OECD Economics Department Working Papers No. 1708

The effect of a carbon tax rise on Iceland's economy

Hansjörg Blöchliger,
Sigurdur Johannesson,
Marias Halldor Gestsson

https://dx.doi.org/10.1787/76a7eaed-en

OECD

Organisation for Economic Co-operation and Development

ECO/WKP(2022)9

Unclassified **English - Or. English**

1 April 2022

ECONOMICS DEPARTMENT

THE EFFECT OF A CARBON TAX RISE ON ICELAND'S ECONOMY

ECONOMICS DEPARTMENT WORKING PAPERS No. 1708

By Hansjörg Blöchliger, Sigurdur Johannesson and Marias Halldor Gestsson

Authorised for publication by Isabell Koske, Deputy Director, Country Studies Branch, Economics Department.

All Economics Department Working Papers are available at www.oecd.org/eco/workingpapers.

JT03492597

Abstract/Resumé

The effect of a carbon tax rise on Iceland's economy

This paper studies the potential impact of higher carbon taxation - to reach the government's emission targets by 2030 - on Iceland's economy. The paper is divided into two parts. *First*, a DSGE modelling exercise suggests that the equivalent of an oil price hike of between 30% and 55% is needed to reach the 2030 target, implying a GDP decline of between 0.3% and 0.6% by 2030. The impact on inflation would be very small. *Second*, a panel regression for the fishing industry reveals that a 40-50% oil price hike would be sufficient to reduce the entire fishing fleet's emissions by 10%, raising total factor costs for the fishing companies by 4-5%. Such a cost hike would hardly threaten the competitiveness of the fishing industry. Both approaches assume that a carbon tax rise would have no effect on production technology.

This Working Paper is an amended version of a technical background paper prepared for the 2021 OECD Economic Survey of Iceland.

JEL codes: C68, H23, Q22.

Keywords: Iceland; environmental economics; DSGE modelling; carbon tax; fisheries.

******

L'effet d'une augmentation de la taxe carbone sur l'économie islandaise

Cet article étudie l'impact potentiel d'une augmentation de la taxe sur le carbone - pour atteindre les objectifs d'émission du gouvernement d'ici 2030 - sur l'économie islandaise. Le papier est divisé en deux parties. Premièrement, un exercice de modélisation DSGE suggère que l'équivalent d'une hausse des prix du pétrole comprise entre 30 % et 55 % est nécessaire pour atteindre l'objectif 2030, impliquant une baisse du PIB comprise entre 0,3 % et 0,6 % d'ici 2030. L'impact sur l'inflation serait négligeable. Deuxièmement, une régression de panel pour l'industrie de la pêche révèle qu'une hausse du prix du pétrole de 40 à 50 % suffirait pour réduire les émissions de l'ensemble de la flotte de pêche de 10 %, augmentant ainsi le coût total pour les entreprises de pêche de 4 à 5 %. Une telle augmentation des coûts ne menacerait guère la compétitivité de l'industrie de la pêche. Les deux approches supposent qu'une augmentation de la taxe carbone n'aurait aucun effet sur la technologie de production.

JEL codes: C68, H23, Q22.

Mots-clés : Islande ; économie de l'environnement ; modélisation DSGE; taxe sur le carbone; industrie de la pêche.

Ce document de travail est une version modifiée d'un document d'information technique préparé pour l'Étude économique de l'OCDE sur l'Islande 2021.

Table of contents

Tables

Figures

Boxes

The effect of a carbon tax rise on Iceland's economy

By Hansjörg Blöchliger, Sigurdur Johannesson and Marias Halldor Gestsson [1]

Introduction

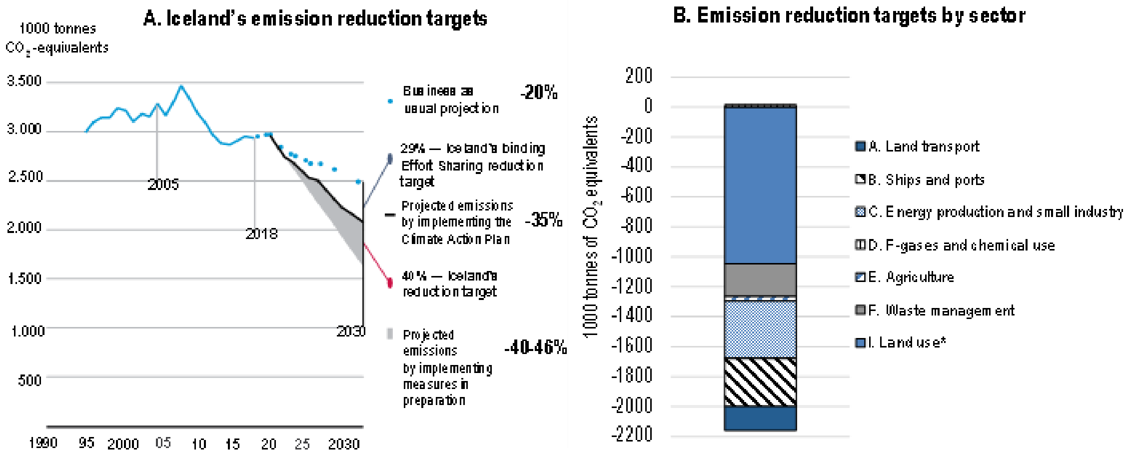
This paper studies the potential impact of a rise in the carbon tax rate on Iceland's economy. It is divided into two parts. A first part shows the results of a Dynamic Stochastic General Equilibrium (DSGE) modelling exercise to assess the impact of an economy-wide carbon tax hike on GDP and the real exchange rate. The second part is dedicated to an empirical estimation of the impact of a higher carbon tax rate on the fisheries sector, Iceland's largest oil consumer and the most important goods export sector.

The economy-wide impact of a carbon tax rise

In 2020, the Icelandic government published a Climate Action Plan that proposes a set of measures to reduce the carbon emissions Iceland is directly responsible for (Government of Iceland, 2020[1]). The action plan assumes a reduction of emissions by 40% from the 2005 level at the 2030 horizon (Figure 1). In a scenario involving a rapid transition to electric cars, emissions are projected to decline by 30-35%; this is taken as the baseline scenario in the below analysis. In a "business as usual" scenario assuming no additional policy measures, emissions are projected to decline by 20%. Heavy industry and aviation, accounting for around 40% of overall domestic emissions, are included in the EU Emission Trading System (ETS) system and therefore left out of the analysis.

[1] Hansjörg Blöchliger is member of the OECD Economics Department (ECO), Sigurdur Johannesson and Marias Halldor Gestsson are from the Institute of Economic Studies at the University of Iceland. The authors would like to thank Andrew Barker, Isabell Koske, Tobias Kruse and Patrick Lenain (all ECO), as well as Enrico Botta and Jane Ellis from the OECD Environment Directorate for valuable comments and suggestions. The paper also benefitted from comments from the OECD Economic and Development Review Committee. Particular thanks go to Gemma Martinez and Michelle Ortiz for editorial assistance.

Figure 1. Iceland wants to reduce carbon emissions by 40%

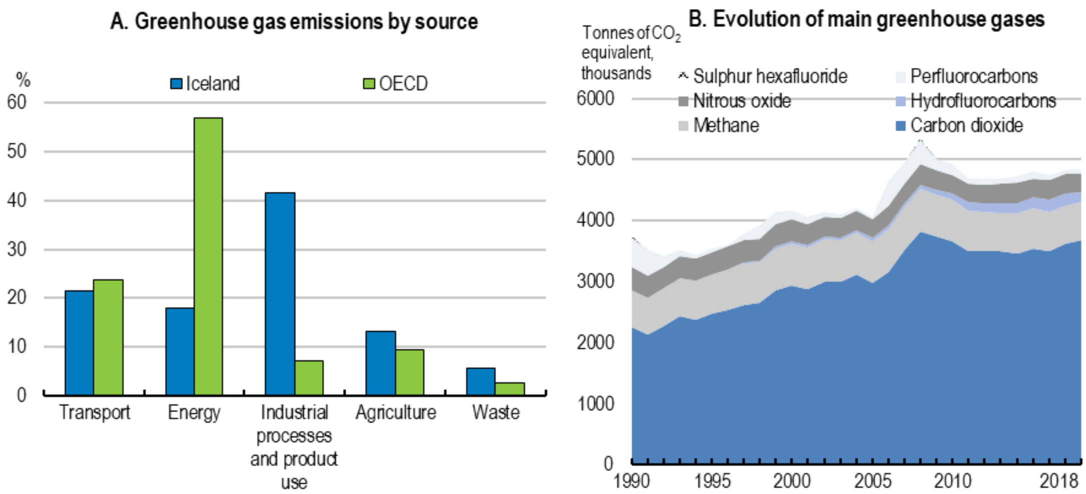


Note: * Land Use, Land-Use Change, and Forestry.
Source: Ministry of Environment and Natural Resources, Iceland's 2020 Climat Action Plan.

Assumptions underlying the carbon tax rise

Emissions from the non-ETS industrial sector - mainly land transport and fisheries - have dropped by 20% between 2005 and 2019, largely due to a fall in oil consumption of fishing vessels, which at least partly reflects new vessels' increased fuel efficiency (Working Group on the Fisheries, 2021[2]). The demand for electric cars or hybrids is growing fast. Using the official 2016 Energy forecast (Energy Forecasting Committee, 2016[3]) for cars´ use of gasoline and a recent forecast for the oil consumption of fishing vessels (Institute of Economic Studies, 2020[4]), overall businesses' carbon emissions are projected to decline by 25-30% between 2005 and 2030 (Energy Forecasting Committee, 2016[3]). In the event of a faster transition to electric cars, prompting a 70% rather than a 30% fall in emissions from the transport sector, business emissions not covered by the ETS would fall by 30-35%. Overall, carbon dioxide emissions from industrial sources still dominate the emission profile (Figure 2).

Figure 2. Industry – mainly land transport and fisheries – contributes most to carbon emissions



Note: Data in panel A refer to 2018.
Source: OECD Environment Statistics database.

The analysis carried out in this paper assumes that the additional 5-10% fall in emissions needed to meet the government target (i.e. to go from a 30-35% to a 40% cut), will be achieved through higher or new carbon taxes. Carbon taxes were introduced in 2009 in Icelandic law, and they have been raised in recent years, with around 57% of carbon now taxed at 60 Euro/tonne or more through the combined effect of the trading system, the carbon tax and excise taxes on energy use. The analysis below simulates an increase from their present level, coupled with new taxes on all carbon emissions, including, for instance, emissions from agriculture, which are, for the most part, not covered by carbon taxes today.

The effect of a carbon price hike on emissions is expressed in the form of price elasticities, assuming that the reaction to a price hike following higher oil prices and a price hike following higher carbon taxes is the same. The unweighted average of the estimated elasticities for all industries is close to -0.3, meaning that a 1% price increase in oil leads to a 0.3% fall in the oil demand of businesses, as estimated in an earlier study (Institute of Economic Studies, 2020[5]). These price elasticity coefficients are then used in the model to assess emission reductions. The margin of uncertainty surrounding the estimate is high, but the estimate is not far away from the results of studies from other countries, using similar methods.[2]

The carbon price trajectory

For simulation purposes, a small open economy DSGE model is used consisting of households (individuals) and firms. Households work, earn labour income, buy domestic and foreign (imported) goods and services, and save by investing in the capital stock and buying foreign bonds. Firms produce goods and services for sale in the domestic and foreign (export) market and use labour and capital, which they rent from the households, and oil as inputs in production. There are no adjustment costs in the model and, hence, it does not include incomplete price adjustment nor capital adjustment costs. Hence, the model does not reflect demand shifts other than those resulting from the carbon tax hike. The Appendix provides a detailed description of the model.

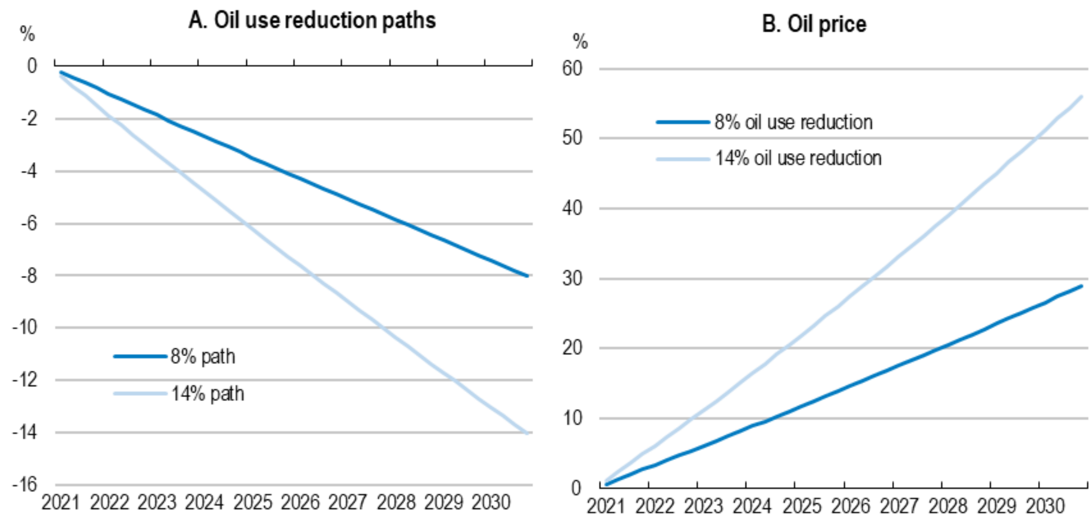
Modelling the impact of carbon tax rises usually requires running a multi-sector computable general equilibrium (CGE) model to capture the heterogeneity of economic sectors. However, such a model does not exist for Iceland. The only existing general equilibrium model of the Icelandic economy is the Central Bank of Iceland’s DSGE model, which is used here (Thorarinsson, 2020[6]). The model features only one sector and one type of fuel, which is oil, accounting for around 90% of energy-related carbon emissions in Iceland (geothermal energy – responsible for carbon leakage when magma chambers are harnessed - accounts for another 9%). The simulations are therefore conducted assuming the same oil price elasticity and the same production technology, including oil use, for all industries in Iceland. This simplification limits the reliability of the simulation results, although it can be argued that oil price elasticity averaged across all industries provides a roughly adequate picture of an economy-wide reduction of oil consumption after a price hike. Still, to account for the limits of Iceland’s DSGE, a sensitivity analysis is carried out. Finally, since the model applies oil price rather than carbon tax elasticities, the required oil price hike needs to be translated into a carbon tax rise using an oil-specific carbon content coefficient.

As mentioned above, emissions are expected to decline by 30-35% under the baseline (no additional carbon price hike) scenario. Against this background, two policy scenarios are estimated. If emissions are assumed to decline by 30% with no further policy action, oil consumption will have to decline by an additional 14% to reach the overall objective of a 40% reduction. If emissions are assumed to decline by 35% with no further policy action, oil consumption will have to decline by 8%. The simulations assume a linear reduction in oil consumption by Icelandic industries over 2021-30 such that consumption in the fourth quarter of 2030 will be 14% (8%) lower than if no additional carbon taxation was introduced. The two

[2] For example, Enevoldsen, Ryelund and Skou Andersen (2007) estimated the elasticity of oil demand in a pooled translog model for nine to 14 industries in Denmark, Sweden and Norway, using data from 1990 to 2003, and found it to vary from -0.4 to -0.6 across the three countries (Enevoldsen, Ryelund and Skou Andersen, 2007[6]).

carbon tax and oil use reduction trajectories are presented Figure 3. Thus, the oil price needs to rise by 55% (30%) by the fourth quarter of 2030 to meet the emission target. Transforming oil prices into carbon prices by applying a total CO_2 content of around 2.39kg/litre of oil yields a carbon price per ton of between 37 000 Isl. kr. (230 Euro)/tonne (30% oil price hike) and 64 000 Isl. Kr. (420 Euro)/tonne (55%).For comparison: an Icelandic firm captures and stores ambient CO_2 at around 1000 Euro/tonne (Financial Times, 2021[7])

Figure 3.Oil consumption and oil price trajectories

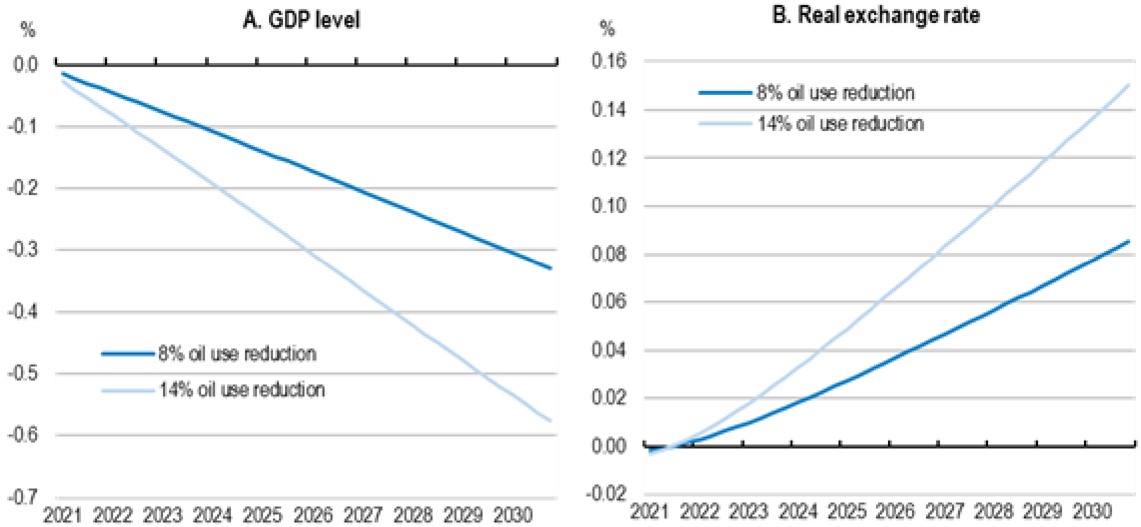


Source: DSGE model simulations.

Impact on the economy

The following figure shows the effects of the carbon tax hike and oil use reduction on GDP and the real exchange rate (Figure 4). According to the simulation, GDP will be approximately 0.6% (or 0.3%) lower and the real exchange rate – reflecting higher import prices - 0.16% (or 0.08%) higher in the fourth quarter of 2030 than in the baseline scenario with no additional carbon tax. Model results suggest that a carbon tax rise in the range of the estimated above has hardly any inflationary impact, similar to empirical results obtained for Europe and Canada (Konradt and Weder di Mauro, 2021[8]).

Figure 4. Effect of a carbon tax rise on GDP and the real exchange rate



Source: DSGE model simulations.

Sensitivity analysis

As noted above, there is considerable uncertainty concerning the production side of the economy in the simulations above. The most important parameters in this context are the price elasticity of oil and the oil cost share in domestic production, which are assumed to be -0.3 and 0.02 in the above simulations, respectively. Tables 1 and 2 show how changes in these parameters affect the simulation results for the 8% oil use reduction path.

Table 1. Sensitivity analysis for the carbon tax rate

Carbon tax rate at the end of 2030 – 8% oil reduction path						
		Cost share				
		1.0%	1.5%	**2.0%**	2.5%	3.0%
Elasticity	-0.2	48%	47%	47%	46%	45%
	-0.25	37%	37%	36%	36%	35%
	-0.3	30%	30%	**30%**	29%	29%
	-0.35	26%	25%	25%	25%	25%
	-0.4	22%	22%	22%	22%	21%

Note: parameter values and results of the above simulation are in bold.
Source: Modelling approach described in the text.

Table 2. Sensitivity analysis for the impact on GDP

GDP in the end of 2030 - 8% oil use reduction path						
		Cost share				
		1.0%	1.5%	**2.0%**	2.5%	3.0%
Elasticity	-0.2	-0.2%	-0.3%	-0.4%	-0.5%	-0.6%
	-0.25	-0.2%	-0.3%	-0.4%	-0.5%	-0.5%
	-0.3	-0.2%	-0.2%	**-0.3%**	-0.4%	-0.5%
	-0.35	-0.1%	-0.2%	-0.3%	-0.4%	-0.4%
	-0.4	-0.1%	-0.2%	-0.3%	-0.3%	-0.4%

Note: parameter values and results of the above simulation are in bold.
Source: Modelling approach described in the text.

The tables show simulation results for the carbon tax rate and GDP at the end of 2030 for various parameter values for the oil price elasticity and the oil cost shares. The GDP simulations results are more sensitive to the oil cost share parameter while the carbon tax rate simulations results are more sensitive to the oil price elasticity parameter. The sensitivity analysis shows that the simulation results for GDP are in the -0.1% to -0.6% range while the simulation results for the carbon tax rate are in the 21% to 48% interval for the chosen parameter value intervals (oil price elasticity: -0.2 to -0.4; oil cost share: 1 to 3%). Oil price elasticities are assumed to remain constant over time, i.e. a rise in the carbon tax is assumed to have no impact on production technologies. Under a more realistic scenario, a higher carbon tax would trigger innovation especially in the area of propulsion technologies such as vessels powered by electrical batteries, hydrogen or methanol. Under such a scenario, more and cheaper substitues for oil would be available, hence price elasticity would rise and the carbon taxes required to reach a certain emission target would be smaller, with a smaller impact on GDP (Box 1).

Box 1. Innovation in vessel propulsion technologies

The empirical analysis above is carried out using historical short-term price elasticities for fuel use, which essentially rely on fuel savings obtained by limiting the speed of the vessel and by reducing the time used for searching for catch. Yet fuel can also be saved by using new technology and by building more energy-efficient ships, such as by designing engines that use less oil and by streamlining the ship's shape. In particular, a considerable rise in carbon taxes is likely to trigger a more active search for alternative energy sources and propulsion technologies.

Recent research and innovation might highlight the potential but also the limits for substituting oil for other energy sources. A new ferry sailing since 2021 to the Westman Islands, off Iceland's south coast, is partly battery powered. The battery lasts 40 minutes and saves 90% of current oil use, according to the ferry company. In spring 2021 there were 87 electrically powered vessels in Norway, a little more than 1% of the total fleet, with most of them being ferries and only a few fishing boats (Norsk Rikskringkasing AS (NRK), 2021[9]). Although the price of batteries – the largest part in the cost of powering vessels with electricity - is declining by 13% per year, battery-driven electric operation might cover only a small portion of the fishing fleet´s energy consumption in the coming decades, mainly because energy density of batteries is still much below that of other fuels. Against this background, batteries do not provide sufficient range needed for high-sea fishing (Ziegler and Trancik, 2021[10]). By the end of 2021, there were no electric fishing vessels operating in Iceland.

Other energy sources could be more promising. The Icelandic Ministry of Industries and Innovation in 2021 published a report on energy carriers such as ammonium, hydrogen or methanol, which are considered more feasible in propelling fishing vessels (Samorka; Ministry of Industries and Innovation; Associated Icelandic Ports and Fisheries, 2021[11]). Regardless of whether electric or gas-powered propulsion will prevail, research in vessel propulsion technology is likely to speed up if carbon taxes are set to rise more rapidly than in the past. Against this background, current long-term price elasticity assumptions are probably at the upper bound, implying that a given emission target would require a smaller carbon tax rise and hence entailing a smaller impact on GDP than assessed in the above empirical exercise.

Carbon taxation of Iceland's fisheries: an impact assessment

The Government Climate Action Plan foresees a reduction in carbon emissions from fisheries by 50 to 60% by 2030 compared to their 2005 level (Government of Iceland, 2020[1]). From 2005 to 2019 overall oil consumption of fishing vessels fell by almost 35%, mainly thanks to technological innovations, the use of larger ships and a smaller catch. According to the Institute of Economic Studies (2020a) forecast, fisheries' oil consumption will fall by around 12% from 2019 to 2030 with current policy settings, implying a reduction of close to 45% from the 2005 level. A further 10-30% reduction in fuel consumption would be needed to reach the government's goal of a 50-60% reduction in emissions from the 2005 level. Against this background, the extent of the increase in carbon taxes on fisheries required to reach that objective is quantified below.

The oil price elasticity in fisheries is estimated using a similar model as the one used in the 2020 study discussed earlier (Institute of Economic Studies, 2020[5]), covering the years 1997-2019. The fishing fleet is divided into six vessel categories: 1) boats of 0-10 tonnes; 2) boats of 10-200 tonnes; 3) boats of 200 and more tonnes; 4) pelagic fishing ships, 5) icefish trawlers; and 6) freezer trawlers. In general, ships and trawlers are larger than boats, with longer expected duration of each fishing episode. Average fuel consumption of boats varies from slightly below 6½ per cent of total costs for the smallest to a little over

8% for the largest. For the larger vessels average fuel consumption varies from slightly over 12% to a little less than 13% of total costs.

Based on these fuel cost shares, the six vessel categories are divided into two groups: a) boats and b) larger vessels. Two pooled translog models are estimated, each using panel data for three vessel categories for 1997-2019. The cost shares of oil, capital and labour are estimated using ordinary least squares (OLS). Since the input shares sum to 1, the cost share of the fourth input (other inputs) is not estimated independently, to avoid collinearity. The estimated equation reads as follows:

$$s_{ij} = \alpha_{ij} + \sum_{i=1}^{4} \beta_{ij}\, lnw_i + \sum_{i=1}^{4} \gamma_{ij}\, s_{ij(t-1)} + \delta_{ij} lny_j + \eta_{ij} t + \epsilon_{ij},$$

where s_{ij} is the current cost shares of input *i* for vessel type *j*, α_{ij} is a constant, w_i are the current prices of input *i*, $s_{ij\,(t-1)}$ are the cost shares of inputs for the previous year, introducing dynamics to the system, y_j is the price corrected production level for vessel type *j*, allowing for a non-homothetic production function, and *t* is a time trend, allowing for changing production technology. The system covers nine (9) equations, with some restrictions on the coefficients, reflecting for instance that cost shares are homogenous of degree zero in factor prices, and the symmetry of price effects on cost shares.

Since estimates of long-term price elasticities can easily become unstable, only estimates of short-term elasticities are reported.[3] As noted earlier, the three categories of boats are pooled together and estimated as a group, as are the three categories of bigger vessels. Results can be summarized as follows:

- The fuel price elasticity for boats is actually positive (0.10) yet highly insignificant (standard error 0.18), so we conclude that price elasticity of fuel is low for boats. Fuel consumption of boats seems to be less sensitive to changes in fuel prices than that of the larger vessels, probably because fuel consumption is a considerably smaller part of total costs.
- Estimated own price elasticities for various inputs for the larger vessels (pelagic fishing ships, ice fish trawlers and freezer trawlers) are shown in Table 3. The pooled elasticity is estimated using 66 observations (3 vessel categories times 22 years = 66 observations). The last column in Table 3 shows the standard error of the estimate, implying that the 95% confidence interval for the uncompensated short-run price elasticity of fuel for the larger fishing vessels is -0.23 to -0.61.

Table 3. Fuel, capital and labour input elasticities of larger fishing vessels

	Uncompensated, short-run own price elasticity	Standard error
Fuel	-0.42	0.09
Capital	-1,18	0.07
Labour	-1,07	0.03

Source: Estimations described in the text.

The estimated oil price elasticity is not far from recent estimates from other countries, albeit towards the lower end. Indeed, in a Swedish survey analysing Baltic trawl fishing for cod, the price elasticity for fuel was estimated at -0.4. An Italian study on trawl fisheries found the fuel elasticity to be -0.5 (OECD, 2018[12]). A lower elasticity means that a higher tax is needed to reach the government carbon emission reduction goal.

The extent to which higher carbon taxes might hurt the fishing industry depends on capital cost in the industry and the additional emission reductions to be achieved. Statistics Iceland estimates the capital cost in the fisheries industry at 6% of the capital stock, which covers both depreciation and other capital costs. In order to achieve additional emission reduction of 10%, the fuel price needs to rise by almost 30%,

[3] See (Edgerton, 1996[14]), p. 67-68.

requiring a four-to-fivefold increase of the carbon tax from the current level.[4] Such a carbon tax hike would increase the total costs of the larger fishing vessels by 2%-4%, which would probably not undermine the competitiveness of Icelandic fisheries, insofar as the latter extract considerable economic rent from exploiting a resource with limited access. However, the larger vessels only account for 70-75% of all fuel used by fishing vessels. Assuming, as estimated above, that smaller boats' fuel use is little or not sensitive to price changes, a 40-50% price rise in fuel is likely needed to reduce the entire fishing fleet's emissions by 10%. That would raise total costs by 4-5% for the fishing companies. However, a carbon tax aiming for an additional 20% or 30% - rather than 10% - reduction in carbon emissions could seriously harm the industry's competitiveness as it could imply a rise of total cost of 10-20%.

[4]This follows the formula $\Delta E = 1 - (1 + \Delta p)^{-0.42}$ where ΔE is the emission reduction to be achieved, Δp the fuel price increase in per cent and -0.42 the price elasticity for fuel.

References

Edgerton, D. (1996), *The Econometrics of Demand Systems*, Kluwer. [14]

Energy Forecasting Committee (2016), *Energy Forecast 2016-2050 (in Icelandic)*, https://orkustofnun.is/eldsneyti/eldsneytisspa/2016/. [3]

Enevoldsen, M., A. Ryelund and M. Skou Andersen (2007), "Decoupling of industrial energy consumption and CO2-emissions in energy-intensive industries in Scandinavia", *Energy Economics*, Vol. 29. [13]

Financial Times (2021), *World's biggest 'direct air capture' plant starts pulling in CO2*, https://on.ft.com/3EzEQAz. [7]

Government of Iceland (2020), *Climate Action Plan*, https://www.stjornarradid.is/library/02-Rit--skyrslur-og-skrar/Adgerdaaetlun%20i%20loftslagsmalum%20onnur%20utgafa.pdf. [1]

Institute of Economic Studies (2020), *A Preliminary update of the fuel consumption forecast 2020-2035 (in Icelandic)*, https://www.stjornarradid.is/library/02-Rit--skyrslur-og-skrar/Br%C3%A1%C3%B0abirg%C3%B0auppf%C3%A6rsla%20%C3%A1%20sp%C3%A1%20um%20eldsneytisnotkun%20%C3%AD%20sj%C3%A1var%C3%BAtvegi%202020-2035.pdf. [4]

Institute of Economic Studies (2020), *The effect of the carbon tax on households and firms (in Icelandic)*, http://hhi.hi.is/sites/hhi.hi.is/files/sjz/kolefni_23.6_2020_2.pdf. [5]

Konradt, M. and B. Weder di Mauro (2021), "Carbon Taxation and Inflation: Evidence from the European and Canadian Experience", *Center for Economic Policy Research Working Paper 16396*, https://ssrn.com/abstract=3928675. [8]

Norsk Rikskringkasing AS (NRK) (2021), *Mindre enn én prosent av båtene i Norge er elektriske: Det skjer altfor lite*, https://www.nrk.no/trondelag/mindre-enn-en-prosent-av-batene-i-norge-er-elektriske_-_-det-skjer-altfor-lite-1.15366167. [9]

OECD (2018), *Informing Fisheries-Related Trade Negotiations. Relative Effects of Fisheries Support Policies, Annex D: Elasticities of substitution and factor supply in the fisheries sector for use in the OECD Fisheries Policy Evaluation Model (FishPEM)*, OECD, Paris. [12]

Samorka; Ministry of Industries and Innovation; Associated Icelandic Ports and Fisheries (2021), *Pathways for Decarbonization of the Icelandic Maritime Sector*, https://samorka.is/wp-content/uploads/2021/12/Decarbonization-IMS_Final-Rev2.pdf. [11]

Thorarinsson, S. (2020), "DYNIMO – Version III. A DSGE Model of the Icelandic Economy", *Central Bank of Iceland Working Paper 84*. [6]

Working Group on the Fisheries (2021), *Green steps in the fishing industry (in Icelandic)*. [2]

Ziegler, M. and J. Trancik (2021), "Re-examining rates of lithium-ion battery technology improvement and cost decline.", *Energy & Environmental Science, 14(4), 1635-1651)*.. [10]

Annex A. The adapted DSGE model

The model is a standard small open economy DSGE model adapted from the Central Bank of Iceland DSGE model (Thorarinsson, 2020). In the model, perfectly flexible prices and no adjustment costs for capital etc. are assumed. The only non-standard element in the model is the production process.

Production

The production process is in two steps.

First, an intermediate input Q is produced using capital K and labor N where a Cobb-Douglas production technology is assumed:

$$Q_t = K_t^{\alpha} N_t^{1-\alpha}, \alpha \in (0,1)$$

Second, domestic goods Y_H are produced using intermediate inputs and oil Z where a CES production technology is assumed:

$$Y_{H,t} = \left[\gamma_Q Q_t^{\frac{\varepsilon-1}{\varepsilon}} + \gamma_Z Z_t^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}, \gamma_Q > 0, \gamma_Z > 0$$

where $\varepsilon > 0$ is the elasticity of technical substitution between intermediate inputs and oil (or the numerical value of the demand price elasticity for intermediate inputs and oil).

In the production of intermediate inputs, capital and labour are chosen such that the cost of production is minimized. This gives the equilibrium condition:

$$\frac{R_t^K}{W_t} = \frac{\alpha N_t}{(1-\alpha)K_t}$$

where R^K is the real rental price of capital and W are real wages. The marginal cost in the production of intermediate inputs MC_Q is:

$$MC_{Q,t} = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}(R_t^K)^{\alpha} W_t^{1-\alpha}$$

In the production of domestic goods, intermediate inputs and oil are chosen such that the cost of production is minimized. This gives the equilibrium condition:

$$\left(\frac{P_{Z,t}}{MC_{Q,t}}\right)^{\varepsilon} = \gamma_Q^{-\varepsilon} \gamma_Z^{\varepsilon} \frac{Q_t}{Z_t}$$

where P_Z is the real price of oil. The marginal cost in the production of domestic goods MC is:

$$MC_t = \left[\gamma_Q^{\varepsilon} MC_{Q,t}^{1-\varepsilon} + \gamma_Z^{\varepsilon} P_{Z,t}^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}}$$

Equilibrium conditions

After deriving the equilibrium conditions (first-order conditions for households and firms and market clearing conditions), the model is linearized by a first-order approximation to a non-stochastic steady state assuming zero net holding of foreign bonds and balanced foreign trade. This gives the following equilibrium conditions:

Households:

$$k_{t+1} = (1-\delta)k_t + \delta i_t$$

$$b_{t+1} = \frac{1}{\beta} b_t + nx_t$$

$$c_t = E_t[c_{t+1}] - r_t$$

$$k_{t+1} = (1-\delta)k_t + \delta i_t$$

$$s_t = E_t[s_{t+1}] - (r_t - r_t^*) - \lambda_t$$

$$\lambda_t = \phi b_t$$

$$c_t = E_t(c_{t+1}) - \big(1 - \beta(1-\delta)\big)E_t[r_{t+1}^K]$$

$$w_t = \varphi n_t + c_t$$

Firms:

$$q_t = \alpha k_t + (1-\alpha)n_t$$

$$k_t - n_t = w_t - r_t^K$$

$$mc_{Q,t} = \alpha r_t^K + (1-\alpha)w_t$$

$$y_{H,t} = \gamma_Q \left(\frac{Q}{Y}\right)^{\frac{\varepsilon-1}{\varepsilon}} q_t + \gamma_Z \left(\frac{Z}{Y}\right)^{\frac{\varepsilon-1}{\varepsilon}} z_t$$

$$q_t - z_t = \varepsilon\big(p_{Z,t} - mc_{Q,t}\big)$$

$$mc_t = \gamma_Q^{\varepsilon} mc_{Q,t} + \gamma_Z^{\varepsilon} p_{Z,t}$$

$$p_{H,t} = mc_t$$

$$p_{H,t}^* = mc_t - s_t$$

$$p_{F,t} = s_t$$

$$p_{Z,t} = \tau_t + s_t + p_{Z,t}^*$$

Market clearing:

$$0 = (1-\omega)p_{H,t} + \omega p_{F,t}$$

$$y_{H,t} = (1-\omega)y_{H,t}^h + \omega ex_t$$

$$y_{H,t}^h = -\eta p_{H,t} + a_t$$

$$ex_t = -\eta p_{H,t}^* + a_t^*$$

$$im_t = -\eta p_{F,t} + a_t$$

$$nx_t = \omega\left(ex_t - im_t - p_{F,t} + s_t + p_{H,t}^*\right)$$

$$y_t = a_t + nx_t$$

$$a_t = \left(\frac{C}{Y}\right)c_t + \left(\frac{I}{Y}\right)i_t + \left(\frac{G}{Y}\right)g_t$$

where i is investment, b households' net holding of foreign bonds, nx net exports, c private consumption, r real interest rates, s the inverse of the real exchange rate, $r^*$the foreign real interest rates, λ an international financial friction variable (inducing stationarity in households' net holdings of foreign bonds), p_H the real price of domestic production, p_H^* the foreign real price of domestic production, p_F the domestic real price of imports (foreign production), τ (one plus) the carbon tax rate, p_Z^* the foreign real price of oil, y_H^h domestic production sold in domestic markets, ex exports (domestic production sold in foreign markets), a domestic expenditure, a^* foreign expenditure, im imports (foreign production sold in domestic markets), y GDP, g government consumption, δ the depreciation rate of capital, β the discount factor, ϕ an international financial frictions parameter, φ the inverse of the Frisch elasticity of labour supply, *1-*ω home bias in international trade and η the (numerical value of) the price elasticity of demand in international trade. C/Y, I/Y and G/Y are steady state values of private consumption, investment and government consumption relative to GDP and Q/Y and Z/Y are steady state values of intermediate inputs and oil relative to GDP.

Approximation

All variables except three are in deviations from their steady state values:

$$x_t = \frac{X_t - X}{X}$$

where X is the steady state value of a variable. Since net holding of foreign bonds and net exports are assumed to be zero in steady state, these variables are expressed relative to GDP:

$$b_t = \frac{B_t}{Y}$$

$$nx_t = \frac{NX_t}{Y}$$

Finally, λ is in level terms.

It is assumed that all relative prices equal unity in steady state:

$$P_H = P_H^* = P_F = P_Z = P_Z^* = 1$$

and that the carbon tax rate equals zero:

$$\mathrm{T} = 1$$

implying that:

$$S = MC = MC_Q = 1$$

since zero mark-ups over marginal costs are assumed for simplicity.

Calibration

The time frequency in the simulations is quarterly. The values for all parameters except ε, γ_Q and γ_Z were obtained from the newly estimated/calibrated Central Bank of Iceland DSGE model:

Parameter	Value	Parameter	Value
δ	0.02	α	0.4
β	0.995	ω	0.42
ϕ	0.005	η	2
φ	3		

The value of ε was set at 0.3, obtained from earlier estimations (Institute of Economic Studies, 2020[5]), while the values of γ_Q and γ_Z were set such that:

$$\gamma_Q\left(\frac{Q}{Y}\right)^{\frac{\varepsilon-1}{\varepsilon}} = \gamma_Q^{\varepsilon} = \frac{Q}{Y} = 0.98$$

$$\gamma_Z\left(\frac{Z}{Y}\right)^{\frac{\varepsilon-1}{\varepsilon}} = \gamma_Z^{\varepsilon} = \frac{Z}{Y} = 0.02$$

where 2% is the approximate ratio of oil expenditure to factor income in Icelandic industries excluding heavy industries and aviation.

Finally, we assume the following consumption, investment and government shares in GDP assuming balanced foreign trade in the steady state:

$$\frac{C}{Y} = 0.58$$

$$\frac{I}{Y} = 0.18$$

$$\frac{G}{Y} = 0.24$$

which are close to the values in the Central Bank of Iceland DSGE model (Thorarinsson, 2020[6]).

Simulation

A simulation is run assuming an oil reduction path as an exogenous change to the economy holding all other exogenous variables constant. This gives resulting paths for the carbon tax rate, GDP and the real exchange rate.