Climate policy does not discourage oil and gas investments and requires global coordination

Abstract

The transition to a global low-carbon economy requires massive investments in low-carbon assets, while also phasing out fossil fuel ones. Co-dependencies and dynamics between these two markets are little explored and result in biased understanding of the effectiveness of policy mechanisms. We fill this gap by exploring whether and to what extent domestic and international climate policies affect investments in oil and gas in presence of low-carbon assets globally. Results suggest that low-carbon and fossil fuels are two separate markets and that tailored policies are needed to halt fossil-fuel production and expand renewable energy penetration. Furthermore, we find that climate policies can lead to unequal reallocation of investments locking more vulnerable countries in high-carbon economies for decades.

Introduction

The world is "at a crossroads" (IPCC, 2022) to secure a liveable future, halt global heating and keep the planet within a 1.5C budget. To avoid a climate disaster (Tollefson, 2022), mitigation efforts must include radical cuts in fossil fuel extraction (McGlade & Ekins, 2015; Meinshausen et al., 2009; Welsby et al., 2021) and consumption (Stern et al., 2016) along the massive deployment of renewable technologies (Clarke et al., 2022) and energy efficiency measures (Erickson et al., 2018; Piggot et al., 2020). Despite the recent renewable growth and its projected installed capacity increase by 85% compared to the previous five years through 2027 (International Energy Agency, 2022), the fossil fuel industry expansion plans do not seem to slow (Rystad Energy, 2022.; The Guardian, 2022) and more than 400 "carbon bombs" globally are threatening the climate agenda (Kühne et al., 2022). Such trends reinforce the need for advanced understanding on how to directly impact investment in specific assets and sectors aligned with Paris-consistent trajectory (Lazarus & van Asselt, 2018).

For decades, policy makers and international actors have deployed different policy mechanisms to the support the energy transition. Demand-side climate policies support low-carbon investments (Chiţimiea et al., 2021) and reduce their associated investments risks (Egli, 2020; Polzin et al., 2019). On the supply-side, previous evidence confirms that the effectiveness of climate policies is influenced by fossil fuel market dynamics (Bauer et al., 2015, 2018) and the existence of strong divestment movements (Cojoianu et al., 2021; Hunt & Weber, 2018). However, little is known on the interplay between climate policy and fossil, low-carbon investments (Mercure et al., 2021), and in particular on whether climate policy works in shrinking the fossil fuel supply side, while low-carbon markets expand. Acting on both the demand and supply side is required to phase down fossil fuel uses (Lazarus & van Asselt, 2018) and to break the "carbon entanglement" in which countries are locked-in (Angel Gurría, 2013).

We fill this gap by quantifying the impact of demand-side climate policies on both fossil fuels, namely Oil&Gas (O&G) and low-carbon investments for 49 economies observed over the 2007-2020 period. As climate policy may induce financial actors to shift their investments to less stringent countries, we explore whether changes in climate policy in a given country affect O&G investments elsewhere. We do that by representing the global economy as a web of interconnected countries. Our model represents the dynamic transmission of climate change to other countries using weighted investments in low-carbon assets as links.

We find that demand-side policies are effective in expanding low-carbon markets, but not powerful in phasing out fossil fuels via reduced investments. Furthermore, we find that lower income countries are disadvantaged with respect to high income ones as climate policy does not reduce exploration capex. Finally, we find preliminary evidence of a “policy leakage”: once stringent, climate policy triggers an investment shift to less climate-focused strategic agendas. These results reveal that the low-carbon and O&G markets follow separate dynamics, but their simultaneous development can enhance a carbon “lock-in” for those countries unable to move away from fossil fuels.

Policy stringency, fossil fuel and low-carbon investments across countries

To understand the effect of climate policies on O&G investment we disentangle exploration and exploitation capital expenditures (capex) (Ahlvik et al., 2022) as main variable of interest. These two components reflect different stages along the value chain, thus capturing different elasticities to policy changes. Exploration capex allows us to investigate potential long-term impacts: stringent climate policy could induce a contraction in future exploration due to asset stranding; or instead create a “Janus risk” where continued investments in O&G create a carbon-dependent world as countries and productive systems do not believe in limiting global warming below 2C (Mitchell et al., 2015). Conversely, the impact of climate policy on operational capex captures short term effects where a stringent climate policy may lead to higher investments to extend the life of existing infrastructures, preventing investments in new facilities. Following almost a decade-long rise, exploration experiences a dramatic drop in 2016 with the US alone contracting its capex by 34 percent with respect to 2015 levels. Exploitation capex is also reduced with top countries cutting their investments by a global 40 percent average. An international agreement by leading oil producers achieves a trend inversion in 2017.

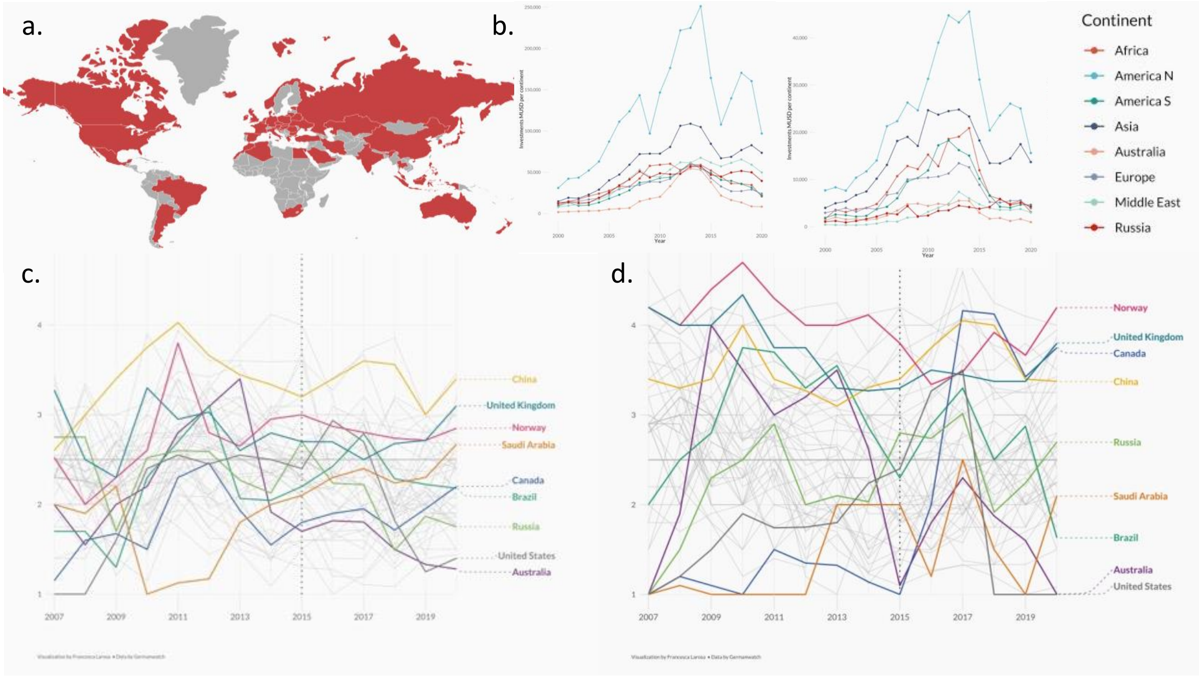

Figure 1 | **a.** Country coverage of the analysis: 49 countries distributed between lower middle, upper middle- and high-income countries; **b.** O&G exploitation and exploration capex. Exploitation capex plateaued between 2010 and 2014 before dropping in 2015. Exploration capex peaked in 2014 for the both the US and Africa; **c.** The CCPIs are indicators ranging from 0 to 5. The top countries per investments in O&G are represented with colour codes; The National CCPI: countries do not follow a shared path, but they present some analogies from 2017 onwards. **d.** The International CCPI: most countries share peaks in 2010 and 2013 and drops in 2019

While slower investments are mostly driven by oil price shocks(International Energy Agency, 2017), the second half of 2010s witnesses an increased climate awareness, which leads to the expansion of domestic and international climate policies. Despite an increased global climate performance, we find that countries are highly volatile and loosely consistent at promoting demand side national and international climate policies. The effect of the Paris Agreement (2015) is modest and delayed. On the international side, countries tend to cluster and act together suggesting some form of coordination to represent particular interests.

We apply a dynamic panel data model (see Methods) to both O&G and low-carbon investments to measure whether national and international CCPIs had any impact in supporting the transition towards a Paris compatible economy. The dynamic panel data model controls for unobserved country-specific factors that affect both investments and climate policy, removing endogeneity issues. As markets follow autoregressive dynamics, we use the iterated version of the Generalised Methods of Moments estimator (GMM), which also allows to control for not strictly exogeneous explanatory variables (Arellano & Bond, 1991; Blundell & Bond, 1998). After performing Granger causality tests and information criteria (see Methods), we lag every independent variable and the autoregressive terms by three periods confirming and updating existing literature (Cojoianu et al., 2021). Our model controls for country and O&G market-specific variables including GDP per capita, Operational (OPEX) and government (GOVEX) expenses, as well as commodity-specific production and a proxy for the country green propensity (Export Low Carbon Technologies). As GOVEX reunites all profit-based taxes, we can use it a proxy for revenues.

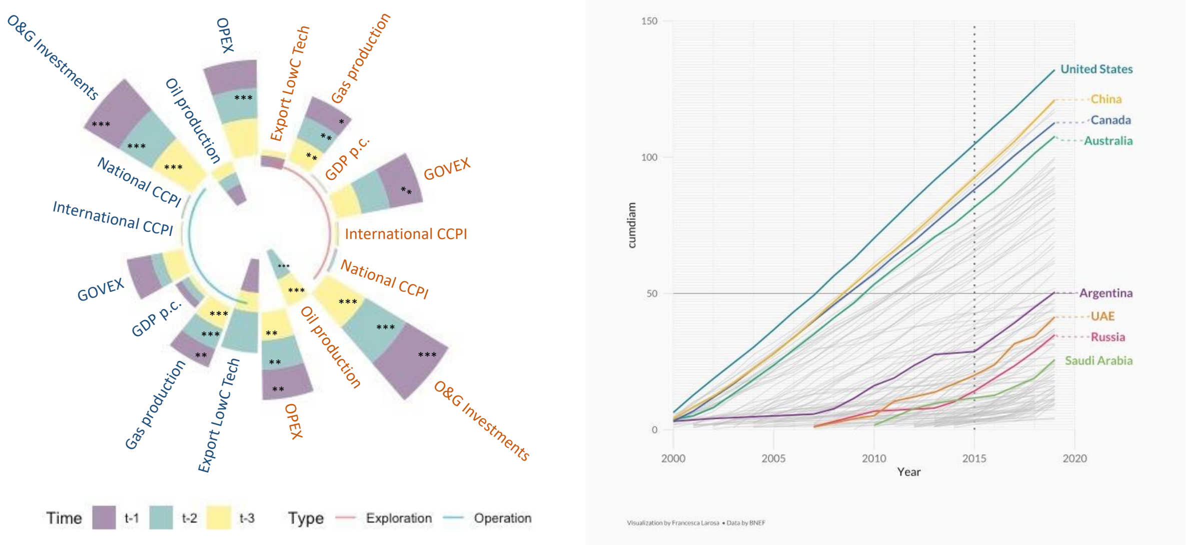

Figure 2 | (left-hand side) Our O&G model displays strong positive and significant investment dependency on both exploitation and exploration capex. (right-hand side) The cumulative low-carbon assets diameter weights the number of actors times the added GWs of installed capacity. The metric captures both the low-carbon market physical growth and how competitive each market is every given year.

To check for the coexisting green market effects, we run our model for the low-carbon assets using wind and solar as proxy for the market. While the standard economic metrics (i.e., additional capacity and investments) represent a valid indication of market expansion, we also aim at capturing how agents shape this evolving landscape. We use the weighted diameter of the network of investments in solar and wind, built using links between companies and countries for any given year (Figure 2).

International and national CCPIs have different impacts on O&G investments (Figure 2) and that coefficients are non-significant. International CCPI reduces O&G investments by 0.3% with 1 time lag, but the coefficient is non-significant. National CCPI is also non-significant and negative with a 2-year lag. Our results reveal that neither policy types are substantially altering the course of O&G financing. Instead, OPEX drives both exploration (+13%) and exploitation (+18%) capex up as operators try to increase efficiency of existing facilities or to find new deposits to counteract rising costs. This intuition is motivated by the contribution of disaggregated cost types (see Table 1, Supplementary Materials). We find a strong and significant path dependency from previous investments. In particular, current exploitation capex is between 10 and 12 percent higher in presence of positive O&G investments between $t-1$ and $t-3$. Current exploration is also affected by past activity with a drop over the past years (2018-2020) as consistent with empirical evidence (Rystad Energy, 2022). The influence of the government (GOVEX) is also positive on both exploration and exploitation capex with significance only in the case of exploration capex. This is consistent with the resource taxation literature, which acknowledges that profit-based taxes create a disincentive to curb exploration and exploitation (Ahlvik et al., 2022; Lund, 2009).

Despite non-significantly altering financing in the O&G industry, climate policies stimulate the development of low-carbon assets. The positive and significant coefficients are driven by the market structure (cumulative diameter), rather than by installed capacity. Credible domestic and international commitments to climate action seem to be more effective in highly competitive and liberalised markets, where incoming players can easily step in business opportunities. This result is reinforced by strong dependency from previous years low-carbon market growth, which mainly acts via installed capacity additions with one year lag.

Our results suggest that a successful and credible climate policy – at both national and international level – should be designed to account for diverse dynamics governing the fossil and low-carbon assets markets. Even in presence of high dependencies from low-carbon technologies exports, we find no significant relationship with current O&G investments. Together with results from the low-carbon market analysis, this evidence suggests that the two O&G and the low-carbon compartments follow separate and not interchangeable trajectories. Moreover, our empirical assessments point towards different investment dynamics consistent with the real world (The Financial Times, 2022).

A case for policy leakage

The assessment of two separate markets point towards the limits of climate policy to shift investments from high to low-carbon assets, as demand-side policies are unsuccessful in contracting both short and long run O&G capex. However, as the world needs to experience a fair and just transition, climate policy must prevent the most vulnerable countries to be locked-in fossil fuel dependent systems (Angel Gurría, 2013). We find this is not the case: lower middle-income countries (Figure 3) increase both their exploration and exploitation capex as national and international climate policies become more stringent. The reverse happens in high-income countries, where climate policy sends the opposite signal.

Path dependency is shared across income groups revealing that investments significantly benefit from an effective ecosystem based on codified standards and established financing structures (Stein, 2017). This may lead to a "resource curse" difficult to break as countries benefit from O&G revenues. Differently from the resource curse literature, which deepens the link between economic growth and endowment of natural resources (Hancock & Sovacool, 2018), countries lock into an investment-driven trap by encouraging exploration and exploitation of O&G within their geographic border. This intuition seems to be confirmed also by the coefficients of commodity-specific production: production has a positive and significant impact on current investments in lower and upper middle-income countries. Few countries nationalise their O&G production. Hence, the curse may be driven by foreign investors' agendas and strategies. Path dependency emerges also in the green market when countries are clustered by the income groups. Competitive and growing solar and wind markets create a virtuous investment circle further attracting new capital towards these technologies. The effect is stronger for high income countries, as they are the top players in the energy transition. However, national climate policy – when implemented – has a positive and significant effect on green market growth.

These findings reinforce the idea that green and O&G markets have distinct dynamics and there is no self-contained "energy investment system" (Ameli et al., 2021), hence no investment shift happens between the two. Instead, our findings suggest that O&G investors can move induce an intra-market investment movement from high to low policy stringent countries.

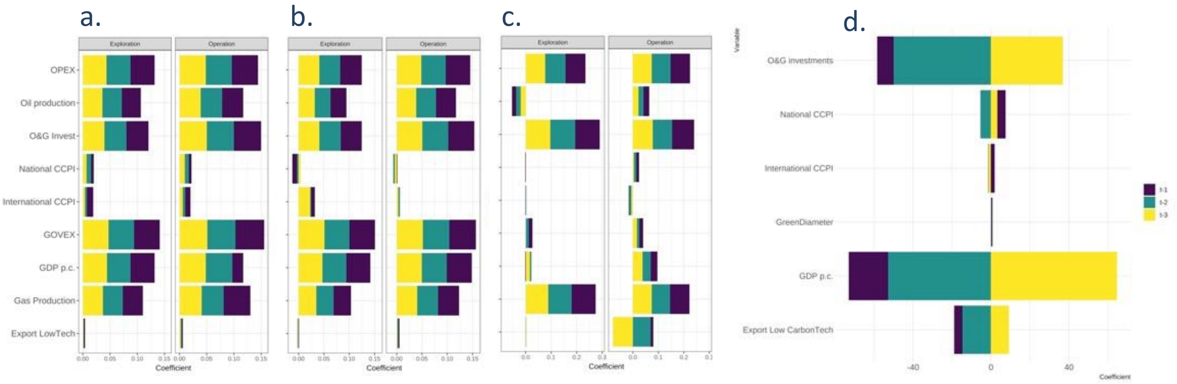

Figure 3 |The impact of climate policy on: operational and exploration capex in lower middle-income (a), higher middle-income (b) and high-income (c) countries. Past O&G investments are top significant for all time lags in every income area. International CCPI increases (with significance 1%) both operation and exploration capex, while decreases operation capex (1% significance level). National CCPI positively impacts lower middle-income countries (significance 1%), but increases O&G investments in high-income countries (significance 1%). The impact of climate policy on low-carbon assets (d) with national CCPI positively and significantly affecting investments in t-1 and t-2. International CCPI is non-significantly affecting the dependent variable. O&G investments are significant only with two-year lags.

To validate this intuition and to check for the existence of a climate policy leakage, we run a Bayesian Global Vector Autoregressive Model (BGVAR), which represents the world as a network of economies (see Methods). We build our weights as bilateral investments in low-carbon assets. Two countries have a direct link if an organisation from country α invests in a low-carbon asset project in country β. Each country-specific model is the outcome of both domestic and *foreign* variables linked by the so-constructed weights. The model captures how climate policy shocks in one country propagate by estimating simultaneously country-specific models in a global model. This allows us to check whether policy leakage in O&G investments is less prone to occur in presence of, but not limited to, strong ties in the low-carbon market.

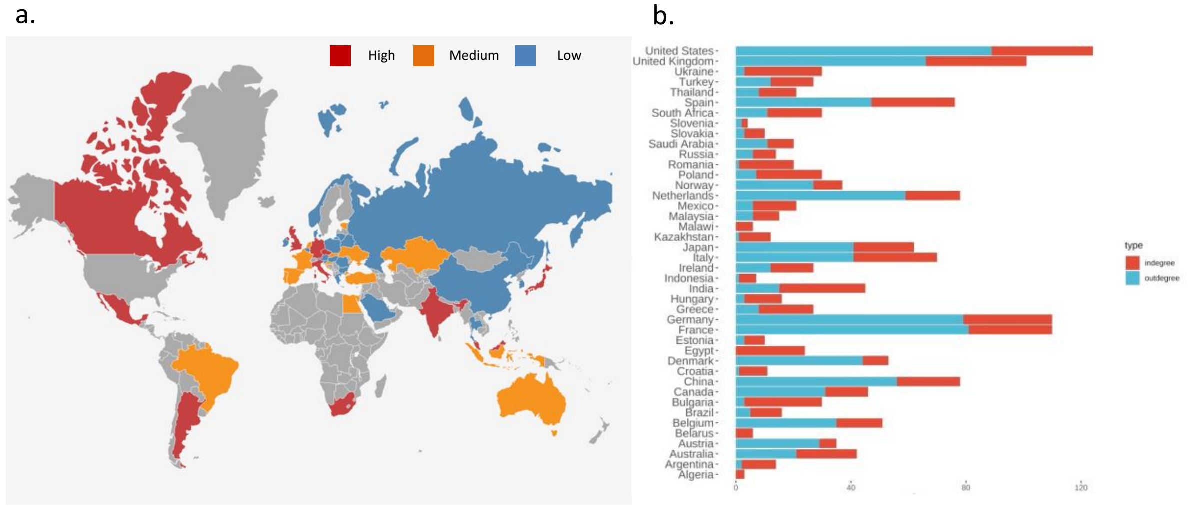

Figure 4 | We build weights to solve the BGVAR model by using bilateral investments in low-carbon assets (wind and solar). Weights range between 0 and 1. **a.** The US links intensity: high [0.5-0.99], medium [0.49-0.1] and low [<0.1]. **b.** Indegree describes how many times countries receive investments from abroad; outdegree states the opposite. United States, France, Germany and United Kingdom are the highest ranked as they supports other countries' low-carbon markets

We find evidence of leakage when big O&G investors enforce more stringent national and international climate policy. We focus on the US as the most prominent O&G investor and top financier of low-carbon assets per number of interactions (degree). For a 1-point increase in the US national CCPI performance, upper and lower middle-income countries experience the largest policy leakage with exploration O&G investments increasing over the first subsequent four years up to 1.8 percent in China and 1.4 percent in Brazil. Operational capex increases mostly in high income economies reinforcing the idea of an efficiency increase of existing infrastructure. Interestingly, exploration capex spikes as an immediate outcome of improved national CCPI, while operational capex requires between one and two additional years on average. This result suggests there may be credibility nuances that deserve a more in-depth study. On the international CCPI side, a 1-point increase in the US performance leads to a reduction of O&G operational investments mostly in high-income countries with Australia ranked first with a contraction of -1.2 percent five years later. Instead, exploration expands in higher middle-income countries in presence of an improvement off the US international CCPI. Brazil (+1.1 percent in year 3) and Malaysia (+1 percent in year 2) are the most affected.

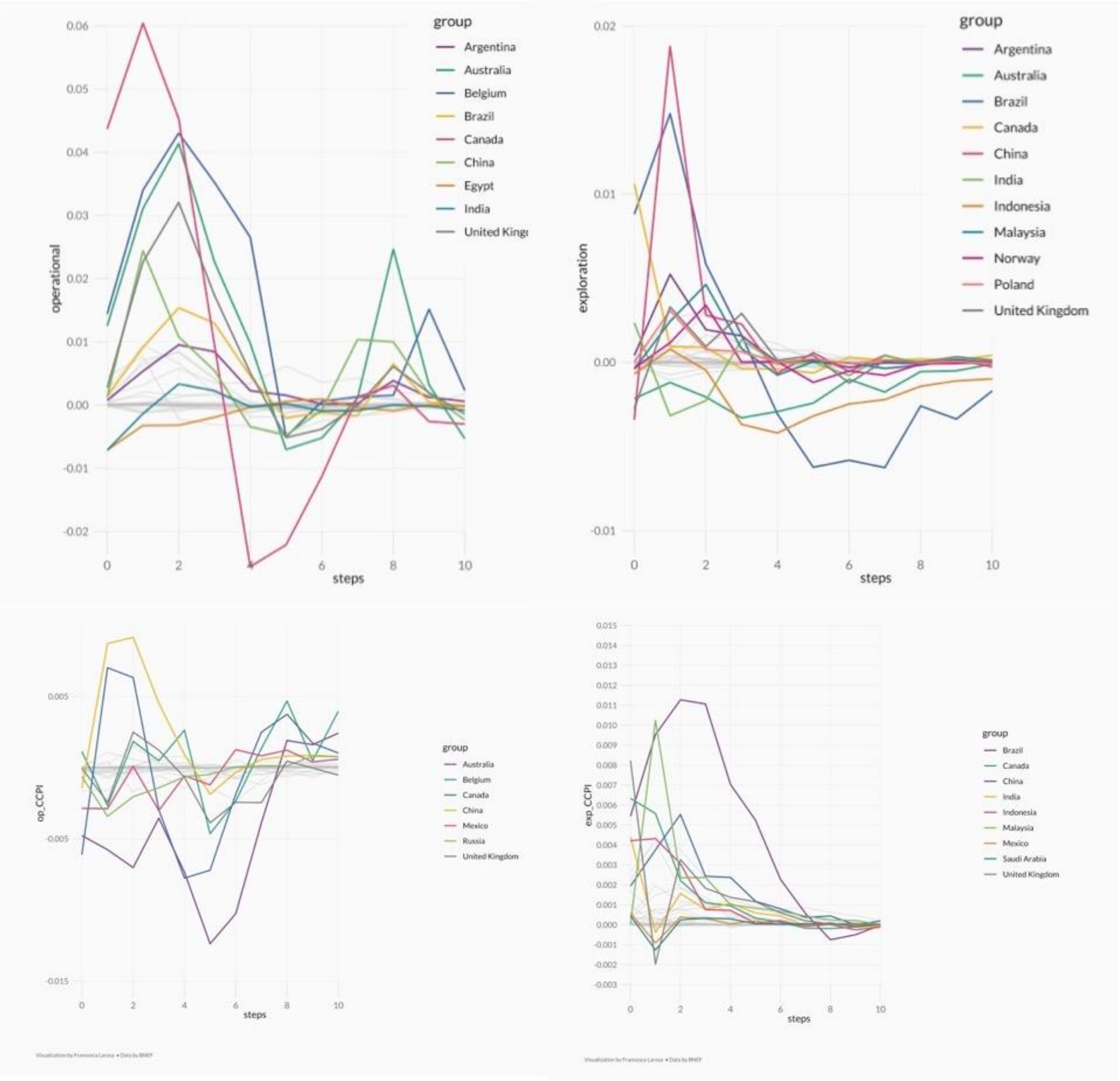

Figure 4 | The effect of a 1-point increase in US CCPN and CCPI over ten period (year) interval. Shocks are not just transmitted via weights. Instead, they propagate to the rest of the world by the contemporaneous estimation of individual country models. We cross-checked this intuition by substituting our low-carbon asset derived weights with bilateral industrial links for a selected pool of countries (see Supplementary Materials). We find very similar, but over-estimated trends: low-carbon investment links enhance the climate policy transmission between +3 and -0.6 percentage points

These results are driven by the ties that exist between the US low-carbon interests and the recipient countries, by the links that exist cross-sectionally between the countries and by the influence of a global variable (oil prices), which is treated endogenously with respect to the US economy (see Methods). Importantly, the BGVAR results confirm that even in presence of established bilateral low-carbon links, a policy leakage in the O&G sector can take place.

Limiting fossil fuels requires ad-hoc coordinated policies

Countries have not achieved yet the required system-wide structural change towards low-carbon production processes. On one hand, investments in O&G assets have continued to grow overtime. For instance, over 2016-20 period G20 allocated $3.2 tn in fossil-fuel support (Cuming & Godemer, 2022). The $598 billion invested in 2020 alone could have funded 833GW of new solar PV (6x solar PV capacity built in 2021). On the other hand, capital flows

towards renewable technologies are still far short of the levels that would be sufficient to meet energy needs in a sustainable way (IEA, 2021). The challenge to move beyond fossil fuels and build a clean low-carbon fueled economy seems even more pressing when it comes to policy. COP27 in Egypt is currently struggling to find a shared agreement about terminology on the fossil fuels, especially in the light of the energy crisis we are currently living.
Our results show that current supply-side climate policy mainly affects low-carbon markets, leaving unaffected the O&G ones. The two markets follow separate dynamics and the expansion of renewable technologies does not restrict investments in O&G and vice versa. Overall, past investment trends are highly influential drivers of current green and O&G markets. This demonstrates a path-dependent process whereby the actual investment environment depends on past investments and positive feedbacks generate increasing returns to investment and market confidence ((Rickman et al 2022, Egli et al 2018). These path dependency effects enable virtuous circles in renewable markets, but also "investment lock-in" in fossil fuel ones, generating an investment-induced resource curse. This effect is particularly stronger in lower and upper middle-income countries, who are left behind in phasing down and out fossils. Hence, tailored policies on both demand and supply side are needed to expand renewable energy penetration, while halting fossil-fuel production. They former would need to target the evolution of renewable market and initiate path-dependent flows for green assets. The latter should escape investment lock-in fossil fuel that puts at risk the pathway towards a low-carbon global economy.

Additionally, climate policies have uneven effects depending on countries' income groups, with most vulnerable areas increasing both their fossil fuel exploration and exploitation investment as domestic and international climate policies become more stringent. These results pave the road for an intra-market policy leakage: whenever credible climate policy is implemented in a place, that may induce investors to move somewhere else. Our policy leakage analysis calls for an in-depth study of policy transmission mechanisms with particular attention to income distributions. When high-income nations improve their performance on an international level, investments in O&G exploration expands in more vulnerable areas the world. A common, global and shared understanding of climate policy goals can avoid these effects and ensure the achievement of a low-carbon transition globally.

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Methods

In order to capture how and to what extent climate policy impacts on O&G investments, we use a balanced panel dataset of 49 economies tracked over the 2007-2020 timeframe by homogenising public and private information from Rystad Energy, Germanwatch, Bloomberg New Energy Finance (BNEF), the IMF Climate Data Portal and the World Bank (see Appendix for details).

O&G investments vary depending on their nature: we distinguish between Exploration and Operation Capex using proprietary data from Rystad Energy. Exploration capex are costs incurred to find and prove hydrocarbons (seismic, wildcat and appraisal wells) based on reports and/or modelled results. Operation capex, instead, includes investment costs related to existing infrastructure, drilling and completion of wells, and modification and maintenance on installed infrastructure. The impact of a country's climate and environmental and its credibility may affect the two differently.

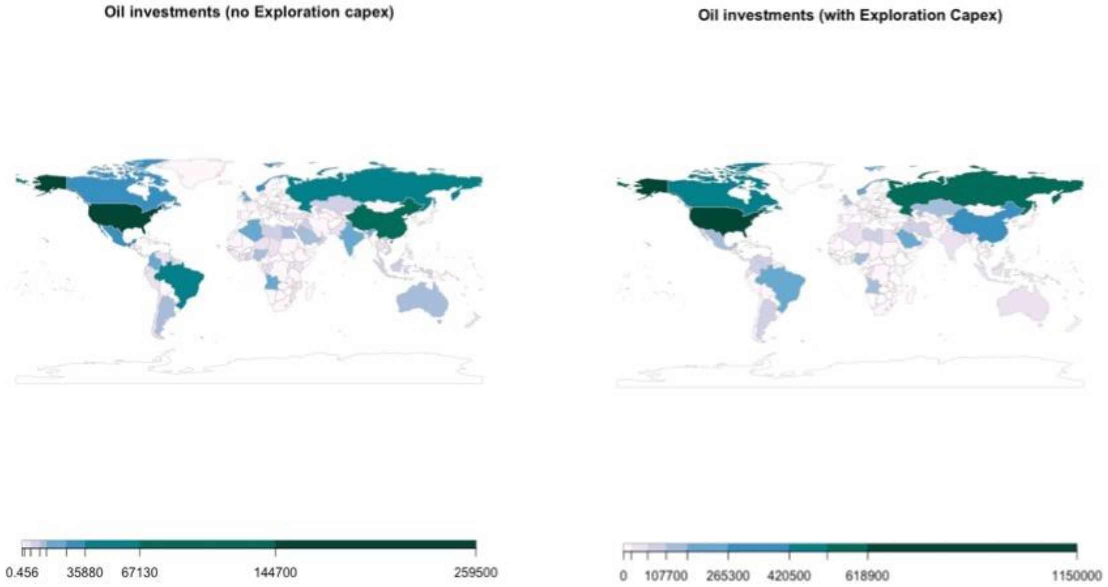

Figure 1M | Operation (left hand-side) and exploration (right hand-side) capex expressed in million USD

Our variable of interest captures demand-side climate policies at domestic (national) and international levels. The correlation matrix (Figure 2Ma) supports this intuition. Produced by Germanwatch e.V., these two indicators range from 1 to 5 and they evaluate countries' performance every year using an expert consultation methodology. For the National component, the indicator assesses how well countries promote concrete policies to support renewable energies, increase energy efficiency and reduce emissions in the electricity, transport, manufacturing and construction industries. On the international side, the indicator evaluates countries' performance at UNFCCC and other international gatherings [1].

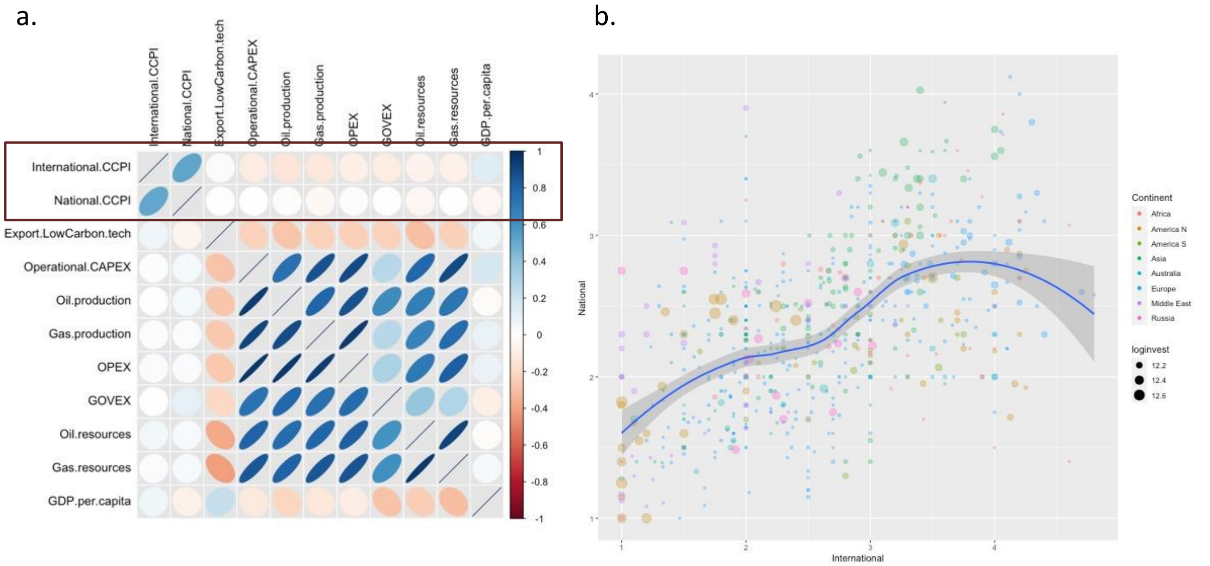

Figure 2M |a. Correlation matrix (Pearson coefficient) provides an indication of the demand-side nature of policies included in the index. b. Correlation between National (y axis) and International (x axis) CCPI. Bubble sizes vary depending on logarithm of investments, while colors indicate continents

First, we use a panel data econometric framework to check whether and under what conditions climate policy has an impact on O&G financing. To achieve this goal, we run a dynamic panel model using Arellano-Bond estimator.

With a great number of countries for a relatively small number of time periods, we apply dynamic panel data models to O&G investments. We validate our results by applying the same process to the low-carbon market. Panel data methods allow us to control for unobserved country-specific heterogeneities and simultaneity issues. In comparison, cross-section data cannot capture previous periods' information for investigating dynamic relationships[2]. We use a dynamic panel data model as investments usually display autoregressive behaviours in empirical analysis. Even when coefficients on lagged dependent variables are not of core interest, allowing for dynamics in the underlying process is critical for recovering consistent estimates of other parameters[3].

The identification strategy is based on time series variations in model (1), meanwhile controlling for time-invariant country-specific characteristics and other relevant factors that may affect both climate policy designing and energy investments[4]. This method allows for geographical (e.g., continent, country) and historical (e.g., path dependency) factors affecting energy investment. It also contains natural resource endowment (e.g., oil and gas production) and economic (e.g., exports and GDP) compounding factors. Model (1) reads as it follows:

$$Y_{i,\delta,t} = Y_{i,\delta,\,t-n} + \beta ClimatePolicy_{\zeta,i,t-n} + \gamma \boldsymbol{X}_{j,i,t-n} + \theta \boldsymbol{Z}_{i,t-n} + \varepsilon_{it}$$

where Y is O&G investments for country *i* , type of investments (i.e., exploration and exploitation capex) and time *t*; climate policy is a country and time-specific double indicator ζ (i.e., national and international climate policy); X is a matrix of country, time and commodity-specific metrics; Z is a country-specific set of variables: Operational expenses (OPEX), governmental take (GOVEX), GDP per capita and an indicator of greenness derived from the World Bank (Export of Low Carbon Technology). We also include time (year) fixed effects. To pick the optimal number of lags, we use the Bayes Information Criterion (BIC) looped over 12 different orders and applied to Autoregressive Distributed Lag Model (ADL) such as ours (see Appendix). We obtained the optimal number of 3.

The use of annual data provides us with adequate time series observations to establish the moment conditions of Generalised Method of Moments (GMM) developed by Hansen (1982)[5]. The GMM provides a framework that controls for unobserved country-specific factors by using a matrix of estimated exogenous instruments. When the panel has more than 3 time series observations, instruments correspond to the first-differenced equations for periods = 3, 4…, T for individual country, thus establishing the moment conditions.

$$E\left(y_{i,t-s}\Delta v_{i,t}\right) = 0 \text{ for } t = 3,4,\dots,\mathrm{T} \text{ and } s \geq 2$$

We apply iterated GMM estimation using country-level robust standard errors. At a minimum, the one-step GMM estimator is a reasonable choice for the initial consistent estimator used to compute the optimal weight matrix and hence to compute the two-step estimator. Having obtained the two-step GMM estimator, we can use our new estimates of the residuals to update the estimate of the optimal weight matrix. We keep going in this route until changes in the estimates of both the parameter vectors and the optimal weight matrix become negligibly small, which defines iterated GMM estimator[6].

To check for the validity of the instruments, we use the Sargan/Hansen test.

We perform a Granger causality test to validate the causal relationship between our dependent and the independent variables (see Appendix). The dynamic panel data model gives evidence of some degrees of independence between the low carbon and O&G markets. However, it does not provide indication of whether climate policy can redirect investments towards less stringent countries (policy leakage). Understanding these mechanisms is essential to design effective measures and to drive a just energy transition which leaves no country behind. To achieve this goal, we run a Bayesian Global Vector Autoregression (BGVAR) Model[7,8]. This approach moves beyond standard OLS and econometric frameworks and considers selected variables as having not just a one-way influence, but more likely a two-way dynamic influence on each other. Therefore, it complements existing studies[9,10].

The BGVAR is an extension of the more general GVAR modelling framework. Both approaches are widely used in financial econometrics and macroeconomic studies[11] as they allow to study the propagation of shocks and their dynamics. The GVAR builds upon two stages. The first stage deals with simple unit-specific models. The second stage combines these models using cross-sectional links to estimate a global representation of the economy. In other words, the model combines unit-specific Vector Error Correction Models (VECM) into a global structure allowing for cross-sectional linkages among countries. In particular, each individual model is related to the others thanks to a set of foreign variables and global variables. Therefore, each country may be affected by events happening in others, giving the sense of how regional macroeconomic shocks actually impact on individual economies.

As such, the GVAR requires a panel data structure with $i = 1, \ldots, N$ units each described by a k_i-dimensional vector of variables y_{it}, endogenous to each unit. Each variable is lagged by P periods. Each vector y_{it} is complemented by a vector k_i^* of lagged and contemporaneous foreign variables y_{it}^* constructed using weights. In their seminal paper, di Mauro and Pesaran (2013)[12] use bilateral trade ratios as links. The literature has explored a wide range of alternatives including capital flows[12], financial linkages[13] or bilateral banking sector exposure[11]. Weights represent the connectivity between countries and they fulfil the following conditions:

$$\sum_{i=1}^{N} w_{ij} = 1 \ and \ w_{ii} = 0$$

For every set of weights w_{ij}. As $y_{it}^* = \sum_{j=1}^{N} w_{ij} y_{jt}$, unit-specific models are described by both domestic and foreign variables as it follows:

$$y_{it} = \alpha_{i0} + \alpha_{i1} t + \sum_{p=1}^{P} \Phi_{ip} y_{it-j} + \sum_{q-0}^{Q} \Lambda_{iq} y_{it-j}^* + \varepsilon_{it}, \qquad \varepsilon_{it} \sim N(0, \Sigma_{it})$$

with α_{i0} and α_{i1} as k_i-dimensional vector coefficients; $\Phi_{ij}(j = 1, \ldots, P)$ as $k_i x k_i$-dimensional coefficient associated with lagged values; $\Lambda_{ij}(j = 0, \ldots, Q)$ is the $k_i x k_i^*$ matrix associated with the weakly exogenous regressors in y_{it}^*. The shocks are idiosyncratic and correlated across regions: that is, for $i \neq j$, the cross-country covariance matrix Σ_{ij} is given by:

$$E(\varepsilon_{it}, \varepsilon_{jt}') = \begin{cases} \Sigma_{ij} \ for \ t = t' \\ 0 \ \ for \ t \neq t' \end{cases}$$

This assumption is crucial in the GVAR: interaction between countries happen through two different channels: (a) domestic y_{it} and foreign ${y^*}_{it}$ variables have a bilateral contemporaneous relation and with their lags; (b) a shock occurring in one country, may present implications in others through cross-country covariance.
The crucial assumption relying below all foreign variables is the weak exogeneity. According to Greene (2002), a set of variables x_t is "weakly exogenous if the full model can be written in terms of a marginal probability distribution for x_t and a conditional distribution for $y_t | x_t$ such that the estimation of the parameters of the conditional distribution is no less efficient than estimation of the full set of parameters of the joint distribution". Global variables are considered to be exogenously determined (such as oil prices or other commodity prices). This restriction mainly implies that each considered economy is small in an open market. The unique exception to this rule may be represented by the United States – which are normally treated differently. Following Di Mauro and Pesaran[12], weak exogeneity implies a contemporaneous relation between domestic and foreign variables. In other words, a change in domestic, foreign or lagged variables may impact the value of the foreign ones.

Rather than using bilateral trade ratios or financial links, we construct our weights to describe the global economy as an interrelated set of bilateral investments in low-carbon assets. We use data from solar and wind projects as collected in Bloomberg New Energy Finance (BNEF). We build a bilateral directed network between the country of the investor and the country of the project.

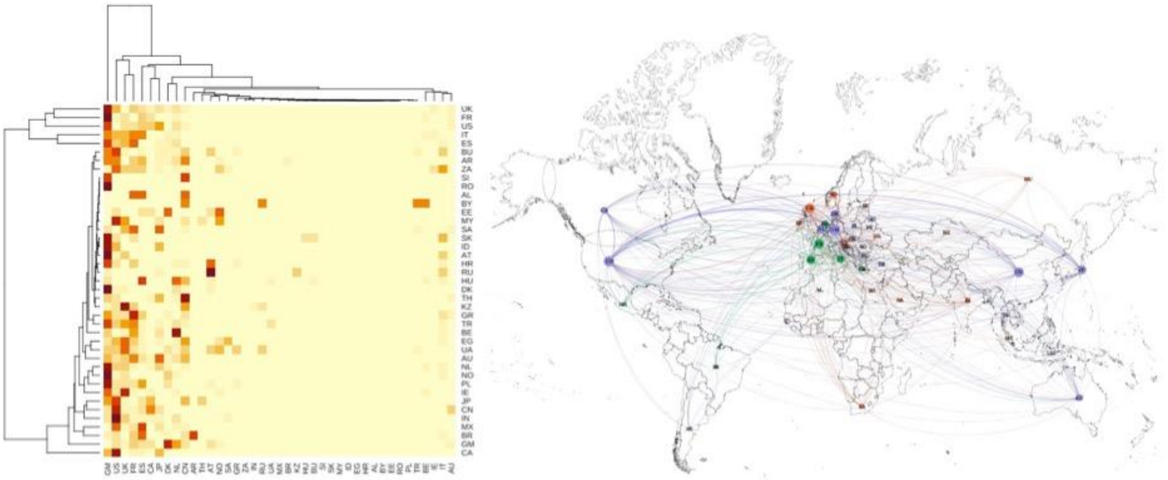

Figure 3M | The heatmap representing the distribution of bilateral weights derived from low-carbon assets. The global network of low-carbon asset investments. Bubble sizes equalises outdegree, while colours are groups. Countries are clustered according to their modularity, a metric that captures how dense connections are within and outside groups

The second stage stacks unit-specific models into a global system of equations. To achieve this, we apply algebraic transformations only assuming that the unit-specific models can be rewritten as:

$$A_i z_{it} = \alpha_{i0} + \alpha_{i1} t + B_i z_{i,t-1} + \varepsilon_{it}$$

with $A_i = \left(I_{k_i} - \Lambda_{i0}\right)$ and $B_i = (\Phi_i, \Lambda_{i1})$.

More compactly, the domestic variables can be rewritten as $\boldsymbol{z_{it}} = \boldsymbol{W_i x_t}$ **,** where $\boldsymbol{x_t}$ is a $k \times 1$ vector grouping all the country-specific variables; $\boldsymbol{W_i}$ is a $(k_i + k_i^*) \times k$ matrix including fixed and known constants built using weights. By substitution, we get:

$$A_i W_i x_t = \alpha_{i0} + \alpha_{i1} t + B_i W_i x_{t-1} + \varepsilon_{it}$$

which, in turn, can be rewritten as

$$G x_t = \alpha_0 + \alpha_1 t + H x_{t-1} + \varepsilon_t$$

The GVAR can be straightforwardly be written as:

$$x_t = G^{-1}\alpha_0 + G^{-1}\alpha_1 t + G^{-1} H x_{t-1} + G^{-1}\varepsilon_t$$

which represents the reduced form of the model and can be easily solved recursively through generation of Impulse Response Functions.

To respect the weakly exogeneity assumption, we are forced to restrict our sample removing ten countries with endogeneity issues. Hence, our global model includes 39 countries (see Appendix) for a total number of 39 individual equations (VARX*) requiring estimation. While the increasing data availability provides researchers with the opportunity to run Global models, the abundance of parameters requiring estimations is a challenge. Bayesian methods overcome this issue[7]. We adopt the Bayesian modification of the GVAR model (BGVAR) to model our economy. For a complete explanation of the BGVAR we refer the reader to Kopp and Korobilis (2010)[14]. For the sake of this discussion, we present the established shrinkage priors we use and we motivate our choice.

Priors reduce model overfitting by introducing precise estimates of the many coefficients in the global model. In absence of priors, impulse response functions can be imprecise as predictive standard deviations can be too large. Priors help to “shrink” forecasts. The literature has explored several priors. The first and widest known type, the Minnesota priors[15], is based on an approximation process achieved by estimating Σ and by assuming it is a diagonal matrix. While this process simplifies prior elicitation, it also involves the replacement of unknown Σ with an estimate. No actual integration within a Bayesian framework takes place. While the Minnesota priors automatise – with shortcomings – the prior elicitation process, other approaches require substantial inputs from the researcher performing the analysis and may lead to biased outcomes. To overcome these issues, we use Stochastic Search Variable Selection (SSVS) first proposed by George et al. (2008)[16]. SSVS specifies hierarchical priors which builds upon a data=driven approach. Given that all the hyperparameters are elicited for the unit-specific model, SSVS approach induces unit-specific degrees of shrinkage on the parameters. Overfitting risk is reduced[7].

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