Report 2022:08

Description of a 1.5°C scenario with chosen measures

Ådne Cappelen, Solveig Glomsrød,
Lars Lindholt, Knut Einar Rosendahl
and Taoyuan Wei

CICERO Senter for klimaforskning

Title	Description of a 1.5°C scenario with chosen measures
Authors	Ådne Cappelen, Solveig Glomsrød, Lars Lindholt, Knut Einar Rosendahl and Taoyuan Wei
Abstract	In the Paris Agreement, it was agreed to limit global warming to well below 2°C, and preferably to 1.5°C, compared to pre-industrial levels. At the follow-up meeting in Glasgow in 2021, the goal was strengthened to 1.5°C. Based on previous studies and a review of the relevant policies and measures to achieve the 1.5°C target, this report describes one specific 1.5°C scenario with chosen measures that will be used in three models, i.e., a global macroeconomic computable general equilibrium model GRACE, a global energy market model FRISBEE, and a Norwegian macroeconometric model KVARTS. Our chosen 1.5°C pathway follows roughly the pathway of total CO2 emissions from fossil fuels combustion in the Net Zero Emission scenario by the International Energy Agency. We present possible supply-side and demand-side measures in the energy sectors that can be implemented to reduce CO2-emissions to achieve the 1.5°C target. We also discuss to what extent we will implement these policies and measures in the three models.
Publisher	CICERO
Sted og dato	Oslo, May 2022
Financed by	Research Council of Norway (grant no. 303486)
Project	Stress-testing the Norwegian economy: The effects of the 1.5°C scenario on global energy markets and the Norwegian economy
Project manager	Knut Einar Rosendahl
Picture on cover	Karsten Würt

Contents

Introduction

This study is prepared for a project "Stress-testing the Norwegian economy: The effects of the 1.5°C scenario on global energy markets and the Norwegian economy" funded by Research Council of Norway. In this project, we have already published a report: "Developing a baseline scenario by soft-linking three models" (Cappelen et al. 2021). In the present paper, we describe how we determine one specific 1.5°C scenario by considering the project objectives, data availability and possibility of implementation in our models GRACE (Aaheim and Rive 2005; Aaheim et al. 2018), FRISBEE (Lindholt and Glomsrød 2018), and KVARTS (Biørn et al. 1987; Boug et al. 2022). Model descriptions are also found in Cappelen et al. 2021).

According to the Paris Agreement, a legally binding international treaty on climate change, adopted by 196 Parties at COP 21 in Paris by the end of 2015 and entered into force on 4 November 2016, an ambitious target has been proposed to limit global warming to well below 2, preferably to 1.5 degrees Celsius (1.5°C), compared to pre-industrial levels. In 2018, a special IPCC report (V. Masson-Delmotte 2018) was released to assess the possible impact of climate change in a world limiting global warming to 1.5°C, which is mimicked by several 1.5°C scenarios generated from various integrated models. In the period of 2018-2020, more than 250 articles have been published addressing issues related to a 1.5°C world while there are only few articles before 2015 . In 2021, IEA released a report (IEA 2021) describing a roadmap for the global energy sector to achieve net zero by 2050, which is necessary for a 1.5°C world. Based on these previous IPCC- studies, this report describes a specific 1.5°C scenario with chosen measures based on a review of the relevant policies and measures.

1. What do we mean by a 1.5°C pathway?

According the IPCC 1.5°C special report (V. Masson-Delmotte 2018), a 1.5°C pathway refers to a pathway limiting median global warming to below 1.5°C at least in 2100 and maybe with >50% probability of temporarily overshooting that level at an earlier date. The temperature change is estimated from the time profile of the GHG emissions by a simple (or comprehensive) climate model. Given a pathway of GHG emissions, the estimated temperature change may differ if another climate model is used. Although noticing the uncertain relations between emissions and temperature changes, it is concluded that a 1.5°C world needs that net CO_2 emissions in the electricity sector reach zero around 2050 and the full energy sector reaches net-zero emissions around 2070.

The net zero emissions by 2050 (NZE) scenario of IEA (2021) seems much stricter than the IPCC special report, reaching net zero in 2050 of total CO_2 emissions generated from the full energy sector. Following the explanation associated with the emissions data, total CO_2 emissions in NZE include emissions from the combustion of fossil fuels and non-renewable wastes and from industrial and fuel transformation processes (process emissions) minus CO_2 removals from bioenergy with carbon capture, utilisation and storage (BECCS) and direct air carbon capture and storage (DACCS).

In this study, we will specify a 1.5°C scenario that roughly follows the pathway of total CO_2 emissions from the combustion of fossil fuels in the NZE scenario (IEA 2021) using an integrated model system and with some detail on effects on the Norwegian economy which is currently a large petroleum producer. Depending on data availability and capacity, we may also consider CO_2 emissions from the combustion of non-renewable wastes and process emissions, and CO_2 removals from BECCS and DACCS.

2. Channels to reduce CO_2 emissions in energy sector

Emissions of greenhouse gases (GHGs) including CO_2 are generated from economic activities by using high emission materials (e.g., fossil fuels) and low emission materials (e.g. renewable energy)[1]. The generation of emissions from any economic activity i (e.g. production or consumption) can be roughly represented by the formula below,

$$GHG_i = \left(\alpha_i \cdot \frac{F_i}{M_i} + \varepsilon_i \cdot \frac{R_i}{M_i}\right) \cdot \frac{M_i}{Y_i} \cdot Y_i \qquad (1)$$

where α and ε are emissions per unit of high emission materials F and low emission materials R, respectively. $M = F + R$ are total materials used to realize the purpose of the economic activity (Y), e.g., produce economic output or satisfy consumers' welfare (utility). The changes in emissions can be expressed by

$$\Delta GHG_i = \underbrace{\left(\alpha_i \cdot \frac{F_i}{M_i} + \varepsilon_i \cdot \frac{R_i}{M_i}\right) \cdot \frac{M_i}{Y_i} \cdot \Delta Y_i}_{Activity\ changes} + \underbrace{\left(\alpha_i \cdot \frac{F_i}{M_i} + \varepsilon_i \cdot \frac{R_i}{M_i}\right) \cdot \Delta \frac{M_i}{Y_i} \cdot Y_i}_{Efficiency\ improvement}$$

$$+ \underbrace{\left(\alpha_i \cdot \Delta \frac{F_i}{M_i} + \varepsilon_i \cdot \Delta \frac{R_i}{M_i}\right) \cdot \frac{M_i}{Y_i} \cdot Y_i}_{Substitution\ of\ materials} + \underbrace{\left(\Delta\alpha_i \cdot \frac{F_i}{M_i} + \Delta\varepsilon_i \cdot \frac{R_i}{M_i}\right) \cdot \frac{M_i}{Y_i} \cdot Y_i}_{Removals\ of\ emissions}$$

This formula presents four channels to reduce emissions:

- **C1**. Activity changes by shrinking "dirty" activity (e.g. coal production) and promoting "green" activity (e.g. renewable energy production).
- **C2**. Efficiency improvement. Improve material efficiency by lowering the material use per unit economic activity level ($\frac{M}{Y}$). A typical example is that energy efficiency can be improved to produce a given amount of goods/services (or satisfy a given demand of consumers) by less energy use during production (or consumption).
- **C3**. Substitution of materials. Reduce the use of high-emission materials to lower its share in total material ($\frac{F}{M}$) or increase the use of low-emission materials to increase its ratio to high emission material ($\frac{R}{F}$). In the energy sector, this can be that fossil fuels are replaced by renewable energy due to various reasons such as relative price changes induced by mitigation policies (carbon taxes, renewable energy subsidies, and mandatory regulations). It can also be the case of substitution among fossil fuels (e.g., coal is replaced by natural gas).
- **C4**. Removals of emissions (or negative emissions). Reduce the emissions per unit of material use (α and ε) by e.g. BECCS and DACCS.

In the energy sector, the emissions can be generated from economic activities of energy supply and consumption. On the one hand, energy is supplied from energy production

[1] Our models only include CO_2.

activities, where more energy production implies more economic activity level (Y in Eq. 1). Besides the production activity level, the emissions from energy production activities are also related to materials used in the production activity. On the other hand, energy can be consumed in other economic activities, where energy is one of the materials used in these activities and leads to consumption-based emissions.

These four channels can be affected by various drivers, policies and measures. Mitigation policies can be related to carbon pricing, clean technology promotion and performance standards. Carbon pricing policies can be implemented through measures of a tax or fee on carbon emissions, or a market-based cap-and-trade system like EU-ETS with emission allowances. Technology promotion policies provide incentives for low-emission technology deployment and can be implemented through measures like subsidies and direct public funding. Performance standard policies set certain minimum or average levels of technical performance for specific products and activities and can be implemented by market-based or non-market-based measures.

According to ETC/CME (2021), most mitigation measures in European countries are economic instruments (e.g., subsidies or feed-in tariffs) and regulations (e.g., energy efficiency standards) primarily targeting energy-related GHG emissions. These measures are generally implemented at the national level and may affect one or more of the four channels above.

In Section 3 below we present sectoral measures. We classify all the sectoral measures to be one or more of the above four channels as shown in the end of the description of each measure.

3. Supply-side and demand-side measures in the energy sector

As we primarily focus on energy supply and consumption, this section provides more details on the possible mitigation measures for sectors that produce and/or consume energy in their economic activities. These measures are primarily taken from IEA (2021) supplemented with information from other sources.

3.1 Supply of fossil fuels

- Avoid approving new coal mines (or mine extensions), and oil and natural gas fields.
- Taxation of fossil fuel production.
- Increase the required rate of return so that the oil and gas producers reduce investment to increase their cash flow.
- Apply CCUS in coal production.
- Produce hydrogen from natural gas in facilities with CCUS.

3.2 Supply of low-emissions fuels

- Increase capacity to produce low-emissions fuels including biogases, hydrogen and hydrogen-based fuels.

<u>Biofuels</u>

- More production of biofuels from advanced feedstocks such as wastes and residues and woody energy crops grown on marginal lands and cropland not suitable for food.
- Expand the supply of biofuels to transportation vehicles, not only passenger vehicles and light trucks, but also heavy road freight, shipping and aviation.
- Produce biomethane by upgrading biogas produced from anaerobic digestion of feedstocks such as agricultural residues like manure and biogenic municipal solid waste, thereby avoiding methane emissions that would otherwise be released.
- Apply CCS during the production of biofuels.

<u>Hydrogen and hydrogen-based fuels</u>

- Expand production based on low-carbon technologies like water electrolysis and natural gas in combination with CCS.
- Promote hydrogen supply in heavy industry (mainly steel and chemicals production) and in the transport sector.
- Convert hydrogen into other hydrogen-based fuels, mainly ammonia for shipping and electricity generation, synthetic kerosene for aviation and synthetic methane blended into gas networks.

- Promote hydrogen use in gas-and coal-fired power plants to substitute for gas and coal and to balance increasing electricity generation from solar PV and wind and to provide seasonal storage.

3.3 Electricity generation

- Promote electrification in relevant activities.
- Expand capacity of electricity generated from renewables like floating wind and solar PV.
- Phase out the least-efficient coal plants.
- Invest in electricity grids.

3.4 Energy demand from industry

- Expand electrification in industries.
- Avoid fossil fuels in industries.
- Expand direct use of renewables.
- Promote technologies based on hydrogen, bioenergy, and CCUS technologies in industries.
- Adopt measures to increase material and energy efficiency.
- Promote recycling and re-use of plastics and more efficient use of nitrogen fertilizers.
- Increase blending of alternative materials into cement to replace a portion of clinker.

3.5 Energy demand from transport

- Expand the use of hydrogen fuel cell or battery electric vehicles including heavy trucks.
- Promote the use of low-emissions fuels in long-distance transport like aviation and shipping.
- Incentivize consumer uptake of low-emissions transport behavior.
- Improve energy efficiency.
- invest in supply infrastructure of clean energy including hydrogen refueling stations.
- Promote a shift towards high-speed rail and rein in expansion of long-haul business travel, e.g. through taxes on commercial passenger flights.
- Promote the use of ammonia and hydrogen in maritime shipping.

3.6 Energy demand from buildings

- Promote electrification in buildings.
- Promote the most energy efficient models via e.g. digitalization and smart controls.
- Retrofit existing building stock worldwide and require all new buildings comply with zero-carbon-ready building standards.
- Avoid new fossil fuel boilers incompatible with hydrogen.
- Promote new heat pumps.
- Phase down natural gas use for heating.
- Promote behavior changes, e.g., in temperature settings for space heating or reducing excessive hot water temperatures. Other behavior changes may include greater use of cold temperature clothes washing and line drying, and facilitate the decarbonization of electricity supply.
- Improve the efficiency of electric appliances and lighting.

4. How to implement in relevant models

4.1 Measures in GRACE

GRACE is a multi-sector, multi-region recursive dynamic computable general equilibrium (CGE) model for the global economy (Aaheim and Rive 2005; Aaheim et al. 2018). To following the pathway of CO2 emissions from fossil fuel use in NZE, we introduce several measures in GRACE based on the baseline scenario presented in Cappelen et al. (2021). We first introduce national policies represented by CO2 taxes on all CO2 emissions from fossil fuel use of all production sectors and households in the model. The regional CO2 taxes are assumed to be the same as regional CO2 prices estimated based on the NZE scenario (IEA 2021) as shown in the Appendix.

Second, we increase the energy-augmented technologies (or factor specific technological progress in the use of energy) of all sectors of production and households at reasonable rates. For example, we can assume that the energy-augmented technologies of all sectors improve by 1% yearly for fossil fuel final use and by 2% yearly for electricity final use during 2020-2050 meaning a yearly reduction of 1% and 2%, respectively, of the amount of energy used to produce a unit of economic output. Notice that we have not introduce hydrogen production and consumption in GRACE, which we plan to do at a later stage.

Third, we can lower costs of electricity generated from renewables and increase the costs of fossil electricity generation. We can also increase costs of primary factors of thermal power generation by e.g., 5% yearly. Another assumption we may introduce can be setting upper limits on thermal power generation, e.g., 98% of the previous-year level from 2020.

Fourth, we would expect that in the future, the substitution between fossil fuels and electricity in final energy use would be easier. Hence, the substitution elasticities between fossil fuels and electricity in GRACE should be shifted up to allow easier substitution even given other things being equal., the substitution elasticities can be increased gradually from 2020 to 2050 for final energy users including households and production sectors. Since electricity can be generated from both fossil fuels and renewable energy, then the substitution elasticities between fossil-fuels and renewable electricity can also be shifted up to allow renewable electricity easier to replace fossil-fueled electricity from the supply side.

Finally, the simulated pathway of CO2 emissions might still be above the NZE pathway. Hence, we could introduce another measure of reduction in the availability of natural resources for fossil production. For example, we can assume that natural resources available for fossil fuel production are gradually reduced by ~5% yearly from 2020 to

2050. We can also assume certain difference between the simulated emissions and the NZE emissions to be removed by BECCS or DACCS.

We will distinguish between measures across sectors and regions if possible. However, it is unlikely for GRACE to consider all the sectoral measures in Section 4 as the model is a macroeconomic model abstracting from considerable details at the sectoral level. For example, there are only three transport sectors in the model: air, water and other transport.

Currently there is no simulation of removals of emissions in the model. We plan to introduce a simple module to capture CCS. Another option is to assume that CCS follows an exogenous pathway to remove CO_2 over time based on other studies, which means that the model allows additional emissions from fossil fuel use equivalent to the exogenous amount of CO_2 removals.

4.2 Measures in FRISBEE

FRISBEE is a partial equilibrium model of the global energy markets. The model covers coal, oil, gas and bio, and further, electricity generation based on either of the fossil fuels or non-fossil feedstock, assisted by a transformation sector. For each energy good global demand equals supply.

The demand side has two final end-users: industry and households (incl. services). The intermediate users are the power sector, heat sector and CHP sector (combined cycle heat and power sector). As FRISBEE only have one industry and an aggregated household sector it will be hard to consider most of the sectoral measures listed above in Section 3. Hence, instead of directly considering these detailed sectoral measures, we introduce measures that is better suited for the model.

To reach the consumption profiles in NZE, we will first introduce the corresponding estimated CO2-prices for each sector/region as shown in the Appendix and study the effects on consumption of each fossil fuel. Then we may increase the CO2 tax further to capture other national policies targeting energy related emissions.

In addition, we will introduce the regional exogenous volumes of non-fossils (renewables and nuclear) in electricity generation according to NZE. Prior to that we may have to increase the supply of electricity to align with the relatively high electricity demand in NZE compared to the STEPS baseline scenario, which is calibrated to the Stated Policy Scenario (STEPS) in IEA (2019) where population, labour supply and GDP of Norway is replaced by data from KVARTS (Cappelen et al. 2021). This can be done by lowering the costs of electricity production or increasing the substitution possibilities between fossil fuels and electricity (through higher cross-price elasticities in both households and industries.

We will introduce the exogenous amount of bioproducts in households and industry (making some assumptions of the volumes that correspond to NZE). As the present model is without hydrogen supply and demand, and we may also want to introduce exogenous amounts of hydrogen in households and industry in line with NZE).

To reach the demand for a specific fuel in our baseline scenario STEPS, we adjusted the income elasticity of the specific fuel. This is of course an option also when we will align (further) with the energy development in NZE (but do not strive for a perfect hit). When we change the elasticities to reach NZE, we must be careful that this may entail lowering the costs of mitigating emissions from fossil fuels to an extent that may be unrealistic.

Energy efficiency is highlighted in NZE. To increase the amount of electricity demand, we might want to increase the autonomous energy efficiency improvement (AEEI) in the demand for electricity. Further, If the simulated demand of the various energy goods in the different regions is far off targets according to NZE, we might want to adjust relevant parameters values on the supply side (for gas we had to change parameters also on the supply side to get closer to the baseline demand in STEPS). (Remembering that measures on the consumer side also will affect production in most cases.)

On the producer side will first insert the corresponding (exogenous) crude oil price from NZE. To lower the regional investment and production profile in line with NZE for oil and gas we might want to reduce the amount of undiscovered resources in a region (or the amount of discovered, but not developed reserves), increase taxes and/or increase the required rate of return.

Natural gas demand overshot the level in STEPS. To adjust supply, we increased the capital cost (or rather increased the rate of cost increase wrt. accumulated supply, i.e. we increased depletion effect). When it comes to oil and gas, other parameters affecting capital and operational costs could also be altered.

To lower coal supply we may want to increase the effect of accumulated supply on costs, and maybe also reduce technological progress.

Regional electricity production can be adjusted by changes in fuel efficiency (conversion rates) and generation costs.

4.3 Measures in KVARTS

KVARTS is a large scale macro-econometric model of the Norwegian economy. It is a recursively dynamic model with a flexible dynamic structure specified to capture both quarterly and more long run features of the Norwegian economy. 11 private industries are specified including crude oil and natural gas exploration and electricity production. Currently Norway relies to a very large extent on electricity from hydro power and some wind power production that made up 8 percent of total production in 2021. No coal or natural gas is used for production of electricity and Norway has no nuclear power production/plants. For each industry as well as the household sector, electricity and fuels are substitutes in production/consumption. The aggregated energy use is further aggregated to total material inputs which then is aggregated with a value added of labor and capital. Factor specific technological progress has been included in the model to make the model more similar to GRACE and FRISBEE. Electricity is produced using factor inputs just as any other industry. Norway has a surplus of electricity that is currently being exported (net) to other European country trough pylons to the UK, Sweden, Germany etc. As demand for hydro power is increasing in order to substitute fuels it is expected that the net surplus of electricity may disappear before 2030 unless the increase in output becomes larger than what is currently planned. The use of biofuels is limited but expected to increase.

Referring to Section 4.1 earlier we implement the following policies in the KVARTS simulations. First CO2 taxes will be raised. A detailed treatment of indirect taxes is specified in the model among which is the CO2 tax. Next, we implement factor specific technological progress in the use of energy to accommodate the assumption in GRACE. We can also increase the elasticity of substitution between electricity and fuels in industries.

4.4 Consistency of measures among the three models

Table 1 summarizes the measures in the three models listed above. In the three models, the same CO2 taxes (or prices) will be adopted. In FRISBEE, additional CO2 taxes may be introduced to capture other mitigation policies.

In the models we can introduce certain efficiency measures in final energy use although GRACE and KVARTS have several industrial sectors while FRISBEE has only one industry sector. It is possible for GRACE and KVARTS to consider certain sectoral measures listed in Section 3. All three models have one household sector where we can introduce energy efficiency improvement.

The values of elasticities between products can be adjusted in all the models. Income elasticity of both household and industry consumption of final energy can be adjusted in FRISBEE, while the substitution possibilities are adjusted by varying cross-price elasticities. Substitution elasticities between the various energy goods can be adjusted in GRACE and KVARTS.

In electricity generation, the unit costs of both fossil-fueled and non-fossil-fueled technologies can be adjusted in al the models. Non-fossil-fueled electricity generation is exogenous in FRISBEE while endogenous in GRACE as a whole. In GRACE, the fossil-fueled electricity generation can be set t an upper limit. In FRISBEE, the conversion rates of fossil fuels in electricity generation can also be adjusted.

To lower supply of fossil fuels, all the models can reduce the available natural resources and adjust technological progress.

Currently all the three models assume exogenous bioenergy and hydrogen production and consumption although a hydrogen module is planned at least for the GRACE model later.

Table 1. Possible measures to achieve a 1.5C scenario in three models of GRACE, FRISBEE, and KVARTS

Measure	**GRACE**	**FRISBEE**	**KVARTS**
1. CO2 taxes/prices	Yes	Yes	Yes
2. Efficiency in final energy use			
Energy-augmented technological progress	Yes		Yes
Autonomous energy efficiency improvement (AEEI)		Yes	
3. Adjust values of elasticities			
Shift elasticity of substitution between power generated from fossil fuels and non-fossil fuels	Yes		
Shift elasticity of substitution between energy goods in final energy use	Yes		Yes
Adjust substitution between energy goods by varying the cross-price elasticities		Yes	
Adjust income elasticity of fuels used by households and industry		Yes	
4. Power generation			
Adjust fuel efficiency (conversion rates)		Yes	
Adjusting unit cost of power generation	Yes	Yes	Yes*
Introduce upper limit of thermal power generation	Yes		Yes*
Exogenous non-fossil power generation	No*	Yes	No*
5. Fossil fuel production			

Measure	GRACE	FRISBEE	KVARTS
Lower available natural resources for fossil production (e.g. reduce undiscovered reservoirs)	Yes	Yes	Yes*
Increase the required rate of return of oil and gas producers to lower investment		Yes	
Increase capital and/or operational costs		Yes	
Lower technological progress in fossil fuel production	Maybe	Yes	Maybe
7. Exogenous bioenergy and hydrogen	Yes*	Yes[2]	Yes

* This might be changed later along with further modeling development.

Any measure we introduce to the three models above would directly or indirectly affect the first three of four mitigation channels identified in Section 3 (the fourth channel can be affected by BECCS or DACSS, which is exogenous in the current version of the models). For example,

- Carbon taxes disturb relative prices between fossil fuels and other products, which discourage production of fossil fuels and promote production of renewable electricity. The additional energy costs due to carbon taxes induce less energy use for a given economic activity. Consumers are motivated to use less fossil fuels and more renewable electricity.
- The advance of energy-augmented technologies in production sectors can reduce energy use (fossil fuels or renewables) to produce a given amount of a product, improving energy efficiency. The reduction in energy use leads to lower energy prices if energy is supplied at the same level as before, which implies lower production costs, motivating producers to expand their production activities. The technological advance might also lead to changes in relative prices between fossil fuels and renewables, which then affect the substitution between the energy carriers. Likewise, improvement in energy efficiency in electricity consumption of both household and industries will increase electricity consumption for given income and prices.
- A reduction in the availability of natural resources for fossil production lowers the production of fossil fuels, which push their prices higher and discourage the use of the fossil fuels and indirectly encourage the use of renewables. The general higher energy prices would induce producers and consumers to use less energy for a given economic activity, meaning improving energy efficiency.

[2] At present only bioenergy is modelled.

5. Concluding remarks

In this report, we associate a 1.5°C scenario with a pathway corresponding to the CO2 emissions from fossil fuels use as presented in the NZE scenario of IEA (2021). After reviewing available measures to achieve a 1.5°C scenario, we explain how the 1.5°C scenario can be simulated by three models (GRACE, FRISBEE, and KVARTS) in this project from a calibrated baseline scenario (Cappelen et al. 2021). For the global models GRACE and FRISBEE, we try to reach the global NZE target in 2050, while for KVARTS we try to reach the target for Norway in 2050.

The next step will be to examine alternative combinations of the possible measures in each of the three models and decide the most plausible combination to achieve the chosen 1.5C scenario as described in Section 1 based on a measure of cost efficiency or some other criteria.

We will take the NZE variables for Norway that comes out of GRACE and FRISBEE and implement in the KVARTS model, i.e., oil and gas production profiles and investment profiles; oil and gas prices; and GDP for other countries from GRACE to define export possibilities. KVARTS will have hydrogen supply which we take from GRACE.

6. Appendix. Estimated CO2 prices for electricity, industry and energy production in the NZE scenario (IEA 2021).

All scenarios consider the effects of other policy measures beside CO2 pricing, such as coal phase-out plans, efficiency standards and renewable targets (IEA 2021). As these policies interact with carbon pricing; it is important to emphasize that CO2 pricing is not the marginal cost of abatement as is often the case in other modelling approaches (NGFS, 2021). For example, many emerging market and developing economies in the NZE are assumed to implement a variety of direct policies to transform their energy systems and so the level of CO2 prices is lower there than elsewhere. Nonetheless, according to the IEA (2021) CO2 prices provide an important backstop for fuel switching and for some investment decisions in sectors and countries that have few other policies to reduce emissions. It is also assumed that parallel policies are introduced to avoid differences in CO2 price levels leading to the relocation of industrial (and other) activities. CO2 prices are applied to other non-CO2 emissions, such as methane.

In the NZE, for example, carbon prices are in place in all regions, rising by 2050 to an average of USD 250/tonne CO2 in advanced economies, to USD 200/tonne CO2 in other major economies (in China, Brazil, Russia and South Africa), and to lower levels elsewhere. We have estimated the CO2 prices for the regions in our global models which are not covered by IEA (2021)[3].

Table 2. Estimated CO2 prices for electricity, industry and energy production in selected regions in scenario "Net Zero Emissions by 2050". USD (2020) per tonne of CO2.

Region		2030	2040	2050
NOR	Norway	130	205	250
UKI	United Kingdom	130	205	250
WEU	Western Europe	130	205	250
EEU	Eastern Europe	115	189	231
USA	United States of America	130	205	250
CAN	Canada	130	205	250
OEP	OECD Pacific regions including South Korea and Taiwan	130	205	250

[3] The estimations can be obtained from the authors upon request.

Region		2030	2040	2050
ANZ	Australia and New Zealand	130	205	250
JPN	Japan	130	205	250
RUS	Russia	90	160	200
CAR	Caspian region	15	35	55
OPC	OPEC Core region including Kuwait, Qatar, Saudi Arabia, and United Arab Emirates	15	35	55
OPR	OPEC Rest region including Algeria, Angola, Gabon, Iran, Iraq, Libya, Nigeria, and Venezuela	15	35	55
CHI	China	90	160	200
RAS	Rest of Asia	25	50	72
AFR	Africa	49	92	121
BRA	Brazil	90	160	200
LAM	Latin America	78	128	162

References

Aaheim, A., A. Orlov, T. Wei and S. Glomsrød (2018). GRACE model and applications. Report. Oslo, Norway, CICERO. **2018:01**.

Aaheim, A. and N. Rive (2005). A Model for Global Responses to Anthropogenic Changes in the Environment (GRACE). Report. Oslo, Norway, CICERO. **2005:05**.

Biørn, E., M. Jensen and M. Reymert (1987). "KVARTS-a quarterly model of the Norwegian economy." Economic Modelling **4**(1): 77-109.

Boug, P., T. v. Brasch, Å. Cappelen, R. Hammersland, H. Hungnes, D. Kolsrud, J. Skretting, B. Strøm and T. Vigtel (2022). "Fiscal policy, macroeconomic performance and the industry structure in a small open economy." Discussion paper (forthcoming).

Cappelen, Å., S. Glomsrød, L. Lindholt, K. E. Rosendahl and T. Wei (2021). Stress-testing the Norwegian economy: The effects of the 1.5°C scenario on global energy markets and the Norwegian economy, Statistisk sentralbyrå**:** 46.

ETC/CME. (2021). "Overview of reported national greenhouse gas policies and measures in Europe in 2021." Retrieved 19 Jan., 2022, from https://www.eea.europa.eu/themes/climate/national-policies-and-measures.

IEA (2019). World Energy Outlook 2019. International Energy Agency.

IEA. (2021). "Net Zero by 2050: A Roadmap for the Global Energy Sector." Retrieved 19 Jan., 2021, from https://www.iea.org/reports/net-zero-by-2050.

Lindholt, L. and S. Glomsrød (2018). "Phasing out coal and phasing in renewables – Good or bad news for arctic gas producers?" Energy Economics **70**: 1-11. DOI: 10.1016/j.eneco.2017.12.015.

V. Masson-Delmotte, P. Z., H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, In press.

CICERO is Norway's foremost institute for interdisciplinary climate research. We help to solve the climate problem and strengthen international climate cooperation by predicting and responding to society's climate challenges through research and dissemination of a high international standard.

CICERO has garnered attention for its research on the effects of manmade emissions on the climate, society's response to climate change, and the formulation of international agreements. We have played an active role in the IPCC since 1995 and eleven of our scientists contributed the IPCC's Fifth Assessment Report.