Master's Thesis – Master Sustainable Business and Innovation

Exploring a safe and just operating space for the Dutch energy system

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Glossary

CBS	Central bureau for statistics (the Netherlands)
CCUS	Carbon capture, utilisation, and storage
CH_4	Methane
CO_2	Carbon dioxide
DSO	Distribution system operator
EU	European union
EV	Electric vehicle
GHG	Greenhouse gases
GWP	Greenhouse warming potential
IEA	International energy agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
Li-ion	Lithium-ion
MLP	Multi-level perspective
NO_x	Nitrogen oxides
PED	Positive energy district
PM	Particulate matter
PV (panels)	Photovoltaic panels
SDG	Sustainable development goal
SF_6	Sulphur hexafluoride (isolating gas)
TSO	Transmission system operator

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Abstract

Introduction

Current policies steering the energy transition are mostly focussed on preventing GHG emissions, even though energy systems have other ecological and social impacts through air pollution, land use, health, and inequalities. By adopting the doughnut economy framework's multiple ecological and social boundaries a safe and just operating space for the Dutch energy transition can be envisioned. The factors influencing the pathway towards an energy system within the doughnut are mapped in the multi-level perspective.

Theory

The doughnut economy framework consists of an ecological ceiling based on biophysical planetary boundaries and a social foundation consisting of social sustainable development goals, although not all doughnut boundaries are relevant in the Dutch energy system context. The multi-level perspective is used to map influencing factors and energy system dynamics within landscape and regime levels, also policies are expected to be an especially important influencing factor for sustainable transitions.

Methodology

The study uses a qualitative method consisting of literature research and expert interviews, which are used to determine relevant doughnut boundaries, and study the impacts on these boundaries by the four components of the energy system, production, transport, storage, and use. The expert interviews provide insights into expectations of an energy system complying to the relevant boundaries and the influencing factors of this energy transition pathway. The interview data was transcribed and analysed in a deductive and inductive coding process.

Results

Relevant ecological boundaries of the doughnut are climate change, air pollution, land conversion, and biodiversity, while the social boundaries relate to equality in the current population, intergenerational equality, health, and financial resources. The main social boundary interactions were at the energy use component, while ecological interactions occurred mostly at the production, transport, and storage. Placing these findings in the multi-level perspective, landscape influences on the energy transition towards doughnut framework compliance cause frictions in the regime, while the regime also contains numerous constraints in the areas of policy, technologies, markets, incumbents, and culture.

Discussion/Conclusion

How an energy system compliant with doughnut boundaries would look, is not only influenced by the boundaries of the doughnut itself. Also, socio-technical landscape influences, such as geospatial constraints, or geopolitical instabilities lead to pressures on the regime which are currently not anticipated on sufficiently by the energy system actors and policymakers. The energy system actors can influence socio-technical regime areas like energy policy, which plays an important role determining the energy system compliant with the doughnut economy framework.

1. Introduction

The use of energy is the cause of more than 75% of the European union's (EU) greenhouse gas (GHG) emissions. Therefore, decarbonisation of the energy system is critical to achieving carbon neutrality by 2050 (European Commission, 2022). However, the energy system is also connected to other negative environmental impact categories, such as air pollution and land use (Laurent et al., 2018; US Environmental Protection Agency, 2021). So, sustainable development of our energy system requires an approach which considers impact categories next to GHG emissions.

The concept of planetary boundaries is a theory that defines a safe operating space, consisting of nine biophysical boundaries, such as climate change, land use, and air pollution, that should not be transgressed. Otherwise, environmental change likely leads to unhabitable earthly conditions for humanity (Rockström et al., 2009; Steffen et al., 2018). Past studies have used theories like the planetary boundaries in business and policy settings to articulate the absolute environmental limits on Earth (Algunaibet et al., 2019; Clift et al., 2017; Galaz et al., 2012).

Furthermore, for the sustainable development of the future energy system, it is essential that the energy system can support the energy demand that is needed to guarantee a sufficient quality of life. Multiple energy-related factors are part of the Dutch central bureau for statistics' (CBS) "broad well-being monitor", indicating that there is a close connection between the energy system and social wellbeing (CBS, 2021). Additionally, energy systems affect social aspects such as inequality and poverty, through the central function it has in society (Idenburg & Weijnen, 2018).

The concept of having planetary boundaries as well as social boundaries resonates with the doughnut economy framework by Raworth (2017). It proposes a safe operating space for humanity on Earth that exists of an ecological ceiling and a social foundation (Raworth, 2017). Because the energy system has both ecological and social impacts, it is necessary for sustainable energy transitions that both these impacts are recognised.

A sustainable transition, such as the transition towards a state where the Dutch energy system stays within the doughnut economy framework requires improvements in the ecological and social performance of the energy system (Geels, 2011). These can only be realised by changes in multiple other systems, varying from consumer practices to the value chains of energy production technologies, resulting in a complex and long term process (Elzen et al., 2011; Geels, 2011). Such transitions are called socio-technical transitions because the changes occur in various areas, such as technology, policy, markets, consumer practices, infrastructure, cultural meaning, and scientific knowledge, and can be caused by multiple actors (Geels, 2004). Mapping the developments and barriers alongside the energy transition requires a framework that recognises influencing factors on different levels and areas, such as the multi-level perspective (Geels & Schot, 2007).

To this date, a transition towards an energy system capable of complying with the planetary and social boundaries has not been studied. Many studies attempted to envision the future state of a sustainable energy system by incorporating life cycle assessment (LCA) impact categories, or planetary boundaries in an energy system (Algunaibet et al., 2019; Vandepaer et al., 2020). However, LCA impact categories insufficiently covers biodiversity and social impacts, and the planetary boundaries do not recognise social impact categories besides the energy system cost. Also, Derkenbaeva et al. (2022) and Musabasic (2015) studied the relevance of the doughnut boundaries in an energy context without mentioning how the energy system could comply with the relevant boundaries. Concerning influences besides the boundaries, the influencing factors in low-carbon energy transitions we studied (Geels et al., 2017), but this was not the case for a transition towards a desired energy system state that considers other aspects next to decarbonisation. So, these are theoretical knowledge gaps to be filled. Therefore, the main research question is:

How do socio-technical factors influence the Dutch energy transition towards an energy system complying with the boundaries of the doughnut economy framework?

To address the main research question, it is essential to study the relevant boundaries of the doughnut economy framework, in the context of the Dutch energy system. These relevant boundaries are used to structure and locate the impacts of the energy system components. This is necessary to study whether certain technologies or practices within components fit in an energy system complying with the doughnut boundaries. Consequently, the external factors determining the pathway towards an energy system that falls within these ecological and social boundaries can be identified. Therefore, the following sub-questions are relevant:

- What are the relevant ecological and social boundaries of the doughnut economy framework for the Dutch energy system?
- How do the developments in the energy system components interact with the ecological and social boundaries of the doughnut economy?
- What are the perceived factors influencing the Dutch energy transition?

Answering these sub-questions provides the relevant boundaries of the doughnut economy framework for the Dutch energy system. Secondly, the Dutch energy system's impacts on the relevant ecological and social constraints of the earth are identified, resulting in expectations for a doughnut compliant energy system. Next to that, a multi-level perspective is adopted to map the factors influencing the Dutch energy system's transition towards doughnut compliance. Addressing these questions provides a societal contribution by creating a deeper understanding of the dynamics in the transition towards an energy system within the safe and just operating space of our society. This is the beginning of a path towards a future society capable of preserving habitable living conditions on Earth

In this study, IPCC's definition of energy systems is adapted to fit the research scope of the Dutch energy system. Also, energy storage is taken up in this definition as energy storage is an important part of carbon-neutral energy systems (Child & Breyer, 2016; Victoria et al., 2019). Therefore, an energy system is defined as *all components related to the production, transport (and conversion), storage, and use of energy that is delivered through the Dutch energy distribution network* (IPCC, 2014). Consequently, fuels used for transportation and energy sourced from biomass that is not distributed through the Dutch energy distribution network are not considered in this study. The emphasis of this study lies on the energy system of electricity and gas, but due to the interconnection and replaceability of electric or gaseous energy with thermal energy (Liu et al., 2021), thermal energy production, storage, and use are also considered. Furthermore, the technologies considered in the components are commercialized before 2027, to ensure large-scale application before 2050, the year in which a net zero (emissions) energy system is planned (International Energy Agency, 2021).

To lay out the structure of the report, the theoretical background section explains the doughnut economy framework, its ecological and social components, and links to energy systems. Furthermore, the theory of a socio-technical transition towards a future energy system within the doughnut is introduced. Consequently, the methodology section covers the qualitative approach that is taken to answer the research questions. In the results section, the findings from the literature study and interviews are reported and structured in the sub-research questions. Furthermore, the discussion incorporates the limitations and recommendations for future research.

2. Theoretical background

In the theoretical background, the doughnut economy framework is introduced and separately discussed in the ecological and social boundaries sections. In these sections, the energy system associations with the boundaries are outlined. Furthermore, a multi-level perspective is adopted to study the socio-technical transition that is the energy transition.

2.1 Doughnut economy framework

According to Raworth (2017), humanity has used GDP as a compass toward economic progress for the past centuries, leading to degenerative economies while depleting the world on which our happiness relies. Furthermore, these economies are divisive and enrich the wealthiest one percent of the world at the expense of the rest.

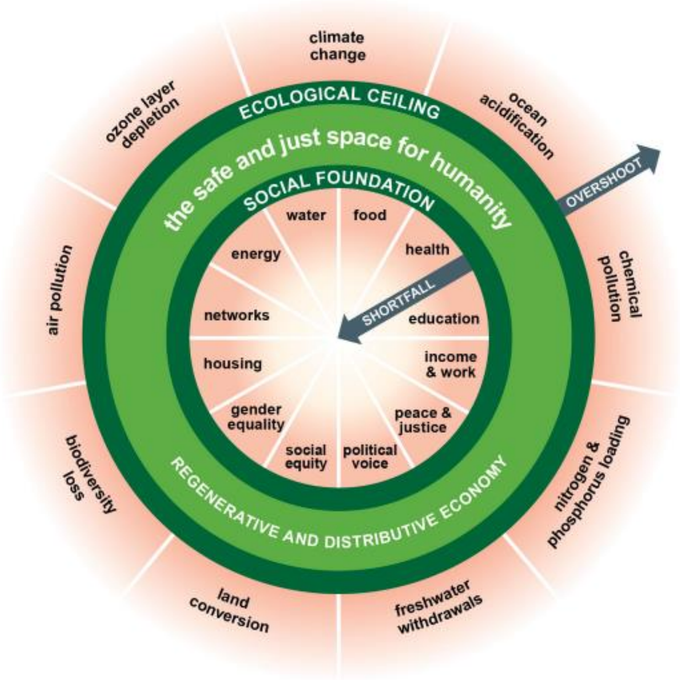

Figure 1 Doughnut economy framework (Raworth, 2017)

Therefore, a new compass is needed that does consider the welfare of the planet's ecosystems and the inequality issues amongst the population. This resulted in the doughnut economy framework (Figure 1), an adapted version of the planetary boundaries framework which also incorporates the social foundation based on the social categories of the SDGs. The outcome is the quantification of space for humanity that is not only safe but also just (Raworth, 2017). This theory is a relevant compass for navigating energy transitions' diverse ecological impacts (Laurent et al., 2018) and deep embedding in the societal foundation (Idenburg & Weijnen, 2018).

Due to the ecological and social scope of this study, the doughnut economy is a relevant framework to use when exploring sustainable development pathways of the Dutch energy system. The unique perspective of the doughnut framework allows for an integrated sustainability approach to the energy system. Compared to other frameworks considering both social and ecological aspects, such as the sustainable development goals (UNDP, 2022) and its derivatives like broad welfare (CBS, 2021), the doughnut economy framework recognises more specific social and ecological impact categories. This enables a more articulated impact analysis.

To this date, only two studies (Derkenbaeva et al., 2022; Musabasic, 2015) were found applying this framework in an energy-related context. Musabasic (2015) studied how and which ecological and social considerations are mentioned in energy and climate change scenarios. In this study, the planetary boundary of Stratospheric ozone depletion was the only dimension that was not considered in the selected scenarios. Furthermore, positive energy districts (PEDs) have been studied in light of the complex adaptive system and doughnut economy frameworks (Derkenbaeva et al., 2022). This has led to the insight that the main social foundation to be considered is access to energy, while the main ecological concerns are climate change and air pollution. But as PEDs are of considerably smaller scope than energy systems in the Netherlands as a whole, further examination of relations between energy systems and the concepts of the social foundation and ecological ceiling is needed.

2.1.1 Ecological Boundaries

The planetary boundaries (Rockström et al., 2009) are the theoretical underpinnings of the ecological ceiling introduced in the doughnut economy framework (Raworth, 2017). There is convincing evidence that human activities, initiated by the industrial revolution, are responsible for the earth to move into a new *epoch*, the Anthropocene, after a stable period of 10,000 years called the Holocene. This epoch is characterised by a change in environmental conditions towards a "*less biologically diverse, less forested, much warmer, and probably wetter and stormier state"* (Steffen et al., 2007). It is essential to preserve the conditions of the Holocene because only those conditions have proven to be capable of supporting modern society (Fanning & O'Neill, 2016). Therefore, Rockstrøm et al. (2009) have identified nine biophysical boundaries of the Earth that cannot be transgressed without worsening living conditions for humanity, thereby defining a safe operating space for humanity. These biophysical boundaries have been set in the following boundaries, referring to different systems of the earth: Climate change, biodiversity loss, biogeochemical flow (nitrogen and phosphorus), stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, atmospheric aerosol loading (air pollution), and novel entities.

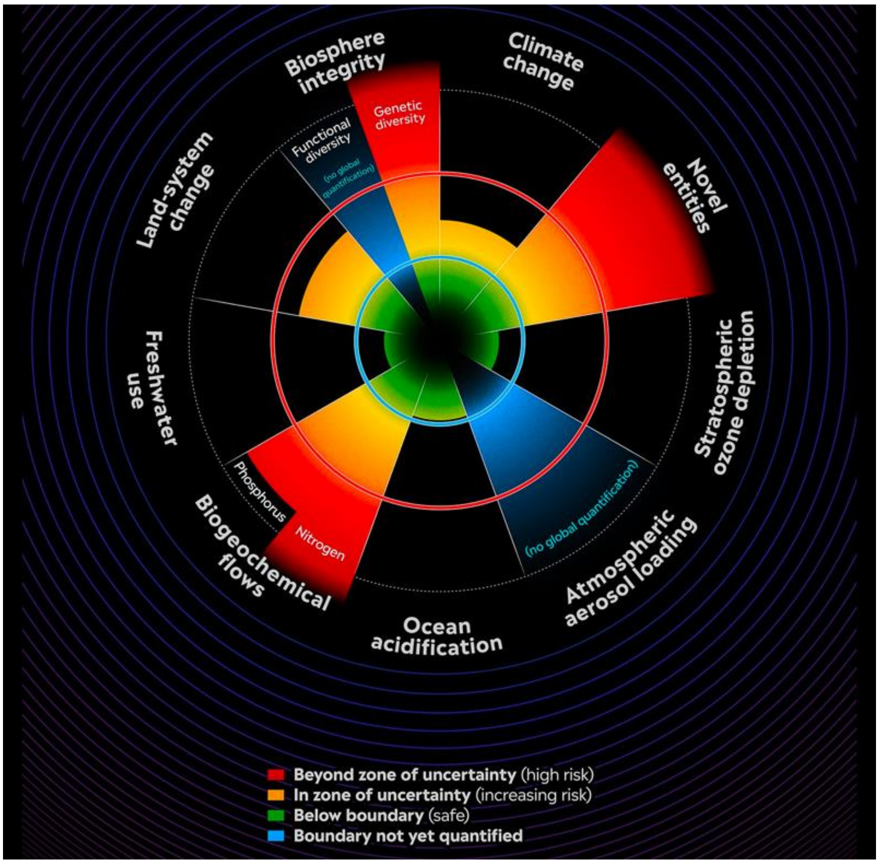

Figure 2 Recent planetary boundary statuses (Persson et al., 2022; Steffen et al., 2018)

Figure 2 shows the current state of the boundaries. Although the last two of these boundaries have not been quantified officially yet in the initial studies in the field of planetary boundaries (Rockström et al., 2009; Steffen et al., 2018), the latest research has concluded that the novel entities boundary has been exceeded as well (Persson et al., 2022). From Figure 2 can be concluded that both boundaries for biochemical flows have been exceeded, as well as the genetic diversity boundary for biodiversity. Furthermore, concerning the categories of Climate change and Land-system change, the CO_2 concentration, and the area of land as a percentage of originally forested land have entered the uncertainty zone. The uncertainty zone encapsulates the gaps, weaknesses, and uncertainties in the scientific underpinning of the study (Steffen et al., 2018).

Finding a configuration of the energy system fitting within all planetary boundaries that are impacted by the energy system is essential, because disregarding relevant boundaries in energy policy making can lead to burden shifting. This is known as lessening impact in one category but worsening another (Algunaibet & Guillén-Gosálbez, 2019; Ehrenstein et al., 2020). The energy system is currently on the path of transgressing five boundaries that are impacted by other factors than GHG emissions because current energy policy efforts are more inclined to focus on GHG emissions (Algunaibet et al., 2019). However, the energy system modelled for 2030 and minimising the transgression of all planetary boundaries leads to increased impact on planetary boundaries other than climate change, which exemplifies the risks of burden shifting.

2.1.2 Social boundaries

This section outlines the several ways the energy system interacts with the social foundations of our society. The social foundation is built upon the sustainable development goals (SDGs) that relate to social issues, such as health and equality amongst the Dutch population. Firstly, the connection between the social SDGs and the social foundation of the doughnut is explained. Then the improving and worsening boundaries of the social foundations in the Netherlands are highlighted and discussed in relation to the energy system. Furthermore, the possible interactions between the energy use component and the social foundations are outlined.

Connection to social Sustainable Development Goals

The 11 boundaries constituting the social foundation of the doughnut economy framework are derived from the social sustainable development goals (SDGs) (Raworth, 2017). The United Nations' SDGs were created to *provide a shared blueprint for peace and prosperity for people and the planet, now and into the future* (UN Department of Economic and Social Affairs, 2015). So, next to addressing the climate-related challenges, the SDGs are designed to remedy the social issues concerning health, education, inequality, and poverty, therefore a suitable underlying framework for the social boundaries. The social foundation boundaries and the social SDGs they are derived from are: Food (SDG 2), health (SDG 3), education (SDG 4), income & work (SDGs 1 & 8), water & sanitation (SDG 6), energy (SDG 7), networks (SDG 9.c & 1.5), housing (SDG 11), gender equality (SDG 5), social equity (SDG 10), political voice (SDG 16.7), and peace & justice (SDG 16).

Improving social impact categories in the Netherlands

Not all boundaries are equally relevant in the context of energy systems in the Netherlands, as they are generalised to a global scale, so not all boundaries are directly linked to energy system impacts and applicable to a developed country such as the Netherlands. In a report by the CBS (2021), the following developments were observed in the indicators relating to the SDGs, thus social boundaries, in the context of the Netherlands. For SDG 6 positive developments are visible and for SDGs 2, 3, 5, 8, and 16 there is a moderately positive trend visible, so the Netherlands appear to provide a sufficient social foundation concerning these boundaries. The energy system can still fall short in one of these boundaries, it is important to consider them in the study. For example, health impacts (SDG 3) can still occur in the future due to changing living conditions (CBS, 2020, 2021), or air pollution which is one of the most important boundaries (Derkenbaeva et al., 2022).

Worsening social impact categories in the Netherlands

On the contrary, the indicators of SDGs 1, 4, and 10 are moving away from the targets that were set (CBS, 2021), meaning that there are currently insufficient structures in the Netherlands to prevent a decrease in welfare in the social boundary of income & work, education, and social equity. For these downward trending indicators relating to the doughnut's social foundations, it is important to study the connection with the energy system.

Concerning the boundaries of social equity (equality between different groups in the population) and income & work (economic welfare), it was found that an equitable distribution of burdens and merits related to changes in the energy system is essential. Energy systems complying with the planetary boundaries could lead to higher electricity prices (Algunaibet et al., 2019). Also, they are negatively affected by policies like carbon tax and reduced fossil fuel subsidies (UNDP, 2020). Rises in energy prices affect the purchasing power of lower-income households more than higher-income households (Anker-Nilssen, 2003; UNDP, 2020). Not only because their opportunities to save energy are smaller, compared to higher-income households which possess a larger amount of non-essential appliances to turn off. Also, lower-income households have a relatively high budget share of electricity expenses, so a price increase would lead to a higher effect on their total expenses. This is also the case for a country with extensive social welfare policies like the Netherlands, as energy poverty is not well enough integrated into current policies (Feenstra et al., 2021).

Energy-related social impact categories

Trends that are especially relevant to consider in the Dutch energy system, are the developments in the social boundary of energy (SDG 7). Inland energy consumption and energy intensity of the Dutch economy are decreasing and the percentage of renewable energy in the energy mix is increasing. However, these positive trends are visible in all European countries (CBS, 2020). Compared to Europe, the developments in the areas in the Netherlands are far from sufficient, as it is one of the most energy intensive countries in Europe and the renewable energy share is the lowest in Europe (CBS, 2021). The Netherlands is trending towards the status of a laggard in the energy transition, in terms of energy intensity and renewable energy share. These (lack of) developments are an indication of the importance of accelerating the energy transition in the Netherlands. Also from a social perspective, it affects (future) living conditions and intergenerational inequalities (Steffen et al., 2007).

Energy use and the social foundation in general

Multiple studies measuring the quality of life incorporated health, education, network, and income & work related indicators (Bridge et al., 2016; Mazur, 2011; Pasten & Santamarina, 2012), and are therefore approaching the definition of the social foundation of the doughnut framework. These indicators increase as the percentage of the population with access to electricity increases (Bridge et al., 2016). However, others have found that there is a maximum increase in quality of life caused by energy or electricity use, especially in developed countries like the Netherlands (Mazur, 2011; Pasten & Santamarina, 2012). Mazur (2011) has reasoned that this is the case because the quality of life has improved so much in the last century, that there is little room for further gain in the selected indicators for quality of life. Considering future developments in the energy sector, Pasten and Santamarina (2012) expect that the rate where no additional quality of life is gained will lower towards 2040. Although, this estimation does not consider the energy embodied in (food) products, and renewable energy sources, such as solar energy, which should be considered in this study.

Furthermore, (energy and health) indicators used in the previous paragraph, such as the percentage of the country with access to electricity and infant mortality to measure the quality of life are possibly not suitable for the context of the Netherlands. Trends in these indicators would suggest that the quality of life does not increase with energy consumption in the Netherlands, while the results could be different when indicators are used that are more fitting for the Netherlands. Therefore, for the doughnut framework for the Dutch energy system, the relevant impact categories could be measured with other indicators than the doughnut framework in a global context.

In a study which did consider the quality of life or social foundations in a Dutch context about the interactions between energy saving practices and the social foundation, Dutch consumers believed that their quality of life would not be affected when the savings did not exceed 24% of the household energy use (Gatersleben, 2001). Here the savings resulted from easy energy-saving behaviour, such as lowering room temperature or replacing inefficient devices (Gatersleben, 2001). However, participants were less willing to participate when asked to engage in larger energy-saving behaviours, like reducing car use, holidays, and meat consumption (Lindenberg & Steg, 2007). However, this behaviour is also affected by external factors like financial, technological, political, cultural, psychological, and environmental factors, exemplifying the importance of considering external factors (IPCC, 2014). Also, external factors, like income equality, economic growth, and infrastructure, affect to what extent energy use contributes to the social foundation (Vogel et al., 2021).

Concludingly, not all social boundaries appear to be relevant in the context of the Dutch energy system. Instead, a pre-selection of relevant categories can be made, without a guarantee that only these are relevant. The health boundary is relevant to consider given the present and future impact of the energy system on human health (CBS, 2020, 2021; Derkenbaeva et al., 2022). Furthermore, the economic welfare of households (jobs and income) is impacted through the costs of energy (systems) and the socio-economic inequalities (social equity) caused by the energy costs and other policy developments (Anker-Nilssen, 2003; UNDP, 2020). Thus, these two social boundaries are relevant to consider. Next to that, the effect of energy systems on intergenerational inequalities is important, as the emissions of energy systems now, affect future living conditions (Steffen et al., 2007). Furthermore, energy use only leads to higher performance on the social foundations to a certain extent, when measured with indicators fitting a global context (Bridge et al., 2016; Mazur, 2011; Pasten & Santamarina, 2012). This might be different for the Netherlands as there appears to be less willingness for extensive energy savings, which can affect the Dutch social foundations (Gatersleben, 2001; Lindenberg & Steg, 2007).

2.2 Socio-technical transitions

The transition towards an energy system (regime) complying with the ecological and social boundaries of the doughnut economy framework could be affected by factors other than the doughnut boundaries. To map the developments influencing this energy transition path, it can be useful to look at it from multiple levels. This way, the various levels and areas in which influencing factors can present themselves are taken into account. Therefore, a multi-level perspective (MLP) is an insightful way to map the influencing factors towards an energy system within the doughnut economy (Geels & Schot, 2010). Compared to other transition or innovation system theories, such as the mission-oriented innovation system or MIS (Hekkert et al., 2020), the MLP is more suitable to consider social/cultural aspects, and focus on dynamics of the entire energy system instead of one innovation. The MLP is used to explain technical transitions, which are defined as a change in the way of fulfilling societal functions in the long term (Geels, 2002). According to Geels and Schot (2010), technical transitions involve both changes in technology and societal functions, e.g., consumer energy use, energy policies, infrastructures, cultural meanings, and business models, and therefore they are called socio-technical transitions.

The energy transition towards compliance with the social and ecological boundaries of the doughnut economy is an example of a social-technical transition. A visualisation of the MLP, complemented with the doughnut economy framework can be found in Figure 3. The MLP is a framework that allows for the analysis of these changes on three levels: the socio-technical regime, the socio-technical landscape, and the niche (Geels, 2002).

2.2.1 Socio-technical landscape

The socio-technical landscape refers to *"the wider exogenous environment"* (Geels, 2002), it includes factors which can hardly be influenced by energy system actors, such as the material environment, and shared cultural beliefs. Examples of this are society's energy dependency, climate change, a growing population, multi-lateral agreements, or the Russian invasion of Ukraine. Also, the developments in the boundaries of the doughnut economy framework are part of the socio-technical landscape, as they represent the states of ecological systems and social foundations on a global scale and are not directly influenced by the energy system. Pressures from the landscape arise from these developments (Geels, 2002), but not all doughnut economy boundaries are equally relevant for the Dutch energy transition, which will be discussed in the results of sub-question 1.

2.2.2 Socio-technical regime

The energy system regime includes the current markets (and user preferences), (industry) incumbents, science, (government) policy, cultures, and technology. Incumbents within the Dutch energy system, such as energy (technology) producers, DSOs, and large energy users, can play an important role in the energy transition as they often possess the resources to steer future directions of the energy sector. In the MLP, Geels (2002) assumes that the (fossil-based energy) regime is initially stable. But incumbents motivated by landscape pressures or regime tensions can create substantial changes in the energy system through the reallocation of human and financial resources, to develop or implement new technologies (Geels & Schot, 2007). However, incumbents remain dependent on the current configurations of the socio-technical regime of the energy system, such as energy policies, energy use preferences and habits, and infrastructures existing of current technologies. Incumbents adopting novel technologies can influence regime elements by improving technological innovation, increasing knowledge, and influencing policy development (Erlinghagen & Markard, 2012). Consequently, the actors within the energy system regime, can contribute to an energy system regime facilitating compliance with doughnut boundaries.

2.2.3 Niche

The niche level is the start-up phase where new technologies and actors originate, grow, and sometimes fail. Niche technologies in the energy transition can be oriented towards different energy system components. However, niche innovations typically lack the required resources or circumstances in the regime, such as energy policy, infrastructure, incumbent strategy, or market, which inhibits the possibility of scaling up. However, the focus of this research lies on established technologies and components of the energy system, so the dynamics between niche and regime are not prioritised.

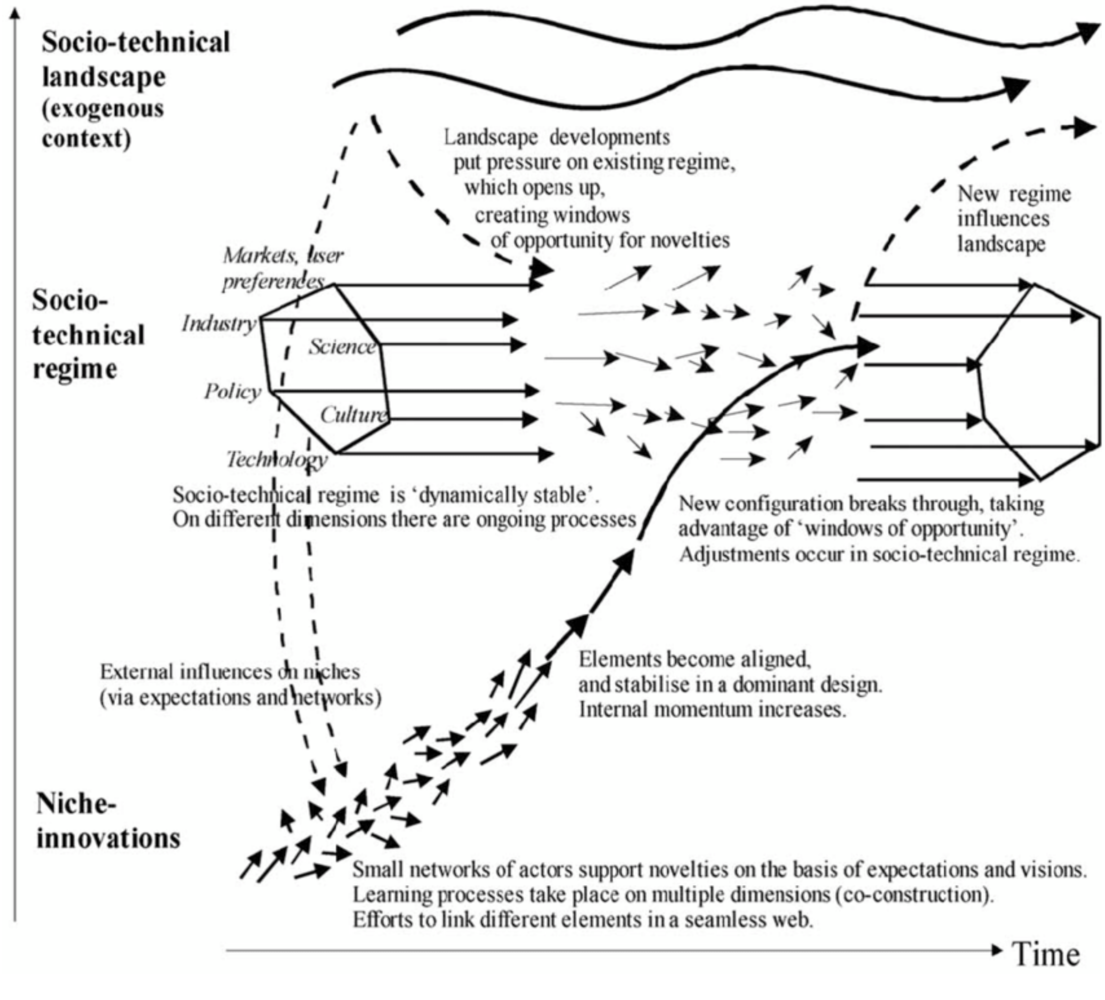

Figure 3 The multi-level perspective (Geels & Schot, 2007)

2.2.4 Sustainable transitions

The MLP model can be used to look at the Dutch energy transition through the interconnected levels to give deeper insights into the mechanisms and interactions behind this transition. Dynamics between levels and frictions in the transition can become visible. According to Geels (2011), socio-technical transitions to a more sustainable future differ from other transitions in three ways. Firstly, because the transition is initiated by the desired state of the future instead of commercial opportunities, companies in the sector lack incentives to act now. Secondly, on the user side, there is a lack of incentive because sustainable solutions do not offer obvious user benefits and often score lower on the price/performance compared to established technologies. Thirdly, the domains where sustainability transitions are often needed such as the energy system, are often dominated by large firms having vested interests in the current infrastructures.

Consequently, incentivizing initiatives and consumption of sustainable products is essential. "*Public authorities and civil society will be crucial to address public goods and internalize negative externalities, to change economic frame conditions, and to support 'green' niches"* (Elzen et al., 2011). Also, a re-orientation of large existing firms' (incumbents) energy strategies could be necessary, because their resources can accelerate the development of the sustainability transition (Elzen et al., 2011).

3. Methodology

In the methodology, the research design covers how the methods that are chosen will address the research questions. The data collection will outline the data gathering process and the selection criteria for both literature and expert interviews. Data analysis entails a detailed description of the literature data and interview data processing steps. The methodology is completed with the ethical considerations of this study.

3.1 Research design

This study approaches the research question: "*How do socio-technical factors influence the Dutch energy transition towards an energy system complying with the relevant boundaries of the doughnut economy framework?"* with a qualitative research angle. The research follows a two-phase approach divided into a literature research phase and an expert interview phase. As described by Littig & Pöchhacker (2014): "*an expert interview is a semi-standardized interview with a person ascribed the status of an expert*". Semi-structured expert interviews are required to gain an understanding of a complex field like the social and ecological considerations in the energy transition. Also, the interviews had an exploratory element by asking open questions like *"Which developments are required in your component of expertise?"*, resulting in varying answers, providing insights in landscape developments or developments pertaining to different regime areas of the energy transition.

Successful expert interviews require sufficient prior knowledge of the subject by the interviewer, as the kind of knowledge communicated in the interview depends on the image the expert has of the researcher (Pfadenhauer, 2009). Therefore, the first step, literature research, is an important aspect of the methodology, also it enables the possibility for triangulation of the findings with other experts or grey and scientific literature, which improves external validity.

Through integrating scientific literature and expert interviews, the overlap between the energy system impacts and the social and ecological boundaries of the doughnut economy framework is identified. Consequently, it is determined which boundaries are relevant to be considered in this study, by comparing the significance of the impacts on the boundaries and distinguishing social impact themes in the expert interviews. This allowed a visualisation of a safe and just operating system for the Dutch energy system, using the doughnut economy framework (Raworth, 2017).

Secondly, the relevant doughnut economy framework boundaries were used to structure the impacts of the energy system technologies, that were found in academic literature and/or mentioned in the expert interviews. Furthermore, the positive developments mitigating impact on the boundaries were pointed out by energy system experts.

Thirdly, expert interviews are used to derive expectations about the future state of the energy system, with the potential of recognising the relevant boundaries. The interviews contain sections covering the developments or innovations needed in the energy system, and how future developments could affect ecological or social boundaries. This is used to understand the factors influencing these developments in the energy system. The nature of these influencing factors is divergent, for example, they can be economic, political, social, cultural, or technical. To generate a complete image of the socio-technical conditions in which the energy transition takes place across different energy system components, a socio-technical innovation system perspective is taken, adopting a multi-level perspective (Geels & Schot, 2007).

3.2 Data collection

3.2.1 Literature study

Scientific and grey literature will be the primary source of data that is used to answer the first and second sub-questions. To answer the first sub-question, peer-reviewed scientific literature will be reviewed with a semi-structured method to synthesise the current state of knowledge of the social and ecological impacts of various energy system components (Snyder, 2019). In this phase information about all ecological and social impact categories was considered in every energy system component. Scientific fields of study that were used to discover relationships between energy and the doughnut boundaries are articles linking the energy system with land use, water use, and biodiversity (Dale et al., 2011; Hamiche et al., 2016; Janssen et al., 2020; Kati et al., 2021). Life cycle assessment studies are also a valuable source of information to uncover the social and ecological impacts of energy system components (Hertwich et al., 2015; Jorge & Hertwich, 2013; Masanet et al., 2013). Furthermore, studies researching the field of energy and equity, and the SDG performance of the Netherlands were used to discover relevant interactions between energy and social boundaries (Idenburg & Weijnen, 2018).

3.2.2 Interviews

For this study, interviewees needed to be knowledgeable about the relevant social/ecological impacts, as well as the future developments in their energy system component of expertise. To ensure the interviewees possessed this expertise, a selection of 20 experts was made using the network of consultants employed at a DSO, connections throughout the university, and LinkedIn. This selection existed of researchers, managers, or consultants/advisors active in the different energy components. Consequently, an email was sent containing an introduction to the research, emphasising the focus on ecological/social impacts, and future developments. Herein was asked if the candidate was familiar with the topics that were mentioned. After a verifying question, about their experience and topics of expertise (visible in the interview guide in Appendix III), the procedure determined that the interviews were conducted with individuals who are sufficiently informed of ecological/social impacts and future developments in their energy system component of expertise. Table 1 in Appendix I contains the expert identification codes, which are used to anonymise and differentiate between the different experts, it also contains their subjects of expertise and organisations of employment.

Interviews with researchers as well as energy component experts were arranged through convenience sampling by using the university network as a student and the network of the DSO. Also, purposeful sampling is used by (LinkedIn) messaging or emailing managers in relevant positions in the energy system components. This resulted in a sample of 10 experts employed at a DSO and 10 experts employed at other organisations in the energy system.

The semi-structured interviews were predominantly conducted via Microsoft Teams, enabling high quality recordings and less traveling time as interviewees were spread throughout the Netherlands. The interviews were recorded and/or transcribed if verbal consent was given regarding the informed consent document (Appendix II), which was sent on the morning before the interview. The recordings were used to transcribe the interviews via the transcription function in Microsoft Teams or the coding program Condens.

3.3 Data analysis

3.3.1 Literature study

Google Scholar was used to find scientific articles for the literature review. Furthermore, Google Search was used to retrieve relevant grey literature. Firstly, the found articles are reviewed based on content and relevance for the study. Secondly, articles older than five years might not contain the most recent insights, so only after a thorough examination of critical notes by articles that cited this study, the study was used. Data from grey literature sources can be considered if the source is an established and widely trusted organisation like the international energy agency (IEA), CBS, IPCC, or governmental organisations. In the search strategy, the following search terms were used:

[Fill in Energy system component] AND [Fill in specific doughnut economy dimension] OR ecological OR environmental OR social OR LCA AND impact OR effect OR influence

Furthermore, the impacts that were found in academic literature were placed in Excel sheets for each of the energy system components, structured by sub-component (or technology) and boundary. The datasheets enabled a structured approach to store qualitative (and in rare cases quantitative) information about the wide range of components and impact categories.

3.3.2 Interviews

The interview transcriptions were analysed by the same researcher who conducted the interviews, this resulted in a higher probability of considering subtleties like body language, increasing the transactional validity. The coding process is established using a 6-step hybrid approach, existing of inductive and deductive coding, as shown in Figure 4 (Fereday & Muir-Cochrane, 2006). Although the procedure is presented step-by-step, the steps were often repeated following an iterative process.

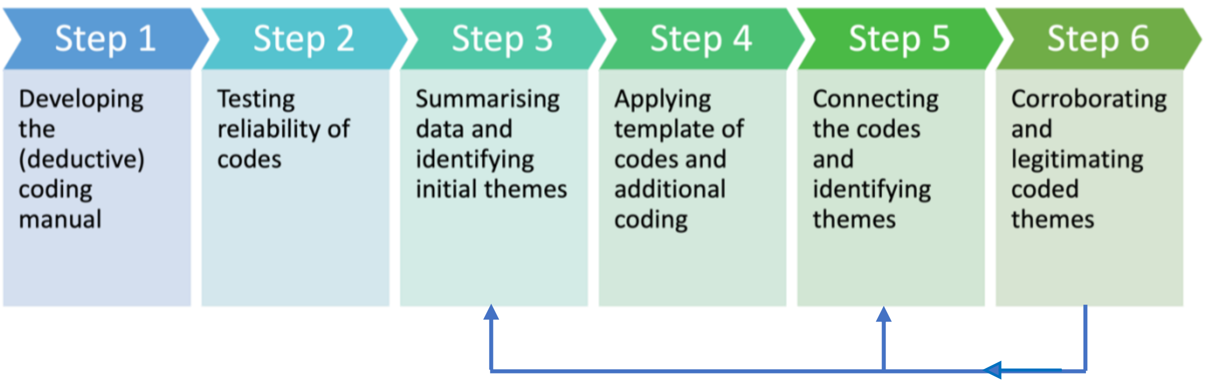

Figure 4 Six-step hybrid coding method (Fereday & Muir-Cochrane, 2006)

Firstly, the transcriptions were analysed using the deductive coding manual (step 1) based on codes that were derived partly from literature, existing of positive or negative impacts on doughnut framework boundary per energy system component, and future developments in the energy system. The coding manual was tested on reliability (step 2) by checking the content of the codes every two interviews that were coded and in case there was scepticism about the application of the right code, a new code was started to prevent inaccurate categorisation of quotes.

Secondly, the coding process had an inductive element through the incorporation of topics of discussion that appeared in the interviews and were not covered by the predefined codes but were ought relevant. Through scanning and summarising the data (step 3), initial themes and such financial or policy impacts within energy system components, or international/national developments were identified and added to the coding manual. Step 4 consisted of the actual coding process using the codes of the coding manual, followed by connecting the codes under themes (step 5) when they were part of a larger development in the energy system.

In step 6 the main emphasis lied on checking the legitimacy of the themes, developments, or influential factors that were found in the codes by iterating between steps 5 and 6. The iterations between the different coding steps were essential to ensure the inductive themes were grounded in the original expert quotes. Also, coding assumptions from the early phases of the coding process were verified by iterating back to step 3. This resulted in the realisation that the international/national development codes, represented socio-technical landscape and regime factors, due to the distinction between the exogenous and non-exogenous character of the influencing factors. Consequently, the MLP (Geels, 2004) was included as a model to structure the influencing factors.

3.4 Ethical considerations

To ensure an ethical research setting, it was important to give the interviewees sufficient time to consider their participation in this interview and the implications it could have. Therefore, the informed consent form (Appendix II) was sent on the morning before the interview. Also, the terms of the informed consent were discussed before every interview and the verbal consent of the interviewees was asked to ensure optimal cooperation. When one of the terms was not agreed upon, this was solved by working around the matter (e.g., a request for no automatic transcription was solved by manual transcription).

The interviewees and employers are anonymised in the report, to protect not only the individual but also the organisation they work for. Furthermore, the interviewees' privacy was protected by predominantly executing the coding and transcribing process in a closed room.

4. Results

Firstly, the research question concerning the relevant doughnut economy boundaries is discussed by synthesizing literature findings and expert interviews (Section 4.1). This approach is also used to answer the second research question regarding the interactions between energy system components and the relevant doughnut economy boundaries (Section 4.2). In the energy system components, four different categories are distinguished corresponding to the definition: *all components related to the production, transport, storage, and use of energy that is delivered through the Dutch energy distribution network.* (IPCC, 2014). The interactions between the energy system components and the ecological and social boundaries of the doughnut framework are structured using the four components and sub-components. Furthermore, the expected future developments (Section 4.3) of an energy system complying with the doughnut boundaries and how these developments are influenced by external factors appearing in the multi-level perspective (Section 4.3.2).

4.1 Relevant doughnut economy framework boundaries

The relevant boundaries of the doughnut economy framework (Raworth, 2017) are structured in a social and ecological section. Most relevant boundaries can be applied to the entire Dutch energy system, although some boundaries are only relevant for certain technologies.

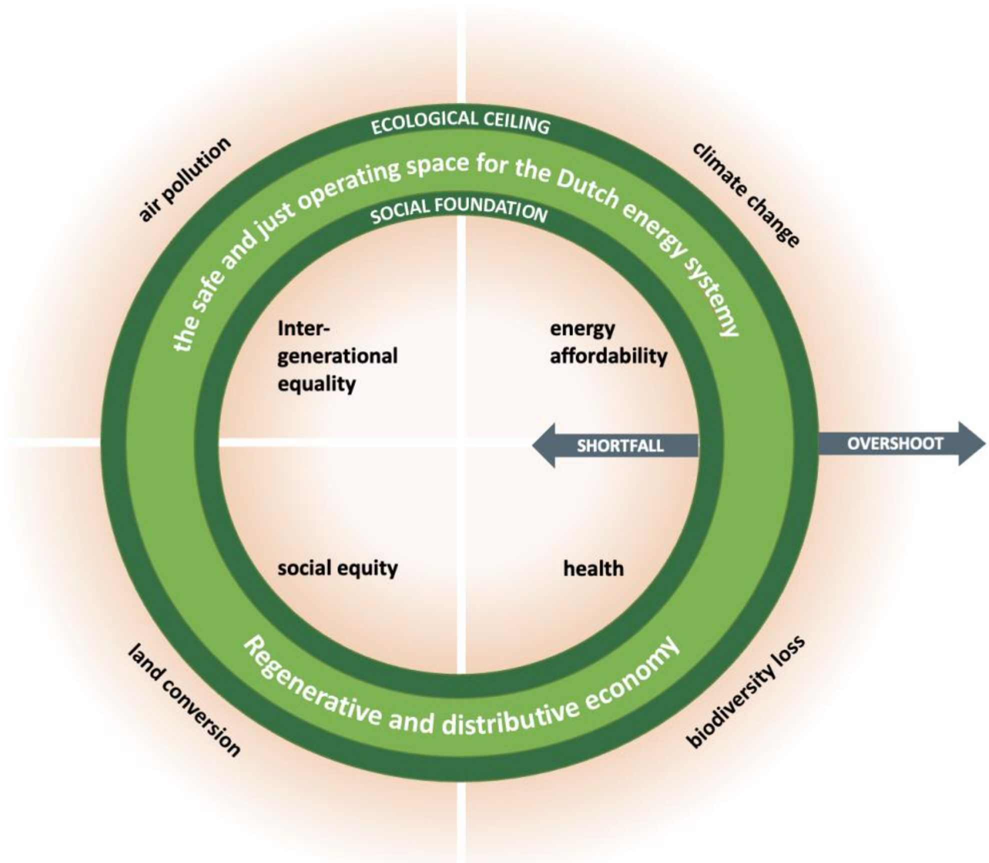

Figure 5 Doughnut economy framework for the Dutch energy transition (adapted from Raworth (2017)*)*

4.1.1 Relevant ecological boundaries

Ozone depletion is the only impact category moving in a positive direction globally, this is due to strict policies severely limiting the emission of substances negatively affecting the ozone layer (UNEP, 2022), so the boundary is less urgent than it was (expert 5). The main contributor to ocean acidification is the emission of CO_2, which is also an important contributor to climate change. Climate change covers more types of emissions and is better known by academics and energy experts compared to ocean acidification. Concerning the impact category of novel entities, the only unavoidable impact in the novel entities dimension that was mentioned in the interviews is nuclear waste (expert 11), so this category is only discussed in Section 4.2.1.8 covering nuclear energy. Furthermore, for bio-based energy (biogas and biomass), the boundaries to water use and phosphorus/nitrogen loading are considered relevant (Masanet et al., 2013). In the production of coal-based electricity, phosphorus/nitrogen loading are also relevant, so these impact categories will only be discussed in these sections (Masanet et al., 2013).

Concludingly, four relevant ecological boundaries of the Dutch energy system are climate change, land conversion (or impact), biodiversity, and air pollution.

4.1.2 Relevant social boundaries

Concerning the social impact categories, the affordability of the energy system is an important element in the considerations of how the energy system should look like. This connects to the doughnut impact category of no poverty, only in the case of the energy system it relates to poverty caused by the energy system, called energy poverty. This phenomenon is also influenced by factors outside the energy system like insulation of houses, and income, furtherly discussed in Section 4.2.4.1. Secondly, socio-economic inequalities in the current generation that can be caused by (a transition of) the energy system are important to consider in the implementation of regulations or technologies (experts 13, 18) (Idenburg & Weijnen, 2018). A third relevant impact category is the extent to which intergenerational inequalities are prevented by facilitating the energy transition towards an energy system with minimal effects on future living conditions (Idenburg & Weijnen, 2018). This is now an impact category the Netherlands falls behind compared to other European countries (CBS, 2020). Both impact categories regarding inequalities (intra-generational and inter-generational) relate to the doughnut framework impact category, social equity (Raworth, 2017). Health impact is the fourth dimension of the doughnut economy framework, this impact category considers the impact of energy system components (value chains) on human health, corresponding to the doughnut economy dimension, health (Raworth, 2017).

So, relevant social boundaries of the doughnut economy are energy affordability (referring to boundary income & work and energy), inequalities in the current population, and between current and future generations (referring to social equity and energy). Also, human health impact is an important boundary, referring to the social boundary of health.

4.2 Interactions Energy system and doughnut boundaries

In the following sections, the interactions between the sub-components of the energy system and the relevant ecological and social boundaries of the doughnut economy framework are discussed.

4.2.1 Energy production

The impact of the production of energy depends on the energy source that is used. In this study the following energy sources are considered: coal, gas, solar, wind, hydro, biomass, thermal, and nuclear.

4.2.1.1 Coal

Ecological boundaries

The climate change impact through GHG emissions during the mining and the combustion of coals vary depending on the type of coal the power plant uses (hard coal, lignite) and if it is combined with carbon capture, utilisation, and storage (CCUS), which reduces the emissions with 75% (Hertwich et al., 2015; Masanet et al., 2013). Coal mining is also capable of disrupting wildlife and habitats (Masanet et al., 2013). Next to that, the biochemical impact in terms of phosphorus emissions of coal energy is higher than renewable alternatives like solar (± 13 times) and offshore wind (± 500 times). CCUS also has a negative effect on phosphorus emissions (Hertwich et al., 2015). "*During the mining process of coal, fresh water can be contaminated. Also, coal-based thermoelectric power generation withdraws water for cooling purposes"* (Masanet et al., 2013). Coal-to-power affects land-system change through the (surface or underground) mining of coal and the land occupied by the power production facility and differs from renewable energy technologies in terms of the irreversibility of the soil impacts (Masanet et al., 2013). Concerning air pollution, the particulate matter (PM) emissions of coal-based electricity production through mining and combustion are significantly (approximately 100 times) higher than renewable alternatives like wind and solar (Hertwich et al., 2015; Masanet et al., 2013).

Social boundaries

Coal-based electricity production is one of the most affordable means to produce electricity, thereby it positively impacts the affordability of energy (EIA, 2022). However, it is not renewable or clean, as it releases various toxic emissions such as SO_2, NO_x, and mercury compounds (Masanet et al., 2013). Therefore, it negatively impacts the boundaries of health and intergenerational equality.

4.2.1.2 (Green and natural) gas

Ecological boundaries

The use of gas as an energy source impacts climate change through GHG emissions during combustion, fugitive CH_4 during well completion, and CH_4 leakage in distribution to the power plant. A natural gas combined cycle power plant emits 25% less than the cleanest coal-based technology, the integrated gasification combined cycle power plant (IGCC). CCUS reduces the climate change impact by approximately 50% (Hertwich et al., 2015; Masanet et al., 2013). Another significant impact of gas production is the processing of high calorific gas to low calorific gas by adding nitrogen to make the gas compatible with Dutch gas boilers, this consumes a lot of electricity according to expert 15. An alternative to natural gas is green gas (or biogas), which can be produced by fermenting agricultural waste streams, therefore emitting less GHG from a renewable source (Pierie et al., 2016). Gas-based power production impacts land through the gas extraction and its impacts on the soil, also land is occupied by the gas power plant (Masanet et al., 2013). Also, patterns of deforestation coincide with the road networks that are associated with gas exploration and development (Dale et al., 2011). Green gas, on the other hand, is only partly responsible for the land used to create bio-waste. Drilling and extracting gas from the earth possibly disrupts wildlife and habitat. Brine scars caused by natural gas extraction, adversely affect local vegetation unless active restoration is conducted (Dale et al., 2011). Green gas is associated with the biodiversity loss caused by agricultural land use. Air pollution caused by particulate matter emissions is higher for gas-based power production than for coal-based systems and increases when it is combined with CCUS. Green gas combustion equally leads to air pollution impact (Xue et al., 2018).

Social boundaries

Gas was one of the most affordable sources to produce electricity in the Netherlands, but due to political tensions in Europe, the gas price is rising (NOS, 2022). On the other hand, the production costs for green gas are falling, increasing the competitiveness of green gas technologies (IEF, 2022). Also, natural gas is neither renewable nor clean as extraction techniques like hydrofracking can provoke local groundwater toxicity issues, next to air pollution (Masanet et al., 2013). Expert 12 mentioned that energy producers are researching where the procured gas is extracted and if there is an impact that can be minimalised or prevented. The production of green gas using agricultural waste streams is renewable but does lead to air pollution, which has adverse health effects (Xue et al., 2018).

4.2.1.3 Solar energy

Ecological boundaries

Even though solar energy produces renewable energy, the energy needed to manufacture a solar panel leads to GHG emissions, although significantly lower than fossil energy sources (Masanet et al., 2013). The emissions of solar energy are also determined by the placement of large-scale solar power plants, as removing vegetation will also lead to GHG emissions and lower carbon sequestration (Turney & Fthenakis, 2011). Furthermore, solar energy is less suitable for the Dutch climate compared to southern climates as one interviewee stated: "*Solar panels in the Sahara produce three times as much power as they do here, which means that the ecological footprint of a solar panel here is three times higher*". This ecological footprint includes the land used during mining and manufacturing and land occupation by large-scale solar projects. There is also an impact on local ecosystems during operation (primarily for large-scale solar), although expert 20 mentioned: "*Current policies (of the solar sectoral organisation) demand solar parks to pay attention to fit into the local environment and ecosystem*". Given the additional land use which leads to biodiversity impact by large-scale solar systems, the impacts associated with solar energy depend on the amount of integrated solar panels in unused surfaces, such as roofs or facades. Furthermore, the manufacturing of solar panels does cause some air pollution, depending on the type of solar panel (Hertwich et al., 2015; Masanet et al., 2013). According to Turney & Fthenakis (2011), the emissions of pollutants into the air are significantly lower than those from traditional power sources.

Social boundaries

Privately owned solar panels can lead to financial advantages, "*Now, you are a thief of your wallet when you don't have solar panels on your roof"* as stated by expert 13. Although these advantages are possibly not accessed equally through society, the access to solar panels is dependent on individual factors according to expert 14: "*There are differences in knowledge and capacities to apply for subsidies and the additional financial resources to invest in renewable energy systems"*. Another dimension, as stated by expert 18, is a lack of physical space (living in an apartment) or financial incentive (renting a house) to place renewable energy systems. In the manufacturing process of certain types of solar panels, toxic and flammable materials like cadmium and arsenic are used, these can lead to health risks (Masanet et al., 2013; Tsoutsos et al., 2005). Although currently health impacts in the value chain are not often considered, expert 14 mentioned: "*This might change for example when a scandal gets uncovered, or labour conditions get included in social impact measurement methods*". Also, social resistance is not uncommon for large-scale solar projects, but expert 20 stated: "*The local environment is taken seriously, we conduct research and see whether mitigating measures are needed*". Also, transparency is an important aspect of the procedures according to expert 12.

4.2.1.4 Wind energy

Ecological boundaries

The main cause of GHG emissions for wind turbines is the manufacturing of turbines, which averagely requires less energy per unit of energy generated than solar panels. It also depends on the location (onshore and offshore) and the type of foundation (steel or gravity-based) (Hertwich et al., 2015; Masanet et al., 2013). Land use is minimal compared to most other energy sources, there is still site preparation, infrastructure and on-site turbine construction, although the land impact depends on the location and type of foundation (Dale et al., 2011; Hertwich et al., 2015; Masanet et al., 2013). Furthermore, wind energy affects biodiversity through the impact it has on bird deaths and injuries (Masanet et al., 2013). Although, "*Recent developments allow wind turbines to be shut down when a flock of birds approaches*" according to expert 11. The manufacturing process of the turbine emits air polluting substances, but less per unit of energy generated than solar panels (Hertwich et al., 2015; Masanet et al., 2013)

Social boundaries

Due to the increase in scale and efficiency of wind turbines, the financial competitiveness has also grown according to experts 11 and 12. Therefore, it became a relatively affordable, renewable, and clean way of electricity production. Although, to produce wind turbines rare earth metals are required. These are generally extracted in countries where fabrication conditions can lead to health risks (ActionAid, 2018; Schlör et al., 2018). When placed properly within current regulations, wind turbines cannot be related to adverse health effects and Dutch policy prevents wind turbines from operating if needed (Dutch Ministry of Economics and Climate, 2021; Knopper et al., 2014). Even though offshore wind turbines were more expensive than onshore, resistance and lack of space have led to the development of offshore wind projects, according to expert 11.

4.2.1.5 Hydro

From the literature review appeared that hydropower is only possible to a limited extent in a flat country like the Netherlands (Milieucentraal, 2022). the optimal locations suitable for hydropower are already being exploited (Manders et al., 2016). There are several ecological, social, and legal barriers that prevent hydropower to gain a large share in the Dutch renewable energy mix (Hadderingh et al., 1988; Hoes et al., 2017). This is confirmed by two experts (14 and 19) mentioning: "*Hydropower is not a realistic option in the Netherlands without some drastic adaptations to the Dutch landscape*".

4.2.1.6 Biomass

Ecological boundaries

Biomass-based electricity impacts climate change, through the combustion of biomass, carbon loss caused by (change in) land use, and emissions of the energy used to produce and transport biomass (Masanet et al., 2013). According to Fargione et al. (2008), biomass' impact on climate change heavily depends on the type of land that is converted and the type of crops that are produced. Expert 11 mentioned that the Netherlands has a geographical disadvantage to produce biomass because there is less sun compared to countries closer to the equator. So, Dutch biomass requires more land to produce the same amount of energy, next to the fact that biomass already uses a substantial amount of land (Masanet et al., 2013). Also, monoculture is often used to produce biomass, which negatively affects biodiversity, according to expert 11 and Masanet et al. (2013). Land use and biodiversity impacts for biomass also differ from land used for renewable technologies like solar and wind, as the latter to some extent allow other uses of the same land (Santangeli et al., 2016). Furthermore, biomass is associated with the emissions of air-polluting substances like SO_2, NO_x, and particulate matter (Masanet et al., 2013). Also recognised as important impacts by expert 11. As opposed to most energy sources, the disturbance of biochemical flows is a relevant boundary through the usage of fertilisers, pesticides, sediment, and cooling water discharge during thermoelectric power generation (Masanet et al., 2013). Although the ecological impacts of biomass as an energy source seem severe, these are based on the assumption of large-scale agricultural biomass. According to expert 11, an alternative is using local waste streams as an energy source, this would alleviate the impact on categories like land use, climate change, and biodiversity partially. To the expert, it seems politically logical to demand a guarantee of the origin of the biomass.

Social boundaries

From the perspective of having affordable, relatively clean, and renewable energy, it makes sense to use local waste streams to produce electricity from biomass, although this is only possible on a small scale according to experts 11 and 19. The emissions of air polluting substances (according to expert 11) and the use of pesticides and fertilisers have adverse health effects (Masanet et al., 2013). Sustainable certification contributes to the development of more sustainable biomass, for example by setting standards for cultivation and impacts on indigenous people according to expert 12.

4.2.1.7 Thermal

Geothermal-based electricity production is not economically viable due to the geological properties of the Netherlands, which influences the temperature of the water that can be extracted (Antics & Sanner, 2007). Although, the direct use of (geo-, aqua-, or industrial processes) based thermal heat for heating purposes is possible in the Netherlands, the application possibilities differ between houses and neighbourhoods. According to expert 13, these differences occur due to the availability of heat sources (e.g., surface water, geothermal, or industrial heat), the possibility to install collective heat systems, and the insulation of homes. Application possibilities that were discussed by experts 4 and 13 and supported by Figure 8 by Ramsak (2020) are the following:

1. Collective thermal systems based on heat from industrial processes, surface water, or geothermal, possibly complemented with electrified (or currently gas-based) heat generation.
    - When there is a heat source, possibility for a heat network, and sufficiently isolated houses.
2. Individual electrification of space heating (e.g., air/water-based heat pumps), possibly combined with small-scale geothermal energy.
    - When there is possibly a heat source, no possibility for a heat network, and the house is sufficiently isolated.
3. Individual heat systems by using green gases like biogas or hydrogen from the current gas network (discussed in the sections about gas and hydrogen).
    - When none of the criteria is fulfilled.

Therefore, I will discuss the ecological and social impacts of the different options.

Ecological boundaries

Fossil-based energy or electricity (in the current electricity mix) used to produce heat in a collective or individual heat system, causes GHG emissions. Depending on the electricity mix, both individual and collective, systems are emitting fewer GHGs than the current heat system, which primarily exists of individual gas boilers. But, collective systems will to a lesser extent contribute to climate change than individual electrified systems, due to higher efficiencies (Liu et al., 2021).

According to expert 4, there are regulations ensuring that geothermal heat systems maintain the soil quality by regulating the moistness of the soil and the temperature of the sources. Furthermore, expert 4 mentioned an event exemplifying the caution for seismic effects which impact the research for geothermal sources. Also, according to expert 13 "*Several geothermal sources can be reached from one location above the ground, so the footprint is minimal*".

Concerning biodiversity, the impact on ecosystems through soil compaction and soil admixing can influence the viability of future vegetation, although the impacts for the (Dutch) low-temperature geothermal systems are less severe (Dhar et al., 2020). This is confirmed by two experts (4 and 13), who were unaware of any effect of geothermal energy on ecosystems in or above the soil. However, concerning heat from surface water, according to expert 4: "*For the return of cold surface water after use, strict regulations are depending on migratory fish movements, although for larger bodies of water these impacts are less severe*". Expert 13 mentioned that there is still a lot of unused aqua thermal potential in larger rivers.

The impact on air pollution of heat systems depends on the amount of energy that is needed next to the heat source if one is used. Jeandeax et al. (2021) found clear differences between particulate matter emissions of biomass-based energy and (natural gas or) electricity. These differences also exist between the electricity mixes in Europe, because of the share of coals in the electricity mix.

Social boundaries

The affordability of the energy depends on the efficiency of the system that is implemented, the more efficient a heat source is used, the lower the costs of the heating system. Therefore, when a collective heat system is possible, this will carry the least societal costs. However, an individual can decide to implement an individual system when that option is more attractive, or the collective system takes too long to be implemented. Therefore, expert 13's concerns are: "*If no collective decision is taken, we will end up with a lot of individual systems, leading to collective heat systems with higher societal costs*". Although this effect could be limited if the energy users' freedom to choose energy systems is reduced in favour of the common good. Furthermore, the extent of future-proofness of the heating system depends on the heat source that is used, the amount of energy needed next to the source and the energy source used for this energy (Jeandaux et al., 2021). Furthermore, similar to the individual investments in solar panels, thermal systems will affect social equality when people who have the possibility to do capital-intensive investments in heat systems and insulation will do it. The rising costs of collective systems, carried by people without the possibility to do individual investments, will eventually disadvantage the less wealthy segment of society, according to expert 13. This social issue of keeping energy affordable equally could be remedied by policies like levelled-off energy prices or subsidised collective heat systems. Furthermore, health impact depends on the energy needed to complement the thermal energy source, this corresponds with the air pollution section.

4.2.1.8 Nuclear

Ecological boundaries

Nuclear energy influences climate change through uranium ore mining and processing and is comparable to the climate change impact of solar, looking at the emissions per unit of electricity produced (Masanet et al., 2013). However, expert 11 stated: "*Recycling (enriched) nuclear fuel could improve the efficiency of nuclear energy, but this practice was not common due to financial motivations*". Also, there is land use by nuclear power plants, uranium mining and contamination of the soil by radioactive elements. There is also a potential impact on ecosystems caused by radioactive elements, and the mining of uranium (Masanet et al., 2013). Furthermore, there is some impact on air pollution by nuclear energy, the magnitude of the impact is larger than wind but smaller than solar per unit of energy produced. The probability of chemical pollution through a globally catastrophic fallout was estimated as low (Masanet et al., 2013). This was confirmed by expert 11, who also recognises that nuclear plants are a potential target for terrorist organisations, although the safety precautions at nuclear facilities are extensive (Byrne & Toly, 2006). However, if there is a nuclear disaster, the consequences also deteriorate the impact on other social and ecological boundaries, like biodiversity, land conversion, and health (Masanet et al., 2013).

Sociological boundaries

According to expert 11, "*Nuclear power plants are very expensive, and it takes a long time to build, but it is a good business case for an investor because the operational costs are very low. Although the issues concerning safety and storage of radioactive waste remain*". Therefore, it would be a viable option to keep the keep energy costs low. Coplan (2006) states that nuclear waste will remain dangerous across civilisations, although there is a lower immediate risk of large impact. Nuclear energy will not only lead to intergenerational inequality but also inequality between past and future civilisations. Furthermore, nuclear energy is not a renewable energy source, as it requires uranium mining leading to impacts on land and indigenous communities (Byrne & Toly, 2006). Due to radioactive waste and a low risk of a nuclear accident there is an impact on human health. Expert 11 offered the future perspective of nuclear fusion, where there is no long-lived nuclear waste and no risk for nuclear accidents, although it is currently (and in 2050) not possible on a large scale. Expert 12 agreed that it would change the entire energy system.

4.2.2 Energy transport

The delivery of energy concerns the infrastructure that is used to transport energy in the form of electricity or gas in the transmission or distribution system. Also, conversion is an important aspect of the distribution of electricity.

4.2.2.1 Electricity transport (transmission and distribution)

Ecological boundaries

The climate change impact of electricity distribution and transmission systems is mainly due to the power losses during the distribution of electricity. The distribution system causes higher losses because, lower voltage causes higher losses and distribution networks are more complex which leads to higher material consumption per unit of energy that is transported (Turconi et al., 2014). Currently, losses from the distribution system are compensated by buying energy partly from a renewable source and partly fossil, but this could improve by compensating the losses exclusively with renewable energy (expert 9).

Aside from the losses, transporting a higher voltage of electricity requires more material, this is reflected in the (manufacturing) emissions per km (Jorge et al., 2011). Concerning the change in land use, for distribution systems, there is no change in land use because the distribution system in the Netherlands is mainly underground (apart from the substations). The transmission system transports electricity above ground using pylons which has an impact on the natural environment, this is acknowledged by TenneT, the Dutch transmission system operator (TSO) (Jorge & Hertwich, 2013; TenneT, 2020). This is in accordance with a study by Doukas et al. (2011) finding that the construction of overhead power lines exceeds the land use impact of underground power cables. Also, the transmission system impacts biodiversity through the number of bird deaths caused by power lines (Bevanger & Brøseth, 2001). Although, according to expert 3 "*Sometimes, the amount of bird deaths caused by power lines is related to a change in the environment, like the removal of a row of trees. When we realise this, we take measures to make the power lines more visible to birds*".

The impact on air pollution of distribution systems mainly stems from the manufacturing process of power cables and cable traces. While for the transmission system, this is mainly the manufacturing of the masts and conductors (Jorge et al., 2011).

Social boundaries

The costs of transportation of electricity determine the affordability of electricity, therefore keeping electricity losses low prevents energy poverty to a limited extent. To keep losses as low as possible the current distribution and transmission system need to be strengthened, so more electricity can be transported with limited losses (Van Melle et al., 2016). Although this will lead to higher transportation costs as well. Primarily, energy losses can be kept low by matching demand and supply, this is challenging in a time where the energy mix share of intermittent energy sources is growing, while increasingly electrifying heating and transport needs (electric vehicles and heat pumps) (Van Melle et al., 2016).

Due to grid congestion, expert 9 confirmed "*In some areas electricity users or suppliers are restricted from a connection to the electricity network, although so far there is no indication of increased social inequalities*". It can even drive a future-proof business case, like maximising the use of their production of electricity (expert 1). Although net congestion does limit possibilities to connect new users, there are policy developments prioritising energy users with a larger societal relevance, like newly developed housing projects according to experts 9 and 7.

Concerning intergenerational equality, several experts (5, 7, 9, and 16) stated grid congestion issues make it unlikely that the current grid infrastructure will be able to facilitate the transition to a future energy system based on renewable and intermittent energy. Especially, when the current energy use practices remain unchanged and if the distribution system operator is legally not allowed to use energy storage technologies to buffer electricity (expert 9). Therefore, how the electricity transportation system can facilitate the transition to clean and renewable sources, depends on more factors than the DSOs and TSOs strengthening power cables alone. Attempting to facilitate the energy transition and relieve the impact on intergenerational equality, expert 9 envisages the role of the DSO as a facilitator of decentral energy systems. In this role the DSO would support local actors developing a decentral electricity net, primarily depending on local energy production and use. While others (experts 11 and 15) see possibilities in TSOs strengthening the international electricity system connections, to take advantage of more efficient energy production elsewhere.

Concerning health effects of electricity transporting systems, studies have found no correlation between diseases and magnetic fields of overhead power lines or transformer buildings, but following precautionary principles, measures are taken by the GGD (GGD Leefomgeving, 2022; TenneT, 2018). On the other hand, electricity transportation indirectly contributes to human health, as access to energy is vital for a sufficient quality of life (Bridge et al., 2016; Mazur, 2011; Pasten & Santamarina, 2012).

4.2.2.2 Electricity conversion

Ecological boundaries

Climate change impact of transformers mainly exists of power losses in the use phase, assuming it lasts 40 years, therefore maximising efficiency has the highest impact (expert 10). Next to that, manufacturing the transformer and the transformer substation also causes GHG emissions (Turconi et al., 2014). Circuit breakers and switchgear have a climate change impact because of the use of isolating gas (SF_6), which has a GWP of 23.800 (Turconi et al., 2014). The losses are only 0,1% per year, but this still has a considerable impact, which is recognised by expert 9 who stated: "*The alternative, insulation with air, would require more space*". The land required for transformer buildings is often an issue. Although the building does not require much space expert 9 experienced: "*Often transformers need to be placed in a populated area, so there are a lot of restrictions. Also, the distribution system operator is often involved in the last phase of a project, fortunately, this is changing lately*". Although due to limited land use there is no significant impact on ecosystems, there have been recent developments in the design phase of substations. "*Ecological research is done at substation locations to improve existing ecosystems"* (expert 3). Air pollution is mainly impacted during the production of raw materials needed for transformers (Turconi et al., 2014).

Social boundaries

The efficiency of the distribution and transmission systems partly depends on transformer efficiencies, therefore it could contribute to lower losses and costs of electricity transportation. No connection between transformers and social inequalities was found. Transformer technologies are facilitating the transition towards renewable energy as transformers are increasingly more often designed to deal with decentral electricity production and intermittent loading according to expert 8. Health impacts derived from transformers entail air pollution in the production phase (Turconi et al., 2014) and the possible but unproven impact of magnetic fields of transformers (GGD Leefomgeving, 2022; TenneT, 2018).

4.2.2.3 Gas transport (transmission and distribution)

Ecological boundaries

The climate change impact of the Dutch gas transportation system depends on the area's urban density (Oliver-Solà et al., 2009) and the leakage of CH_4 (Fu et al., 2021). The urban density of the area determines the quantity of the materials needed. The leakage of CH_4 is determined by the quality of the distribution pipes, which is good in the Netherlands as opposed to some neighbouring countries, according to expert 16. Next to that, "*GHG emissions can be minimised by maximising the amount of biogas that can be fed into the distribution system through increasing the measurements of gas flows and digitalising the gas transportation system*" (expert 16).

Furthermore, constructing and placing gas pipelines can have a considerable impact on land (Fu et al., 2021). Similarly, "*The removal of gas pipelines (in a scenario where the Netherlands is discontinuing the use of natural gas) would also impact the soil"* (expert 16). Also laying pipelines would cause habitat fragmentation and cross valuable ecosystems (MET, 2020). The impact of the gas transportation system on air pollution did not come forward in the literature nor the interviews.

Social boundaries

The gas transportation network facilitates the distribution of gas, which until recently was an affordable energy source. Limiting the leakage of gas is a possible contribution to an affordable energy price. No connection was found between social (in)equalities and the gas transportation system. It requires little effort to make the gas transportation system suitable to transport different kinds of sustainable gaseous energy carriers, like biogas, hydrogen, or methanised hydrogen (expert 16 and 17). So, the Dutch gas transportation system is ready to facilitate the energy transition. Furthermore, health impacts of the gas transportation system are caused by gas leaks which can lead to explosions (Montiel et al., 1996), although there are fewer accidents caused by gas than in electricity grids according to expert 15.

4.2.3 Energy storage

The storage of electricity is an important component in an energy system relying on intermittent energy generation. The following storage possibilities were considered: (Lithium-ion) batteries, power-to-gas (hydrogen and methanised hydrogen), and (aquifer) thermal energy storage.

4.2.3.1 Batteries (lithium-ion)

Ecological boundaries

The climate change impact of lithium-ion batteries (from now on mentioned as batteries) is mainly caused by GHG emissions in the manufacturing phase (Agusdinata et al., 2018; Emilsson & Dahllöf, 2019). Expert 2: "*Lithium-ion battery types mainly contain different types of rare earth metals, which have several negative consequences, such as large emissions of* CO_2". Also, Lithium mining processes cause physical land rearrangements, which can interfere with groundwater carrying soil layers (Wanger, 2011). Furthermore, biodiversity is impacted by the mining processes of Lithium (Gutiérrez et al., 2022; Wanger, 2011). Additionally, in the production process the manufacturing of battery cells, the production of positive electrode paste, and the negative current collector are the main contributors to particulate matter formation, which is one of the causes of air pollution (Ellingsen et al., 2014).

Social Boundaries

According to Expert 2, the Li-ion battery technology is a way of storing energy that has small conversion losses compared to other storage technologies, although the electricity can be stored over a limited timeframe. Due to large-scale electric vehicle applications, batteries became an affordable way to store energy in short periods of time, which is useful in short periods with little energy production. On the other hand, materials required for batteries are increasing in price, becoming less affordable over time, or being replaced by less scarce (and heavier) materials (Expert 2). Similar to the inequality between solar panel owners and households without solar panels, there is also inequality between people who can and cannot afford a battery to use their produced electricity more efficiently. Due to the intermittent nature of renewable electricity production, battery storage in short periods between electricity production can facilitate the transition to greener electricity, while reducing the need to reallocate energy use practices to the availability of electricity. However, due to the short timeframe and limited capacity of batteries, the technology is not suitable for seasonal energy storage (expert 2). Furthermore, batteries can have adverse health effects. Firstly, fires caused by batteries in cars or houses can lead to harm or death (ANV, 2019). Secondly, there are health risks associated with lithium mining from brine, like water availability and pollution (Agusdinata et al., 2018; Wanger, 2011). Thirdly, in the production of other raw materials such as graphite, cobalt, and nickel, there are significant health risks (Thies et al., 2019).

4.2.3.2 Hydrogen

Ecological boundaries

Electricity to hydrogen conversion is paired with significant losses, as shown in Figure 8 (Appendix IV) by Ma et al. (2018), meaning that the impact of the electricity that is lost is also accounted to the produced hydrogen. Concerning the climate change impact, for the production of grey hydrogen, the emissions associated with electricity production dominate the emissions of the construction of the hydrogen alkaline electrolyser, but this is irrelevant in the case of green hydrogen (Koj et al., 2017; Tschiggerl et al., 2018). Therefore, the fuel cell components, stack framework, and balance of power components cause the most GHG emissions during the construction phase (Koj et al., 2017). Land use is not relevant in the case of hydrogen production, as an electrolyser does not require much space and is flexible concerning the site location (Vo et al., 2017). According to expert 4, there are also developments to produce hydrogen at offshore wind turbines, which has no influence on land use. Because there is no extensive land use, the impact on biodiversity is insignificant (Vo et al., 2017). The production of the cell's anode, cathode, and cell frame in the construction phase also impacts air pollution through the emission of particulate matter, although in the case of grey hydrogen the main cause is the electricity source (Koj et al., 2017).

Social boundaries

Compared to batteries, hydrogen production and storage is currently a more affordable green technology to store energy in large quantities over a longer period, according to expert 15. Therefore, the technology is a feasible option to keep electricity affordable in longer periods where there is no production of renewable electricity. Although Dillman & Heinonen (2022) pointed out that hydrogen is subjective to the same price volatility as current oil and gas infrastructures, possibly leading to a false sense of financial security. The possible increase in energy costs will have a larger impact on less wealthy households increasing inequality in the Netherlands (Dillman & Heinonen, 2022). Also, boilers need to be replaced to use 100% hydrogen as an energy source for heat. According to expert 17, hydrogen can facilitate the transition to renewable energy sources, "*Hydrogen is future-proof because, in a certain way, it electrifies the energy system eliminating CO_2 emissions, while using existing gas transportation infrastructures*". Also, society is not yet convinced of the adequacy of hydrogen safety levels (Ingaldi & Klimecka-Tatar, 2020), possibly due to the lower ignition threshold of hydrogen compared to natural gas according to expert 16 (ANV, 2019).

4.2.3.3 Methanised hydrogen

Ecological boundaries

The climate change impact of methanised hydrogen is equal to the combustion of natural gas and requires CO_2, therefore it needs to be combined with carbon capture, utilisation, and storage (CCUS), which requires energy (Reiter & Lindorfer, 2015). Furthermore, the climate change impact of the construction of an electrolyser and methanation unit is relevant for methanised hydrogen (Federici et al., 2022; Tschiggerl et al., 2018). Similar to hydrogen, methanised hydrogen does not have a large impact on land and biodiversity (Vo et al., 2017), although due to extra processes such as CCUS and methanation, the impact is higher than hydrogen. Also, underground storage of methane can lead to leakage of CO_2 which affects ecosystems above ground (Ma et al., 2018). Next to the air pollution impact from the electrolyser construction (Koj et al., 2017), most likely the construction of CCUS, the methanation unit, and combustion of methanised hydrogen also impact air pollution through particulate matter emissions.

Social boundaries

Compared to hydrogen, methanation of hydrogen is a less energy efficient way of storing energy in the long term, as the conversion of hydrogen to methane is less efficient (Figure 8,

Appendix IV), and it requires a combination with CCUS, which also consumes energy (Ma et al., 2018). However, methane does not require modifications at houses and there are large-scale storage possibilities for methane, because "*Current natural gas storage facilities can be used, which allow for a storage of six-month supply*" according to expert 17. The same objections regarding social inequalities apply to methanised hydrogen as for hydrogen, although the magnitude of the effects can be different because of the differences in storage capacities, efficiencies, or utilisation purposes. According to expert 17, methanised hydrogen will support the transition to renewable energy, because "*In the future, there will remain a need for hydrocarbons for types of fuel or medicine, therefore synthesising hydrocarbons from a CO_2-free source like hydrogen is a good alternative*". Concerning the impact of methane storage on human health, escaped CO_2 accumulates to a certain concentration causing suffocation, blowouts, or pollution of drinking water (Ma et al., 2018).

4.2.3.4 Geothermal storage

Ecological boundaries

The climate impact of geothermal storage is determined by the temperature difference between the warm and cold storage (Sommer et al., 2015), due to the difference in additional energy that is needed for further cooling or heating to the desired temperature (Stemmle et al., 2021). Other causes of emissions are the (sub)surface and well construction and decommissioning (Stemmle et al., 2021). Most impacts on land use occur during the operation phase caused by the energy source that is used, also the materials needed for the geothermal storage contribute to land use (Moulopoulos, 2014). Geothermal storage could affect subsurface ecosystems due to long-lasting and reoccurring alterations of groundwater temperature (Griebler et al., 2016). Furthermore, particulate matter is emitted through energy consumption and wastewater treatment (Moulopoulos, 2014).

Social boundaries

According to expert 4, currently, the main barrier to geothermal energy storage is the cost of energy storage. However, expert 13 envisages a future where the costs of these systems will decrease due to scale advantages. Therefore, it is an option to keep energy affordable in the future. Possible inequalities related to thermal energy production also apply to storage, as the location determines the efficiency of geothermal storage. Thermal storage is recognised by various experts (1, 3, 4, and 16) as an essential component of storage in the energy transition. Furthermore, according to expert 4, thermal storage is sometimes necessary for aqua thermal energy production. This prevents water from flowing back to the heat source from being too cold, causing ecosystem disturbances, instead cold water can be stored underground to be used in warmer periods for cooling purposes. Health impacts due to ATES can occur due to the alteration of microbial communities in drinking water sources (Bonte et al., 2011). Also, the preparation of areas for ATES can influence human health (Moulopoulos, 2014; Stemmle et al., 2021).

4.2.4 Energy use

Energy use covers the Dutch direct consumption of energy (electricity, gas, and thermal) by households (16%) and the Dutch indirect consumption of energy through purchases from products fabricated by industries (24%) and agriculture (7%) (IEA, 2019). The direct ecological effects of energy use depend on the source and quantity of energy that is used and the opportunities to produce renewable energy (Omer, 2014). Therefore, the ecological effects depend on the possibilities for users to change the source, the efficiency, or opportunities for renewable energy production and consumption. Furthermore, the ways how energy use affects the social impact categories are summed up.

4.2.4.1 Direct energy use of households

Ecological boundaries

Energy use in households leads to climate change, air pollution, land use, and biodiversity impact in the energy system. Ecological impacts through the quantity of the consumed energy are heavily dependent on the insulation of houses, which can be solved by the renovation of aged houses (expert 14). However, it also depends on urban planning, as the building density and height differences contribute to the energy needed to keep the indoor and outdoor temperatures comfortable (Omer, 2014).

According to expert 6: "*the behavioural aspect of energy use is an important influence on the energy quantity that is consumed, although the possibilities to influence behaviour are limited, as long as there is no differential pricing based on high and low renewable energy production*". Experts 2 and 6 confirmed this by mentioning that financial incentives have influenced the timing of energy use through the price difference between nightly and daily electricity, and negatively priced electricity earlier this year. Also, demonstrating a sufficient quality of life when using less energy is a way to influence behaviour according to expert 14.

Social boundaries

The relation between energy use and affordability of energy is defined by more factors than the height of the energy bill, and the height of their income alone (Mulder et al., 2021). It also depends on the energetic qualities of houses (Mulder et al., 2021) and the extent to which an individual can undertake measures to increase the energetic performance (experts 14 and 6). The energy bill depends on the costs of energy production, transport, and possibly storage. In the future, the costs of energy can become location dependent as efficiencies (of energy production, storage or transport) or possibilities to choose the source of energy (heat networks or hydrogen neighbourhoods) can differ.

Currently, "*The extent to which an individual can act on high energy bills is very low, they can only set the thermostat on 19 degrees (Celsius)*" (expert 6). On the other hand, the lucrativeness of investing in insulation, heat pumps, and solar panels have increased, but as mentioned in the ecological boundaries sections of these renewable energy production technologies, there are barriers to act upon these opportunities.

The income and capital of individuals is also an important factor affecting the severity of energy poverty. Although the extent to which income or capital can be changed is minimal, this can help the inclusion criteria for energy poverty. "*When not considering the capital of a household, there appears to be a lot of energy poverty in wealthy places with large and energy inefficient houses. Because the energy bill is averagely larger in comparison to their income, while this is not causing poverty*" (expert 14).

Regarding inequalities, according to Carley & Konisky (2020) low-income and coloured households are more likely to live in energy inefficient houses, or own energy inefficient appliances which require more energy to heat or cool to adequate conditions. Also, access to low-carbon and efficient technologies accompanying the energy transition (electric or low-carbon vehicles, efficient appliances, and renewable energy technologies) are almost exclusively seized by higher-income households (Carley & Konisky, 2020). Expert 18 confirmed this by pointing out that it is necessary to include ethnic minorities and lower-income households in pilot studies for innovations or policies in the energy sector. A sampling bias can have adverse effects on the uptake of innovations or notice of policies amongst the population. "*Financial aspects of innovation tend to be overlooked if the sample exists of rich people … high complexity of products is also overlooked when the pilot sample exists of higher educated persons … certain cultural habits are not taken into account*" (expert 18).

The relation between energy use and the facilitation of the energy transition has two sides. Firstly, to consume more renewable energy consumers can also take up the role of renewable energy producers themselves. Therefore, the role of renewable energy producer should be promoted amongst different types of households concerning income levels, education levels, cultural groups, and possibly other characteristics. Secondly, current energy consumption patterns and quantities exist because there was energy production at any time of the day (Idenburg & Weijnen, 2018). However, to adapt to the intermittent availability of electricity, a change in energy consumption patterns is required. Various experts (5, 9, and 14) acknowledge the need for a change in consumption patterns as there are limitations to transportation systems and storage possibilities.

Human health can be affected by energy use through unhealthy living conditions due to energy poverty, which can lead to competing needs such as a comfortable in-house temperature and money for food, water and other hygienic products (Jessel et al., 2019). Expert 18 argued that developments like real-time or dynamic energy pricing could force people to only use energy at home when it is inexpensive, which can lead to unhealthy choices and can become challenging when functioning normally in society (e.g., holding a job, raising children). These are important consequences to consider when implementing measures that attempt to steer energy use behaviour.

4.2.4.2 Indirect energy use through consumption: Industries

Ecological boundaries

Climate change and air pollution impacts through the consumption and use of products depend on the energy use that is used to manufacture that product. Important factors are the energy intensity of the manufacturing process and the energy source that is used. As the Netherlands has a large energy-intensive industrial sector due to historically low prices of gas, electrifying industrial processes is a challenge, but it is needed in the energy transition (expert 19). But, according to expert 19, the opportunities to produce the required renewable electricity on industrial sites are limited, as the industrial energy demand is high compared to the limited space suitable for renewable energy. According to experts 13 and 19, non-electrifiable processes can use hydrogen to reach certain temperatures, also methane combined with CCUS would be an option (Vogt et al., 2019). Furthermore, the climate change impacts can be reduced when industrial residual heat is used.

The climate change impact through the product's use phase depends on the energy efficiency of the product itself. Developments in EU regulation on energy performances of electrical appliances have led to more efficient appliances in the European, but also the global market.

Although industrial companies can have significant negative land use and biodiversity impacts, the impacts related to energy use are not apparent from expert observations and literature.

Social boundaries

"*Electrification and use of hydrogen in the industry demand large quantities of renewable electricity, possibly leading to higher competition between sectors*" (Expert 19). Consequences such as increasing renewable electricity prices will have adverse effects on individuals risking energy poverty. The effect of energy use in the industry sector on inequalities depends on the financial competitiveness of Dutch industrial companies running on renewable energy. Lower competitiveness can lead to reduced levels of employment, causing an unequally large burden on employees in the industrial sector (Bijnens et al., 2022). The industrial sector has a large potential for optimising energy use during renewable energy peak production, thereby facilitating a larger share of renewable energy consumption, instead of storage (Nillesen et al., 2021; Torriti et al., 2010). According to expert 19, creating financial incentives is essential to the deployment of this potential, which would have a significant contribution as the industry; is mainly financially motivated, is the largest energy-using sector in the Netherlands, and has relatively energy-intensive processes (IEA, 2019). The impact of industrial energy use on human health depends on the source of energy that is used. Electrification of processes or using hydrogen will reduce the emission of air-polluting substances. However, "*The transition to renewable alternatives, requires transformations in manufacturing processes, potentially leading to unforeseen risks*" (expert 19). These unforeseen risks could affect occupational safety.

4.2.4.3 Indirect energy use through consumption: Agriculture and horticulture

Ecological boundaries

Climate change and air pollution impacts through the consumption of agricultural and horticultural products depend on the energy required for processes necessary for different types of products. According to expert 17, "As *biogas is supply dependent, the most efficient application is to establish a local biogas grid using the current gas infrastructure, limiting the utilisation of biogas to the rural area where it is often produced"*. This is a relevant alternative energy source for agricultural usage compared to current sources of energy such as diesel. Furthermore, the rural possibilities of renewable electricity technologies are promising, as there is a large amount of space and surface suitable for solar and wind energy. Expert 1 pointed out: "*High energy prices and the outlook of CO_2 prices in agriculture provide financial incentives to maximise the production and utilisation of large amounts of renewable energy in the agricultural and horticultural sector"*.

According to expert 1, there are several examples of positive ecological effects of optimising energy use and the production of renewable energy at agricultural and horticultural companies. Firstly, optimising the use of electricity can increase the nutritional value of feed that can be produced for the livestock, reducing the need for importing feed from countries where biodiverse lands are converted to farms. Secondly, adopting more energy-intensive processes to optimise renewable energy use in farms can also allow farmers to internalise the next processing steps in the value chain, which would remove the necessity for intermediate transportation of the products. Thirdly, heat storage and hydrogen storage, are ways to store the surplus of produced electricity when re-allocating energy use is not possible. Lastly, land conversion otherwise caused by solar projects could be prevented when agricultural and horticultural companies employ renewable energy technologies on buildings.

Social boundaries

Maximising renewable energy deployment at farmers would have a positive effect on the affordability of energy as it increases the renewable energy supply. Expert 1 suggests *"Renewable energy production could contribute positively to the inclusion of farmers in society"*. By restoring the image of farmers being the providers of society, the inequalities stemming from operating in a currently underappreciated sector could be alleviated. New practices of farmers concerning maximising energy use, re-allocation of processes, and energy storage could accelerate the energy transition, thereby contributing to intergenerational equality. Current energy use at agricultural or horticultural companies causes emissions of substances with adverse health effects, but this could change with the transition to cleaner energy forms (Ghisellini et al., 2016).

4.3 Pathway towards an energy system within the doughnut economy
In this Section, the future energy system is laid out based on the expectations of experts on various energy system components. This representation of the future energy system would navigate around the present and future ecological and social challenges emerging in their unique perspectives. However, the future energy representations of various experts differ in certain areas, as they depend on divergent assumptions about future barriers and uncertainties in the socio-technical landscape and regime elements, such as markets, technologies, and policies. Therefore, the dependencies of this future energy system are mapped using MLP.

4.3.1 Expectations of future energy system within the doughnut
This section reports the expectations of experts regarding the Dutch energy system fitting within the doughnut economy framework. They are structured in general developments that are expected across multiple energy system components (production, transport, storage, and use) and developments specific to single components of the energy system.

4.3.1.1 General developments
Firstly, across the energy system components, production, transport, storage, and use, there were several common themes, such as circularity. Due to expectations regarding material scarcity (expert 5), experts argue that materials should be used as efficiently as possible, benefitting the reduction of virgin material extraction (experts 19, 10), the extension of the product lifetime (expert 10), and the recyclable design of products (experts 2, 11). Furthermore, due to the expected reduction in fossil resources for plastics, alternatives like biodegradable material will become more apparent (experts 3, 10, 19).

Also, experts agreed that the future energy system will exist of multiple technologies or infrastructures, such as wind/solar technologies, thermal/gas/electricity networks, and short/long-term storage, because of material constraints (expert 9), complementary energy production patterns and different optimal production sites (experts 11, 6, 12).

Cleaner and safer production methods is also a theme occurring across energy system components. There is no insight into social or ecological impacts caused in value chain phases (e.g., mining, manufacturing, and decommissioning) of technologies, such as wind turbines, solar panels, batteries, and transformers. Currently, companies have information about the composition and the origin of the product through the raw material passport, but experts recognise the need for a versatile system containing more quantitative data regarding the ecological and social impacts of a product (experts 5, 9, 3, 10). Also, experts argue that the impacts caused in the value chain can be reduced by policies or certifications demanding gradual improvements in labour conditions and production emissions (experts 9, 15).

4.3.1.2 Energy production
Experts agreed that future energy production will continue to consist of multiple renewable energy technologies, such as wind turbines, solar panels, and heat pumps. Also, biomass-based and nuclear energy were mentioned as potential future energy sources, although with some doubts about whether they would comply with the relevant doughnut boundaries.

Furthermore, the scale and location where solar panels and wind turbines can be deployed are affected by policies regarding the level of energy collaboration in Europe and resistance to renewable energy projects. When there is more international energy collaboration, the Netherlands will mostly deploy wind energy as solar energy is significantly less efficient compared to countries closer to the equator. Also, the Netherlands is a small country with limited space for large-scale energy projects like large wind turbines and solar parks, and community resistance against these projects does occur. The combinatory effect of these two uncertainties will determine to what extent wind turbines can be placed onshore or offshore, and whether solar panels need to be placed on (or integrated with) other surfaces like roofs, facades, or windows. The possibilities for thermal energy systems deployment mainly depend on geographical factors as described in Section 4.2.1.7 about thermal energy impacts.

Biomass as an energy source is associated with various ecological impacts such as land use, biodiversity, and air pollution, which also affects the social boundary of human health. Therefore, experts (19, 11, 14) agree that when doughnut economy boundaries are respected, only local biological waste streams can be used for energy purposes.

The extent to which nuclear energy could fit in the doughnut economy depends on the level of risk impacting ecological (land use/impact, biodiversity) and social (human health) boundaries that is accounted to nuclear technologies through the dangers of nuclear accidents. Nuclear fusion, another form of nuclear energy, is more promising as the energy source of the future, as experts point out the significant benefits regarding risks for accidents and the potential scale of energy production. However, confirmed by experts (12, 11) this technology will probably not contribute to the decarbonisation of the Dutch energy system before 2050 as the technology is not expected to contribute to the energy mix on a sufficient scale (European Commission, 2021).

4.3.1.3 Energy transport

As mentioned in the general developments, experts agree that the Netherlands will depend on multiple transportation systems, respectively for thermal, electric, and gaseous energy. Whereas the possibility and sustainability of a thermal energy network is dependent on a threefold of factors described in Section 4.2.1.7, and a thermal expert (13) stated that where (geo-, aqua-, or residual heat-based) thermal energy is possible and feasible, this will often be the most sustainable source of thermal energy.

The network for gaseous energy is already present, but due to the Netherlands stepping of natural gas as an energy source, according to experts (17, 16), this network is a valuable resource to transport other sources of gaseous energy. The future gas network could be based entirely on hydrogen or hydrocarbon energy form (such as natural gas), by feeding in biogas or/and methanised hydrogen. However, experts (15, 17, 16) see a development towards a separate hydrogen-based infrastructure (hydrogen backbone) next to the hydrocarbon-based infrastructure. In this way, facilitating an area-by-area transition to an emission-free energy carrier based on urgency and lack of alternative energy sources. Therefore, it is most likely that the hydrogen backbone will be designed to facilitate hydrogen use in large industrial users (expert 19) and old city centres with limitations regarding thermal energy networks and insulation of houses (experts 17, 13, 19). Furthermore, one expert (16) argued digitalisation of gas flows is important to efficiently transport gas and prioritise more sustainable gases in the transportation systems

Experts do agree that due to the electrification of fossil-based energy needs, such as temperature regulation and transport, and the increasing intermittency of energy production, electricity distribution/transmission systems and conversion components (transformers) will be strengthened and adapted (experts 9, 1, 8). For TSOs it is increasingly important to ensure a sufficiently strong connection with neighbouring countries, allowing more international energy collaboration (experts 12, 11), although the extent of energy collaboration heavily depends on energy policy developments, as will be discussed in the regime section. On the other hand, due to increasing autonomous electricity production and congestion on the electricity grid, the DSO expects a part of their role to develop into the role of facilitating and designing solutions for energy use, sharing, and balancing, a concept that is termed as an "energy hub" (expert 9). Furthermore, prioritisation of grid connection requests based on the requester's societal relevance is expected to occur more commonly in the future, due to grid congestion (experts 7, 9, 12).

4.3.1.4 Energy storage

Energy storage will become important in the future energy system due to increasing surpluses of renewable energy production, in size and frequency (experts 12, 19, 2). Although one expert (2) argues that due to energy losses in the process, energy storage needs to be minimised, instead energy use can be adapted, or limit renewable energy production on rare occasions. Storage technologies can differ in application scale, timeframe, mobility, and energy form that is stored, therefore experts mention different storage technologies in different situations (experts 1, 2, 3, 6). Due to fast technological developments around sustainable storage technologies on the niche level and the policy developments around international energy collaboration on the regime level, it is uncertain how important energy storage will be, and which technologies will be dominant in a future energy system within the doughnut economy. On the landscape level, geological properties are also a factor determining the possibilities of gaseous and thermal energy storage, as thermal storage depends on the availability of an aquifer, for which exists good conditions in the Netherlands (Fleuchaus et al., 2018; Lu et al., 2019). Concerning the quantity of gas storage depends on current underground gas storage capacities, which differ for hydrogen and hydrocarbon-based gas.

4.3.1.5 Energy use

Experts expect the pricing model for energy will become differential/dynamic/real-time (experts 18, 9, 19, 6), meaning that the time of use will be an important factor in determining the price of energy. This will incentivise individuals to consume energy in times of large supply and/or low demand. One expert (14) shared a prospect where personal CO_2/carbon budgets could regulate individuals in their direct energy use and indirect energy use through the consumption of products.

Due to climate change, increasing insulation in houses, and increasing welfare, future energy use patterns are expected to shift to warmer periods as households in the Netherlands will increasingly demand energy for cooling purposes (experts 6, 14). Although improving the insulation of houses leads to a net reduction in energy use, consequently also reducing vulnerability to energy poverty (expert 14).

Furthermore, experts (7, 13) believe that the energy needs of companies or districts will be increasingly considered in the spatial planning of municipalities and location decision criteria of companies, as the location will partly determine energy production patterns. The location dependency of energy is also a challenge when trying to keep energy prices equal in different areas (experts 18, 13).
In the commercial sector, experts (1, 19) recognise a significant commercial and sustainable potential to act on energy price differences through re-allocation of processes

4.3.2 Multi-level perspective

The transition pathway to the described future energy system regime fitting within the doughnut economy framework is dependent on influencing factors creating barriers and uncertainties in different areas visible on multiple levels. The areas and levels where these factors occur are visualised in Figure 6.

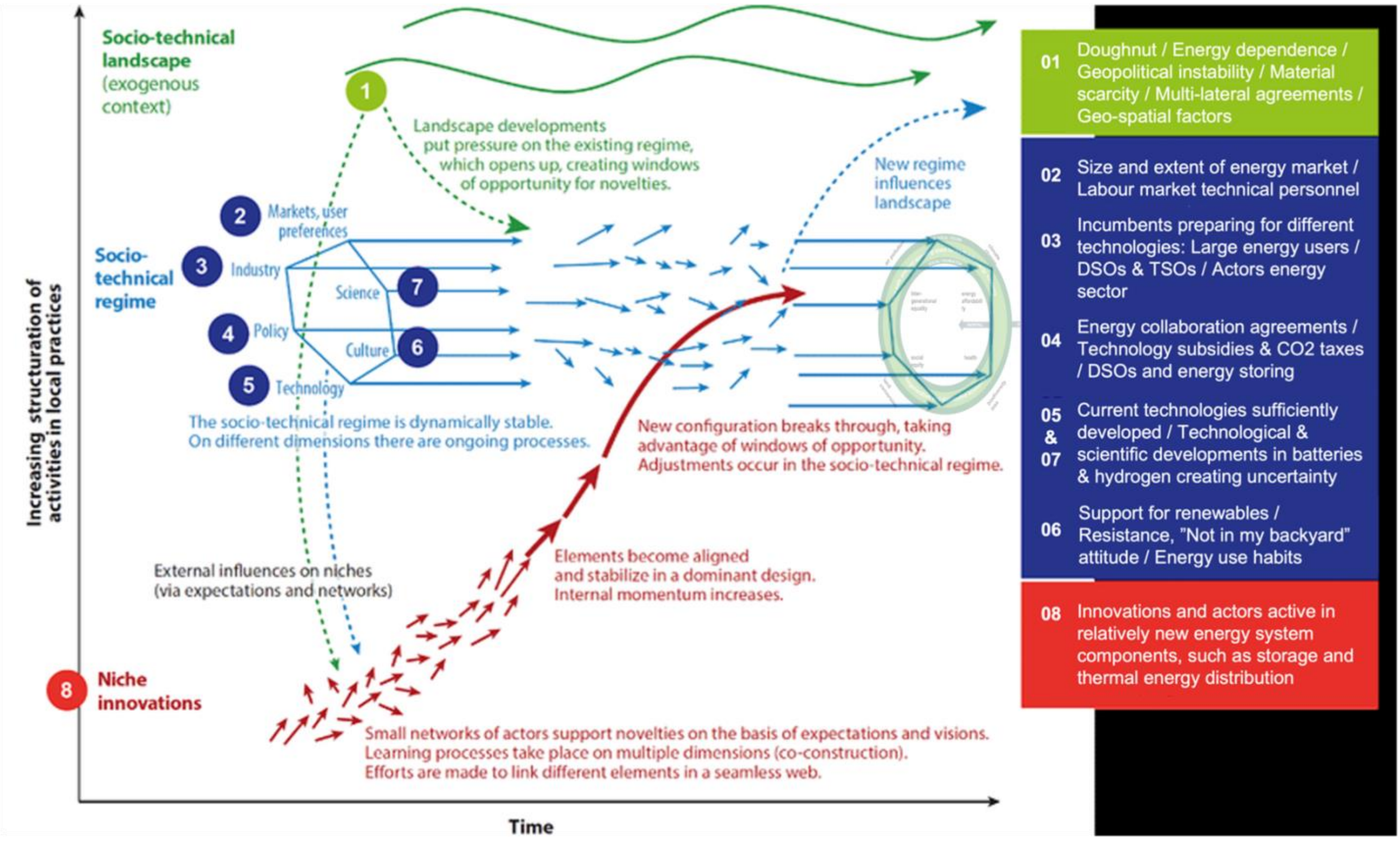

Figure 6 Influencing factors of a safe and just energy transition in the Netherlands (adapted from Geels & Schot (2007) and complemented with the doughnut economy framework (Raworth, 2017)*)*

4.3.2.1 Socio-technical landscape

This section outlines the developments affecting the Dutch energy system falling outside the influential spheres of the actors of the Dutch energy system.

Development of earth system states recognised as biophysical boundaries in the planetary boundaries affect the conditions on earth, which were also acknowledged in the doughnut economy (Raworth, 2017; Rockström et al., 2009). The other side of the doughnut, the social foundation (Raworth, 2017) reflecting the several basic living requirements, comprises the living conditions on earth wherein the energy system operates. The interactions of the relevant ecological and social boundaries of the doughnut with the Dutch energy system are apparent from Section 4.2. Although the energy system does affect the social and ecological boundaries, there are also other systems or factors influencing the ecological and social boundaries. Therefore, the boundaries are exogenous influencing factors of the energy system, the acknowledgement of the energy system's effects on these boundaries, triggers policy, technology, and cultural regime changes

Next to the biophysical and social developments recognised by the doughnut economy, experts recognised other exogenous factors in physical or social form influencing the Dutch energy system. As the Netherlands is a relatively highly populated country, experts (7, 9, 13, 16) experience the scarcity of space as a barrier to the development of large-scale projects. Also, especially for the storage of gaseous energy, there are limitations concerning the quantity of hydrogen that can be stored underground due to the geological properties of the Netherlands (experts 17, 16). Furthermore, the geographical position of the Netherlands is suboptimal for solar or bio-based energy (experts 11, 15). Another highly important physical barrier is the limitations regarding the availability of materials required in the energy system (copper, rare earth metals, and possibly plastics in the future), which is an important driver for circularity and bio-based materials in the energy system.

Secondly, experts recognised social developments interacting with the Dutch energy system apart from the social foundations of the doughnut economy. Half of the experts argued that every change, innovation, or development requires financial incentives or a regulatory force, as the Netherlands is built on capitalist principles, which is a characteristic barrier to sustainable transitions (Elzen et al., 2011). The lack of incentive to act leads to the exhaustion of social and ecological resources (experts 2, 15, 7). Although there are indications of a response in the form of advocation of degrowth and sufficiency motivated by the dangers of violating the social and ecological boundaries of the earth. Furthermore, Dutch society is completely dependent on and used to having access to energy at all moments of the day (experts 7, 9, 12, 3), according to experts (12, 15) this is partly due to the historical abundance of natural gas reserves in the Netherlands (Lintsen et al., 2018). This causes friction in a transition to a future where the current infrastructure is not developed enough to deliver energy continuously, given the intermittency of renewable energy sources. Potentially this leads to a period of societal adjustment to a decrease in energy reliability or large and costly efforts to increase the strength of the grid. Another barrier is the shortage of technically skilled workers (experts 17, 16, 6, 12), required for the transformation of the energy system, which is partly caused by the lack of value the Dutch society attaches to technical competencies (expert 17).

There are also exogenous influences from the (geo-)political arena. Multi-lateral agreements like the Paris agreement consolidate the intentions of countries regarding GHG emission reductions (5), while the EU green deal is more binding, obligating countries to sustainable development in general (experts 12, 6, 8). Furthermore, according to experts (11, 12, 7, 3, 18, 2), the conflict between Russia and Ukraine has extensive geopolitical consequences in terms of energy/material dependencies (between countries), energy/product prices, and energy sources used for electricity production (Rijksoverheid, 2022).

4.3.2.2 Socio-technical regime

The socio-technical regime exists of current circumstances that can be influenced by actors in the Dutch energy system.

Firstly, differences in market expectations lead to different expectations about the renewable energy supply and demand. One expert (6) argues that in the future renewable energy would still be expensive and scarce due to market forces, while others have concerns about the lack of storage possibilities when energy supply exceeds demand, which could lead to misconceptions about how much energy storage is required in the future (experts 15, 6). Also, the unknown market size and geographical scope of the future energy (hydrogen, electricity) market, which is partly dependent on policy, creates uncertainty about the necessary quantity of Dutch energy production and storage, for it is not known if and how much electricity or hydrogen can be purchased abroad (experts 7, 2, 11, 15). The unknown degree of future distribution and transmission system connections creates uncertainties in the market potential of (grid balancing) business models based on storing and selling energy currently on the niche level (experts 2, 16).
Regarding non-energy markets, the landscape-level development towards lower valuation of technical competencies negatively affects the labour market for technical personnel in the energy sector, which slows down the progress of the Dutch energy transition (experts 3, 16, 12, 17, 6).

Secondly, incumbents in the energy system are re-orienting and preparing for a transition towards an energy system based on renewable energy sources, without exactly knowing which technologies will be more important than others (experts 7, 2, 15, 9). Large energy users, DSOs, and TSOs are developing capabilities to transport and use hydrogen (experts 17, 4), while simultaneously preparing and facilitating the electrification of processes (experts 19, 3, 9). This is also the case for agricultural and horticultural energy users, but additionally, there is a large amount of unused renewable energy production potential, and high energy prices create commercial opportunities (expert 1). Also, multiple experts have addressed the fact that a renewable energy system requires storage, which is an activity a DSO or TSO is legally not allowed to do. This creates possibilities for other commercial actors in the energy system to act on (experts 2, 16), e.g. Shell investing in hydrogen and acquiring solar and energy storage companies currently active on the niche level (Shell PLC, 2021, 2022).

Thirdly, the (future) energy sector is dependent on European and national policies, for example, environmental protection regulations regarding renewable energy production technologies (experts 4, 13, 20), how emissions will be taxed (expert 1), and who can transport and store which energy forms (expert 16, 17). Furthermore, political agreements, partly determine to what extent Europe (and other continents) collaborate in terms of energy transport and storage (expert 7, 12). Policy also includes subsidies regarding the adoption and development of new technologies, or energy use adaptation programs (experts 1, 19, 13, 14). Changes in these policies will determine the direction and pace of the Dutch energy transition.

The expectations for the future energy system are also reliant on assumptions about new scientific and technological developments. Most participants believe that the currently available technologies should be sufficient to move to an energy system within the doughnut economy (experts 13, 15, 8). However, experts (4, 2) on storage argue that there are still significant improvements necessary and possible with new technological developments in batteries and hydrogen. Therefore, there is still competition on the niche level of the MLP between various energy storage technologies, such as different types of lithium-ion batteries (expert 2) and different electrolyser technologies (expert 4). The outcomes of these competitions are difficult to predict as it depends heavily on influencing factors appearing in the MLP, such as incumbents, policies, markets, and material availability.

Lastly, cultural values in the Dutch society influencing the energy transition are aggregated under the cultural dimension. Even though the Dutch population generally supports renewable energy (expert 14), resistance against large energy projects still occurs and is defined by a "not in my backyard" attitude. The resistance is caused by the previously mentioned (landscape level) high population density and tradition of negotiating and cooperating despite the opposing views of the participating parties, a concept that is labelled the "Polder model" (Proka et al., 2018). This results in lengthy decision-making processes and extensive policies reducing the social impacts of large-scale solar, or wind projects close to the living space (experts 12, 20). Therefore, wind projects are increasingly often developed offshore (expert 11), and solar projects are often integrated with other purposes (experts 20, 14), with both containing profit-sharing structures (expert 14).
Dynamic/differential/real-time energy pricing can interfere with current energy use habits, stemming from cultural values (expert 18). This interference can lead to resistance to change.

4.3.2.3 Niche

The niche level is largely out of scope as the considered energy system technologies are mostly developed and mature. Although it is important to note that in a relatively new energy system components like storage and thermal energy production and distribution, there are still relevant innovations at the niche level. Therefore, relevant interactions of niche level developments with regime elements are mentioned in the regime section.

5. Discussion

In the discussion the main limitations of this study are mentioned, the theoretical contribution is outlined, and recommendations for future research are highlighted.

5.1 Limitations

Firstly, a comprehensiveness research scope was created by researching all relevant ecological and social impacts of every component in the energy system to provide a complete image of the impacts occurring throughout the entire energy system. Because of the broadness of the scope, potentially not all ecological or social impacts were found in the literature study or interviews. This is also due to the fast developments in multiple parts of the energy sector, as constant technological development can diminish, increase, or cause an impact on other boundaries, while these impacts are possibly not yet academically studied.

Limitations of the narrowness of the scope relate to the thermal energy component of the energy system not being included in the initial scope of the study. However, it was included later due to the substitutability of thermal, gaseous and electric energy (Liu et al., 2021) and expert opinions. This resulted in a lesser focus on the thermal aspects of the energy transition compared to electricity or gas. Future research could focus on all energy forms in the energy system equally. Due to limiting the scope to energy systems, energy required for the transportation system is not considered in the study, therefore developments like bidirectional charging of electric vehicles are outside the research scope. The integration of car batteries in the electricity grid is a promising development, as it could potentially provide grid balancing services. Future research could consider transport in the energy system and find other interdisciplinary synergies e.g., between housing and energy, in the form of building integrated PV panels.

A limitation to the study's geographical scope is that only the energy produced and used in the Netherlands is considered. But the (food) products purchased in the Netherlands are predominantly produced abroad, therefore the impacts related to the energy required for these (food) products (indirect energy use) are not connected to the Netherlands. These impacts are not considered in this study, but future research could consider the energy system impacts from foreign energy use for (food) products.

Concerning the external validity of the study, some of the relevant doughnut boundaries and influential factors that were found are specifically relevant to the Dutch energy system context. Consequently, this leads to a limited external validity making the outcomes of the study less generalizable for other countries and sectors. However, the methodology behind the study could be applied in other countries or sectors to map influential factors in the sustainable transitions.
In this research the coding themes were verified during the coding process to ensure reliable use of codes. Nonetheless, the entire coding process was done by one researcher, so a more objective coding audit using investigator triangulation was not possible under the circumstances. Also, internal validity was optimised by conducting 50 percent of the expert interviews with experts from outside the organisation hosting the research.

5.2 Theoretical contribution

The theoretical contribution of this study is the operationalisation of innovation system theory to map the influencing factors of an energy transition pathway towards a future where other impacts than climate change are considered. Until now, energy transition scenarios and legislation mostly focussed on achieving a decarbonised energy system (European Commission, 2022; International Energy Agency, 2021). To explore the energy transition towards a future where other ecological and social impacts are considered, the multi-level perspective (Geels & Schot, 2007) is combined with the doughnut economy framework (Raworth, 2017). Integrating the relevant doughnut boundaries in the MLP as landscape developments capable of influencing the energy system regime and being influenced by the regime, provides a deeper understanding of how a safe and just operating space for humanity can be achieved through change and innovation.

5.3 Future research

this research provides a starting point for determining an energy transition pathway compliant with relevant ecological and social boundaries of the doughnut economy framework. The qualitative exploration of the socio-technical factors influencing the transition pathway provides reliable and comprehensive data supporting the underlying assumptions of quantitative research. A logical next step would be to quantify the relevant boundaries, impacts, and other influential factors to enable a modelling approach to construct energy transition pathways compliant with the doughnut economy framework. Using the approach of Algunaibet et al. (2019) supplemented with social boundaries and influencing factors like geospatial constraints, a doughnut compliant energy system can be modelled.

Furthermore, this study adopted the multilevel perspective to characterise the numerous barriers and developments that restrict energy transition developments. This resulted in an accurate descriptive representation of the current barriers hindering the transition to a doughnut compliant energy system. The next step is taking a solution-oriented approach by using a mission-oriented innovation system (MIS) by Hekkert et al. (2020) to assess the performance of different functions of the energy transition innovation system. Possible solutions can be based on the function performance analysis.

Lastly, interdisciplinary studies building upon the fields of energy pricing policies (Steg et al., 2006), social impacts of energy use (Idenburg & Weijnen, 2018), and energy conservation abilities (van den Broek, 2019) are needed. It is vital for a future energy system complying with the social boundaries to discover if consumers can be responsibly left to the powers of the energy market regarding time-sensitive energy prices, without risking energy poverty. Consumer energy use practices and possibilities of reallocating these practices need to be researched to assess potential social risks and risk mitigatory solutions.

6. Conclusion

This section answers the research questions by synthesising the most important insights from the results section. In this study, relevant doughnut economy framework boundaries in the Dutch energy system context and impacts by energy system components on these boundaries are identified. These impacts are the basis of expert expectations of a transition pathway towards a future Dutch energy system complying with the doughnut economy boundaries and factors influencing this pathway. This addresses the main research question "*How do socio-technical factors influence the Dutch energy transition towards an energy system complying with the relevant boundaries of the doughnut economy framework?*".

The four relevant ecological boundaries for the Dutch energy system are characterised by energy system impacts through air emissions (**air pollution, climate change**) and physical presence (**land conversion, biodiversity**) of the energy system or its value chain. Relevant social boundaries exist of two boundaries relating to potential **inequalities** caused by the energy system, between groups in the current population and between the current population and future populations. Next to that, the **financial** and **health** consequences of the energy system are considered relevant social boundaries.

Based on the impacts of energy system components on these boundaries, the energy system can only realistically comply with the doughnut economy framework when: Firstly, manufacturing processes of future energy technologies become **safer and cleaner**, and systems are set in place to **analyse the production sustainability** of energy system technologies. Secondly, the system exists of **multiple technologies** due to differences in; production patterns, efficiencies over time, geographically dependent efficiency, material necessities, and cost efficiency, while **regulating the differences in energy prices** caused by the different technologies that are used.

For energy production within the doughnut, renewable energy needs to be **decentralised and integrated in current land use and communities** to prevent resistance. Also, **renewable energy technology adoption** should be fostered throughout all societal layers. Doughnut compliancy requires **utilisation of bio-waste streams** to produce biogas on a limited scale due to space and emission constraints, and **sustainable deployment of thermal energy sources** depending on geographical conditions.

The system will transport energy within doughnut boundaries by **efficient utilisation of current assets and grids**, preventing land and manufacturing impacts. Although **new thermal energy grid development** can be desirable when energy efficiency is improved, a source is available, and there is space, all depending on geographical factors. Phasing out natural gas flows provides possibilities for an **area-by-area transition to a green gas like hydrogen**. The extent to which the **electricity grid requires strengthening** to ensure equitable electricity access depends on energy use reallocation, electrification, gas or thermal grids fulfilling energy needs, and storage capabilities.

Concerning storage, doughnut compliancy leads to the **minimisation of storage** due to the associated inevitable energy losses, instead **lowering or reallocating energy use** is preferred. Energy storage within the doughnut depends on the timeframe, costs, end-use, and size of the storage technology in that specific situation. Although due to **energy losses (and**

emissions) associated with (methanised) hydrogen, the application should be confined to **energy use purposes without other options**.

Concerning the use of energy within the doughnut boundaries, decentralisation of energy production leads to **increased interaction between social boundaries and energy**, due to private investment possibilities, integration in the living environment, and supply dependent energy use and pricing. The extent to which the social boundaries are affected depends on **policy measures** designed to protect the population and redistribute financial resources. For both ecological and social boundaries, it depends on the extent to which **energy use practices can be reallocated** by consumers and companies.

All in all, many different potential landscape pressures determine the energy transition pathway next to the relevant doughnut boundaries. These various pressures can cause friction if the required response on pressures is constrained by other pressures. E.g., material (and consequently energy) scarcity requires coordinated international cooperation to ensure sufficient materials for renewable energy technologies, but geopolitical tensions create a desire for energy and material independency, which inhibits collaboration. Currently anticipations on the landscape pressures (e.g., circularity, biodegradability, and community involvement in renewable energy) by actors in the energy system is not sufficient to navigate the energy transition around the pressures and comply with the doughnut boundaries. Furthermore, the pathway is determined by factors occurring within the regime, such as (cultural) energy use habits, energy policies, energy technology, and -market developments, which can be steered by actors in the energy sector. Through collaboration, energy system actors (and policymakers) can navigate around the landscape pressures while staying within the boundaries, by reconfiguring the energy system regime accordingly.

7. Policy recommendations

Following the conclusions, mainly ecological boundaries, together with the social boundaries of affordable energy and intergenerational equality are relevant for DSOs. This entails minimising the use of (scarce) material, biodiverse land, technical personnel, and financial resources. DSOs attempting to stay within the relevant doughnut boundaries can prepare the electricity grids for a transition towards renewable energy technologies. Simultaneously, there are trade-offs involved in the losses prevented, the increase in renewable energy use caused by grid strengthening, and the impacts associated with the production of the cable.

So, next to grid strengthening, DSOs can anticipate intermittent energy production by developing the capabilities to employ a time-sensitive pricing model to financially incentivise energy use reallocation. However, to comply with the doughnut boundaries a DSO should consider energy affordability and social equity consequences of the time-sensitive pricing model. Furthermore, facilitating the substitutability of electricity with (green) gas or thermal systems can alleviate the pressure from the electricity grid. Furthermore, influencing policies preventing DSOs from storing electricity is required for a DSO to have multiple options for balancing a grid which is increasingly dependent on intermittent energy sources.

Also, optimising mining and manufacturing safety and emissions in the value chain of assets and materials used by a DSO is needed to stay within the boundaries, even though the activities occur outside of the Netherlands. To take decisions based on ecological and social impacts in the value chain, energy system actors like DSOs need systems where ecological and social impact data can be retrieved and analysed.

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Appendices

Appendix I: Interviews

Table 1 Information experts interviews containing the expert identifying code, component expertise, and the employing organisation type.

Expert code	Job title/Expertise	Organisation
1	Researcher of energy use at agricultural companies	University in the Netherlands
2	Consultant energy storage	DSO
3	CSR Advisor	Electricity TSO
4	Consultant thermal energy and hydrogen	DSO
5	CSR Advisor	DSO
6	Advisor energy and sustainable housing	Housing project developer
7	CSR Manager	DSO
8	Specialist transformers	DSO
9	Energy consultant	DSO
10	Sustainability manager	Transformer producer
11	Hydrogen energy consultant with previous experience in biomass, wind, and nuclear energy	DSO
12	Chief CSR officer	Energy producer
13	Consultant thermal energy	DSO
14	Program director socio-economic energy research	Scientific research institute
15	Business developer	Gas TSO & renewable energy data platform
16	Consultant gas distribution	DSO
17	Consultant gas distribution	DSO
18	Program manager specialised in democratically responsible innovations	Scientific institute for applied technology and urban design
19	Researcher of energy use in the industrial sector	University in the Netherlands
20	Developer of large-scale solar projects	Renewable energy producer

Appendix II: Informed consent

INFORMED CONSENT FORM

Utrecht University

for participation in:

Exploring a safe and just operating space for the Dutch energy system

To be completed by the participant:

I confirm that:

- I am satisfied with the received information about the research.
- I have been given opportunity to ask questions about the research and that any questions that have been risen have been answered satisfactorily.
- I had the opportunity to think carefully about participating in the study.
- I will give an honest answer to the questions asked.

I agree that:

- The data to be collected will be obtained and stored for scientific purposes; the collected, completely anonymous, research data can be shared and re-used by scientists to answer other research questions.
- Video and/or audio recordings may also be used for scientific purposes.

I understand that:

- I have the right to withdraw my consent to use the data.
- I have the right to see the research report afterwards.

Name of participant : ___________________________________

Signature: _____________________________________ Date, place: ___ / ___ / ____, ____________

Appendix III: Interview guide

In te vullen voor interview Naam: Kort vooronderzoek: Expertise component: Relevante impact categorieën van dit component: Ecologisch: Sociaal:

Algemeen (10 min.):
Hoe gaat het met u/je?

Checken: Consent, Opname, Transcriptie

Context van interview verduidelijken:
Ik schrijf mijn scriptie voor de studie Sustainable Business and Innovation, bij Qirion energieconsultancy, wat een onderdeel is van Alliander. Tijdens deze scriptie doe ik onderzoek naar hoe het Nederlandse energiesysteem eruit zou moeten/kunnen zien, rekening houdend met de sociaal en ecologische grenzen afgeleid van het donut economie model. *(Eventueel Donut economie model laten zien)*

Heeft u hier nog vragen over?

Expertise vaststellen en gemakkelijke vragen om in te komen (10 min.):
Wat houdt uw werk in?
- Hoe verhoudt dit zich tot het (Nederlandse) energiesysteem? En de energietransitie?

Zijn er onderwerpen gelieerd aan het energiesysteem waarin u op de hoogte bent van de recente ontwikkelingen?
- Zo ja, welke?

Ik heb u genoteerd als iemand die kennis heeft van het component/onderwerp [vul in componenten], Klopt dat?

Innovatie/ontwikkelingen energiesysteem (20 min.):
Denkt u dat er ontwikkelingen/veranderingen nodig zijn in [vul in componenten] in het energiesysteem?

- Zo ja, welke? Op welke gebieden (technisch, beleid, businessmodellen, infrastructuur etc.)?
- Waarom wel of niet?

Kunt u voorbeelden noemen van recente innovaties of ontwikkelingen in [vul in componenten] in het energiesysteem?
- Voorbeelden noemen

Wat zijn de voornaamste doelen/uitkomsten van deze recente ontwikkelingen?
- Gevolgen voor materiaalgebruik, efficiëntie etc.
- In hoeverre is CO_2 uitstoot vermindering een doel van de innovatie?
- Wordt er hierbij ook rekening gehouden met ecologische/milieu impact categorieën naast de uitstoot van broeikasgassen? (Biodiversiteit, land gebruik, fosfor en stikstof uitstoot etc.)
- Op welke manier wordt de sociale/menselijke impact van een innovatie meegenomen? (Gezondheid, ongelijkheid, werkgelegenheid etc.)

Voorbeelden ontwikkelingen:
- Stijgende isolatiewaarden in huizen (efficiëntie)
- Minder lithium nodig in batterijen (materiaalgebruik)
- Progressievere energieprijzen (beleid)
- Creëren van business case voor het opslaan en verkopen van elektriciteit.

Is er sprake van Burden shifting? Gaat verbetering in een bepaalde ecologische of sociale impact categorie ten koste van een andere categorie?
- Waarom wel/niet?

Toekomstige innovaties/ontwikkelingen (20 min.):
In hoeverre kunt u inschatten waar toekomstige ontwikkelingen op gaan focussen?
- Kunt u voorbeelden noemen van ontwikkelingen die naar verwachting belangrijk gaan zijn in de toekomst?
- Wat is uw mening over deze ontwikkelingen? Goed/slecht? Waarom?

Pak Donut economie model erbij
Kijkende naar de sociale ondergrens van het donut economie model, waar zouden ontwikkelingen in [vul in componenten] in het energiesysteem op moeten/kunnen focussen om de positieve impact op deze sociale grenzen te verhogen in Nederland?
- Welke (realistische) ontwikkelingen zouden juist een negatief effect hebben op de sociale/menselijke grenzen?

Kijkende naar de ecologische bovengrens van het donut economie model, waar zouden ontwikkelingen in [vul in componenten] in het energiesysteem op moeten/kunnen focussen om de impact op deze ecologische grenzen te verlagen in Nederland?
- Welke (realistische) ontwikkelingen zouden juist een negatief effect hebben op de ecologische/milieu grenzen?

Appendix IV: Alternatives for natural gas

Figure 7 Alternatives for heating with natural gas (Ramsak, 2020)

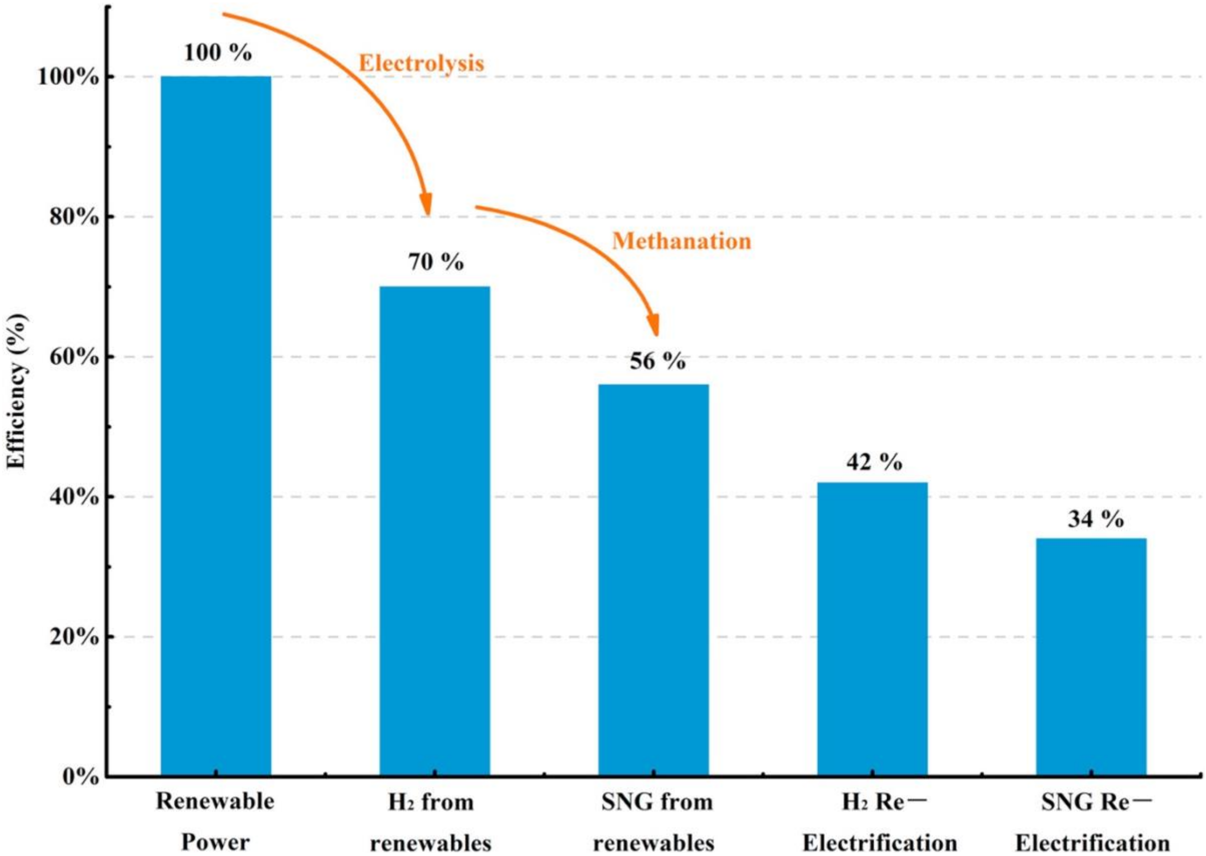

Figure 8 Conversion losses (methanised) hydrogen (Ma et al., 2018)