Phasing out natural gas in the EU

A cost-benefit analysis comparing different timeframes for phase-out

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Abstract

The EU has, in response to the rising climate crisis, Russia's war in Ukraine, and the high price of natural gas, decided to reduce its consumption of natural gas. This decision has initiated more depth in the discussion regarding the energy transition towards renewable energy. The aim of this study is to research, through a cost-benefit analysis (CBA), the economic plausibility of replacing imported natural gas with solar and wind power. Three potential phase-out scenarios, that follow different time frames and intensities, are compared with each other and with a counterfactual scenario. The net present value (NPV), benefit-cost ratios (BCR), and the break-even times (BET) are calculated and compared, to determine when the respective scenario can be economically argued for from a societal point of view. One main finding examining the NPVs and BCRs is that the benefits of the energy transition are price volatile to the price of natural gas. When the price was assumed to be high the ranking always preferred the faster phase-out. Decreasing the costs of renewable energy did not impact the turn-out when the price was high. However, when the price was low, decreasing the costs of renewable energy benefited postponing investments into the future. Further, the BET calculations showed that all scenarios, when the values were based on future projections, had benefits overtake costs before the year 2058. For greater validity and analysis of the full impact of natural gas, future research should extend the study to include both infrastructure and natural gas production.

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List of acronyms

ACER - The EU Agency for the Cooperation of Energy Regulators

BCR - Benefit-cost ratio

BET - Break-Even time

CBA - cost-benefit analysis

CCS - carbon capture and storage

CO_2 - carbon dioxide

ECF - European Climate Foundation

EIA - U.S. Energy Information Administration

GDP - gross domestic product

GHG - greenhouse gas

IPCC - Intergovernmental Panel on Climate Change

IRE - intermittent renewable energy

IRENA - International Renewable Energy Agency

LCOE - levelized cost of energy

NPV - net present value

O&M - operation and maintenance

SCC - social cost of carbon

SDR - social discount rate

1. Introduction

In response to the Paris Agreement, the EU has set the target of net-zero greenhouse gas (GHG) emissions by 2050 (European Commission., n.d.-a). To reach this target, the EU aims to improve energy efficiency, further elaborated in the EU directive *amending Directive 2012/27/EU on energy efficiency* (Directive 2018/2002). The goal is to reduce energy consumption by at least 32.5% and increase the share of renewable energy to at least 32% by 2030, in comparison to the projected energy levels for 2030 calculated in 2007 (Directive 2018/2002; European Commission, n.d.-a; Hafner & Raimondi, 2021). Especially wind and solar power, defined as intermittent renewable energy (IRE), will have an important role in the future energy supply in the EU (Janota et al., 2022).

The Russian war against Ukraine has further elevated the discussion on the EU's import dependence on fossil fuels. One of the most debated imports is natural gas, where Russia accounts for 45% of imports to the EU (European Commission, 2022a). Already before the war, as a result of the cold winter of 2021 and the lifting of Covid-19 restrictions, the price of natural gas increased significantly (Milov, 2022). The war has shaken the structure of the market, and the economic sanctions directed at Russia by the international community, have contributed to a greater increase in global energy prices (European Commission, 2022b; World Economic Forum, 2022). The war has instigated the REPowerEU plan. A plan that aims to make the EU independent from Russian fossil fuels by 2030, by improving the region's response to high energy prices, obtaining a more diverse supply, and refilling the gas storage in the region (European Commission, 2022a).

In the beginning of 2022, the EU introduced the taxonomy, a tool to reach the goals set in the Paris Agreement (European Commission., n.d.-a). In short, it is a classification system for actors to work based on a common definition of sustainability (EU, 2020). In the summer of 2021, the EU decided to include natural gas in the taxonomy, explained in the *Explanatory memorandum amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities,* arguing that the energy sources are critical for the transition to renewable energy (C/2022/0631 final). Even though natural gas is the cleanest fossil fuel, civil society has criticized the decision to include it in the taxonomy with the argument that it counteracts Agenda 2030 and that, instead, the ambition should be to phase-out natural gas before 2035 to reach the climate goals (Climate Action Network, 2021; European Civil Society Gas Manifesto, 2021).

The interest in different alternatives for a phase-out of natural gas has increased. Due to the recency of the taxonomy and the war in Ukraine, very little is currently known about the plausibility of the fast removal of imported natural gas within the EU. This is especially the case when looking at the possibility to replace natural gas with renewable energy rather than other import suppliers or fossil fuel alternatives. Based on a cost-benefit analysis (CBA), evaluating three different timeframes of phase-out, this report aims to contribute to the research gap. The scenarios that we have constructed are unique for this report and will be compared to evaluate which speed of phase-out can be economically argued for from a perspective to maximize social welfare. Furthermore, the time it would take for the social benefits to outweigh the costs will be examined.

This study aims to compare the benefits and costs of a phase-out of imported natural gas by investing in intermittent renewable energy (IRE) in the EU following three different timeframes. The following questions are observed and compared for our three chosen scenarios:

1. "Taxonomy" (S1) initiates a phase-out between 2030 and 2049.
2. "Russian Natural Gas" (S2) initiates a phase-out of Russian imported natural gas between 2023 and 2030 and the remaining imported natural gas between 2031 and 2049.
3. "Pressure from Civil Society" (S3) initiates a phase-out between 2023 and 2035.

Questions

A. Which timeframe of phase-out of imported natural gas in the EU is the most preferred, based on the highest net present value?
B. Do the benefit-cost ratios for the different scenarios validate the results in question A?
C. Will the benefits outweigh the costs until 2049? If not, when?

The method used to answer the question is a CBA constructed based on earlier research and recommendations for the EU by Sartori et al. (2014).

2. Background

2.1 Taxonomy

Since June 2020, the EU's taxonomy has been under development, and in 2022 the EU introduced the first delegated act of the taxonomy (European Commission, 2020). The purpose of the taxonomy is to supply actors such as investors, companies, and nations with a tool to achieve the 2015 Paris Agreement where an array of goals was ratified to enable collective sustainable action for future decades to limit the global temperature increase (Gielen et al., 2019; Janetschek et al., 2019). The taxonomy is a framework that facilitates investors with directives that help determine which activities are sustainable (EU, 2020). In 2021, the EU decided to add natural gas to the taxonomy in a delegated act and classify the energy source as sustainable (C/2022/0631 final). This decision was settled under the criterion that the activities that use natural gas replace the sources with renewable energy sources by the year 2035 (C/2022/0631 final). The inclusion of natural gas as a sustainable investment has been questioned since it does not align with the EU's ambitions to lower GHG emissions and reach the goals set in the Paris Agreement (Climate Action Network, 2021; European Civil Society Gas Manifesto, 2021).

2.2 Consumption of Energy and Natural Gas in the EU

2.2.1 Consumption of natural gas

Of the total supply of energy in 2020, gas accounted for 22.3% (Eurostat, n.d.; Eurostat, 2020). Gas refers to both manufactured gases, which are produced from other fossil fuels, and natural gas. The manufactured gases, however, only account for a small fraction (Eurostat, n.d.; Eurostat, 2020). The EU Agency for the Cooperation of Energy Regulators (ACER) (n.d.), also concludes that gas used in the EU is primarily natural gas, and that about 4% of total gas consumption is low-carbon gases such as biogas. Furthermore, the EU imports about 80-90% of its total gas supply where imports from Russia account for 45% (ACER, n.d.; European Commission, 2022a). This is, however, expected to change because of new initiatives to decrease dependency on Russia after the invasion of Ukraine (European Commission, 2022a).

Gas is used in household consumption, industry, and as a supply for power generation to produce electricity (ACER, n.d.). The dependency on gas in 2020, was greatest in the Netherlands where gas stood for 38.1% of the energy supply, while Malta and Cyprus had 0% of gas dependency (Eurostat, n.d.). In absolute numbers, Germany and Italy are the largest users of natural gas (Eurostat, 2020). The demand for natural gas is clearly unevenly distributed over the EU.

2.2.2 Future demand for energy and natural gas

When estimating future energy needs, several factors need to be considered. Sartori et al. (2014) explain that demographic factors such as population size, economic trends such as growth in the gross domestic product (GDP), climate conditions as well as changes in energy price and energy efficiency development all impact future energy demand. Also, the interaction between these factors makes approximations for the future even more complex. For example, in the EU, the population size is expected to decrease, which motivates a lower energy demand, while the ambitions to increase living standards and work towards growing economies suggest an increase in energy needs (United Nations, 2017; EU, n.d.-a). Furthermore, it will be increasingly hard to predict the need for heating and cooling, given that climate change leads to unusual weather events (Fronzek & Carter, 2007). Furthermore, when the production of a good, such as energy, becomes more efficient it can lead to a decrease in the price (Azevedo, 2014). Depending on the price elasticity, a decrease in the price caused by the efficiency of production or other factors can lead to higher demand for energy (Azevedo, 2014).

One of the EU's main goals related to energy demand is to increase energy efficiency by 32.5%. This goal is based on the projections of energy consumption for the year 2030 made in 2007 (Directive 2018/2002). The goal for the annual decrease in energy sales to final customers is set at 0.8% of the average of 2016, 2017, and 2018. The EU Proposal *for a directive of the European Parliament and the Council on energy efficiency (recast)*, suggests that the annual decrease would be raised to 1.5% (COM (2021) 558 final). The new goal highlights the importance of transparency and information regarding energy savings, as well as the importance of fighting energy poverty for consumers (European Commission, n.d.-b).

The EU's goal for future gas use is to decarbonize the gas market by the European Green Deal where the EU aims to be carbon neutral by 2050 (European Commission, 2021a). This will be achieved by a phase-out of carbonaceous gases, such as natural gas, by replacing them with biogases and hydrogen (ACER, n.d.). Furthermore, the REPowerEU plan focuses on lowering the EU's dependency on Russian natural gas by diversifying gas suppliers and energy mixes which can lead to an acceleration of the phase-out of natural gas in the EU (European Commission, 2022a).

Yet, natural gas is expected to be consumed in small amounts even in 2050. Firstly, this is because natural gas is argued to be an appropriate transition fuel between fossil fuels and RE, because it is more energy-rich, has lower levels of pollutants, and is a more efficient source of energy compared to other fossil fuels (Gürsan & de Gooyert, 2021; Leichenko & O'Brien, 2019). Natural gas, a gas that primarily consists of methane, releases half the level of carbon dioxide (CO_2) emissions compared to the combustion of coal and is, therefore, one of the cleanest fossil fuels (Bradshaw & Boersma, 2020). However, because it primarily consists of methane, a gas with 34 times stronger warming potential over 100 years compared to CO_2, the transportation of natural gas needs to be secured to prevent leakage of uncombusted natural gas (Bradshaw & Boersma, 2020; Marks, 2022). A second reason to continue the consumption of natural gas is that RE is more volatile in production compared to natural gas (Bertsch et al., 2016). Therefore, there is a need for a small amount of natural gas consumption to cover peak usage and create flexibility in the system (Bertsch et al., 2016). To compensate for the GHG emissions caused by this natural gas consumption, improvement of other technologies such as carbon capture and storage (CCS) is needed (Bertsch et al., 2016).

For this study, we have assumed a 0.8% and 1.5% annual decrease in energy demand, the goals of the EU Directive 2018/2002. Therefore, we have not incorporated the factors mentioned previously, such as population growth, into the method. The argument for this is based on the fact that the aim of decreasing energy consumption is targeted toward increasing efficiency within end-use sectors such as buildings and transport, and the EU Commission does not mention that these goals are to be affected by, or adapted to, other factors influencing energy demand (European Commission, n.d.-b). Furthermore, the EU has goals to decrease the use of fossil gases, even if the total energy demand would increase (ACER, n.d.). Therefore, it came across as redundant and highly theoretical to include a version where the demand for natural gas would have a long-term trend of increasing until 2050 and this alternative was, therefore, excluded.

2.3 Investments for the energy transition

The transition towards a European Union that primarily uses intermittent renewable energy (IRE), is discussed in academia and the EU has highlighted the need to encourage investments into renewable energy to reach the goal of 32% RE by 2030. Creutzig et al. (2014) find that if Europe collaborates to increase investments in IRE it will not only mitigate climate change impacts but also create economic growth, decrease the negative balance of trade, and potentially have a decisive impact on employment opportunities. As recently as 2019, investment in capacity building for RE was around 54.6 billion USD in Europe (United Nations Environment Programme et al., 2020). Creutzig et al. (2014) highlight the importance of the EU in making sure that not only the more well-off countries in the region have the capabilities to transition to clean energy, but also those in the periphery, especially highlighting the inclusion of Southern European countries. Currently, the European Commission (n.d.-c) is implementing the “EU renewable energy financing mechanism” (further referred to as “financing mechanism”) as a response to the fact that different member states have different capacities to enable the transition to RE. The mechanism is based on contributing countries giving financial aid to host countries where the RE projects are carried out (European Commission, n.d.-c). It is a tool that helps weaker nations with RE investments, whilst making sure that RE is installed in places most suitable for generating energy, ultimately increasing efficiency within the production of energy (European Commission, n.d.-c).

The energy transition also requires a significant number of investments to develop the energy infrastructure and techniques for transportation and storage of RE, on both the national and regional levels (Polzin & Sanders, 2020). Earlier research by the International Energy Agency (IEA) (2021, p.21-22), can give an indication of the scope of investments that should be allocated to infrastructure, such as developing the energy grid. In their research, 4 trillion USD is to be invested in energy annually, on a global scale, from 2020 to 2050, where investments in infrastructure totals about 0.8 trillion USD. This indicates that the cost for building RE capacity would increase by 25% if infrastructure where to be included. Furthermore, there are methods that can reduce the necessary investments for a transition to a RE-based energy system (Cerniauskas et al., 2020). An example of additional investments for the energy transition, is the production of hydrogen from RE since this transition enables the storage of RE (Bastien & Handler, 2006). Cerniauskas et al. (2020) perform a cost assessment of the natural gas pipeline system in Germany and conclude that the transmission costs for hydrogen can be significantly reduced if the pipelines that are used to transport natural gas today, are reused to transport hydrogen.

The speed of the energy transition will rely on the development of IRE capacity through reduced costs of solar photovoltaics and wind power (Gielen et al., 2019). The cost of wind power is expected to fall by 37-49% by 2050 which will affect the investments needed to produce RE (Wiser et al., 2021). Wiser et al. (2021) look at the levelized cost of energy (LCOE), which is the total cost per unit of energy produced during the lifespan of the powerplant. LCOE, therefore, includes installation costs, cost of operation and maintenance (O&M), and fuel costs averaged and time discounted over the production capacity and lifespan of the project. The authors conclude that cost reductions in all components of LCOE will contribute to lowering the total costs. International Renewable Energy Agency (IRENA) (2021) makes the same conclusion and extends it to include solar power. Wiser et al. (2021) attribute previous changes in LCOE costs to technological innovations, industry maturity, higher competitiveness in the market, and other factors such as changes in the prices of input materials. Industry maturity includes factors such as production at a larger scale, decreases in risks, and increases in industrialization (Wiser et al., 2021).

2.4 Energy prices

The price volatility of natural gas has become noticeable in the current climate where many consumers have received higher energy bills (Saefong, 2022). The rapid price increase is the result of several factors, one being the upheaval of Covid-19 restrictions that meant an elevated energy demand (Milov, 2022). The winter of 2021-22 came with very cold weather, causing an increased energy demand, as well as bringing about an understanding that the EU’s natural gas storage has been reduced (Alvarez & Molnar, 2021; Milov, 2022). Temperature, storage, and supply shocks can influence price changes of natural gas when looking at it from a short-term perspective, while the long-term price of natural gas is heavily reliant on the price of other fossil fuels, through substitution effects (Nick & Thoenes, 2014). For the European market, Bradshaw and Boersma (2020, p. 88), however, contradict this conclusion by explaining that the EU prices are set by the supply and demand of natural gas and not by other fossil fuels.

Investments directed at the research and development of fossil fuels should be limited, and instead, public support should be directed at encouraging patents for RE innovation and technology (Noailly and Smeets, 2021). Noailly and Smeets (2021) explain that firms active within innovation for RE are more sensitive to financial shocks in contrast to firms within fossil fuel innovation. They assign this difference to the market failures and lack of trustworthy public support for RE commitments (Noailly and Smeets, 2021). By lowering the risks involved in RE investments, the investments would be able to act as insulation toward future price increases of natural gas (Gielen et al., 2022). The study by Berry (2005) explains how increased wind energy can act as a hedge against high natural gas prices because wind power is an energy source with a more stable price. The general conclusion is that the price volatility of RE is lower than that of natural gas (Gielen et al., 2022). However, it can vary depending on factors such as the geographic market (Rintamäki et al., 2017).

2.5 Delimitations

To specify the scope of our research, we have chosen to look at the EU as a whole, to give a valuable analysis. The energy market within the EU is highly interconnected, creating difficulties if one were to look at one or several countries independently (Curds & O'Riordan, n.d.). Adding to this, the cross-border flow of energy in the EU makes it complicated to identify where production and investments are to happen (Chen et al., 2020).

Our second limitation is that we intend to calculate the costs and benefits of phasing out natural gas imports, by replacing them with IRE. The calculation will be performed on the production of IRE and the consumption of imported natural gas. Therefore, the study will not include the infrastructure element or natural gas production including the installation of new infrastructure or the O&M costs for existing natural gas pipelines or energy grid. The reasoning behind this is that including infrastructure would notably complicate the calculations, and involve a considerable increase in variables, the article by Kiss et al. (2016) demonstrates the extent. Groth and Scholtens (2016) is an example of a study that also chooses not to include the cost of infrastructure, to simplify their calculations. Further, Stern (2020) explains how the development of the infrastructure system would need to evolve rapidly and include, for example, CCS technology, to ensure future interest in natural gas investment. Investments in infrastructure, CCS, or alternative RE technologies have not been included in this report in order to narrow down the scope and focus on the identified research gap. However, to give an indication of how the cost of infrastructure could affect our results, a limited calculation, when the costs per year are increased by 25%, based on the approximation by IEA (2021), is presented and discussed.

Another delimitation is that the study is only performed on imported natural gas, which can be explained by the fact that the EU imports up to 90% of total natural gas (European Commission, 2022a). Including domestic production would elevate the data collection with various variables connected to the producing process and, therefore, the domestic production of natural gas is not incorporated. Research also shows that some natural gas consumption is needed in the EU, to cover the volatility of RE supply, and it is reasonable to assume that the 10% of domestic production can cover the peaks in energy demand (Bertsch et al., 2016). By restricting the scope to imported natural gas, the infrastructure element of domestic natural gas production could also be discarded.

Further, the study will constrain the investments in RE to only look at solar and wind power, the IRE sources. Creutzig et al. (2014) explain that Europe's energy transition is reliant on these two sources as they are expected to be the largest sources of renewable energy in the future. This is in comparison to biomass, hydropower, and geothermal energy, which do not have the same capacity strength (Creutzig et al., 2014). Heide et al., (2010) continue to explain how solar and wind power can constitute the optimal mix when looking at Europe as a whole because North Europe has more potential regarding wind power, whilst solar power has a larger capacity of production in Southern Europe. Leichenko and O'Brien (2019) further disclose the complementarity of solar and wind, as solar produces more energy during the day and wind produces more energy during the evening and nighttime. Heide et al. (2010) propose that wind constitutes 55% and solar 45% of the total energy mix and these percentages will be the basis of one scenario. The opposite composition of 65% solar and 35% wind power will also be examined in light of the reasoning put forth by the European Climate Foundation (ECF) in *Roadmap 2050: a practical guide to a prosperous, low-carbon Europe* (from now referred to as Roadmap 2050) (ECF, 2010, p.51). The Roadmap 2050 is a plan for the EU, containing concrete policy suggestions and sectoral objectives to reach the goal of climate neutrality by 2050 (EFC, 2010).

3. Theory

3.1 Cost-Benefit Analysis

The method used in this report is a cost-benefit analysis (CBA), a tool that measures and compares efficiency, as well as determines how to economically manage resources (Boardman et al., 2014). CBA can, for example, be used before analyzing different alternative projects to help in decision making, or after analysis of similar projects to evaluate if a certain type of project is worthwhile. By constructing a CBA the present net benefit for different projects can be calculated and compared (Boardman et al., 2014). In general, projects with a positive net benefit should be implemented. This conclusion is based on the Kaldor-Hicks criterion, which defines a successful project as one where the losers can be compensated by those who gain, whilst those who gain are still better off than before (Boardman et al., 2014). A plausible conclusion is that the project with the highest net benefit has the greatest possibility to compensate the losers in the project (Boardman et al., 2014). The net present value, which is used as an indicator to answer our first research question, is the sum of the net benefits for all years included in the analysis (Sartori et al. (2014). A social discount rate (SDR) has been used to calculate the sums into present values. Sartori et al. (2014) describe different indicators for CBA evaluations and make a distinction between economic and financial net present value. For this report, we will only focus on the economic net present value (further on written as NPV), which has “the social planner” perspective when determining the costs and benefits in society (Sartori et al. (2014).

The method of CBA also depends on the idea of opportunity costs, where the act of choosing one alternative means other alternatives are excluded (Boardman et al., 2014). If the alternative uses more expensive resources, the result is either higher costs or lower benefits. For example, to continue burning fossil fuels will lead to costs connected to CO_2 emissions. By choosing a RE-dominated alternative, less CO_2 is emitted, which implies that the costs of emissions decrease. These avoided costs are defined as an opportunity cost that becomes a benefit in the alternative project where emissions decrease. To be able to compare alternatives, a counterfactual scenario, accounting for the opportunity costs, needs to be determined. The counterfactual scenario establishes a reference scenario where everything is kept the same as today. (Boardman et al., 2014) Our counterfactual scenario is described in 4.2.1.

Boardman et al. (2014) clarify that CBA can be a powerful tool for decision-making and evaluation of projects, but that there are some shortcomings. For example, losses and gains need to be translated into monetary values, a difficult and subjective process. It can also be difficult to objectively assign a monetary value to, for example, lives lost or environmental assets that are impossible to restore (Boardman et al., 2014). Inclusion of ethics, for example related to the distribution of costs and benefits between different stakeholders, adds complexity to the model (Boardman et al., 2014). Furthermore, even if CBA focuses on maximizing net benefits so that the winners can compensate the losers, it is not guaranteed that any transaction takes place. If no one ensures this compensation, this concept stays theoretical. Lastly, the result of the CBA can vary significantly depending on the SDR, introducing further complications which are described in 3.2 (Boardman et al., 2014).

3.2 Social discount rate

The general idea with the social discount rate (SDR) is that having access to money now is considered more valuable than having access to money in the future (Sartori et al., 2014). Boardman et al. (2014) explain that it is a concept that reflects the opportunity cost of the investments done today that could have been used for other projects or investments. The higher the SDR the less weight is given to the future and with a discount rate of 0 the future is equally valued as today (Boardman et al., 2014).

The choice of SDR is contested in academia because it involves deciding on a particular value that represents the relation between the present and the future (Fleurbaey et al., 2018; Marten & Newbold, 2012). Discounting is especially difficult to do over long periods (Mooij et al., 2012). Fleurbaey and Zuber (2015) show that the general formula for the discount rate is dependent on inequalities, growth rates, and risk in consumption and return to investments. They highlight that when constructing a SDR, it is important to consider equality within generations, between generations as well as the distribution of costs and benefits between different groups in a population (Fleurbaey & Zuber, 2015).

For this report, the risk regarding the existence of a future population is of significant interest since the continued usage of fossil fuels can have disastrous effects on living conditions in the future. Fleurbaey and Zuber (2015) explain that this is the risk regarding future fatal events, also called catastrophic risk, a rather new concept in academic research. Fleurbaey and Zuber (2015) present Weitzman as influential with the much-discussed “dismal theorem”, explaining that if there is a risk for fatal events or catastrophes then a lot of weight should be given to the future. If there are any present-day investments that can prevent these risks they should be made (Fleurbaey & Zuber, 2015).

To summarize, several different factors influence the SDR. Aspects of inequality, risk, economic growth, and timeframe of interest can contribute to and interact in the calculations for SDR. For CBA in the EU a higher discount rate (5%) is recommended for countries that are in a catch-up phase because it is considered more important to invest in today's population to give them a good life and reduce inequality (Sartori et al., 2014). Richer countries can have a lower discount rate (3%) and afford to value the welfare of future populations higher (Sartori et al., 2014).

3.3 Social cost of carbon

The social cost of carbon (SCC) included in our model, measures the negative externalities of greenhouse gas (GHG) emissions (Fleurbaey et al., 2018). According to Hope and Newbery (2006), it is a strategy to capture the discounted social cost of emitting an extra tonne of carbon, in this study, from burning natural gas. This contrasts with the “private cost” which only reflects the economic cost of producing, for example, fossil fuels (Fleurbaey et al., 2018). The damage caused by GHG emissions is a contemporary example of a market failure, as the impacts of climate change are not sufficiently paid for and, therefore, become a negative externality (Newbery et al., 2019). A negative externality is when the cost of production or consumption is not paid for by a third party, such as the environment and/or future generations. Examples of negative externalities are biodiversity loss, loss in crop yield, and worsened human health, both physical and mental (Centemeri, 2009; Leichenko & O'Brien, 2019).

Performing SCC calculations are complex due to the impact that chosen scientific, economic, and ethical assumptions have on the resulting SCC value (Brouwer et al., 2008; Hope & Newbery, 2006). The assumptions include the chosen SDR, the distribution of costs and benefits between richer and poorer countries, as well as between individuals, and the correction for risk aversion (Hope & Newbery, 2006; Newbery et al., 2019). There is also profound uncertainty regarding when and where future climate effects will happen, and what future generations will consider valuable (Hope & Newbery, 2006). The choice of SDR has a significant impact on the SCC because the chosen SDR gives more or less weight to future generations, who to some extent, will bear the cost of the damage from GHG emissions. This relates to the impact of the equality aspects on SDR described in 3.2. Using an SDR of 0.1% to calculate SCC, decided on through equity weighting, leads to an SCC of 85 USD/tCO_2 (Hope & Newbery, 2006). An SDR of 5-6%, based on the market interest rates, adopts a lower SCC value of 8 USD/tCO_2 (Fleurbaey et al., 2018).

The report by the Carbon Pricing Leadership Coalition (CPLC) (2017) supported by the World Bank Group among others, concludes, as has Intergovernmental Panel on Climate Change (IPCC) (2014), that the SCC used in academia often significantly undervalues the social costs and damages caused by GHG emissions. For example, irreversible tipping points for natural systems and singular large-scale events are often underestimated (CPLC, 2017). The CPLC approach determines a price on emissions based on today's economic situation, that would influence today's markets enough to reach the goals of the Paris Agreement. The prices given are 40-80 USD/tCO_2 until 2020 and 50-100 USD/tCO_2 until 2030 (CPLC, 2017). In contrast to the SCC, this pricing does not account for the externalities connected to the CO_2emissions but instead uses carbon prices as a market tool to reach environmental goals (CPLC, 2017).

4. Scenarios

In this section the reference scenario and the three alternative scenarios are described and compared.

4.1 Counterfactual scenario

The counterfactual scenario is a scenario that is necessary to define to be able to compare the alternative scenarios. In this study, the reference scenario assumes that imports of natural gas in the EU continue at the same level as today. This contrasts with the EU's ambitious targets for phasing out fossil fuels, indicating that this scenario is not probable (Gielen et al., 2019; Hafner & Raimondi, 2021). In more detail, this assumption also means that the use of natural gas is assumed to not increase. This is an assumption drawn from the fact that, to our knowledge, there are no stated long-term targets in the EU to invest in increasing natural gas imports (ACER, n.d.). Even though the reference scenario does not reflect the EU's goals it has value as it displays the development within the energy sector if investments would continue as today. It is a reference that makes it possible to compare and conclude results from the alternative scenarios (Sartori et al., 2014). Additionally, the opportunity cost can be discussed from the base scenario.

4.2 The three alternative scenarios

For all three scenarios, the following assumptions apply:

- The amount of natural gas being phased out is replaced by solar and wind power.
- The production of renewable energy takes place within the EU and no energy needs to be imported into the EU to cover for the phase-out of natural gas.
- The phase-out of natural gas is assumed to be linear over the period of active phase-out.
- The amount of imported natural gas equals 14 893 416.78 TJ per year and is based on an average of the recent ten years where data is available (2011-2020) (see Appendix 1, Table 1).
- Costs are given in real prices in USD with 2020 as the base year.

- The additional carbon dioxide (CO_2) emissions of intermittent renewable energy (IRE) installation are excluded. They are assumed to be a one-time occurrence that would be approximately similar between the three scenarios and that would, therefore, have a low impact on the ranking of the timeframes.

Diagram 1

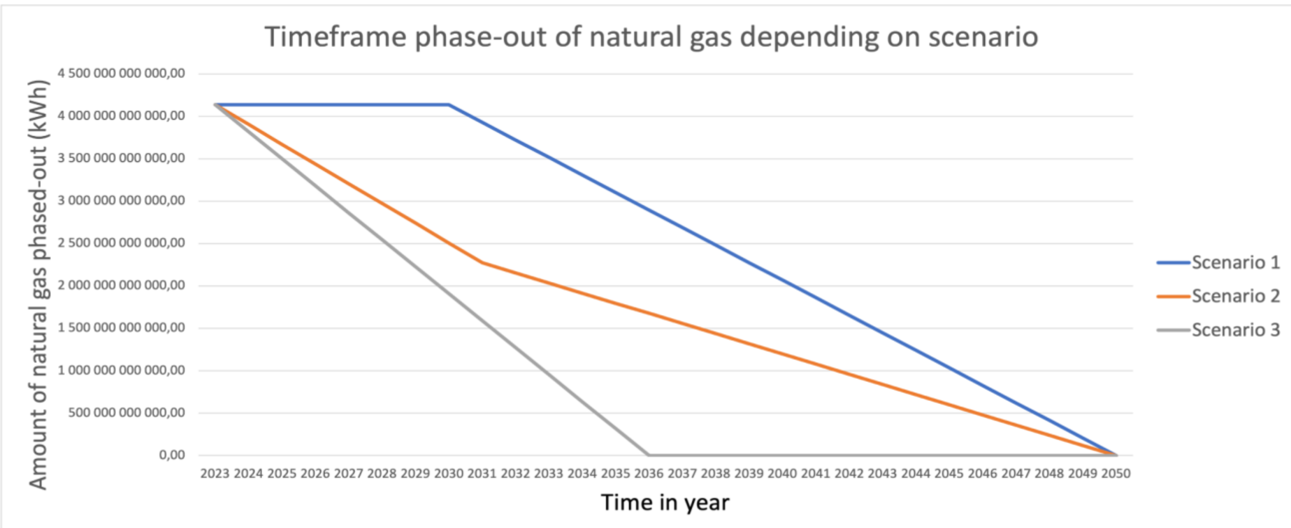

Diagram 1 illustrates the timeline for the phase-out of natural gas for scenarios 1, 2, and 3 for the period 2023 to 2050. Total phase-out of 14 893 416.78 TJ yearly consumption.

4.2.1 Scenario 1 - Taxonomy

This scenario illustrates the path that the EU, given today's efforts, is headed. In 2022, it was decided that natural gas should be included in the taxonomy, provided that activities involving natural gas must phase-out natural gas out of their operations from 31 December 2030 to 2035 at the latest (C/2022/0631 final). The remaining activities that are not part of the taxonomy still have to adapt to the EU's other goal of not extending natural gas contracts beyond 2049 (European Commission, 2021b). Scenario 1 simplifies these decisions into a scenario where natural gas is phased out between 2030 and 2049. There is still the possibility that some companies choose to start phasing out natural gas before 2030, but the scenario is based on the idea that the regulations will have the biggest impact on phasing out natural gas imports within the EU during the period 2030 to 2050.

4.2.2 Scenario 2 - Phasing out Russian imports as soon as possible

Given the new security situation in the world, REPowerEU, a new incentive from the EU, has been suggested to reduce dependence on imports of fossil fuels, in particular natural gas, from Russia before 2030 (European Commission, 2022a). Russia accounts for 45% of gas imports into the EU today (European Commission, 2022a). Phasing out these imports as soon as possible is also interesting from an environmental perspective since it accelerates the phase-out of natural gas, leading to lowering emissions. More specifically, scenario 2 means that 45% of the imports, accounting for imports from Russia, is phased out from 2023 until 2030 and replaced with renewable energy. The remaining amount of imported natural gas will be phased out between 2031 and 2050 following the EU's target policies and regulations in the taxonomy.

4.2.3 Scenario 3 - Pressure from civil society

The final scenario is based on a letter signed by 20 environmental organizations, WWF and Greenpeace amongst others, calling for natural gas to be completely phased out of the EU by 2035 to tackle the climate crisis (Climate Action Network, 2021; European Civil Society Gas Manifesto, 2021). This scenario is also in line with the report released recently by the IPCC (2021), which highlights the urgency of the climate crisis, by asserting that emissions must be reduced from 2025 to reach the goals set in the Paris Agreement (Cooper & White, 2022). In sum, this scenario means that imported natural gas would be phased out of the EU from now, starting in 2023, until the end of 2035.

5. Method

The chosen method of cost-benefit analysis (CBA) is performed by comparing costs and benefits between the counterfactual scenario and the three alternative scenarios. The process for the analysis follows the steps presented in the "European Guide to CBA" by Sartori et al., (2014). The method section is divided into 5.1 which displays the formulas used in this study, 5.2 which explains the details and assumptions taken, and 5.3 which describes the installation and operation and maintenance (O&M) cost for renewable energy (variables v and a), and 5.4 which presents a table with the variables and the corresponding values used in this study.

Three variables are calculated to compare the different scenarios: the Net Present Value (NPV), the Break-Even Time (BET), and the Benefit-cost ratio (BCR). The NPV is the difference between the benefits and costs of the given scenario in present value. BET is a time measurement when the NPV is set to zero for the scenarios and the BCR is the ratio between the costs and benefits of each scenario. The NPV and the BCR are advised by Sartori et al. (2014) to compare different values while the BET is used to determine when (in years) a project is seen as beneficial.

5.1 Formulas

5.1.1 General formulas

For NPV, BET, and BCR the costs (*C*) and benefits (*B*) must be calculated. The difference is referred to as the net benefit (NB). The NPV is calculated using NB.

$$NB_t = B_t - C_t \qquad NPV = \sum \frac{NB_t}{(1+r)^t}$$

Where *t* is the number of years, *t*=0 is 2022 and *r* is the social discount rate (SDR).

The same formula is used to calculate BET, however, here the value of NPV is set to 0 and the variable of interest is the time *t* in years from 2022.

$$0 < \sum \frac{NB_t}{(1+r)^{BET}}$$

To calculate the BCR the following formula is used where the present value of benefits is divided by the present value of costs:

$$BCR = \frac{\Sigma \frac{B_t}{(1+r)^t}}{\Sigma \frac{C_t}{(1+r)^t}}$$

5.1.2 Formulas for Costs

The costs for year t include the installation cost for the renewable energy where future energy demand and technological improvements have been accounted for:

$$C_t = RES_t + OM_t$$

RES_t is the installation cost for renewable energy in year t and OM is the O&M for the accumulated amount of renewable energy installed until year t. It is calculated through

$$RES_t = \frac{ng_t}{8766} * (c - t * v)$$

ng_t is the amount of natural gas energy in kWh phased out in the year t. Dividing by 8766, which is the number of hours per year, will convert the amount from kWh to kW. c represents the cost per kW installed capacity and v is the decrease in installation cost of renewable energy per year in kW.

$$ng_t = ng_b - (t * d)$$

d is the decrease in energy consumption per year and ng_b is the amount of phase-out of natural gas per year in kWh. This is the amount of natural gas that is phased out given that the imports would not be affected by changes in energy demand. It is calculated by dividing the total annual import of natural gas by the number of years of active phase-out for each scenario. ng_t equals zero for S1 between 2023 and 2029 when the phase-out process has not started. Similarly, ng_t equals zero for S3 after 2036 when the phase-out is complete. For S2 there are two different ng_b, one for the period 2023 to 2030 when 45% of the imports are phased out and another ng_b for the time 2031 to 2049 when the remaining 55% is phased out.

$$OM_t = OM_{t-1} + om_t$$

The OM_t function contains OM_{t-1} which is the O&M cost for the amount of renewable energy installed until the year before beginning with t=1 for 2023, and om_t which is the additional cost of O&M caused by the new renewable energy installments taking place during the year *t*. om_t is calculated through

$$om_t = ng_t * (k - t * a)$$

ng_t and *d* are the same as for calculating *RES*. *k* is the cost of O&M per energy unit for the year 2022. *t* represents time in years where *t*=0 is 2022 and *a* is the decrease in O&M costs per year for newly installed renewable energy.

In an additional calculation, the total costs for each year, C_t, is increased with 25% to simulate the extra costs connected to infrastructure. NPV is calculated using this increased cost as well.

5.1.3 Formulas for Benefits

The benefits for year *t* will be:

$$B_t = I_t + E_t$$

I is the opportunity cost of imported natural gas. *E* is the social cost of carbon dioxide emissions reduction.

$$I_t = NG_t * P_t$$

NG_t is the total amount of natural gas in kWh that has been phased out until year *t* and *P* is the price of imported natural gas for the year *t*.

$$NG_t = NG_{t-1} + ng_t$$

NG_{t-1} is the total amount of natural gas phased out the year before and ng_t is the same as in the *RES* formula.

$$P_t = \frac{p + t * q}{293{,}1}$$

Where *p* is the price of natural gas for the year 2022 and *q* is the predicted price change of natural gas per year in 2020 USD per MMBtu. The division with 293.1 is used to recalculate the values to USD per kWh since 1 MMbtu equals 293.1 kWh (Bradshaw & Boersma, 2020).

$$E_t = CO_{2,t} * SCC$$

SCC is the social cost of carbon dioxide.

$$CO_{2,t} = NG_t * M$$

M is the amount of carbon dioxide per kWh of energy produced from natural gas. The $CO_{2,t}$ is the saved amount of carbon dioxide (CO_2) emissions for year *t*.

5.2 Details and assumptions

The formulas presented above compose the scope of our study. The following section aims to explain the details, assumptions, and context in which they are used.

5.2.1 Precautionary strategy

To manage the risk of uncertainty regarding the energy sector's future development, in terms of, for example, prices and energy use, the principle of taking the highest projected costs and the lowest predicted benefits will be used. Handling risk and future uncertainties through this approach is suggested by Sartori et al. (2014) and we choose to refer to this as the *precautionary strategy*. The strategy impacts the model in the sense that it will slightly overvalue costs and undervalue benefits so that the net benefit sums up at the lower range of its true value. There is still a risk connected to the uncertainties with the values used but to further overvalue costs and undervalued benefits might lead to unrealistic values and possibly useless results (Sartori et al., 2014). Therefore, the approximations of values are based on earlier research and data and are balanced between following the precautionary strategy while still being realistic.

5.2.2 Costs

When calculating costs for the different scenarios, costs for initial investment and O&M costs are included. The most recent data on RE price is from 2020 and, therefore, assumed to be the same for the year 2022.

Investment cost

Investment costs are based on today's estimates to build energy stations for wind and solar power. Two versions of this estimate are used. First, the solar-based, following predictions made by the ECF (2010) in the Roadmap 2050, is applied (details can be found in Appendix 1 Table 12). In this scenario, 80% of total energy consumption is supplied by intermittent renewable energy (IRE) where the division is solar power at 65.2% and wind power at 34.8% (EFC, 2010, p. 51). The second version, the wind-based, follows the predictions made by Heide et al. (2010) who calculate the future energy supply to be met by 45% solar and 55% wind within the EU. For both versions, the makeup of onshore and offshore wind is determined by the distribution in the Roadmap 2050 scenario, where the onshore wind makes up 56.3% and offshore wind makes up 43.7% of total wind production (see Appendix 1 Table 11) (ECF, 2010).

The installation cost for the different IRE techniques is based on the estimated global average calculated by IRENA (2021). These values were set at 1355 USD/kW for onshore wind, 3185 USD/kW for offshore wind, and 883 USD/kW for solar power in 2020 (see Appendix 1 Table 13).

Operation and maintenance costs

The global average cost of intermittent renewable energy in 2020 was estimated at 0.020 USD/kWh for onshore wind, 0.030 USD/kWh for offshore wind, and for PV solar 0.002 USD/kWh (IRENA, 2021) (see Appendix 1 Table 13).

5.2.3 Benefits

The calculations of benefits of the different projections are done by calculating the costs of the counterfactual scenario. The opportunity costs include the cost of importing natural gas and the social cost of CO_2 emissions that the use of natural gas entails. This requires values on the imported amount of natural gas, the price of natural gas, and the social cost of carbon.

Price of natural gas

For prices (*p*) and price changes (*q*), estimates from the World Bank and the U.S Energy Information Administration (EIA) have been used. The spot price of natural gas can vary depending on the exact gas market and geographic location. In this study, the market price of natural gas relates to the European market when possible and when there is no prediction for the European market the calculations are based on global market prices. The World Bank finds the price to be 12.60 USD/MMBtu in 2022 which is a large increase from 2020 years price values of 3.24 USD/MMBtu (Gusev, 2022). In sum, there is immense uncertainty about the future price of natural gas and, therefore, we decide to look at both a high price of 12.60 USD that decreases with time and a low price of 3.24 USD that increases with time.

The World Bank estimates that the price of natural gas will decrease from 12.60 USD/MMBtu to 6.50 USD/MMBtu between the years 2021 and 2035 and this decrease has been used to estimate a price decrease connected to the high price of 12.60 USD (see Appendix 1 Table 14) (Gusev, 2022). Since the World Bank has no estimation of price increases going from low prices, the projections by EIA are used instead. EIA estimates the global price of natural gas to increase from 2.68 USD/MMBtu at the beginning of 2022 to 4.86 USD/MMBtu in 2035 and 7.54 $/MMBtu in 2050 (Gusev, 2022). Based on this estimation the annual price increase in relation to the lower price of 3.24 USD is approximated (see Appendix 1 Table 14). The data available is not updated to include the possible effects that the Russian invasion of Ukraine may entail.

The social cost of carbon

The conclusion drawn by the CPLC and IPCC is that the SCC value is hard to define and often underestimated (CPLC, 2017). Previous research indicates SCC values between 8 and 85 USD/tCO_2 which we have as a base for the approximated SCC (Fleurbaey et al., 2018). The CPLC and IPCC on the other hand use market-based prices equaling the cost of carbon between 40 and 100 dollars per ton of CO_2 (CPLC, 2017). From these two objectives, we have chosen a wider range than 8 and 85 and set the value of SCC to 0, 50, and 100 USD per ton of CO_2. To clarify, in this report we set the price as a social cost and not as a market price of emissions. CO_2 is calculated by using the conversion rate of 56.1 kg CO_2e/TJ (Krey et al., 2014). This number is translated to the amount of CO_2 per kWh which in our formula is the variable *M*. The full calculations can be found in Appendix 1 Table 3-5.

5.2.4 Installation and operation & maintenance costs for renewable energy

For installation and O&M costs for renewable energy, the long-term prospect is that the cost over time will decrease per produced energy unit. However, changes in costs are volatile between years (Bertsch et al., 2016). Because of this, it is hard to make predictions for changes in installation (*v*) and O&M (*a*) costs for renewable energy. To handle this uncertainty alternative values for *v* and *a* have been estimated based on available data regarding changes in the levelized cost of energy (LCOE) for the period 2011-2020. On average, the LCOE for the IRE technologies has decreased by about 64% over the ten-year period (IRENA, 2021). By applying this proportion to the current average cost of installation and O&M cost and dividing it by ten to have the change per year the values *v*=33.35 USD/kW and *a*=0,00028 USD/kWh is given (see Appendix 1 Table 16-17). This is merely an approximation of cost decreases per year within IRE costs and is not used to give predictions about future costs. Instead, it is a tool to simulate reasonable cost reductions based on recent trends to see what effects it has on the results. Following our precautionary strategy, we also include an option where the costs of installing renewable energy do not change, *v*=0 and *a*=0.

5.2.5 Future energy use

The "European Guide to CBA" addresses that future energy use has a significant impact on the outcome of an energy sector CBA (Sartori et al., 2014). As mentioned in 2.3.2, future energy demand depends on many factors and is, therefore, difficult to calculate. The option of future energy needs will be limited to three options. The first two options follow the EU's objective for energy efficiency where a 0.8% decrease is in force today and a 1.5% decrease has been proposed, both based on the average consumption 2016-2018 (COM (2021) 558 final; Directive 2018/2002). In this report, these goals for energy savings are assumed to be proportional to all energy sectors, including the import of natural gas and demand for renewable energy, and are extended until 2050. 0.8% and 1.5% decrease will be used to estimate the impact of varying levels of energy demand reductions in variable *d*. The third option is based on the precautionary strategy where *d*=0, meaning that the need for energy does not change over time.

5.2.6 Social Discount Rate

To calculate the NPV and BCR, a SDR of 3% and 5% will be used based on EU recommendations (Sartori et al., 2014, p. 55).

5.3 Variables

Table 1

Variables	**Values**	**Source**
Social discount rate (r)	3% and 5%	Sartori et al. (2014)
Installation cost renewable energy (c)	Solar based: 883 USD/kW Wind based: 2154.71 USD/kW	IRENA (2021). Appendix 1 Table 13
Decrease in installation cost of renewable energy (v)	0 and 33.35276 USD/kW	IRENA (2021). Appendix 1 Table 17
Decrease in energy demand (d)	0% and 0.8% and 1.5% of the annual average energy consumption (year 2016-2018)	Eurostat (2011-2020). Appendix 1 Table 7-9
Natural gas phase-out per year (ng in kW)	See Appendix 1 Table 3-5	Eurostat (2011-2020).
Natural gas phase-out per year (ng in kg CO2)	See Appendix 1 Table 3-5	Eurostat (2011-2020).
Cost of O&M per unit energy per year (k)	Solar based: 0.002 USD/kWh Wind based: 0.0244 USD/kWh	IRENA (2021). Appendix 1 Table 13
Decrease in O&M costs per year for newly installed renewable energy (a)	0 and 0.00028 USD/kWh	IRENA (2021). Appendix 1 Table 17
Price of natural gas year 2022 (p)	12.60 and 3.24 USD/MMbtu	Gusev (2022)

Price change per year (q)	-0.218 and 0.1683 USD/MMbtu	Gusev (2022). Appendix 1 Table 15
Social cost of carbon (SCC)	0, 50 and 100 USD/tCO_2	CPLC (2017) and Fleurbaey et al. (2018)

Table 1 lists all the variables and their corresponding letters. The specific values that recur through the report are found in the middle column and in the right column, the sources can be found.

6. Results & Analysis

The results that follow compare the net present value (NPV) and benefit-cost ratio (BCR) between the three scenarios to reach a conclusion on which is ranked 1st, 2nd, or 3rd place, demonstrating also how the ranking changes when the variables included change. The results have been color-coded with orange shades for solar-dominated combinations and blue shades for wind-dominated combinations. Table 2 is an exception from this, where the whole table is color-coded in blue and represents both solar and wind-dominated combinations. The more preferable a scenario is the lighter the color. The reasoning behind the exposition is that the comparison is primarily between three different timeframes, and the exact absolute values are only indications of the amount that is needed for this study. However, to give an idea of the range of values for NPV and BCR, the highest and lowest values for each intermittent renewable energy (IRE) mix are presented in Appendix 2 in Tables 1 and 2. The NPV takes values between 844 billion and -25 billion USD for the high price of natural gas and 212 billion and -157 billion USD for the low price.

The results are structured accordingly, 6.1 describes the NPV ranking for the high price, 6.2 gives detail about the results when a low price was assumed, and the impact of changing IRE costs. The results continue with 6.3 and 6.4 which describe the BCR and the break-even time (BET) respectively. Lastly, in 6.5, calculations that include infrastructure and the relationship between total costs and the social cost of carbon (SCC) are presented.

6.1 High price

Following the World Bank's projection of 12.60 USD/MMBtu with a price reduction of 0.218, scenario 3 (S3) ranks highest, scenario 2 (S2) second highest, and scenario 1 (S1) is the least preferred option. This can be seen in Table 2 and was the result of both NPV and BCR calculations. The ranking remains the same under all combinations when our chosen variables of change in IRE costs (*v* and *a*) were changed. This trend also holds when the social discount rate (SDR) is changed from 3% to 5%, when SCC is changed between 0, 50, and 100, when the energy demand is unchanged and decreased by both 0.8% and 1.5%, and when looking at the solar-based and wind-based alternatives. The precautionary strategy implies that costs are given the highest estimates and benefits are given the lowest estimates. The strategy means no change in IRE costs, *a*=0 and *v*=0, and no change in energy demand, *d*=0. When the precautionary strategy is applied for a high price the results are not affected and S3 continues to be the highest-ranked. An extension of Table 2 can be found in Appendix 2 Tables 3-10.

Table 2

Price 12,60 $/MMBtu		**Scenario 1**	**Scenario 2**	**Scenario 3**
for SDR 3% and 5%				
SCC 0, 50 and 100	d=0	3	2	1
	d=0,8%	3	2	1
	d=1,5%	3	2	1

Table 2 ranks the scenarios between 1st and 3rd place when the initial price (in 2022) is 12.60 $/MMBtu for both solar and wind-based mixes. Social discount rate (SDR) was changed between 3% and 5%, and social cost of carbon (SCC) was changed between 0, 50, and 100, and energy demand (d) took the values 0, 0.8%, and 1.5%. The extended version can be found in Appendix 2 Tables 3 to 10.

6.2 Low price

Table 3 illustrates the ranking between the three scenarios based on NPV where a lower price of 3.24 USD/MMBtu is used. In comparison to the results in Table 2, the combination of the other variables has an impact on the results. Particularly the chosen SDR, the combination of wind and solar power, and the decrease in energy demand and IRE costs gave varying outcomes in the results. However, the change in SCC did not have an impact on the ranking of scenarios. Table 3 is extended for different SCC values in Appendix 2 Tables 11-14.

Table 3

Price 3,24 $/MMBtu		S1	S2	S3	S1	S2	S3
SDR		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
3%	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	1	2
5%	d=0	2	3	1	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 3 demonstrates the ranking between scenarios 1, 2, and 3 from the NPV calculations. The upper section has a social discount rate (SDR) of 3% and the lower section has an SDR of 5%. The solar-dominated combinations are in the middle of the table and wind-dominated combinations are on the right. Change in energy demand (d) takes the values 0%, 0.8%, and 1.5%. Installation costs and operation and maintenance cost for renewable energy (v and a) are assumed to be zero in Table 3.

Table 3 shows the rankings for a low price when there are no changes in IRE costs. To begin with, the upper left section of Table 3 where SDR is 3% and the mix of IRE is dominated by solar power shows a clear preference for S3, followed by S2 and then S1. The opposite relationship between the scenarios (1, 2, 3) is the outcome when the SDR is 5% and wind dominates the IRE mix, as seen in the lower right section of Table 3. Looking at d=0 in Table 3 the result when the precautionary strategy is applied can be seen. This result indicates which scenario is preferred when weight is given to risk aversion in the method since the precautionary strategy is a way to handle uncertainty and risk with approximations of future values. When the strategy is applied the results show that S3 is the most preferred for solar-based options and wind-based options with a SDR of 3% while S1 is the highest ranked for wind-based options when the SDR is 5%.

The ranking of the scenarios changes, in comparison to Table 3, when IRE costs are changed, both separately and together. The combinations where both installation (v) and operation and maintenance (a) costs change are shown in Tables 4 and 5 indicated by changing from $v0$ and $a0$ to $v1$ and $a1$. Table 4 has SDR 3%, and Table 5 has SDR 5%. A decrease in installation costs means *v* equals 33.353 USD/kW (referred to as *v1* in the tables) and a decrease in operation and maintenance (O&M) costs means *a* equals 0.00028 USD/kWh (referred to *a1* in the tables). A change in only O&M costs (*a)* gives a marginal benefit to S3 for some versions of changes in energy demand (*d*) while a change in only installation costs (*v)* benefits S1. For full results see Appendix 2 Tables 9-12.

Table 4

Variables	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
v0, a0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	1	2
v1, a1	d=0	2	3	1	2	3	1
	d=0,8%	3	2	1	1	3	2
	d=1,5%	3	2	1	1	2	3

Table 4 features the ranking of scenarios 1 through 3 when the social discount rate is 3% from the NPV calculations. In the upper section, both the installation cost of renewable energy and the operation and maintenance cost of renewable energy is zero (v0 and a0). In the lower section, both installation cost and operation and maintenance costs are changed to equal 33.35276 USD/kW and 0.00028 USD/kWh respectively.

Table 5

Variables	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
v0, a0	d=0	2	3	1	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
v1, a1	d=0	1	3	2	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 5 features the ranking of scenarios 1 through 3 when the social discount rate is 5% from the NPV calculations. In the upper section, both the installation cost of renewable energy and the operation and maintenance cost of renewable energy is zero (v0 and a0). In the lower section, both installation cost and operation and maintenance costs are changed to equal 33.35276 USD/kW and 0.00028 USD/kWh respectively.

When both variables *v* and *a* are changed the impact of changing installation costs outweighs the impacts of changes in O&M costs and the general effect is that S1 is benefited and takes a higher ranking, compared to when both variables equal zero. The change in ranking for SDR 3% demonstrates this as S1 goes from being the lowest-ranked to the highest-ranked for wind-based when *d*=0.8% and *d*=1.5%, and from third to second place for *d*=0%. There is also a small change in the solar-based mix for SDR 3% when *d*=0%, where S1 goes from third place to second place. In SDR 5% the ranking corresponds to the solar-based mix where S1 goes from second place to first place when *d*=0%. An important note here is that S1 was already ranked first for most cases in SDR 5%, which was not the case for SDR 3%.

6.2.1 Change in energy demand

The results are in general consequent of the different values of change in energy demand (d). Since this variable affects both the cost and benefit side in the model and there is no clear result showing that the model is more sensitive for just higher or lower changes in energy demand, a general trend for d is hard to clarify. Because of this, together with the fact that changes in future energy demand are uncertain and that the general trend for the other variables over different d is solid, we chose to exclude a more detailed analysis of the result connected to changes in d.

6.3 Benefit-cost ratio for low price

The calculations of the benefit-cost ratio (BCR) summarized in Tables 6 and 7 demonstrate the relationship between the three scenarios. Only the combination where *a0* together with *v0* and *a1* together with *v1,* is used. This combination shows decreases in installation and O&M costs together since the effect of changing *v* and *a* has the same directional impact on the BCR value (see Appendix 2 Tables 15-18).

Table 6

Variables	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
v0, a0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
v1, a1	d=0	1	2	3	1	3	2
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 6 features the ranking of scenarios 1 through 3 when the social discount rate is 3% from the BCR calculations. In the upper section, both the installation cost of renewable energy and the operation and maintenance cost of renewable energy is zero (v0 and a0). In the lower section, both installation cost and operation and maintenance costs are changed to equal 33.35276 USD/kW and 0.00028 USD/kWh respectively.

Table 7

Variables	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
v0, a0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
v1, a1	d=0	1	2	3	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 7 features the ranking of scenarios 1 through 3 when the social discount rate is 5% from the BCR calculations. In the upper section, both the installation cost of renewable energy and the operation and maintenance cost of renewable energy is zero (v0 and a0). In the lower section, both installation cost and operation and maintenance costs are changed to equal 33.35276 USD/kW and 0.00028 USD/kWh respectively.

The results from the BCR in comparison to NPV do not show as much variation and the return to costs for the different scenarios are similar within different energy mixes. The BCR shows that for the higher price, S1 being ranked the lowest and S3 being ranked the highest, holds no matter how the other variables change. However, for low prices when the price increases, the results show that when the cost of IRE decreases (*a1* and *v1*) the ranking of scenarios changes, so that S1 becomes the highest-ranked and S3 in most cases becomes the lowest-ranked. For BCR, in contrast to the results for NPV, both *a1* and *v1* result in S1 being more preferred where changes in installation costs have the biggest effect. The effects are especially clear for SDR 5% but apply to SDR 3% too. The only versions that stand out are for wind-based mix 3% where S3 is the second-ranked and S2 is the lowest-ranked for *d*=0%.

6.4 Break-Even Time

For the Break-Even Time (BET) the calculations are limited so that the variables for change in IRE costs (*v* and *a*) and change in energy demand (*d*) are set to zero, in accordance with the precautionary strategy where prices of installing IRE will not decrease. This limitation is because we have approximated the values for the variables to be reasonable until 2049 according to the EU's goal of net-zero greenhouse gas (GHG) emissions by 2050, and, therefore, they might be misleading after 2049. The same might be true for the value of price change (*q*), which is why both *q*=0 and values where the prices increase or decrease, are shown in Table 8.

Table 8

BET					
SDR = 3%	**Initial Price**		**3,24**		**12,6**
	Price change (q)	**0**	**0,168333**	**0**	**-0,218**
S1	Solar based	>2100	2052	2038	2044
	Wind based	>2100	2054	2040	2050
S2	Solar based	>2100	2050	2031	2032
	Wind based	>2100	2053	2032	2034
S3	Solar based	>2100	2048	2031	2033
	Wind based	>2100	2052	2033	2036
SDR = 5%	**Initial Price**		**3,24**		**12,6**
	Price change (q)	**0**	**0,168333**	**0**	**-0,218**
S1	Solar based	>2100	2054	2038	2045
	Wind based	>2100	2057	2040	2052
S2	Solar based	>2100	2054	2031	2032
	Wind based	>2100	2058	2033	2035
S3	Solar based	>2100	2053	2031	2033
	Wind based	>2100	2058	2033	2036

Table 8 shows the break-even time (BET) when benefits outweigh costs for all three scenarios, the social discount rate (SDR) of 3%, and 5%, for solar and wind-based energy mixes, initial prices, and with or without price changes.

For a high initial price of 12.60 USD/MMBtu for natural gas, almost all scenarios had a BET before 2049, and the benefits outweigh the costs during the project time. The only two BETs over 2049 were for the first scenario with a wind-based mix when there was a price reduction over time. The BET was in 2050 when SDR was 3%, and in 2052 when SDR was 5%. The BET, when a lower price of 3.24 USD/MMBtu was assumed, no price increase, none of the scenarios, no matter the SDR, paid back before the year 2100. However, when the price increase was introduced, the BETs decreased. For the solar-based mix, S3 took the value 2048 and for the rest of the scenarios, all BETs had a value of 2050 to 2058. This indicates that all scenarios would have a positive NPV within a decade after the time scope of the study. The results of BET show that SCC does not have an impact, see the next section for further results on the importance of SCC in the calculations.

6.5 Infrastructure and SCC

In this study, the cost of energy infrastructures, such as the cost of the energy grid and natural gas pipelines, has been excluded to limit the scope. To strengthen our result, we have performed additional calculations that consider how the infrastructure could impact our research where the costs for each year, C_t, have been increased by 25%. The increase of 25% is based on the approximation by IEA (2021), which report that out of the 4 trillion USD that is to be invested annually, on a global scale, 0.8 trillion USD should be invested in infrastructure. The additional NPV calculations are not the focus of our research and, therefore, they were limited to when the precautionary strategy was applied and when the SCC was set to zero so that costs took the maximal value and benefit took the minimum value. The results show that the additional cost does not impact the results for a high price of 12.60 USD/MMBtu as the results show the orders S3, S2, and S1, the identical order as the one presented in Appendix 2 Table 3. For the low price of 3.24 USD/MMBtu, S1 was the most preferred, and S3 was the least preferred for all combinations of variables except one. In comparison to our previous results, presented in Table 3, the inclusion of infrastructure costs gives a higher ranking for S1, even for the lower SDR. The full result can be seen in Appendix 2 Table 19. The results indicate that including infrastructure costs would benefit S1 where the phase-out of natural gas is postponed into the future.

Overall, the results have shown that the SCC does not impact the order of the ranking and this relationship is further examined. The total social cost of carbon per year is compared to the total benefits each year. In this calculation, the SCC took the highest applied value of 100 USD/tCO_2 and the cost of importing natural gas was set to the lowest value of 3.24 USD/MMBtu. The result shows that when natural gas is phased out for the scenarios, the SCC only accounts for at most about 0.2% of total benefits per year. The full result is shown in Appendix 2 Table 20.

7. Discussion

In 7.1 the findings related to high price, low price, changes in installation and operation and maintenance (O&M) costs, energy demand, and the impact of the social cost of carbon (SCC) will be elaborated on and discussed. We aim to answer which timeframe of phase-out of imported natural gas in the EU that can be economically argued for, both from calculation of net present value of benefits and from benefit-cost ratios. Our third question related to when the benefits outweigh the costs is also analyzed. 7.2 elaborates on the strengths and weaknesses of our study, 7.3 discusses ethical elements and 7.4 concludes with ideas for future research.

7.1 Main findings

The main findings, presented in the following section, show that a high present price of natural gas prefers a fast phase-out based on both net present value (NPV) and benefit-cost ratio (BCR). For the low price, there is more variation, where a higher social discount rate (SDR) will prefer postponing investments to the future, while a lower SDR will prefer a faster phase-out. Another main conclusion is that changes in installation and O&M costs can have a slightly varying impact on the results. The general conclusion, however, is that decreases in intermittent renewable energy (IRE) costs make it increasingly worthwhile to postpone investments further into the future, given that the price of natural gas is low. Further, the results show that SCC does not impact the preference for fast or slow phase-out. For realistic assumptions regarding prices of natural gas, the BET shows that all scenarios have benefits exceeding costs until 2058.

7.1.1 Price level

A key finding when observing the NPV and BCR rankings is that the model shows high price sensitivity since the result is very much dependent on the price of natural gas. The sensitivity is visible in that when the price is high and decreasing, the preferred phase-out is the one where all imported natural gas is phased out until 2035, while for the lower price of natural gas the result depends on the other factors included in the model. The clear preference for early phase-out, when the price is high, can be explained by the fact that the cost of importing natural gas does not continue for the same amount of years as for a slower phase-out. For lower prices of natural gas, the cost that a long period with imports would entail is not as significant as for high prices. This means that the preferred phase-out, with a low price, is more dependent on other factors affecting costs. The absolute values also signal that the price of natural gas will have a significant impact as the NPV amounts to 844 billion dollars when calculating p=12.60, whilst the lower price adds up to 211 billion dollars (see Appendix 2 Table 1 and 2). To put these values into context 844 billion dollars is 5% of the EU's GDP year 2019 (EU, n.d.-b).

Of the two price scenarios, the higher price corresponds more directly to the current market situation because it incorporates the shock of the cold winter in 2021, the aftermath of Covid-19, and the lack of storage in Europe (Milov, 2022). The war between Russia and Ukraine has further elevated this price increase (Alvarez & Molnar, 2021). As seen in Table 2 the high price indicates a preference for a fast phase-out. Since the assumption of the high price from the World Bank incorporates the recent events, the higher price can be argued to be a more realistic estimate for future prices than the lower price estimates set by EIA that does not include the price shock.

The high price of natural gas indicates high price volatility resulting in greater uncertainty and risk for actors such as investors (Bertsch et al., 2016). Investments in RE are not prone to the same level of uncertainty and risk because the expected future price is more stable (Berry, 2005; Gielen et al., 2019). Therefore, transitioning towards renewable energy would involve lowering the price volatility and risks within the energy supply overall. On the other hand, research by Noailly and Smeets (2021) has shown that the risks with investments in renewable energy are higher than for fossil fuels. This risk is, however, more connected to the system and policies in place, rather than price changes, and could be handled by a stronger commitment from the public sector to RE and by changing policies and regulations within the EU (Noailly & Smeets, 2021).

The precautionary strategy has been applied throughout our method as an approach to handle risk and uncertainty regarding approximations of future values of the variables by the recommendations by Sartori et al. (2014). Also, this strategy has shown to be sensitive to price changes, since the results did not change within higher prices of natural gas faster phase-out was continuously the best alternative. However, when looking at low prices, even with the precautionary strategy taking the highest estimates on costs and the lowest of benefits, showed that faster phase-out was the best alternative for SDR 3%. It was only when future investments were given less weight with SDR 5% that the precautionary strategy preferred a slower phase-out. When prioritizing risk aversion it can be argued that the best alternative is to phase-out natural gas as fast as possible. This conclusion is given from the fact that the price volatility of natural gas is greater than for RE and that when uncertainty was accounted for in our method, by the precautionary strategy, faster phase-out had the highest NPV and BCR in the majority of cases.

7.1.2 Changing IRE costs and energy demand

The general result when changing the installation and O&M costs for IRE, for lower prices of natural gas, has shown to benefit the scenario where the investments are postponed into the future. Projections for the future imply that costs of IRE are going to decrease over time, giving incentives to follow a slower phase-out (IRENA, 2021). At the same time, given that Wiser et al. (2021) assigned changes in IRE costs to industry maturity and competitiveness, there are reasons to argue for a faster phase-out, where larger investments in RE are done as soon as possible. Larger commitments for RE from the EU, especially those that follow the "financing mechanism" enabling efficiency within energy production, would encourage competition in the market and help the industry mature, whilst also ensuring that the benefits of the investments are seen throughout the region (European Commission, n.d.-c). In this report, changes in installation and O&M costs are seen as exogenous to the model, but by considering them as both affecting and depending on the scope and time of investments, other results could have been found.

7.1.3 Social Cost of Carbon

Changing the SCC between 0, 50, and 100 has not had any significant impact on our results. As previously mentioned, SCC is a way of including negative externalities of GHG emissions. The result indicates that the ranking of the scenarios would be the same even if the cost for externalities were included. One explanation is that between the three scenarios, the difference in NPV is relatively small since the period that this report examines, from now till 2050, is rather short and the differences in the timing of phase-out are not significant enough to be affected by SCC.

Furthermore, the value of the SCC depends on several factors that can change its importance in the cost-benefit analysis (CBA). As mentioned, the cost of SCC can take different values depending on what SDR is used to calculate it. If the "dismal theorem" is assumed and all investments to avoid future disasters should be made then the SCC might be set to substantially higher than 100 USD/tCO_2 (Fleurbaey & Zuber, 2015). Setting the SCC at an infinitely high value can be argued for if it is evident that emissions today will lead to irreversible losses of environmental values that are fundamental for human existence. A high SCC could exceed all costs of investment and, therefore, any project that can lower the most amount of emission the fastest would be the best alternative in a CBA. At the same time, resources are limited, and it can be argued that generations living today also have the right to a good life. Therefore, setting a price of SCC that is so high, where the best alternative always is to make investments for future generations, can also be problematic if it leaves today's generations with little resources to improve their welfare. (Fleurbaey & Zuber, 2015)

Another argument to increase the SCC is that CPLC (2017) and IPCC (2014) conclude that the price of SCC is generally set too low, the negative externalities are undervalued, and the timeframe of calculation is too short. Bradshaw & Boersma (2020) states that carbon dioxide (CO_2) emissions can remain in the atmosphere for up to 10 000 years, a period that is difficult to account for in the calculations of the cost of carbon. Based on the result from this study, where at most about 0.2% of total benefits are accounted for by the SCC per year, it can be questioned whether the price set by CPLC is reasonable, even as a tool to influence the market to reach the Paris Agreement. If the SCC instead was seen as a market price on CO_2 emissions, it would not have been efficient in changing the result to lower emissions faster. The ineffectiveness of costs related to emissions, in this case, might be because natural gas is a relatively low carbon-intense fossil fuel, and the price of 100 USD might have a bigger impact on studies regarding other fossil fuels. However, the results from this study can give incentives for future research to evaluate if the price of carbon, both as a social cost and as a market price, might be too low today.

7.2 Strengths and weaknesses

The method of CBA used in this report is based on earlier research and the "European Guide to CBA" (Sartori et al., 2014). Predictions regarding future trends and data regarding present trends, that are assumed to be similar in the future, make up the basis of our model. To predict changes in prices, energy demand, and technical development is at best a difficult challenge, at worst impossible. Handling uncertainty of future trends has been a challenge in this report. The chosen strategy has been to base our well-argued assumptions on research and data. The precautionary strategy as well as the array of possible outcomes tested are other actions that this report has taken to handle the uncertainty of the future.

Furthermore, we have chosen not to go into detail in exact numbers for NPV and BCR since the variables used are approximations of future values and changes in assumptions regarding future trends for the variables can affect these numbers significantly. Even if we consider the approximations of the variables to be too uncertain to give exact numbers, they are still based on research that with high certainty can conclude general trends for the variables, for example, that costs of RE will decrease over the long term. The credibility of the report is strengthened by the general trends seen for the variables included and that the different versions of variables included in the model cover several possible futures. The number of different versions included in the report further complicates the presentation of exact numbers for all indicators, which gives us further reason to focus on the ranking of the scenarios rather than on the exact numbers in the result.

One limitation that structured this paper was that the costs of infrastructure and production of natural gas were excluded. Existing research indicates the complexity as the infrastructure and production of natural gas would amount to a large addition of variables (Groth & Scholtens, 2016; Kiss et al., 2016). Cerniauskas et al. (2020) exemplify the complexity of estimating infrastructure costs by explaining that current natural gas infrastructure can be reused for hydrogen power. This means that it is difficult to proclaim the results from this study plausible for the EU on their own.

The result from our limited calculations, where a 25% increase in costs was assumed to include infrastructure costs, showed that the costs did not impact the results for the high price of natural gas, and a fast phase-out was still preferred. For the low price, however, the inclusion of infrastructure costs benefited from postponing the phase-out. It is rather reasonable to believe that the cost of infrastructure and production will have an impact, at least for the low prices of natural gas. More extensive research that includes infrastructure would be necessary for the EU, to choose an economically possible strategy, but these results can be an indicator of how our results can depend on costs excluded from the model.
Another aspect that was excluded was the importance and role of fossil fuels such as coal and oil. It would have given the study a more realistic setting if the calculations included these energy sources because they cause greater carbon dioxide emissions and are relevant to the goals set up by the EU. It would then be possible to have an expanded discussion on the role of natural gas as a transition fuel. The study would, however, be significantly more extensive, there of the restriction. Despite the limitations presented, the study provides several indications for the specific circumstances that prefer a faster or slower phase-out of natural gas in the EU.

7.3 Ethical discussion

The chosen method of CBA has several shortcomings that shape the conclusions put forth. To begin with, it is impossible to include every possible benefit and cost of a certain project, some variables that add to the costs and benefits are also difficult to monetize (Boardman et al., 2014). The discussion of how to value human life and value future generations regarding the SDR relates to this weakness in the model (Boardman et al., 2014). The results play out differently if the value of life is determined through economic earnings or potential savings in health care costs (Boardman et al., 2014). Furthermore, the value of money differs between individuals, primarily depending on the current economic status of the person, something that is not integrated into the CBA method (Boardman et al., 2014).

A necessary discussion, related to the ethical dimensions of our study, is how costs and benefits are distributed which, in this report, presents itself on a regional level. Since the dependency on natural gas is unevenly distributed within the EU, a phase-out would lead to differences in costs and benefits between member states. For richer countries, there is a larger possibility to value future populations higher and use a lower SDR than for less well-off nations (Sartori et al., 2014). This gives incentives for poorer countries to take greater notice of the results with a 5% SDR where investments in IRE were postponed into the future while richer countries have less support to postpone a phase-out of natural gas.

In the study by Creutzig et al. (2014) the most inclusive strategy, that contributes to a fairer and more equal region, would be to invest in the periphery. The rationale for directing investments to the periphery countries is that it would increase their economic growth, create work opportunities, and provide more security regarding energy supply overall (Creutzig et al., 2014). The “financing mechanism” by the EU Commission is an example of this. It is a tool to distribute costs and benefits connected to RE installment within the region. Related to the CBA method, the mechanism exemplifies how the concept of winners compensating the losers is not only theoretical, which is a point of critique to the method. Instead, incentives like the “financing mechanism” shows it is possible to accomplish the compensation.

Ensuring that all citizens have access to secure energy, is a goal set by the EU Commission as a part of the Energy Efficiency Directive (Directive 2018/2002). It is, therefore, important to highlight the need to support member states that are more dependent on fossil fuels such as natural gas, to prevent these countries from having to choose between securing energy supply to their citizens or following EU regulations aimed at lowering climate impact or dependency on Russian imports. The aim of this report has not been to research the political aspects of the energy transition. However, it is important to look at the plausibility of our results from points of view that both incorporate ethical standpoints of distribution of costs and benefits and the applicability of the results based on the political climate.

7.4 Future research

A natural extension of this study is to include the cost of infrastructure and production of imported natural gas to consider the full impact of natural gas as an energy source. As mentioned earlier, Nick & Thoenes (2014) examine the long-term effect of price changes for natural gas and conclude that it is sensitive to changes in oil and coal prices. This is a topic that could be further investigated as the transition to net-zero emissions depends greatly on the timing of investments. It would also be interesting to go more in-depth into the distribution of costs and benefits that a phase-out would imply. A topic that could be valuable in discussions on climate justice. Lastly, performing this study with even more values for each variable, for example, a higher SCC or an increase in energy demand would contribute even more to the conclusions that can be drawn from this study.

8. Conclusion

Present and future climate-related risks, the current global energy instability, and the EU's taxonomy all tie into the broader discussion of how the EU is to sustain energy security and political stability in the future. This study has aimed to investigate a phase-out of natural gas in the EU through investments in renewable energy. The calculations on net benefits for three potential phase-out timeframes indicate that the outcomes are very price sensitive.

When the price of natural gas is high and is assumed to decrease the net present benefits and benefit-cost ratio are larger in scenario 3 compared to the two other scenarios indicating that a faster phase-out is the best alternative from an economic point of view. When the price of natural gas is low and assumed to increase over time the results vary more depending on changes in energy demand, future costs of renewable energy, the mix of wind and solar power that are installed, and the social discount rate applied. In general, decreases in costs of renewable energy and giving less value to future costs with a higher social discount rate benefits scenario 1, where phase-outs are postponed into the future. When uncertainty in the method is met, by using the highest estimates for costs and the lowest for benefits, the majority of the results show that alternative 3, with the fastest phase-out of natural gas, is the most beneficial. For risk aversion, a fast phase-out can also be argued for because future prices of natural gas are more volatile than prices of renewable energy. All future alternatives where price change was probable, showed that the benefits will outweigh the costs within 40 years.

Higher pressure to mitigate the climate crisis, an increase in armed conflicts and wars and financial and political instability have changed the conditions and incentives for the goals and action plans set by the EU to phase-out natural gas until 2050. This report has not explored all possible alternatives for phase-out or accounted for all possible outcomes in relation to variables used, such as future costs of renewable energy, energy demand, and prices of natural gas. However, the results from our model indicate that there are arguments for a faster phase-out of natural gas than what is set in the EU taxonomy or in the new plans to reduce dependency on Russian imports. Having a fast phase-out of natural gas can come with both economic benefits and risk aversion. Further research is needed to confirm the results, but we hope this report can create incentives to look into larger investments for a faster phase-out of fossil fuels in the EU.

Reference list

ACER. (n.d.). *Gas factsheet*. ACER. Retrieved May 16, 2022, from https://www.acer.europa.eu/gas-factsheet

Alvarez, C. F., & Molnar, G. (2021, October 12). *What is behind soaring energy prices and what happens next? – Analysis*. International Energy Agency. Retrieved May 11, 2022, from https://www.iea.org/commentaries/what-is-behind-soaring-energy-prices-and-what-happens-next

Azevedo, I. M. (2014). Consumer End-Use Energy Efficiency and Rebound Effects. *Annual Review of Environment and Resources*, *39*(1), 393–418. https://doi.org/10.1146/annurev-environ-021913-153558

Bastien, J., & Handler, C. (2006). Hydrogen Production from Renewable Energy Sources. *2006 IEEE EIC Climate Change Conference*. https://doi.org/10.1109/eicccc.2006.277218

Berry, D. (2005). Renewable energy as a natural gas price hedge: the case of wind. *Energy Policy*, *33*(6), 799–807. https://doi.org/10.1016/j.enpol.2003.10.005

Bertsch, J., Growitsch, C., Lorenczik, S., & Nagl, S. (2016). Flexibility in Europe's power sector — An additional requirement or an automatic complement? *Energy Economics*, 53, 118–131. https://doi.org/10.1016/j.eneco.2014.10.022

Boardman, A. E., Greenberg, D., Vining, A., & Weimer, D. (2014). *Cost-benefit analysis: concepts and practice* (Pearson New International Edition). Chapter 1-2. Pearson Education Limited.

Bradshaw, M., & Boersma, T. (2020). *Natural Gas*. Polity Press.

Brouwer, R., Brander, L., & van Beukering, P. (2008). "A convenient truth": air travel passengers' willingness to pay to offset their CO2 emissions. *Climatic Change*, *90*(3), 299–313. https://doi.org/10.1007/s10584-008-9414-0

Centemeri, L. (2009). Environmental Damage as Negative Externality: Uncertainty, Moral Complexity and the Limits of the Market. *E-Cadernos CES*, *05*. https://doi.org/10.4000/eces.266

Cerniauskas, S., Jose Chavez Junco, A., Grube, T., Robinius, M., & Stolten, D. (2020). Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a Germany case study. *International Journal of Hydrogen Energy*, 45(21), 12095–12107. https://doi.org/10.1016/j.ijhydene.2020.02.121

Chen, Y. K., Koduvere, H., Gunkel, P. A., Kirkerud, J. G., Skytte, K., Ravn, H., & Bolkesjø, T. F. (2020). The role of cross-border power transmission in a renewable-rich power system – A model analysis for Northwestern Europe. *Journal of Environmental Management*, *261*, 110194. https://doi.org/10.1016/j.jenvman.2020.110194

Climate Action Network. (2021, June 17). 20 Organisations release an EU fossil gas manifesto for a 2035 phase out. [Press release]. https://caneurope.org/20-organisations-release-eu-fossil-gas-manifesto-2035-phase-out/

Cooper, N., & White, A. (2022, April 6). *IPCC report: urgent climate action needed to halve emissions by 2030*. World Economic Forum. Retrieved April 18, 2022, from https://www.weforum.org/agenda/2022/04/ipcc-report-mitigation-climate-change/

Carbon Pricing Leadership Coalition. (2017, May). *Report of the High-Level Commission on Carbon Prices.* https://static1.squarespace.com/static/54ff9c5ce4b0a53decccfb4c/t/59244eed17bffc0ac256cf16/1495551740633/CarbonPricing_Final_May29.pdf

Creutzig, F., Goldschmidt, J. C., Lehmann, P., Schmid, E., von Blücher, F., Breyer, C., Fernandez, B., Jakob, M., Knopf, B., Lohrey, S., Susca, T., & Wiegandt, K. (2014). Catching two European birds with one renewable stone: Mitigating climate change and Eurozone crisis by an energy transition. *Renewable and Sustainable Energy Reviews*, *38*, 1015–1028. https://doi.org/10.1016/j.rser.2014.07.028

Curds, M., & O'Riordan, E. (n.d.). *Physical gas flows across Europe and diversity of gas supply in 2015*. Asset Publishing Gov.Uk. Retrieved April 14, 2022, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/579632/Physical_gas_flows_across_Europe_in_2015.pdf

Delegated regulation C/2022/0631 final. */... amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities,* European Commission. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=PI_COM:C(2022)631

Directive 2018/2002. *amending Directive 2012/27/EU on energy efficiency*. European Parliament Council of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0210.01.ENG

European Civil Society Gas Manifesto. (2021). EU climate and energy policies must deliver a fossil gas phase out in Europe by 2035. https://caneurope.org/content/uploads/2021/06/Fossil-Gas-Manifesto-2021.pdf

European Commission. (n.d.-a). *2030 climate & energy framework*. Retrieved April 26, 2022, from https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy-framework_en

European Commission. (n.d.-b). *Energy efficiency directive*. Retrieved May 20, 2022, from https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en

European Commission. (n.d.-c). *EU renewable energy financing mechanism*. Retrieved May 17, 2022, from https://energy.ec.europa.eu/topics/renewable-energy/financing/eu-renewable-energy-financing-mechanism_en

European Commission. (2020). *EU taxonomy for sustainable activities*. European Commission - European Commission. Retrieved May 23, 2022, from https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en

European Commission. (2021a, July 14). *Commission proposes new Energy Efficiency Directive*. Retrieved April 14, 2022, from https://ec.europa.eu/info/news/commission-proposes-new-energy-efficiency-directive-2021-jul-14_sv

European Commission. (2021b, December 15). *Commission proposes new EU framework to decarbonise gas markets, promote hydrogen and reduce methane emissions*. European Commission. Retrieved May 19, 2022, from https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6682

European Commission. (2022a, March 8). *REPowerEU: Joint European action for more affordable, secure and sustainable energy* [Press release]. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511

European Commission. (2022b, April 8). *Question and answers on the fifth package of restrictive measures against Russia*. European Commission - European Commission. Retrieved May 13, 2022, from https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_2333

European Union. (n.d.-a). Aims and values. European Union. Retrieved May 23, 2022, from https://european-union.europa.eu/principles-countries-history/principles-and-values/aims-and-values_en

European Union. (n.d.-b). *Ekonomi*. Retrieved May 10, 2022, from https://european-union.europa.eu/principles-countries-history/key-facts-and-figures/economy_sv

European Union. (2020, March). *Taxonomy: Final report of the Technical Expert Group on Sustainable Finance*. European Union. https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/200309-sustainable-finance-teg-final-report-taxonomy_en.pdf

Eurostat. (n.d.). *Shedding light on energy in the EU: What kind of energy do we consume in the EU?* Retrieved May 17, 2022, from https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-3a.html?lang=en

Eurostat. (2011–2020). *Imports of natural gas by partner country* [Dataset]. Eurostat. https://ec.europa.eu/eurostat/databrowser/view/NRG_TI_GAS__custom_2777846/default/table?lang=en

Eurostat. (2020). *Supply, transformation and consumption of gas* [Calculated inland consumption of natural gas respectively manufactured gases in Terajoule in 2020]. Eurostat. https://ec.europa.eu/eurostat/databrowser/view/NRG_CB_GAS__custom_2732980/default/table?lang=en

Fleurbaey, M., Ferranna, M., Budolfson, M., Dennig, F., Mintz-Woo, K., Socolow, R., Spears, D., & Zuber, S. (2018). The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy. *The Monist*, *102*(1), 84–109. https://doi.org/10.1093/monist/ony023

Fleurbaey, M., & Zuber, S. (2015). Discounting, risk and inequality: A general approach. *Journal of Public Economics*,*128*, 34–49. https://doi.org/10.1016/j.jpubeco.2015.05.003

Fronzek, S., & Carter, T. R. (2007). Assessing uncertainties in climate change impacts on resource potential for Europe based on projections from RCMs and GCMs. *Climatic Change*, *81*(S1), 357–371. https://doi.org/10.1007/s10584-006-9214-3

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*, 38–50. https://doi.org/10.1016/j.esr.2019.01.006

Gielen, D., Taylor, M., & Jinks, B. (2022, February 24). *Renewables and Green Gas: The Only Viable Antidote to High Fossil Fuel Prices*. IRENA. Retrieved May 18, 2022, from https://www.irena.org/newsroom/expertinsights/2022/Feb/Renewables-and-green-gas

Groth, T., & Scholtens, B. (2016). A comparison of cost-benefit analysis of biomass and natural gas CHP projects in Denmark and the Netherlands. *Renewable Energy*, *86*, 1095–1102. https://doi.org/10.1016/j.renene.2015.09.032

Gürsan, C., & de Gooyert, V. (2021). The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition? *Renewable and Sustainable Energy Reviews*, *138*, 110552. https://doi.org/10.1016/j.rser.2020.110552

Gusev, M. (2022, April 26). *Natural Gas Price Forecast: 2021, 2022 and Long Term to 2050*. Knoema. Retrieved April 27, 2022, from https://knoema.com/infographics/ncszerf/natural-gas-price-forecast-2021-2022-and-long-term-to-2050

Hafner, M., & Raimondi P.P. (2021) Priorities and challenges of the EU energy transition: From the European Green Package to the new Green Deal. *Russian Journal of Economics*. Volume 6, Issue 4, Pages 374 - 389. https://doi.org/10.32609/j.ruje.6.55375

Heide, D., von Bremen, L., Greiner, M., Hoffmann, C., Speckmann, M., & Bofinger, S. (2010). Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. *Renewable Energy*, *35*(11), 2483–2489. https://doi.org/10.1016/j.renene.2010.03.012

Hope, C., & Newbery, D. (2006). Calculating the Social Cost of Carbon. *Energy Policy Research Group, Cambridge Judge Business School, University of Cambridge*. https://doi.org/10.17863/CAM.5125

International Energy Agency. (2021). Net Zero by 2050 A Roadmap for the Global Energy Sector. International Energy Agency. https://iea.blob.core.windows.net/assets/0716bb9a-6138-4918-8023-cb24caa47794/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf

Intergovernmental Panel on Climate Change. (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. https://www.ipcc.ch/report/ar5/syr/

Intergovernmental Panel on Climate Change. (2021, November). *Climate Change 2022 Mitigation of Climate Change*. Intergovernmental Panel on Climate Change. https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf

International Renewable Energy Agency (2021) *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency. Abu Dhabi. https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

Janetschek, H., Brandi, C., Dzebo, A., & Hackmann, B. (2019). The 2030 Agenda and the Paris Agreement: voluntary contributions towards thematic policy coherence. *Climate Policy*, *20*(4), 430–442. https://doi.org/10.1080/14693062.2019.1677549

Janota, L., Surovezhko, A., & Igissenov, A. (2022). Comprehensive evaluation of the planned development of intermittent renewable sources within the EU. *Energy Reports*, *8*, 214–220. https://doi.org/10.1016/j.egyr.2022.01.093

Kiss, A., Selei, A., & Takácsné Tóth, B. (2016). A Top-Down Approach to Evaluating Cross-Border Natural Gas Infrastructure Projects in Europe. *The Energy Journal*, *37*(01). https://doi.org/10.5547/01956574.37.si3.akis

Krey V., O. Masera, G. Blanford, T. Bruckner, R. Cooke, K. Fisher-Vanden, H. Haberl, E. Hertwich, E. Kriegler, D. Mueller, S. Paltsev, L. Price, S. Schlömer, D. Ürge-Vorsatz, D. van Vuuren, and T. Zwickel. (2014): Annex II: Metrics & Methodology. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-ii.pdf

Leichenko, R., & O'Brien, K. (2019). *Climate and Society: Transforming the Future*. Polity Press.

Marks, L. (2022). The Abatement Cost of Methane Emissions from Natural Gas Production. *Journal of the Association of Environmental and Resource Economists*, *9*(2), 165–198. https://doi.org/10.1086/716700

Marten, A. L., & Newbold, S. C. (2012). Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide. *Energy Policy*, *51*, 957–972. https://doi.org/10.1016/j.enpol.2012.09.073

Milov, V. (2022). European gas price crisis: Is Gazprom responsible? *European View*, *21*(1), 66–73. https://doi.org/10.1177/17816858221084761

Mooij, R. A., Keen, M., Parry, I. W. H., & de Mooij, R. A. (2012). *Fiscal Policy to Mitigate Climate Change*. INTERNATIONAL MONETARY FUND. https://www.elibrary.imf.org/view/books/071/12762-9781616353933-en/ch04.xml

Newbery, D. M., Reiner, D. M., & Ritz, R. A. (2019). The Political Economy of a Carbon Price Floor for Power Generation. *The Energy Journal*, *40*(1). https://doi.org/10.5547/01956574.40.1.dnew

Nick, S., & Thoenes, S. (2014). What drives natural gas prices? — A structural VAR approach. *Energy Economics*, *45*, 517–527. https://doi.org/10.1016/j.eneco.2014.08.010

Noailly, J., & Smeets, R. (2021). Financing Energy Innovation: Internal Finance and the Direction of Technical Change. *Environmental and Resource Economics.* https://doi.org/10.1007/s10640-021-00602-9

Polzin, F. & Sanders, M. (2020). How to finance the transition to low-carbon energy in Europe? *Energy Policy*, *147*, 111863. https://doi.org/10.1016/j.enpol.2020.111863

Proposal COM (2021) 558 final. *For a directive of the European Parliament and of the Council on energy efficiency (recast)*, European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0558

Rintamäki, T., Siddiqui, A. S., & Salo, A. (2017). Does renewable energy generation decrease the volatility of electricity prices? An analysis of Denmark and Germany. *Energy Economics*, *62*, 270–282. https://doi.org/10.1016/j.eneco.2016.12.019

European Climate Foundation. (2010). Roadmap 2050 Volume 1: Technical and Economic Analysis. *Roadmap 2050 A Practical Guide to a Prosperous, Low-Carbon Europe*. Volume 1. European Climate Foundation. https://www.roadmap2050.eu/attachments/files/Volume1_fullreport_PressPack.pdf

Saefong, M. P. (2022, February 11). Natural Gas Has Seen Big Price Swings. Why Investors Should Buckle Up. *Barron's*. Retrieved June 6, 2022, from https://www.barrons.com/articles/natural-gas-prices-51644450483

Sartori, D., Catalano, G., Genco, M., Pancotti, C., Sirtori, E., Vignetti, S., & del Bo, C. (2014, December). *Guide to Cost-Benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014–2020*. European commission. https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf

Stern, J. (2020). The role of gases in the European energy transition. *Russian Journal of Economics*, *6*(4), 390–405. https://doi.org/10.32609/j.ruje.6.55105

United Nations. (2017). *World Population Prospects*. United Nations. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/files/documents/2020/Jan/un_2017_world_population_prospects-2017_revision_databooklet.pdf

United Nations Environment Programme, Frankfurt School of Finance & Management, The Frankfurt School – UNEP Collaborating Centre for Climate & Sustainable Energy Finance, & BloombergNEF. (2020). *Global Trends in Renewable Energy Investment 2020.* https://stg-wedocs.unep.org/bitstream/handle/20.500.11822/32700/GTR20.pdf?sequence=1&isAllowed=y

Wiser, R., Rand, J., Seel, J., Beiter, P., Baker, E., Lantz, E., & Gilman, P. (2021). Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nature Energy*, *6*(5), 555–565. https://doi.org/10.1038/s41560-021-00810-z

World Economic Forum. (2022, April 29). *The consequences of the war in Ukraine will be far-reaching*. Retrieved May 11, 2022, from https://www.weforum.org/agenda/2022/04/an-unfair-war-economic-social-and-security-consequences-of-the-russian-invasion-into-ukraine/

Appendices

Appendix 1

Import of natural gas

In Table 1 the annual imports of natural gas is displayed for the years 2011 to 2020 taken from Eurostat (2011-2020) and in Table 2 the average import for this time period is shown.

Table 1

2011	2012	2013	2014	2015
14 515 596.04	14 156 490.36	14 236 323.75	13 301 195.24	14 232 408.28
2016	**2017**	**2018**	**2019**	**2020**
14 718 592.72	16 362 167.18	15 342 660.02	16 755 116.79	15 313 617.41

Table 1: Imports of natural gas in Terajoule (gross calorific value) for the period 2011-2020 for EU 27. (Eurostat, 2011-2020)

Table 2

NG	Average imports 2011-2020
Tj	14 893 417

Table 2: Average imports of natural gas in Terajoule (gross calorific value) of the period 2011-2020 for EU 27, calculated from values in Table 1.

Annual phase-out of natural gas

The amount of phase-out per year (ng_t) for the different scenarios is presented in Tables 3-5. The amounts are calculated by dividing the amount presented in Table 2 by the number of years for phase-out. For scenario 2 there are two different amounts of phase-out per year. For the period 2023-2030 the 45% of natural gas, imported from Russia, is phased out. Then for the period 2031-2049 the remaining 55% is phased out. The amounts are presented in different units and are recalculated through the relationship 1 Terajoule = 277 777.7777 kWh = 56.1 kg CO_2 (Krey et al., 2014).

Table 3

S1	2023-2029	2030-2049
ng		**NG/20 years**
TJ	0	744 671
kWh	0	206 853 010 811
kg CO_2	0	41 776 034

Table 3: Amount of phase-out of natural gas per year (ng) for scenario 1 presented in the units of Terajoule, kWh and kilograms of emitted CO_2.

Table 4

S2	2023-2030 (Russian=45%)	2031-2049 (the rest=55%)
ng	**NG*0,45/8 years**	**NG*0,55/19 years**
TJ	837 755	431 125
kWh	232 709 637 163	119 757 006 259
kg CO2	46 998 038	24 186 125

Table 4: Amount of phase-out of natural gas per year (ng) for scenario 2 presented in the units of Terajoule, kWh and kilograms of emitted CO_2.

Table 5

S3	2023-2035	2036-2049
ng	**NG/13 years**	
TJ	1 145 647	0
kWh	318 235 401 248	0
kg CO2	64 270 822	0

Table 4: Amount of phase-out of natural gas per year (ng) for scenario 3 presented in the units of Terajoule, kWh and kilograms of emitted CO_2.

Change in energy demand, d

Change in energy demand (*d*) is calculated by taking the average imports from 2016 to 2018, seen in Table 1, following EU energy efficiency goals (Directive 2018/2002). This number is presented in Table 6.

Table 6

NG	Average imports 2016-2018
Tj	15 474 473

Table 6: average imports of natural gas to the EU 27 for years 2016-2018, calculated from values found in Table 1.

The decrease in energy demand will be 0, following the precautionary principle, 0.8% or 1.5% following the EU goals for energy efficiency (Directive 2018/2002). The values for *d* are calculated by calculating what the annual phase-out, ng_t, would be, as presented in Tables 3 to 5, if the amount that would be phased out would be the average of the imports for the year 2016-2018 instead of 2011-2020. 0.8% and 1.5% of this annual amount are taken which then is the value for *d*, the decrease in the demanded amount of energy from natural gas caused by increases in energy efficiency. The values are recalculated for different values through the relationship 1 Terajoule = 277 777.7777 kWh = 56.1 kg CO_2 (Krey et al., 2014). The different values for *d* for the scenarios are presented in Tables 7-9.

Table 7

S1	2030-2049	d=0.8%	d=1.5%
ng	**NG/20 years**		
Tj	773 724	6 190	11 606
kWh	214 923 240 361	1 719 385 923	3 223 848 605
kg CO_2	43 405 898	347 247	651 088

Table 7: Amount of decrease in demanded natural gas per year (d) for scenario 1 when the decrease is 0.8% respectively 1.5% annually presented in the units of Terajoule, kWh and kilograms of emitted CO_2.

Table 8

S2 Period 1	2023-2030 (Russian=45%)	d=0.8%	d=1.5%
ng	**NG*0,45/8 years**		
TJ	870 439	6 964	13 057
kWh	241 788 645 406	1 934 309 163	3 626 829 681
kg CO_2	48 831 635	390 653	732 475
S2 Period 2	**2031-2049 (the rest=55%)**	**d=0.8%**	**d=1.5%**
ng	**NG*0,55/19 years**		
TJ	447 945	3 584	6 719
kWh	124 429 244 420	995 433 955	1 866 438 666
kg CO_2	25 129 730	201 038	376 946

Table 8: Amount of decrease in demanded natural gas per year, d in the formula, for scenario 2 when the decrease is 0.8% respectively 1.5% annually presented in the units of Terajoule, kWh and kilograms of emitted CO_2.

Table 9

S3	2023-2035	d=0.8%	d=1.5%
ng	**NG/13 years**		
Tj	1 190 344	9 523	17 855
kWh	330 651 139 017	2 645 209 112	4 959 767 085
kg CO_2	66 778 304	534 226	1 001 675

Table 9: Amount of decrease in demanded natural gas per year, d in the formula, for scenario 3 when the decrease is 0.8% respectively 1.5% annually presented in the units of Terajoule, kWh and kilograms of emitted CO_2.

Renewable energy costs

The values for renewable energy costs are based on global averages of installation costs and O&M costs from the International Renewable Energy Agency (IRENA) (2021). The costs in 2020 dollars is presented in Table 10.

Table 10

	Installation cost(USD/kW)	O&M cost(USD/kWh)
Offshore wind	3185	0.03
Onshore wind	1355	0.02
Solar	883	0.002

Table 10: Global average installation costs for different renewable energy in 2020 USD per installed kW. Operation and maintenance costs in USD per kWh (IRENA 2021).

For the mix of solar and wind power installed, the values are based on future prospects from two different sources; the Roadmap 2050 for the EU (ECF, 2010) and Heide et al. (2010). The mix of offshore and onshore wind is only based on the prospect from the Roadmap 2050 (ECF, 2010) since Heide et al. (2010) does not give any indications for this mix. The amount of installed offshore and onshore wind for 2050 in absolute value and in percentages based on the Roadmap 2050 is presented in Table 11. The mix of wind and solar for the two sources are presented in Table 12.

Table 11

Wind mix Roadmap 2050	Energy absolute values (GW)	Proportions
Offshore wind	190	43.70%
Onshore wind	245	56.30%

Table 11: Roadmap 2050 projections for installed offshore and onshore wind power in gigawatts for year 2050 and what percentage each wind type accounts for.

Table 12

		Energy absolute values (GW)	Proportions
Roadmap 2050 (ECF, 2010)	**Wind**	435	34.80%
	Solar	815	65.20%
Heide et al. (2010)	**Wind**	-	55%
	Solar	-	45%

Table 12: Mix of solar and wind in 2050 according to the EU Roadmap 2050 (ECF, 2010) and Heide et al. (2010). For Roadmap 2050 both the absolute values in gigawatt installed and the proportion they account for is presented. For Heide et al. only proportions in percentage are available and presented.

When the calculations for average cost for wind power are made, the proportion of offshore wind from Table 11 is multiplied by the cost (for installation respectively O&M costs) for offshore wind presented in Table 10. The same is done for onshore wind and the two products are added to have the average cost for wind power which is presented in Table 13. In Table 13, the average cost for the renewable energy mix is also presented based on the Roadmap 2050 (ECF, 2010) and Heide et al. (2010). These numbers are calculated by taking the proportion of wind power for each mix, presented in Table 12, times the average costs presented in Table 13. The same is done for solar costs and the two products are added together to form the total installation respectively O&M costs for the two mixes. The costs are presented in Table 13.

Table 13

	Installation cost (USD/kW)	O&M cost(USD/kWh)
Wind	2154.71	0.02437
Solar	883	0.002
Roadmap 2050 (ECF, 2010)	1325.55508	0.00978476
Heide et al. (2010)	1582.4405	0.0143035

Table 13: The average installation cost per kW respectively O&M costs per kWh in 2020 USD for wind power mix of offshore and onshore wind, solar power, wind-solar mix based on

Roadmap 2050 (ECF, 2010) projections for 2050 and wind-solar mix based on Heide et al. (2010) projection for 2050.

Calculating natural gas price change

To calculate price changes, price estimates from the World Bank and EIA are used (Gusev, 2022). The data is shown in Table 14. The price changes are calculated by taking the average price change per year throughout the period for projection. The calculated value can be seen in Table 15.

Table 14

Price projections (USD/MMBtu)	2020	2022	2023	2024	2025	2030	2035	2050
World Bank	3.24	12.60	9.2	8.94	8.68	7.51	6.5	-
EIA (world market)	2.49	-	-	-	-	-	-	7.54

Table 14: price projections from 2020 to 2050 from the World Bank and EIA (Gusev, 2022).

Table 15

Price change	Total USD	Per year	In USD/kWh
World bank 2025-2035	-2.18	-0.218	-0.000743773
EIA 2020-2050	5.05	0.168333333	0.00057432

Table 15: Calculation of price changes following the World Bank between 2025 and 2035 and EIA between 2020 and 2050.

Calculating changes in installation and O&M costs for renewable energy

To calculate the change in costs for intermittent renewable energy (IRE) the weighted average of LCOE found in IRENA (2021) is used. The average price change in percentage is calculated based on this data. This can be found in Table 16. The average price of installation and O&M costs for Roadmap 2050 (ECF, 2010) and Heide et al. (2010), seen in Table 13, are calculated and presented in Table 17. The price change of 64.23% is taken and divided by 28 (years from now till 2050) to get the price change per year until 2050, which is the values for *v* and *a* in the formula. This data can be seen in Table 17.

Table 16

LCOE costs (USD)	Weighted average 2010	Weighted average 2020	Difference	Decrease in %
Offshore wind	0.158	0.083	0.075	47.47
Onshore wind	0.113	0.045	0.068	60.18
Solar	0.381	0.057	0.324	85.04
Average	0.217	0.062	0.156	**64.23**

Table 16: Calculations of average decrease in LCOE costs in USD for offshore and onshore wind power and solar power (IRENA, 2021).

Table 17

	Average price	Cost reduction	Annual cost reduction
Installation cost (*v*) USD/kW	1 454	933.88	**33.35**
O&M costs (*a*) USD/kWh	0.01204	0.00774	**0.00028**

Table 17: the annual cost reduction found by multiplying the average price with the decrease in LCOE costs (64.23%). The cost reduction is then calculated per year.

Appendix 2

In Tables 1 and 2, 0 indicates that *v*, *a* and *d* equal zero, and 1 indicates when *v* equals 33.35 USD/kW and *a* equals 0.00028 USD/kWh.

Table 1

Highest and lowest value Price is 12,60		NPV (dollars)	Scenario	Variables				
				v	a	d	SCC	SDR
Solar based	Highest	844 344 488 724,19	S3	1	1	0	100	3
	Lowest	28 394 634 998,42	S1	0	0	0	0	5
Wind based	Highest	745 164 935 034,80	S3	1	1	0	100	3
	Lowest	-25 292 449 463,00	S1	0	0	0	0	5
Price is 12,60		BCR						
Solar based	Highest	1,976048413	S3	1	1	0	100	3
	Lowest	1,065032102	S1	0	0	0	0	5
Wind based	Highest	1,772797306	S3	1	1	0	100	3
	Lowest	0,9484156	S1	0	0	0	0	5

Table 1 displays the highest and lowest NPV and BCR values for the higher price of 12.60 dollars. Next to the monetary value the corresponding variables scenario, installation cost of renewable energy (v), operation and maintenance cost of renewable energy (a), change in energy demand (d), the social cost of carbon (SCC), and social discount rate (SDR) are listed. When v equals 1 it takes the value 33.35 USD/kW and when a equals 1 it takes the value 0.00028 USD/kWh.

Table 2

Highest and lowest value Price is 3,24		NPV (dollars)	Scenario	Variables				
				v	a	d	SCC	SDR
Solar based	Highest	211 509 564 382,10	S3	1	1	0	100	3
	Lowest	-78 769 365 685,67	S3	0	0	1,5	0	5
Wind based	Highest	112 330 010 692,72	S3	1	1	0	100	3
	Lowest	-157 741 240 655,51	S3	0	0	1,5	0	5
Price is 3,24		BCR						
Solar based	Highest	1,48245009	S1	1	1	0	100	3
	Lowest	0,830566406	S1	0	0	0	0	5
Wind based	Highest	1,241659111	S1	1	1	1,5	100	3
	Lowest	0,739622904	S1	0	0	0	0	5

Table 2 displays the highest and lowest NPV and BCR values for the lower price of 3.24 dollars. Next to the monetary value the corresponding variables scenario, installation cost of renewable energy (v), operation and maintenance cost of renewable energy (a), change in energy demand (d), the social cost of carbon (SCC), and social discount rate (SDR) are listed. When v equals 1 it takes the value 33.35 USD/kW and when a equals 1 it takes the value 0.00028 USD/kWh.

Net present value (NPV) when the price is high

Table 3

Price 12,60 dollars							
NPV v0, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
NPV v0, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 3 displays the ranking of scenarios 1 through 3 from the NPV calculations when there are no changes in installation or operation and maintenance costs of renewable energy (v0 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 4

Price 12,60 dollars							
NPV v0, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
NPV v0, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 4 displays the ranking of scenarios 1 through 3 from the NPV calculations when there is no change in the installation costs of renewable energy but there is a change in operation and maintenance costs of renewable energy (v0 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 5

Price 12,60 dollars							
NPV v1, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
NPV v1, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 5 displays the ranking of scenarios 1 through 3 from the NPV calculations when there is a change in the installation costs of renewable energy but there is no change in operation and maintenance costs of renewable energy (v1 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 6

Price 12,60 dollars							
NPV v1, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
NPV v1, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 6 displays the ranking of scenarios 1 through 3 from the NPV calculations when there is a change in both the installation costs and the operation and maintenance costs of renewable energy (v1 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Benefit-cost ratio (BCR) when the price is high

Table 7

Price 12,60 dollars							
BCR v0, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	D 0	3	2	1	3	2	1
	D 0,8%	3	2	1	3	2	1
	D 1,5%	3	2	1	3	2	1
SCC 50	D 0	3	2	1	3	2	1
	D 0,8%	3	2	1	3	2	1
	D 1,5%	3	2	1	3	2	1
SCC 100	D 0	3	2	1	3	2	1
	D 0,8%	3	2	1	3	2	1
	D 1,5%	3	2	1	3	2	1
BCR v0, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	D 0	3	2	1	3	2	1
	D 0,8%	3	2	1	3	2	1
	D 1,5%	3	2	1	3	2	1
SCC 50	D 0	3	2	1	3	2	1
	D 0,8%	3	2	1	3	2	1
	D 1,5%	3	2	1	3	2	1
SCC 100	D 0	3	2	1	3	2	1
	D 0,8%	3	2	1	3	2	1
	D 1,5%	3	2	1	3	2	1

Table 7 displays the ranking of scenarios 1 through 3 from the BCR calculations when there are no changes in installation or operation and maintenance costs of renewable energy (v0 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 8

Price 12,60 dollars							
BCR v0, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
BCR v0, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 8 displays the ranking of scenarios 1 through 3 from the BCR calculations when there is no change in the installation costs of renewable energy but there is a change in operation and maintenance costs of renewable energy (v0 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 9

Price 3,24 dollars							
BCR v1, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
BCR v1, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 9 displays the ranking of scenarios 1 through 3 from the BCR calculations when there is a change in the installation costs of renewable energy but there is no change in operation and maintenance costs of renewable energy (v1 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 10

Price 12,60 dollars							
BCR v1, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
BCR v1, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 10 displays the ranking of scenarios 1 through 3 from the BCR calculations when there is a change in both the installation costs and the operation and maintenance costs of renewable energy (v1 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Net present value (NPV) when the price is low

Table 11

Price 3,24 dollars							
NPV v0, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	1	2
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	1	2
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	1	2
NPV v0, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	2	3	1	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	2	3	1	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	2	3	1	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 11 displays the ranking of scenarios 1 through 3 from the NPV calculations when there are no changes in installation or operation and maintenance costs of renewable energy (v0 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 12

Price 3,24 dollars							
NPV v0, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
NPV v0, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	2	3	1	1	3	2
	d=0,8%	1	3	2	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	2	3	1	1	3	2
	d=0,8%	1	3	2	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	2	3	1	1	3	2
	d=0,8%	1	3	2	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 12 displays the ranking of scenarios 1 through 3 from the NPV calculations when there is no change in the installation costs of renewable energy but there is a change in operation and maintenance costs of renewable energy (v0 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 13

Price 3,24 dollars							
NPV v1, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	2	3	1
	d=0,8%	3	2	1	1	2	3
	d=1,5%	3	1	2	1	2	3
SCC 50	d=0	3	2	1	2	3	1
	d=0,8%	3	2	1	1	2	3
	d=1,5%	3	1	2	1	2	3
SCC 100	d=0	3	2	1	2	3	1
	d=0,8%	3	2	1	1	2	3
	d=1,5%	3	1	2	1	2	3
NPV v1, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	1	3	2	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	1	3	2	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	1	3	2	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 13 displays the ranking of scenarios 1 through 3 from the NPV calculations when there is a change in the installation costs of renewable energy but there is no change in operation and maintenance costs of renewable energy (v1 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 14

Price 3,24 dollars							
NPV v1, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	2	3	1	2	3	1
	d=0,8%	3	2	1	1	3	2
	d=1,5%	3	2	1	1	2	3
SCC 50	d=0	2	3	1	2	3	1
	d=0,8%	3	2	1	1	3	2
	d=1,5%	3	2	1	1	2	3
SCC 100	d=0	2	3	1	2	3	1
	d=0,8%	3	2	1	1	3	2
	d=1,5%	3	2	1	1	2	3
NPV v1, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	1	3	2	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	1	3	2	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	1	3	2	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 14 displays the ranking of scenarios 1 through 3 from the NPV calculations when there is a change in both the installation costs and the operation and maintenance costs of renewable energy (v1 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Benefit-cost ratio (BCR) when the price is low

Table 15

Price 3,24 dollars							
BCR v0, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
BCR v0, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1

Table 15 displays the ranking of scenarios 1 through 3 from the BCR calculations when there are no changes in installation or operation and maintenance costs of renewable energy (v0 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 16

Price 3,24 dollars							
BCR v0, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	3	2	1	3	2	1
	d=1,5%	3	2	1	3	2	1
BCR v0, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	3	2	1	3	2	1
	d=0,8%	2	3	1	3	2	1
	d=1,5%	1	2	3	3	2	1
SCC 50	d=0	3	2	1	3	2	1
	d=0,8%	2	3	1	3	2	1
	d=1,5%	1	2	3	3	2	1
SCC 100	d=0	3	2	1	3	2	1
	d=0,8%	2	3	1	3	2	1
	d=1,5%	1	2	3	3	2	1

Table 16 displays the ranking of scenarios 1 through 3 from the BCR calculations when there is no change in the installation costs of renewable energy but there is a change in operation and maintenance costs of renewable energy (v0 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 17

Price 3,24 dollars							
BCR v1, a0	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	1	3	2	2	3	1
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	1	3	2	2	3	1
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	1	3	2	2	3	1
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
BCR v1, a0	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	1	2	3	1	3	2
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	1	2	3	1	3	2
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	1	2	3	1	3	2
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 17 displays the ranking of scenarios 1 through 3 from the BCR calculations when there is a change in the installation costs of renewable energy but there is no change in operation and maintenance costs of renewable energy (v1 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 18

Price 3,24 dollars							
BCR v1, a1	3%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	1	2	3	1	3	2
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	1	2	3	1	3	2
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	1	2	3	1	3	2
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
BCR v1, a1	5%	S1	S2	S3	S1	S2	S3
		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
SCC 0	d=0	1	2	3	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 50	d=0	1	2	3	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
SCC 100	d=0	1	2	3	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 18 displays the ranking of scenarios 1 through 3 from the BCR calculations when there is a change in both the installation costs and the operation and maintenance costs of renewable energy (v1 and a1). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 19

Price 3,24 $/MMBtu		**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
SDR		Solar based	Solar based	Solar based	Wind based	Wind based	Wind based
3%	d=0%	2	3	1	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3
5%	d=0%	1	2	3	1	2	3
	d=0,8%	1	2	3	1	2	3
	d=1,5%	1	2	3	1	2	3

Table 19 displays the ranking of scenarios 1 through 3 from the NPV calculations when the costs for each year is increased by 25% to simulate the additional costs of energy infrastructure. There are no changes in installation or operation and maintenance costs of renewable energy (v0 and a0). The top section has a social discount rate of 3% whilst the lower section has a social discount rate of 5%. The solar-dominated combinations are seen on the left side (orange) and the wind-dominated combinations are seen on the right side (blue). The social cost of carbon (SCC) changes between 0, 50, and 100 giving identical results, and the change in energy demand (d) changes between 0%, 0.8%, and 1.5%.

Table 20

	USD (2020)	**%**
Costs of emissions (*E_t*)	83 552 068	0.182366
Costs of imports (*I_t*)	45 732 088 368	99.817634
Total (*B_t*)	45 815 640 436	100

Table 20 displays the opportunity costs that compose the total benefits in the calculations. The amounts are the avoided costs by emissions per year, E_t in the formula, and avoided costs of importing natural gas per year, I_t, for the years when the phase-out of imported natural gas is completed for the scenarios. SCC takes the highest value of 100 USD/tCO_2 and price of natural gas takes its lowest value of 3.24 USD/MMBtu. d, a and v takes the value of 0 and the amounts are presented before a social discount rate is applied.