES deployment and afforestation (or other forms of negative GHG-emissions) need to happen, would still make it improbable to reach the 1,7°C goal. For some leeway, policy makers could aim for an increase close to, but below 2°C increase. This goal increases the carbon budget by 500 Gt CO_2-equivalent emissions, based on budgets reported by the European Space Agency (2022). Keeping global warming under 2°C seems to be feasible with a combination of DG and stringent climate policies using currently available technologies. Designing policies based on currently available technologies was argued to be a more secure way towards a net zero society, compared to the unpredictable arrival of new technologies. If those new technologies do arrive, it will be a nice bonus to the feasibility of climate policies.

9.2 Ecological economic models and MEDEAS

MEDEAS is one of many ecological economic models. It was discussed how these differ in growth theory and modelling techniques. These differences could lead to different policy recommendations. Specifically, MEDEAS experiences a peak oil moment which makes the BAU scenario go onto prolonged recession. This peak oil moment is not standard in ecological economic models. MEDEAS was compared to Eurogreen, which has a degrowth scenario as well. However, Eurogreen does not have a peak oil moment. This leads to significantly different outcomes. The BAU scenario in Eurogreen could keep on growing. MEDEAS and Eurogreen had some similarities as well. For example, both scenarios were comparable in the fraction of RES that are used for electricity generation.

Both models could improve aspects of each other. Energy is developed in more detail in MEDEAS, while Eurogreen has a more extensive social dimension. If models come to significantly different outcomes, it might be interesting to find out which aspects of the model are the causes. This way, the models could learn from one another in.

While developing net zero scenarios it was found that a minimal level of GDPpc has not yet been defined in the literature. This is an significant shortcoming, as this parameter would become the determining factor in choosing the optimal degrowth rate. Two minimal GDPpc thresholds were chosen, which allowed for the comparison of two net zero scenarios. Considering its importance, it could be an interesting point of research to developing such a minimal level of GDP for a decent life.

Another element that could cause different policy recommendations are the used carbon budgets. It was found that many different carbon budgets are available. In the discussion, suggestions were made to harmonize the carbon budget calculation by using CO_2-equivalents. This is a method used in MEDEAS by applying a correction factor on CO_2-emissions, which implies the inclusion of all GHG. These correction factors could be standardized. It would make it easier to compare research and scenarios.

9.3 Ecological economic models within broader economics

Ecological economic models differ significantly from conventional macroeconomic models. Ecological economics assumes limits to the size of an economy due to limits on natural resources, energy inputs and capacity of the environment for assimilating waste. This calls into question the possibility of continuous growth, which is a central tenet of conventional macroeconomics. Ecological economists are not against economic growth, but it should remain within the planetary carrying capacity.

This has lead to the concept of post-growth. It is a school of thought which tries to develop a society that is not dependent on growth to function and can lead to prosperous ways of life. This has sparked discussions between proponents of growth, who argue growth is necessary for society to function and proponents of post-growth, who argue that we are overshooting our planetary boundaries and need to learn how to live within those boundaries. This is where ecological economic models come into play, as they can be used to simulate different scenarios that could bring society within the planetary boundaries while ensuring decent living conditions for the population. So far, models have shown that it is possible to improve both social and environmental conditions.

Jackson and Victor (2020) do wonder if these kinds of societies can still be called capitalistic, as the post-growth scenarios suggest the need for higher redistribution and wage income protection.

Arguments against degrowth have been discussed earlier. For example, critics of degrowth argue that the developing world will still need to keep growing to reach decent material living standards. They also state that degrowth would challenge sustainability the welfare state and debt management by governments. And finally, they argue that people still expect their material wealth to increase in the future.

Usually these critics suggest green growth is the better policy mix to pursue, compared to post-growth. Unfortunately, green growth comes with its own issues. Successful green growth would imply an absolute decoupling of the economy from emissions. Several ecological economists question the possibility of absolute decoupling. They point towards the uncontested relationship between increasing emissions and economic growth. And while relative decoupling has happened, the growth of the economy outpaced the rate of relative decoupling. Total GHGE kept increasing. Thus, DG proponents argue, it is better to prevent emissions by preventing growth.

9.4 Significance of ecological economic models for society

Human activity has caused many problems in the environment. Scientists report that society has gone beyond some of its sustainable limits, for example by Steffen et al. (2015). The nitrogen and phosphorous used mostly in fertilizers cause ecological problems in the nitrogen and phosphorous cycles in nature. Human activities have caused a problematic loss in biodiversity. Land-system change and climate change are close to their limits.

Ecological economist aim to bring society to a point where it can flourish within these boundaries. The models they use, show that reaching a net zero society is possible. In other words: it is possible to live within the ecological limits of the earth. Not only that: they also demonstrate possible pathways towards this goal. This research focussed on GHGE and found that degrowth can be one of the policy instruments that help in attaining net zero emissions in 2050. These scenarios included important investments in efficiency, RES and electrification. Afforestation was an important negative emission policy. The area of land necessary to achieve this would be available if society would evolve towards more vegetarian or plant-based living. Other models showed that guiding society towards a just post-growth transition will include increased redistribution to ensure everyone has a decent living standard. Taking these steps will impact every individual's life.

Scenarios found using ecological economic models can form blueprints for policy makers to base their decisions on. Of course, this is not without its challenges. One of the challenges that has been found during this research is the variety of outcomes that these models can have. These outcomes depend on the design of the model. This will make it more difficult for policy makers to put their trust in ecological economic models. This point was made by Bachner et al. (2020). As a solution they suggest more model validation and cooperation between ecological economic model designers.

In the future it might be necessary to develop a different vision of prosperity to strive towards, one that goes beyond economic output, as the current economic system crosses multiple planetary boundaries. Technology can ease the transition towards sustainability. However, technology cannot be relied on as the be-all and end-all of climate change solutions. Using technology to reach absolute decoupling was deemed difficult to impossible by several authors. An alternative approach could be to lower society's impact on the environment by lowering consumption levels, as Jackson (2016, p. 90) writes: "To live well, and yet to consume less. To have more fun – but with less stuff." Or to aim for a feeling of sufficiency, as Vita et al. (2019) write: "sufficiency assumes that once basic needs are satisfied, wellbeing relies more on health, social relationships, time affluence, and other factors".

10 Bibliography

Ackerman, Frank and Elizabeth A. Stanton (2012). “Climate risks and carbon prices: Revising the social cost of carbon.” In: *Economics* 6, pp. 0–26. ISSN: 18646042. DOI: `10.5018/economics-ejournal.ja.2012-10`.

Akerlof, George A. (2003). “Behavioral Macroeconomics and Macroeconomic Behavior.” In: *American Economist* 47.1, pp. 25–47. ISSN: 23281235. DOI: `10.1177/056943450304700102`.

Althouse, Jeffrey, Giulio Guarini, and Jose Gabriel Porcile (2020). “Ecological macroeconomics in the open economy: Sustainability, unequal exchange and policy coordination in a center-periphery model.” In: *Ecological Economics* 172.August 2019. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2020.106628`.

Bachner, G. et al. (2020). “Uncertainties in macroeconomic assessments of low-carbon transition pathways - The case of the European iron and steel industry.” In: *Ecological Economics* 172.February, p. 106631. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2020.106631`. URL: `https://doi.org/10.1016/j.ecolecon.2020.106631`.

Bardi, Ugo (2019). “Peak oil, 20 years later: Failed prediction or useful insight?” In: *Energy Research and Social Science* 48.March 2018, pp. 257–261. ISSN: 22146296. DOI: `10.1016/j.erss.2018.09.022`. URL: `https://doi.org/10.1016/j.erss.2018.09.022`.

Batker, David (2020). “Implementing ecological economics.” In: *Ecological Economics* 172.August 2019, p. 106606. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2020.106606`. URL: `https://doi.org/10.1016/j.ecolecon.2020.106606`.

BBC (2012). *If we fail to correct current consumption trends, then when will our most valuable natural resources run out?* URL: `https://www.bbc.com/future/article/20120618-global-resources-stock-check` (visited on 04/14/2022).

Bercegol, Hervé and Henri Benisty (2022). “An energy-based macroeconomic model validated by global historical series since 1820.” In: *Ecological Economics* 192.July 2021. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2021.107253`.

Bishop, Richard C. (1978). “Endangered Species and Uncertainty: The Economics of a Safe Minimum Standard.” In: *American Journal of Agricultural Economics* 60.1, pp. 10–18. ISSN: 0002-9092. DOI: `10.2307/1240156`.

Blampied, Nicolás (2021). “Economic growth, environmental constraints and convergence: The declining growth premium for developing economies.” In: *Ecological Economics* 181.July 2020. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2020.106919`.

Brandt, Adam R. (2017). “How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI).” In: *BioPhysical Economics and Resource Quality* 2.1, pp. 1–12. ISSN: 2366-0112. DOI: `10.1007/s41247-017-0019-y`.

Büchs, Milena and Max Koch (2019). “Challenges for the degrowth transition: The debate about wellbeing.” In: *Futures* 105.February 2018, pp. 155–165. ISSN: 00163287. DOI: `10.1016/j.futures.2018.09.002`. URL: `https://doi.org/10.1016/j.futures.2018.09.002`.

Capellán-Pérez, Iñigo et al. (2020a). "MEDEAS - Deliverable 10 (D3.2) Transition scenarios 2." In: pp. 1–174. URL: `https://www.medeas.eu/system/files/documentation/files/Deliverable3.2{\%}28D10{\%}29{\_}Transitionscenarios2.pdf`.

Capellán-Pérez, Iñigo et al. (2020b). "MEDEAS: A new modeling framework integrating global biophysical and socioeconomic constraints." In: *Energy and Environmental Science* 13.3, pp. 986–1017. ISSN: 17545706. DOI: `10.1039/c9ee02627d`.

Capellán-Pérez, Iñigo et al. (2022). *Medeas Model.* URL: `https://www.medeas.eu/model/medeas-model` (visited on 09/13/2022).

Carson, Rachel and Edward O. Wilson (2002). *Silent Spring (50th Anniversary Edition).* 1st ed. New York: Mariner Books, p. 421. ISBN: 0618249060.

Chertow, M. R. (2000). "The IPAT equation and its variants: Changing views of technology and environmental impact." In: *Journal of Industrial Ecology* 4.4, pp. 13–29. ISSN: 10881980. DOI: `10.1162/10881980052541927`.

Club of Rome (2022). *The Club of Rome - History.* URL: `https://www.clubofrome.org/history/` (visited on 04/05/2022).

Coile, Courtney C. and Phillip B. Levine (2011). "Recessions, Retirement, and Social Security." In: *The American Economic Review* 101.3, pp. 110–114. URL: `https://www.jstor.org/stable/29783708`.

Costanza, Robert (1989). "What is ecological economics?" In: *Ecological Economics* 1.1, pp. 1–7. ISSN: 09218009. DOI: `10.1016/0921-8009(89)90020-7`.

Costanza, Robert et al. (2014). "Changes in the global value of ecosystem services." In: *Global Environmental Change* 26.1, pp. 152–158. ISSN: 09593780. DOI: `10.1016/j.gloenvcha.2014.04.002`. URL: `http://dx.doi.org/10.1016/j.gloenvcha.2014.04.002`.

Council of European Union (2022). *5 facts about the EU's goal of climate neutrality.* URL: `https://www.consilium.europa.eu/en/5-facts-eu-climate-neutrality/` (visited on 12/18/2022).

Dafermos, Yannis, Giogos Galanis, and Maria Nikolaidi (2016). *A new ecological macroeconomic model.*

Dafermos, Yannis, Giorgos Galanis, and Maria Nikolaidi (2022). *DEFINE - An ecological stock-flow consistent model.* URL: `https://define-model.org/` (visited on 08/01/2022).

Dafermos, Yannis and Maria Nikolaidi (2022). "Assessing climate policies: an ecological stock–flow consistent perspective." In: pp. 1–20.

Dafermos, Yannis, Maria Nikolaidi, and Giorgos Galanis (2017). "A stock-flow-fund ecological macroeconomic model." In: *Ecological Economics* 131, pp. 191–207. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2016.08.013`. URL: `http://dx.doi.org/10.1016/j.ecolecon.2016.08.013`.

D'Alessandro, S et al. (2018). "EUROGREEN Model of Job Creation in a Post-Growth Economy." In: January, pp. 1–9.

Daly, Herman (1968). "Economics as life science." In: *Journal of Political Economy* 76.3, pp. 398–406.

Daly, Herman (2019). “Some overlaps between the first and second thirty years of ecological economics.” In: *Ecological Economics* 164.June, p. 106372. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.106372`. URL: `https://doi.org/10.1016/j.ecolecon.2019.106372`.

Dávila-Fernández, Marwil J. and Serena Sordi (2020). “Attitudes towards climate policies in a macrodynamic model of the economy.” In: *Ecological Economics* 169.March 2019, p. 106319. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.04.031`. URL: `https://doi.org/10.1016/j.ecolecon.2019.04.031`.

De Steiguer, J. E. (1995). “Three theories from economics about the environment.” In: *BioScience* 45.8, pp. 552–557. ISSN: 00063568. DOI: `10.2307/1312701`.

Delannoy, Louis et al. (2021). “Peak oil and the low-carbon energy transition: A net-energy perspective.” In: *Applied Energy* 304, pp. 1–17.

Distelkamp, Martin and Mark Meyer (2019). “Pathways to a Resource-Efficient and Low-Carbon Europe.” In: *Ecological Economics* 155, pp. 88–104. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2017.07.014`.

Edenhofer, Ottmar, Max Franks, and Matthias Kalkuhl (2021). “Pigou in the 21st Century: a tribute on the occasion of the 100th anniversary of the publication of The Economics of Welfare.” In: *International Tax and Public Finance* 28.5, pp. 1090–1121. ISSN: 15736970. DOI: `10.1007/s10797-020-09653-y`. URL: `https://doi.org/10.1007/s10797-020-09653-y`.

Environmental Protection Agency (2022). *The Origins of EPA*. URL: `https://www.epa.gov/history/origins-epa` (visited on 12/26/2022).

Espinoza, Vicente Sebastian et al. (2022). “Analysis of energy future pathways for Ecuador facing the prospects of oil availability using a system dynamics model. Is degrowth inevitable?” In: *Energy* 259.June 2021, p. 124963. ISSN: 03605442. DOI: `10.1016/j.energy.2022.124963`. URL: `https://doi.org/10.1016/j.energy.2022.124963`.

European Commission (2022). *Climate strategies & targets*. URL: `https://climate.ec.europa.eu/eu-action/climate-strategies-targets{\_}en` (visited on 10/19/2022).

European Space Agency (2022). *Carbon emissions rebound in 2021, new study finds*. URL: `https://climate.esa.int/en/news-events/carbon-emissions-rebound-in-2021-new-study-finds/` (visited on 12/13/2022).

Farley, Joshua and Kaitlin Kish (2021). “Ecological economics: The next 30 years.” In: *Ecological Economics* 190.May. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2021.107211`.

Farmer, Michael C and Alan Randall (1998). “The Rationality of a Safe Minimum Standard.” In: *Land Economics* 74.3, pp. 287–302. URL: `https://www.jstor.org/stable/3147113`.

Fiddaman, Tom et al. (2022). “C-ROADS SIMULATOR REFERENCE GUIDE.” In: URL: `https://img.climateinteractive.org/wp-content/uploads/2022/03/C-ROADS{\_}Reference{\_}Guide{\_}030122.pdf`.

Fitzpatrick, John J. (2020). "Target Ecological Limits and Not Economic Growth." In: *World* 1.2, pp. 135–148. DOI: `10.3390/world1020011`.

Fizaine, Florian and Victor Court (2016). "Energy expenditure, economic growth, and the minimum EROI of society." In: *Energy Policy* 95, pp. 172–186. ISSN: 03014215. DOI: `10.1016/j.enpol.2016.04.039`.

Forster, Piers et al. (2022). *What does the "global carbon budget" mean? Have we got 9 years left?* URL: `https://energypost.eu/what-does-the-global-carbon-budget-mean-have-we-got-9-years-left/` (visited on 12/13/2022).

Georgescu-Roegen, Nicholas (1974). *The Entropy Law and the Economic Process.* 2nd. Cambridge, Massachusetts: HARVARD UNIVERSITY PRESS, p. 457. ISBN: 0674257804. DOI: `10.4159/harvard.9780674281653`.

Gerber, Julien François (2016). "The Legacy of K. William Kapp." In: *Development and Change* 47.4, pp. 902–917. ISSN: 14677660. DOI: `10.1111/dech.12238`.

Giampietro, Mario (2019). "On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth." In: *Ecological Economics* 162.November 2018, pp. 143–156. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.05.001`. URL: `https://doi.org/10.1016/j.ecolecon.2019.05.001`.

Godley, Wynne (2012). *The Stock-Flow Consistent Approach.* Ed. by Marc Lavoie and Gennaro Zezza. 1st ed. London: Palgrave Macmillan, p. 276. ISBN: 978-0-230-29311-3. DOI: `10.1057/9780230353848`.

Gray, Lewis Cecil (1914). "Rent Under the Assumption of Exhaustibility." In: *The Quarterly Journal of Economics* 28.3, pp. 466–489. URL: `http://www.jstor.org/stable/1884984`.

Hafner, Sarah, Aled Jones, and Annela Anger-Kraavi (2021). "Economic impacts of achieving a net-zero emissions target in the power sector." In: *Journal of Cleaner Production* 312.July 2020, p. 127610. ISSN: 09596526. DOI: `10.1016/j.jclepro.2021.127610`. URL: `https://doi.org/10.1016/j.jclepro.2021.127610`.

Hall, Thomas E and William R Hart (2010). "The Samuelson-Solow "Phillips Curve" and the Great Inflation." In: *Department of Economics Working Paper* October, p. 17.

Halttunen, Krista, Raphael Slade, and Iain Staffell (2022). "What if we never run out of oil? From certainty of "peak oil" to "peak demand"." In: *Energy Research and Social Science* 85.October 2021, p. 102407. ISSN: 22146296. DOI: `10.1016/j.erss.2021.102407`. URL: `https://doi.org/10.1016/j.erss.2021.102407`.

Hardt, Lukas and Daniel W. O'Neill (2017). "Ecological Macroeconomic Models: Assessing Current Developments." In: *Ecological Economics* 134, pp. 198–211. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2016.12.027`. URL: `http://dx.doi.org/10.1016/j.ecolecon.2016.12.027`.

Hardt, Lukas et al. (2021). "What structural change is needed for a post-growth economy: A framework of analysis and empirical evidence." In: *Ecological Economics* 179.May 2020, p. 106845. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2020.106845`. URL: `https://doi.org/10.1016/j.ecolecon.2020.106845`.

Heikkinen, Tiina (2020). “A study of degrowth paths based on the von Neumann equilibrium model.” In: *Journal of Cleaner Production* 251. ISSN: 09596526. DOI: `10.1016/j.jclepro.2019.119562`.

Heylen, Freddy (2020). *Macro-economie*. Ed. by Wannes Swings. 4th. Ghent: Owl Press, p. 873. ISBN: 9789089318718.

Hickel, Jason (2020). “The sustainable development index: Measuring the ecological efficiency of human development in the anthropocene.” In: *Ecological Economics* 167.November 2019, p. 106331. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.05.011`. URL: `https://doi.org/10.1016/j.ecolecon.2019.05.011`.

Hickel, Jason and Giorgos Kallis (2020). “Is Green Growth Possible?” In: *New Political Economy* 25.4, pp. 469–486. ISSN: 14699923. DOI: `10.1080/13563467.2019.1598964`. URL: `https://doi.org/10.1080/13563467.2019.1598964`.

Holt, Richard P.F., Steven Pressman, and Clive L. Spash (2009). *Post keynesian and ecological economics: Confronting environmental issues*. Edward Elgar Publishing Limited. ISBN: 9781847206688. DOI: `10.1080/09538259.2011.636599`.

Hone, Thomas et al. (2019). “Effect of economic recession and impact of health and social protection expenditures on adult mortality: a longitudinal analysis of 5565 Brazilian municipalities.” In: *The Lancet Global Health* 7.11, e1575–e1583. ISSN: 2214109X. DOI: `10.1016/S2214-109X(19)30409-7`. URL: `http://dx.doi.org/10.1016/S2214-109X(19)30409-7`.

Howard, Peter H. and Thomas Sterner (2017). “Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates.” In: *Environmental and Resource Economics* 68.1, pp. 197–225. ISSN: 15731502. DOI: `10.1007/s10640-017-0166-z`.

International Energy Agency (2021). “Net Zero by 2050: A Roadmap for the Global Energy Sector.” In: *The International Energy Agency*, p. 224. URL: `https://www.iea.org/reports/net-zero-by-2050`.

International Renewable Energy Agency (2019). *Global Energy Transformation: A Roadmap to 2050 (2019 Edition)*, p. 52. ISBN: 978-92-9260-059-4.

IPCC (2014). “Climate Change 2014: Synthesis Report.” In: 151. URL: `https://www.ipcc.ch/report/ar5/syr/`.

Jackson, Andrew and Tim Jackson (2021). “Modelling energy transition risk : The impact of declining energy return on investment (EROI).” In: *Ecological Economics* 185.March, p. 107023. ISSN: 0921-8009. DOI: `10.1016/j.ecolecon.2021.107023`. URL: `https://doi.org/10.1016/j.ecolecon.2021.107023`.

Jackson, Tim (2016). *Prosperity without Growth: Foundations for the Economy of Tomorrow*. 2nd. New York: Routledge. ISBN: 9781315677453.

Jackson, Tim, Peter Victor, and Asjad Naqvi (2016). “Towards a Stock-Flow Consistent Ecological Macroeconomics.” In: *WWWforEurope* 114, p. 65. URL: `https://www.econstor.eu/handle/10419/146611`.

Jackson, Tim and Peter A Victor (2019). “Unraveling the claims for (and against) green growth.” In: *Science* 366.6468.

Jackson, Tim and Peter A. Victor (2020). “The Transition to a Sustainable Prosperity-A Stock-Flow-Consistent Ecological Macroeconomic Model for Canada.” In: *Ecological*

Economics 177.July, p. 106787. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2020.106787`. URL: `https://doi.org/10.1016/j.ecolecon.2020.106787`.

Jørgensen, S.E. (2008). *Exergy.* URL: `https://www.sciencedirect.com/topics/earth-and-planetary-sciences/exergy` (visited on 12/26/2022).

Kawamiya, Michio et al. (2020). "Two decades of Earth system modeling with an emphasis on Model for Interdisciplinary Research on Climate (MIROC)." In: *Progress in Earth and Planetary Science* 7.1. ISSN: 21974284. DOI: `10.1186/s40645-020-00369-5`.

Keen, Steve, Robert U. Ayres, and Russell Standish (2019). "A Note on the Role of Energy in Production." In: *Ecological Economics* 157.August 2018, pp. 40–46. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2018.11.002`. URL: `https://doi.org/10.1016/j.ecolecon.2018.11.002`.

Kemp-Benedict, Eric (2014). "The inverted pyramid: A neo-Ricardian view on the economy-environment relationship." In: *Ecological Economics* 107, pp. 230–241. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2014.08.012`. URL: `http://dx.doi.org/10.1016/j.ecolecon.2014.08.012`.

Kennedy, Christopher (2022). "The Intersection of Biophysical Economics and Political Economy." In: *Ecological Economics* 192.March 2021, p. 107272. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2021.107272`. URL: `https://doi.org/10.1016/j.ecolecon.2021.107272`.

Kerschner, Christian and Iñigo Capellán-Pérez (2017). "PEAK-OIL AND ECOLOGICAL ECONOMICS." In: *ROUTLEDGE HANDBOOK OF ECOLOGICAL ECONOMICS*. Ed. by Clive L. Spash. 1st ed. Chap. 41, pp. 425–435.

Keyßer, Lorenz T. and Manfred Lenzen (2021). "1.5 °C degrowth scenarios suggest the need for new mitigation pathways." In: *Nature Communications* 12.1, pp. 1–16. ISSN: 20411723. DOI: `10.1038/s41467-021-22884-9`. URL: `http://dx.doi.org/10.1038/s41467-021-22884-9`.

King, Carey W. (2020). "An integrated biophysical and economic modeling framework for long-term sustainability analysis: the HARMONEY model." In: *Ecological Economics* 169.December 2019, p. 106464. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.106464`. URL: `https://doi.org/10.1016/j.ecolecon.2019.106464`.

King, J E (2015). *Advanced Introduction to Post Keynesian Economics.* Northampton: Edward Elgar Publishing Limited, p. 169. ISBN: 9781782548430.

King, Robert G. and Sergio T. Rebelo (1989). "Transitional dynamics and economic growth in the neoclassical." In: *Nber working paper series* 3185.

Kreager, Phillip (2022). *Smith or Malthus? A Sea-Change in the Concept of a Population.* URL: `https://onlinelibrary.wiley.com/doi/full/10.1111/padr.12488` (visited on 12/26/2022).

Lenaerts, Klaas, Simone Tagliapietra, and Guntram Wolff (2021). "Can climate change be tackled without ditching economic growth?" In: *Working Paper.* URL: `https://www.bruegel.org/2021/09/can-climate-change-be-tackled-without-ditching-economic-growth-2/`.

Loschky, David and Maw Lin Lee (1987). “Malthusian Population Oscillations.” In: *The Economic Journal* 97.387, pp. 727–739. URL: `https://www.jstor.org/stable/2232933`.

Lundgren, Jakob (2022). “Unity through disunity: Strengths, values, and tensions in the disciplinary discourse of ecological economics.” In: *Ecological Economics* 191.October 2020, p. 107241. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2021.107241`. URL: `https://doi.org/10.1016/j.ecolecon.2021.107241`.

Marschall, Alfred (1920). *Principles of economics.* 8th. Liberty Fund, Inc., p. 627. URL: `https://eet.pixel-online.org/files/etranslation/original/Marshall,PrinciplesofEconomics.pdf`.

Matthews, H Damon et al. (2020). “Opportunities and challenges in using remaining carbon budgets to guide climate policy.” In: *Nature Geoscience* 13.12, pp. 769–779. ISSN: 1752-0908. DOI: `10.1038/s41561-020-00663-3`. URL: `https://doi.org/10.1038/s41561-020-00663-3`.

McGlade, Christophe and Paul Ekins (2015). “The geographical distribution of fossil fuels unused when limiting global warming to 2°C.” In: *Nature* 517.7533, pp. 187–190. ISSN: 14764687. DOI: `10.1038/nature14016`.

Meadows, Donella, Jorgen Randers, and Dennis Meadows (2004). *The limits to growth: The 30-year update.* Chelsea Green Publishing, p. 338. ISBN: 1-931498-58-X.

Merriam-Webster (2022). *Entropy.* URL: `https://www.merriam-webster.com/dictionary/entropy` (visited on 04/08/2022).

Miller, Ronald E. and Peter D. Blair (2009). *Input-Output Analysis: Foundations and Extensions - 2nd edition.* 2nd ed. New York: Cambridge University Press, pp. 782 / 784. ISBN: 0521739020. URL: `9780521739023`.

Millward-Hopkins, Joel et al. (2020). “Providing decent living with minimum energy: A global scenario.” In: *Global Environmental Change* 65.August, p. 102168. ISSN: 09593780. DOI: `10.1016/j.gloenvcha.2020.102168`. URL: `https://doi.org/10.1016/j.gloenvcha.2020.102168`.

Mimmo, Iannelli and Andrea Pugliese (2014). *An Introduction to Mathematical Population Dynamics: Along the trail of Volterra and Lotka.* Springer International Publishing, p. 351.

Monserand, Antoine (2019). *Degrowth in a neo-Kaleckian model of growth and distribution? A theoretical compatibility and stability analysis.* Tech. rep., p. 12. URL: `https://hal.archives-ouvertes.fr/hal-02012632`.

Moss, Richard H. et al. (2010). “The next generation of scenarios for climate change research and assessment.” In: *Nature* 463.7282, pp. 747–756. ISSN: 00280836. DOI: `10.1038/nature08823`.

Muradian, Roldan (2019). “Frugality as a choice vs. frugality as a social condition. Is de-growth doomed to be a Eurocentric project?” In: *Ecological Economics* 161.March, pp. 257–260. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.03.027`. URL: `https://doi.org/10.1016/j.ecolecon.2019.03.027`.

Murphy, Mark (2019). *The Natural Law Tradition in Ethics.* URL: `https://plato.stanford.edu/entries/natural-law-ethics/{\#}KeyFeaNatLawThe` (visited on 03/01/2022).

National Oceanic and Atmospheric Administration (2022). *What is eutrophication?* URL: `https://oceanservice.noaa.gov/facts/eutrophication.html` (visited on 12/28/2022).

Neumann, James E. et al. (2020). "Climate damage functions for estimating the economic impacts of climate change in the United States." In: *Review of Environmental Economics and Policy* 14.1, pp. 25–43. ISSN: 17506824. DOI: `10.1093/reep/rez021`.

Nieto, Jaime et al. (2020). "An ecological macroeconomics model: The energy transition in the EU." In: *Energy Policy* 145.June. ISSN: 03014215. DOI: `10.1016/j.enpol.2020.111726`.

Nopens, Ingmar (2013). *Modelleren en Simuleren van biosystemen.* Ghent, p. 128.

Nordhaus, William and Paul Sztorc (2013). "DICE 2013R : Introduction and User's Manual." In: October, pp. 1–102.

Nordhaus, William D. (1992). *The 'DICE' Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming.* URL: `http://ideas.repec.org/p/cwl/cwldpp/1009.html`.

– (2017). "Revisiting the social cost of carbon." In: *Proceedings of the National Academy of Sciences of the United States of America* 114.7, pp. 1518–1523. ISSN: 10916490. DOI: `10.1073/pnas.1609244114`.

OECD (2022). *Real GDP long-term forecast.* URL: `https://data.oecd.org/gdp/real-gdp-long-term-forecast.htm{\#}indicator-chart` (visited on 11/03/2022).

O'Neill, Brian C. et al. (2017). "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century." In: *Global Environmental Change* 42, pp. 169–180. ISSN: 09593780. DOI: `10.1016/j.gloenvcha.2015.01.004`. URL: `http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004`.

Owais, Ali (2022). *The IPCC Report 2022: A Summary.* URL: `https://www.azocleantech.com/article.aspx?ArticleID=1584` (visited on 07/15/2022).

Parrique, Timothée et al. (2019). "Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability." In: *European Environmental Bureau.* URL: `www.eeb.org`.

Pearce, David (2002). "An intellectual history of environmental economics." In: *Annual Review of Energy and the Environment* 27, pp. 57–81. ISSN: 10563466. DOI: `10.1146/annurev.energy.27.122001.083429`.

Post-Keynesian Economics Society (2022). *Post-Keynesian Economics.* URL: `http://www.postkeynesian.net/post-keynesian-economics/` (visited on 04/13/2022).

Pruyt, Eric (2013). *Small System Dynamics Models for Big Issues: Triple Jump towards Real-World Complexity.* TU Delft Library. ISBN: 978-94-6186-195-5.

Raworth, Kate (2017). *Doughnut Economics.* London: Random House Business Books, p. 372. ISBN: 9781847941398.

Ritchie, Hannah (2021). *If the world adopted a plant-based diet we would reduce global agricultural land use from 4 to 1 billion hectares.* URL: `https://ourworldindata.org/land-use-diets` (visited on 12/18/2022).

Ritchie, Hannah, Pablo Rosado, and Max Roser (2019). *Meat and Dairy Production.* URL: `https://ourworldindata.org/meat-production` (visited on 12/18/2022).

Roman, Philippe and Géraldine Thiry (2017). "SUSTAINABILITY INDICATORS." In: *ROUTLEDGE HANDBOOK OF ECOLOGICAL ECONOMICS.* Ed. by Clive L. Spash. 1st ed. Chap. 37, pp. 382–392.

Røpke, Inge (2004). "The early history of modern ecological economics." In: *Ecological Economics* 50.3-4, pp. 293–314. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2004.02.012`.

– (2005). "Trends in the development of ecological economics from the late 1980s to the early 2000s." In: *Ecological Economics* 55.2, pp. 262–290. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2004.10.010`.

Safarzyńska, Karolina and Jeroen C J M van den Bergh (2022). "ABM-IAM: optimal climate policy under bounded rationality and multiple inequalities." In: *Environ. Res. Lett* 17. URL: `https://iopscience.iop.org/article/10.1088/1748-9326/ac8b25`.

Saidi, Kais and Anis Omri (2020). "Reducing CO2 emissions in OECD countries: Do renewable and nuclear energy matter?" In: *Progress in Nuclear Energy* 126.June, p. 103425. ISSN: 01491970. DOI: `10.1016/j.pnucene.2020.103425`. URL: `https://doi.org/10.1016/j.pnucene.2020.103425`.

Samsó, Roger and Jordi Solé Ollé (2019). "Pymedeas Model: User's manual." In: 11.691287, pp. 1–625. URL: `www.medeas.eu`.

Sawyer, M. and G. Fontana (2016). "Towards Post-Keynesian Ecological Macroeconomics by." In: *Ecological Economics*, pp. 186–195. URL: `http://eprints.whiterose.ac.uk/87723/`.

Scalia, Massimo et al. (2020). "An Ecology and Economy Coupling Model. A global stationary state model for a sustainable economy in the Hamiltonian formalism." In: *Ecological Economics* 172.April, p. 106497. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.106497`. URL: `https://doi.org/10.1016/j.ecolecon.2019.106497`.

Scilab Enterprises (2015). *TIME_DELAY.* URL: `https://help.scilab.org/doc/5.5.2/en{\_}US/TIME{\_}DELAY.html` (visited on 04/07/2022).

Solé, J. et al. (2020). "Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model." In: *Renewable and Sustainable Energy Reviews* 132.July, pp. 37–49. ISSN: 18790690. DOI: `10.1016/j.rser.2020.110105`.

Spash, Clive L. (1999). "The Development of Environmental Thinking in Economics." In: *Environmental Values 8* 4, pp. 413–435.

– (2017). *Routledge Handbook of Ecological Economics.* 1st ed. New York: Routledge, p. 551. ISBN: 978-1-315-67974-7.

Steffen, Will et al. (2015). "Planetary boundaries: Guiding human development on a changing planet." In: *Science* 347.6223. ISSN: 10959203. DOI: `10.1126/science.1259855`.

Stockhammer, Engelbert (2022). "Post-Keynesian Macroeconomic Foundations for Comparative Political Economy." In: *Politics and Society* 50.1, pp. 156–187. ISSN: 15527514. DOI: `10.1177/00323292211006562`.

Suh, Sangwon (2004). "A note on the calculus for physical input-output analysis and its application to land appropriation of international trade activities." In: *Ecological Economics* 48.1, pp. 9–17. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2003.09.003`.

Svartzman, Romain, Dominique Dron, and Etienne Espagne (2019). "From ecological macroeconomics to a theory of endogenous money for a finite planet." In: *Ecological Economics* 162.April, pp. 108–120. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.04.018`. URL: `https://doi.org/10.1016/j.ecolecon.2019.04.018`.

The Food and Agriculture Organization (2013). *Major cuts of greenhouse gas emissions from livestock within reach.* URL: `https://www.fao.org/news/story/en/item/197623/icode/` (visited on 01/08/2023).

The International Energy Agency (2021a). *Greenhouse Gas Emissions from Energy Data Explorer.* URL: `https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer` (visited on 01/07/2023).

– (2021b). *Renewable electricity growth is accelerating faster than ever worldwide, supporting the emergence of the new global energy economy.* URL: `https://www.iea.org/news/renewable-electricity-growth-is-accelerating-faster-than-ever-worldwide-supporting-the-emergence-of-the-new-global-energy-economy` (visited on 12/18/2022).

– (2022a). *Global energy-related CO2 emissions, 1990-2020.* URL: `https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-1990-2020` (visited on 01/02/2023).

– (2022b). *Renewable power's growth is being turbocharged as countries seek to strengthen energy security.* URL: `https://www.iea.org/news/renewable-power-s-growth-is-being-turbocharged-as-countries-seek-to-strengthen-energy-security` (visited on 01/03/2023).

The World Bank (2020). *COVID-19 to Plunge Global Economy into Worst Recession since World War II.* URL: `https://www.worldbank.org/en/news/press-release/2020/06/08/covid-19-to-plunge-global-economy-into-worst-recession-since-world-war-ii` (visited on 01/07/2023).

Tietenberg, Tom and Lynne Lewys (2018). *Environmental and Natural Resource Economics.* 11th ed. Routledge, p. 587. ISBN: 9781138632295. DOI: `10.4324/9781315620190`.

Tokarska, Katarzyna B. and Nathan P. Gillett (2018). "Cumulative carbon emissions budgets consistent with 1.5 °c global warming." In: *Nature Climate Change* 8.4, pp. 296–299. ISSN: 17586798. DOI: `10.1038/s41558-018-0118-9`. URL: `http://dx.doi.org/10.1038/s41558-018-0118-9`.

TU Wien (2022). *What is Stock-Flow-Modelling?* URL: `https://www.fvv.tuwien.ac.at/institut/kompetenzfelder/system-dynamics-engl/what-is-stock-flow-modelling/` (visited on 04/08/2022).

Turner, Graham M. (2008). “A comparison of The Limits to Growth with 30 years of reality.” In: *Global Environmental Change* 18.3, pp. 397–411. ISSN: 09593780. DOI: `10.1016/j.gloenvcha.2008.05.001`.

– (2014). “Is global collapse imminent? An updated comparison of the limits to growth with historical data.” In: *Melbourne Sustainable Society Institute* 53.9, pp. 1689–1699. ISSN: 1098-6596. arXiv: `arXiv:1011.1669v3`.

United Nations Development Programme (2022). *Sustainable Development Goals.* URL: `https://www.undp.org/sustainable-development-goals` (visited on 04/14/2022).

United Nations Framework Convention on Climate Change (2022). *The Paris Agreement.* URL: `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement` (visited on 10/05/2022).

Victor, Peter A. and Gideon Rosenbluth (2007). “Managing without growth.” In: *Ecological Economics* 61.2-3, pp. 492–504. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2006.03.022`.

Vita, Gibran et al. (2019). “The Environmental Impact of Green Consumption and Sufficiency Lifestyles Scenarios in Europe: Connecting Local Sustainability Visions to Global Consequences.” In: *Ecological Economics* 164.June 2018, p. 106322. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2019.05.002`. URL: `https://doi.org/10.1016/j.ecolecon.2019.05.002`.

Vuuren, Detlef P. van et al. (2011a). “How well do integrated assessment models simulate climate change?” In: *Climatic Change* 104.2, pp. 255–285. ISSN: 01650009. DOI: `10.1007/s10584-009-9764-2`.

Vuuren, Detlef P. van et al. (2011b). “The representative concentration pathways: An overview.” In: *Climatic Change* 109.1, pp. 5–31. ISSN: 01650009. DOI: `10.1007/s10584-011-0148-z`.

WEF (2022). *How hard could climate change hit the global economy, and where would suffer most?* URL: `https://www.weforum.org/agenda/2022/04/climate-change-global-gdp-risk/` (visited on 11/16/2022).

Weisz, Helga and Faye Duchin (2006). “Physical and monetary input-output analysis: What makes the difference?” In: *Ecological Economics* 57.3, pp. 534–541. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2005.05.011`.

Welsby, Dan et al. (2021). “Unextractable fossil fuels in a 1.5 °C world.” In: *Nature* 597.7875, pp. 230–234. ISSN: 14764687. DOI: `10.1038/s41586-021-03821-8`.

World Commission on Environment and Development (1987). *Our common Future.* Vol. 4. 1, p. 12. ISBN: 019282080X.

Zhao, Zi Jian et al. (2020). “Global climate damage in 2 °C and 1.5 °C scenarios based on BCC_SESM model in IAM framework.” In: *Advances in Climate Change Research* 11.3, pp. 261–272. ISSN: 16749278. DOI: `10.1016/j.accre.2020.09.008`.

11 Acronyms

AR Assessment report

BAU Business as usual

C Consumption

CC Climate change

CCS Carbon capture and sequestration

CCU Carbon capture and utilization

CES Constant rate of substitution

CGHGE Cumulative greenhouse gas emissions

CTL Coal to liquid

DG Degrowth

EC European Commission

ECE Ecological Economics

ECEM Ecological Economic Models

ENVE Environmental Economics

ELF Energy Loss Function

EM Ecological Macroeconomic(s)

EROI Energy return on energy investment

ESM Earth System Model(ling)

FB Feedback

FED Federal Reserve

G Government consumption/expenditure

GDP Gross domestic product

GG Green Growth

GHG Greenhouse gas(es)

GHGE Greenhouse gas emissions

GTL Gas to liquid

HDI Human Development Index

I Investment(s)

IAM Integrated Assessment Model(s)

ICE Internal Combustion Engine

IEA International Energy Agency

IOA Input-Output analysis

IPCC Intergovernmental Panel on Climate Change

IR Industrial Revolution

ISEE International Society of Ecological Economics

LTG Limits to Growth

LVM Lotka-Volterra Model

M Import

MLT Mid level transition

NCE Neoclassical economics

NCP Neoclassical Paradigm

NRES Non-renewable energy sources

OECD Organisation for Economic Cooperation and Development

OT Optimal transition

PG Post-Growth

PK Post-Keynesian

PKE Post-Keynesian Economics

PKG Post-Keynesian Growth

PSE Policies for social equity

RBC Real business cycle

RCP Representative Concentration Pathway

RES Renewable energy sources

RSFM Real Stock-Flow monetary model

RURR Remaining ultimately recoverable resources

S Saving(s)

SD System dynamic(s)

SDM System dynamic model(ling)

SFC Stock-Flow Consistent

SMS Safe minimum standard

SCC Social Cost of Carbon

SSP Shared Socioeconomic Pathway

WEF World Economic Forum

X Export

ZG Zero Growth

A Appendices

A.1 BAU-climate and resource variant simulations

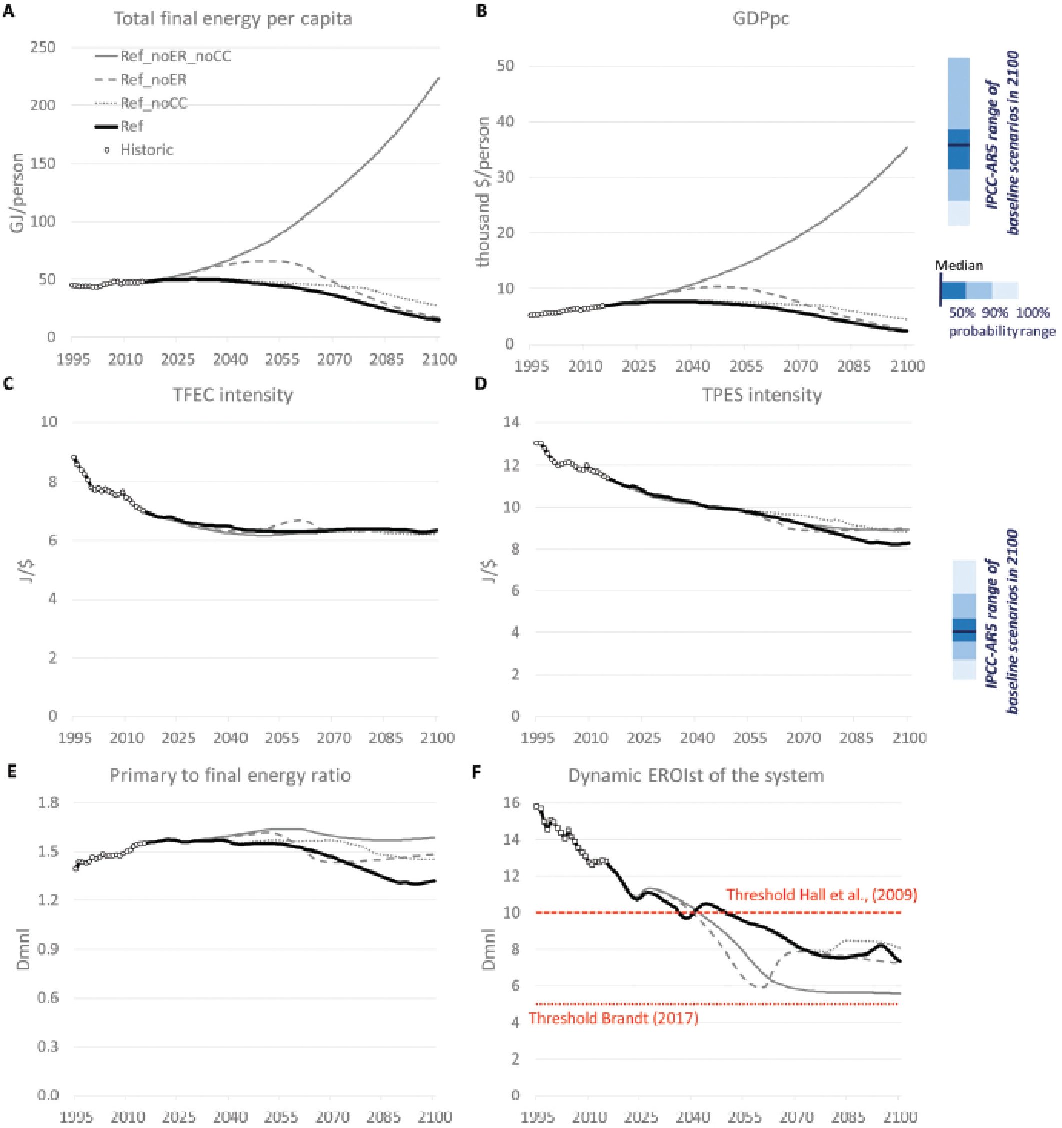


Fig. 8 Final energy consumption per capita, gross domestic product per capita and system efficiency 1995–2100 for the four scenario cases. (A) Total final energy per capita (TFECpc, GJ per person per year). (B) Gross Domestic Product per capita (GDPpc, thousand $ per person, in USD chained linked volumes (1995)). (C) Total final energy consumption (TFEC) intensity (defined as TFEC/GDP, in J per $). (D) Total primary energy supply (TPES) intensity (defined as TPES/GDP, in J per $). (E) Primary to final energy ratio (defined as TPES/TFEC, dimensionless). (F) Dynamic energy return on energy invested ($EROI^{st}$) of the system (dimensionless ratio). Representation of system EROI thresholds to sustain high levels of development in current industrial complex societies from Brandt[154] (∼5 : 1) and Hall *et al.*,[135] (∼10 : 1). Dollars correspond to 1995 US$. Comparison with the IPCC-AR5 range of baseline scenarios for 2100[8] in panels (B and D) median and 50%, 90% and 100% confidence intervals (values have been converted to MEDEAS equivalent units). Source: own elaboration.

Figure 10: BAU-variant simulations, by Capellán-Pérez et al. (2020b)

A.2 MLT-time variant simulation

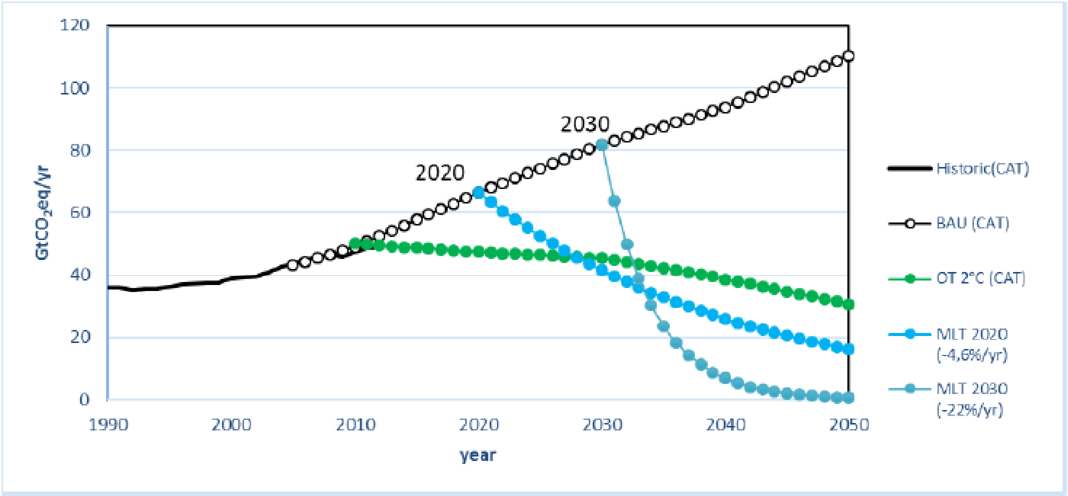


Figure 117: MLT 2020 and MLT 2030 GHG emission are extrapolated from the BAU scenario considering that the global carbon budget is 485 GtCO2 until 2050.The data source for BAU and OT is from Climate Action Tracker (CAT).

Figure 11: MLT-time variant simulations, by Capellán-Pérez et al. (2020a)

A.3 Results of using degrowth and RURR policies on GDP

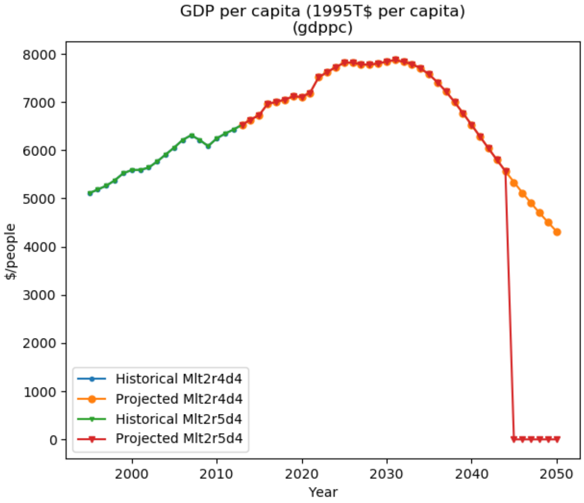


Figure 12: DG and RURR policy simulations using MEDEAS, own work