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ENERGY TRANSITION SCENARIOS IN RUSSIA: EFFECTS IN MACROECONOMIC GENERAL EQUILIBRIUM MODEL WITH RATIONAL EXPECTATIONS

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Abstract

We use a DSGE model for a hydrocarbon-rich country to examine the macroeconomic implications of scenarios that lead to an energy transition. Our findings show that the scenario of the fall in export revenues from brown energy sales is the least preferred for energy transition in terms of welfare loss, while the scenario of imposing higher taxes is more acceptable. The most favourable scenario leading to the smallest drop in public wealth and long-term growth in output and consumption involves the productivity incentives in the green energy sector. We also analyse the impact of mechanisms such as monetary policy inertia, the level of openness of the financial account, technological substitutability between brown and green energy. We found that news about the future implementation of green policies alone cannot trigger the energy transition. Investments become cleaner after the news announcement, but this barely increases green energy production.

Key words: dynamic models, general equilibrium, rational expectations, green energy, energy transition, climate policy, cross-border tax, monetary policy.

JEL codes: D58, E47, E62, E63.

1. Introduction

In this paper, an energy transition refers to a significant shift in the structure of energy consumption from carbon-intensive sources to carbon-free, green energy sources. The energy transition is one of the elements of the global decarbonisation process that is gaining momentum. This process, in addition to the energy transition itself, includes energy efficiency, hydrocarbon capture and storage, and efficient use of soil and forests. The need for decarbonisation and energy transition is driven by the potential for global warming and its significant consequences for the world's population. According to expert reports,[1] a reasonable target for decarbonisation would be to limit the temperature increase to 1.5 °C compared to the pre-industrial era. Otherwise, as noted by specialists, the planet will face catastrophic consequences: extreme weather, rising sea levels, shrinking Arctic sea ice, declining coral populations, and disappearing ecosystems. Meanwhile, a 1 °C increase has already occurred, and preventing average temperatures from rising by more than the remaining 0.5 °C requires a reduction in CO_2 emissions by 45% by 2030 from 2010 levels, and the achievement of carbon neutrality by 2050.

Some countries may have no interest in decarbonisation owing to, for example, a focus on fossil fuel exports or the benefits derived from global warming (*Kotlikoff et al., 2021*). However, decarbonisation and energy transition may become their only alternative, as the majority of countries can apply external economic pressure to push decarbonisation. In this study, we consider a country rich in hydrocarbon fuels. A general equilibrium (DSGE) model is constructed to analyse the pure, i.e. non-mixed options economic policy options that induce such an economy to move towards an energy transition. The model is calibrated for the Russian economy.

The paper considers the following pure economic policies:

1) Fossil fuel importers raise taxes on domestic production of brown fuels. This eventually leads to a decrease in the revenue of the exporter supplying the importer with hydrocarbon fuels and may result in an energy transition in the exporting economy under some circumstances.

2) The exporter raises domestic taxes on brown energy to increase the competitiveness of domestic green energy.

3) The exporter invests in the productivity of the green energy sector.

Mixed policy options, although plausible scenarios for future energy transition, are not discussed in this paper in order to focus on pure policy effects.

Policy (1) is an instrument of the importer. By raising taxes on brown products, importers protect their domestic market and the green technologies they have developed from fossil fuel exporters. Policy (2) is an instrument of the exporting country. Policy (3) can have a dual origin:

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[1] Special Report on Global Warming of 1.5 °C of the Intergovernmental Panel on Climate Change (IPCC).

productivity can be improved either due to the efforts of the exporter alone, or as a result of the exporter copying and adopting technologies developed by the fossil fuel importing country.

The paper studies the effects of pure policy options (1)–(3) from a macroeconomic perspective. The instruments of the study are the construction of impulse response functions in a stochastic model, the calculation of scenario trajectories in a deterministic formulation of the model, and the calculation of long-term equilibria (steady states) reached by the economy in energy transition scenarios. When we analyse instruments (1)–(3), we find out which scenarios and under which conditions may result in energy transition. We also analyse which processes accompany the scenarios, and also which scenarios and under which conditions are preferable with respect to changes in public wealth.

This paper contributes to the existing literature in the following. First, unlike most of the foreign research, our study considers a hydrocarbon export-oriented economy. Second, unlike the vast majority of models with results for Russia (see Section 3), we use an equilibrium model with rational expectations. This makes it possible to take into account the mutual influence of all variables, contrary to bottom-up models (see Section 3), and the effect of agents' expectations, contrary to CGE and bottom-up models. Third, instead of analysing the methods and details of carbon tax implementation, we consider a broader class of scenarios for policies to encourage energy transition. We have not found any examples of a comparison of broad-spectrum energy transition scenarios for an export-oriented economy based on the equilibrium model in the literature. Fourth, the use of the dynamic equilibrium model helps estimate the effect of changes in public wealth under various scenarios, which makes it possible to rank the scenarios properly. Fifth, unlike the studies of the US Federal Reserve (*Fried et al., 2022*) and the ECB (*Coenen et al., 2023*), which are most similar to our study in terms of subject matter and instruments in the form of a DSGE model, this paper is characterised by the use of pure scenarios (meaning that the impact of the instruments on the economy is examined separately) and that the model is relatively simple. Finally, the paper tests the sensitivity of the results to changes in the assumptions and parameters of the model, in contrast to CGE and bottom-up models typical for Russian studies.

2. Green energy: development limits and scenario boundaries

To make the energy transition scenarios under consideration realistic, we need to determine from what level and to what limits green energy can expand.

First of all, it should be noted that Russian research literature and information resources identify several groups of energy sources: solar and wind power stations; renewable energy sources, which include, together with solar and wind power stations, small hydroelectric power stations, geothermal sources and biofuels; and carbon-free power generation, which includes, together with renewable energy sources, nuclear and hydroelectric power stations. The largest contribution to the growth of global generation capacity in the last decade is made by solar and wind power stations (*IEA, 2023*), and therefore, we will refer specifically to playing development of solar and wind power stations, when speaking further about green energy growth scenarios.

In Russia, the share of renewable energy capacity in the total generation capacity is 2.3%, i.e. 5.7 GW (see *Power and Industry of Russia, 19/12/2022*) out of 245 GW (see *Peretok.ru, 13/10/2021*), while the share of solar and wind power stations is 1.8%, i.e. 4.3 GW. However, the share of actually generated energy coming from solar and wind power stations is less than 1.8% and amounted to only 0.7% in 2022 (see *Power and Industry of Russia, 19/12/2022*) and 0.8% in the first half of 2023. This is due to the fact that the installed capacity utilisation factor for solar and wind power stations is low: the output of solar power stations is zero and the output of wind power stations is irregular during winter evening maximums (see *Peretok.ru, 13/10/2021*).

The share that green energy may take in Russia in the coming decades is estimated in various ways. The Russian Ministry of Energy, prior to the special military operation, projected the share of renewable energy sources at 12.5% by 2050 (*see Ministry of Energy, 10/112021*), but it lowered the forecast to 9% in 2023 (see *Big Electric Power News, 16/06/2023*). According to Alexander Ilyenko, Head of the Development Directorate of the Russian Power System Operator (see *Peretok.ru, 13/10/2021*), the share of renewable energy sources amounting to 13–25% ‘has a significant impact on the mode of operation of the energy system’ and requires the establishment of ‘specific mechanisms for rapid regulation of the generation process’. This is related to the irregular nature of power generation by solar and wind power stations. The Russian Ministry of Energy notes (see *Ministry of Energy, 10/11/2021*) that ‘it will be necessary to address the issues of integration of these volumes [12.5% of total generation] of renewable energy sources and also the issues of management of these volumes taking into account their extremely variable dynamics’ in the future. According to a report by the International Energy Agency (*IEA, 2023*), irregularity of renewable energy generation is a global problem, and the global energy industry is trying to solve this problem by installing stationary electric storage battery systems. The installation of such systems demonstrated explosive growth between 2019 and 2022. The IEA undertakes to forecast the renewable energy growth only for the next three years until 2025, when the renewable energy generation capacity is expected to reach 35% of the global generation capacity.

Consequently, the possibility of renewable energy sources taking a significant share of the energy market is doubtful at present and will clearly depend on the evolution of technology. Therefore, for the purposes of this paper, it would be sufficient to consider the limit of green energy development at 25% of the energy market share. The growth is expected to start from the current levels of 0.7% in terms of generation and 1.8% in terms of installed capacity. In addition, for further analysis (see Subsection 7.2), it is important that the issue of the stability of solar and wind power generation will increase as the share of green energy grows. The growing importance of the stability of solar and wind power stations means that such stations may no longer be freely replaceable other energy sources in the future, i.e. brown energy sources may find its strong technological foothold and thus impede the energy transition.

3. Literature review

Two approaches, top-down and bottom-up, are known to be used in economic and energy system modelling (*International Panel on Climate Change, 1996*). A typical example of such processes is the law of energy conservation: 1 kWh from one source plus 1 kWh from another source always equals 2 kWh. Such models are characterised by a large number of equations describing the energy system, and also by the statement of economic problems using linear programming (cost minimisation under given technological constraints). These problems usually have boundary solutions: optimising agents invest all resources in one resource technology, while other instruments receive no investment or a set minimum. Bottom-up models often take the cost of investment and interest rates from the economic system as a given (for the purposes of discounting cash flows when calculating the performance of investment projects). The impact of changes in the energy system on the economy is not considered.

On the contrary, the top-down approach focuses on the macroeconomic description. This requires elastic supply and demand functions in the model, and the principle of energy conservation is not applied, since energy type aggregators are not linear. Top-down models usually describe the mutual influence of the economy and the energy system. However, the energy system itself is described superficially due to computational difficulties in including linear programming problems in the definition of the economic system. Therefore, the disadvantage of this type of models is that the description of the energy system is not detailed enough.

Although there are many papers (e.g. *Rutherford and Böhringer, 2006*; *Tuladhar et al., 2009*; and *Timilsina et al., 2021*) claiming successful integration of bottom-up and top-down approaches, the problem of combining the two approaches, which would give us a detailed description of the energy system and a description of its mutual influence with the economic system, has not been fundamentally solved.

Most of the studies on the topic of decarbonisation in Russia have been carried out using the bottom-up approach. *Golub et al.* (*2019*) note that Russia has significant potential for carbon emission reductions, but investment barriers create substantial risks for the implementation of low-carbon technologies. Based on the bottom-up model, the authors show that the adjusted returns on investment projects turn out to be very high, indicating the risks of investment.

Potashnikov et al. (*2022*) consider an alternative approach to the problem of decarbonisation of the Russian economy, which is usually addressed by increasing energy efficiency in production and adopting costly carbon capture and storage measures. The authors analyse a scenario of decarbonisation through the active development of solar and wind energy, proposing to solve the problem of supply disruptions by using green hydrogen technology. At a fine-detail level, the model shows that there are several possible combinations of wind and solar power coupled with green hydrogen production to achieve 100% decarbonisation of the Russian economy. The need to introduce hydrogen technologies in addition to the creation of redundant storage capacities is also shown in *Kolpakov et al.* (*2022*). According to their calculations, achieving carbon neutrality by 2050 will require an increase in the energy costs to GDP ratio. Therefore, reaching carbon neutrality by mid-century may be an unsustainable scenario, and 'hydrocarbons should play a determining role in energy supply processes for at least another two decades'. *Salikhov* (*2022*) also proposes a range of measures to achieve carbon neutrality by mid-century. One of such measures, according to the author, is to set an environmental emission tax of $37 per 1 tonne of CO_2. *Safonov et al.* (*2022*) also agree that carbon neutrality is achievable, but, in their opinion, ecological modernisation of the Russian economy is necessary, and the loss of part of export revenues is inevitable.

Schwartz et al. (*2022*) draw attention to view that a positive carbon balance of Russia's forests could eliminate the need for businesses to take costly measures to reduce direct carbon emissions. The authors note that industrial decarbonisation measures will still have to be implemented despite the positive forest carbon balance and the proposed effective arrangements aimed at improving forest management. The authors also note such measures to improve forest management as fire risk reduction and reforestation.

Papers stating the calculation of macroeconomic indicators in climate scenarios include the following: *Porfiriev et al.* (*2022*), which proposes a balance between the reduction of greenhouse gas emissions and the risks of slowing GDP growth; and *Makarov et al.* (*2018*), which points to a 0.2–0.5% reduction in Russian GDP growth due to decarbonisation measures and even greater losses if Russia does not ratify the Paris Agreement. The Network for Greening the Financial System (NGFS) comprising central banks and financial institutions considers scenarios for a carbon tax increase to $135 per 1 tonne of CO_2 by 2050 (*NGFS, 2022*). According to calculations, regardless of the initial trajectory of the tax, the introduction of the tax and its increase would lead to an additional 15–16% drop in Russia's GDP by 2050. If carbon neutrality is achieved by mid-century, *Bashmakov et al. (2022)*[2] forecast a significant slowdown in Russia's GDP growth rate until 2050 if productivity growth is weak. *Klepach et al. (2023)*[3] estimate that achieving carbon neutrality would require 'decarbonisation investments' of 0.46–0.73% of GDP annually until mid-century.

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[2] Bashmakov et al. (2022). Russia's carbon neutrality: pathways to 2060.

[3] Okorochkova A., Tinkov N. (2023). Achieving 'carbon neutrality' by the Russian Federation no later than 2060. Ed. by A. Klepach.

A truly top-down model describing the performance of the Russian economy is only *Kotlikoff et al.* (*2021*), which uses a general equilibrium model to calculate the performance of 16 world regions, including Russia. Surprisingly, in the baseline scenario characterised by the continuation of current trends (business as usual), Russia and Canada will benefit from global warming, which assumes an average temperature rise of 3.7 °C by 2200. The gain for Russia is estimated at 3.9% of GDP due to more favourable summer and winter temperatures. In contrast, the other 14 regions stand to lose an average of 20% of GDP from warming. The authors consider a global mechanism of tax allocation between countries enabling a unified strategy that would increase global public wealth.

A separate topic addressed in our paper is the expectation of future changes in climate policy and their impact on the current situation. Based on an equilibrium model, *Fried et al.* (*2022*) find that the probability that future federal climate policy will be implemented in the US has already made firms' investments cleaner. According to calculations, a 75% probability that a carbon tax will be adopted in the next decade is equivalent to a carbon tax effect of $4.91 per 1 tonne of CO_2. This result is consistent with the research of *Mertens and Ravn* (*2012*), *Gomes et al.* (*2017*), and *Andreyev and Polbin* (*2023*). They separate the impact of news occurrence: part of the impact is implemented at the moment of news occurrence, and the rest is implemented at the moment of occurrence of the event that underlies the news. As shown below (see Section 8), the model considered in this paper localises the impact of climate policy at the moment of policy implementation. As in *Fried et al.* (*2022*), investment gets cleaner, but production, surprisingly, does not become cleaner.

As concerns papers not related to Russia, our study is closest in methods and subject matter to the ECB study by *Coenen et al.* (*2023*), which examines the impact of a brown energy tax increase from a macroeconomic perspective. Unlike that paper, first, our model considers an export-oriented economy, where brown energy can be exported or used domestically, instead of a commodity-importing country. Second, we consider pure scenarios, i.e. the individual impact of instruments on the economy, whereas *Coenen et al.* (*2023*) deal only with mixed scenarios.

The set of energy transition scenarios analysed in this paper overlaps with those discussed in the foreign literature. Most of the foreign papers focus on taxation scenarios leading to emission reductions. For example, *Antosiewicz et al.* (*2016*) analyse two alternatives for fossil fuel reduction in eurozone countries: taxes on material costs or taxes on the production output of the industrial, construction and transport sectors. The authors conclude that the first type of policy encourages investments in technology by increasing production efficiency and leads to a 15– 20% rise in long-term GDP and employment relative to the other scenario. *Gupta et al.* (*2022*) compare no-tax, carbon use tax, production tax and consumption tax regimes. The paper takes into account household preferences regarding the quality of the environment. The authors find that whether consumers prefer a clean climate or not, a carbon use tax is the most effective instrument.

In addition to the creation of fiscal drivers, the research literature focuses on alternative methods that can reduce pollution. For example, *Li and Peng* (*2020*) make a comparison between taxes and subsidies that encourage pollution reduction. Subsidies are paid by the government to companies if they reduce emissions. The authors show that both taxes and subsidies lead to improvements in the quality of the environment. However, taxes reduce macro indicators such as production output, consumption, and labour, while subsidies, on the contrary, increase them. *Guo and Xiao* (*2023*) also compare two alternative scenarios: a carbon emission tax versus a carbon emission cap and trade in a deterministic and a stochastic version of the DSGE model. In the deterministic model, a 1% reduction in CO_2 emissions leads to a 0.12% loss of output, a 0.5% decrease in fossil fuel demand, and a 0.05% increase in renewable energy demand. In the stochastic model, the effects of the two options are different: the emission tax does not solve the problem and the scenario is in fact close to no pollution reduction policy. Under certain conditions, a cap-and-trade policy may be more effective from this point of view.

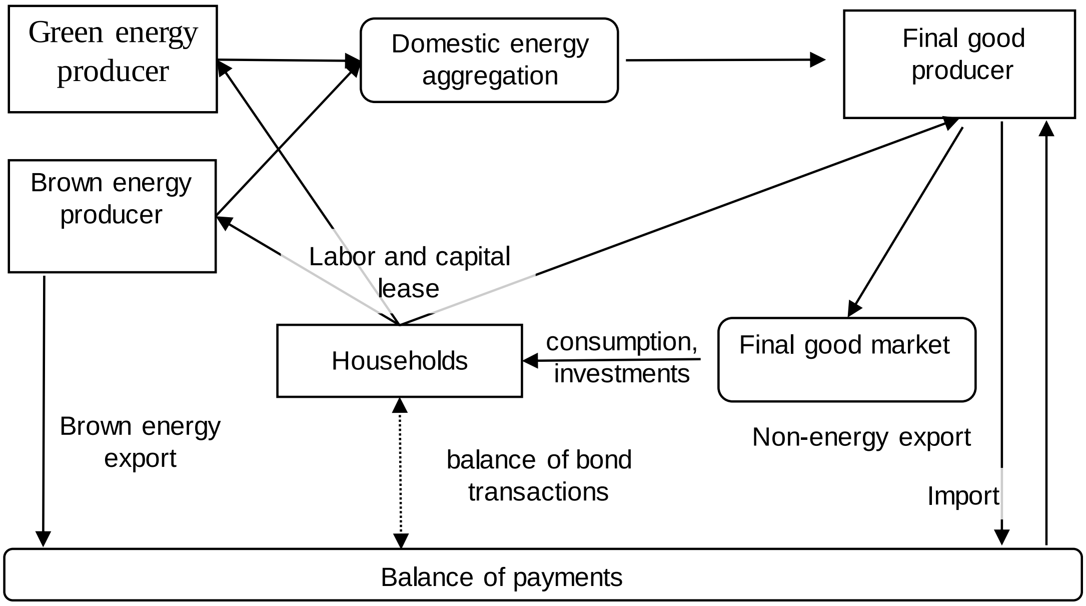
The impact of various decarbonisation policy scenarios on the economy of an energy export-oriented country has not been sufficiently studied to date. A few papers on this topic include, for example, *Blazquez et al.* (*2021*), which investigates the effectiveness of VAT, policies aimed at changing domestic energy prices (converging with export prices), and the introduction of renewable energy to reduce domestic emissions and increase oil and gas exports. The combination of all types of measures leads to a decline in non-oil and gas output. However, total GDP will rise due to a large increase in oil and gas export revenues from the diversion of oil and gas abroad.

Finally, our paper fills a gap in Bank of Russia research on the macroeconomic effects of climate policy, whereas the research already conducted focuses on the issue of financial stability of industries and enterprises (*Morozov et al., 2020*; *Penikas, 2022*; and *Burova et al., 2023*).

4. General model description

The general equilibrium model under consideration describes a small open economy highly dependent on (hydrocarbon) exports. The specific feature of the model is the existence of two sectors, green and brown, competing with each other for the supply of the energy factor of production to the third sector of the economy, producing the final product (Figure 1).

Figure 1. Product flows, labour flows, and some financial flows in model (dotted arrows)



In this paper, the green energy sector is associated with low carbon output and the brown energy sector is associated with high carbon output. Depending on a scenario under consideration, the term ‘energy’ is understood as energy itself or, more broadly, as the output of the power generation, oil production, oil refining, gas, coal, or other fuel industries (such as oil shale and peat production).

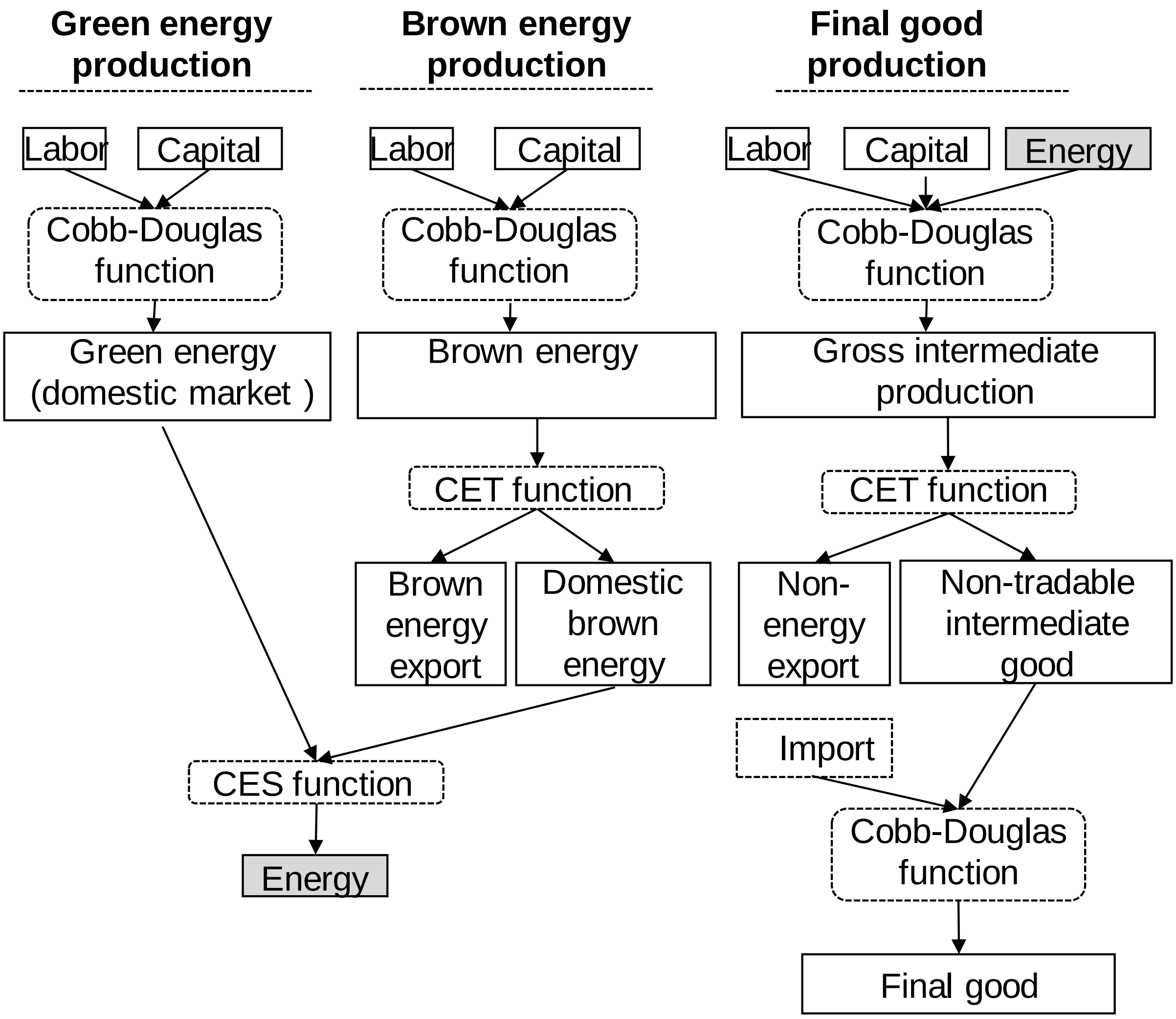
The basic scenarios analysed in our paper are the transitions of the green industry from a near-zero output level to a level comparable to the output of the brown industry. We focus on the economic processes accompanying such transitions.

Although the two competing sectors of energy generation, green and brown, are associated in the study with low and high carbon emissions, no explicit linkage is made to emission levels. In the most general case, we can therefore say that the paper investigates the macroeconomic aspects of the development of a certain competitive sector – from zero to a meaningful level in the structure of the economy.

The model contains three sectors of the economy whose production structure is standard for equilibrium models (see, e.g., *Lofgren et al., 2002*). The three production sectors all use labour and capital, which they borrow from households, at the initial stage of production (Figure 2). The final goods production sector also uses a third factor, energy, produced by other sectors, as well as imports at the final stage of production.

By combining labour and capital, the green energy sector produces output that is entirely used in the domestic market. This model assumption is due to the fact that the infrastructure for the transport of green energy does not currently exist, unlike the infrastructure for brown energy production. That is why the brown energy sector disaggregates the gross output generated by labour and capital into two components: brown energy exports and a domestic component.

Figure 2. Green/brown energy production and final goods production modelling



The domestic component of brown energy output and all green energy produced are aggregated into total energy using the CES function. The use of the CES function to aggregate the two types of energy means that the energy market is, on the one hand, competitive: the distribution of demand for green and brown energy depends on the price ratio of these two types of energy. That is, the higher the price of one type of energy, the lower the demand for that type. On the other hand, the domestic energy market is not perfectly competitive: even if prices for green energy, for example, are very high, the generation of green energy will not be zero. This assumption is standard for top-down models and is not in line with bottom-up models. The latter assume that 1 kWh generated by green energy sources and 1 kWh generated by brown energy sources are completely equivalent in energy terms. The assumption made in our study that the two types of energy are not fully equivalent is justified by the fact that we are considering a macroeconomic model describing the economy of an entire country. This means that such factors as energy transport and uneven coverage of the territory by energy sources are important. There are regions in Russia where the brown energy endowment is low and the conditions for green energy production are better. This implies that each type of energy will have advantages in certain regions nationwide, and the assumption of complete interchangeability of energy types is not relevant. *Potashnikov et al.* (*2022*) provide an example of how optimal green energy production tends to be concentrated in certain regions.

First, the final goods production sector aggregates labour, capital, and energy (Figure 2). The obtained gross product is disaggregated into non-energy exports and domestic intermediate product based on the CET function. Then, the domestic intermediate product is aggregated with imports, resulting in the final product output spent on consumption and investment.

The model describes households in a standard way. They lend labour and capital to producers, can make savings in foreign bonds,[4] spend on consumption, and decide on the rate of investment in production capital[5] based on prevailing capital yields and investment costs.

We assume that capital for production sectors is not interchangeable, while workers are hired by producers in a common market.

This model relies on the standard neo-Keynesian approach to describe a number of imperfections: the rigidity of nominal domestic prices and nominal wages, costs of household investment in foreign bonds, and investment costs. The cost of investment in foreign bonds characterises the extent to which the financial account is closed.

The objective of monetary policy is inflation targeting in accordance with the Taylor rule. Monetary policy is assumed to be highly inertial. The model does not describe fiscal policy.

Appendix A provides a detailed specification of the model.

5. Shock mechanisms

5.1. General assumptions for simulation of shock effects

In Section 5, the focus is on the long-lasting (permanent) effects of one-off shocks. Shock effects are interesting to analyse since, first, this analysis explains the macroeconomic mechanisms of spillovers throughout the economy. These same mechanisms are at play in scenarios in Section 6, exploring the impact of a series of shocks in terms of the deterministic

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[4] Households' savings in foreign bonds is a method for modelling cross-border financial flows in DSGE models. The standard explanation for assigning this variable to households is that the model does not separate the national population into true owners of large financial capital and the rest of the population unable to conduct cross-border transactions.

[5] Households' management of investments in production capital is explained by the fact that model households are not divided into true owners of production and the rest of the population. The model household agent performs both the role of an owner and the role of a worker providing labour for hire.

concept. Second, when economically logical shock effects are exposed, they serve as a model validity check.

The shocks discussed in this section are formulated according to the stochastic concept, suggesting that agents perceive the environment as exposed to accidental effects. In the first period of time, the shock comes unexpected to agents.

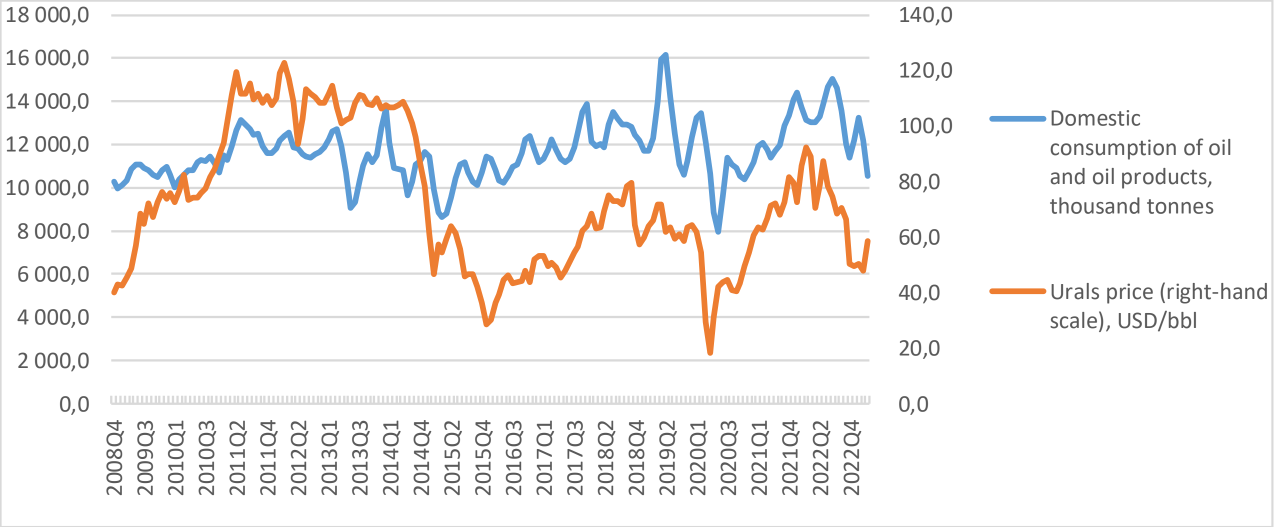
The figures in Subsections 5.2–5.4 show impulse response functions for the following three economic states: 1) inertial monetary policy with an open financial account; 2) non-inertial monetary policy with an open financial account; and 3) inertial monetary policy with a closed financial account. The emergence in the model of a closed financial account is due to high costs of investment in foreign bonds and corresponds to zero investments in such bonds. The differences in impulse response functions are presented in Subsection 7.1.

The type of long-term equilibrium for the calculation of the shocks is such that is defined by the green sector's low share (2%). This may be behind the 'too low' or 'too high' scale of response of the green energy production variables.

As follows from the analysis below, the effects of shocks on brown and green energy strongly depend on assumptions about brown energy production, see equation (26). That is, our calculations assume that the parameter φ_b of CET functions (26), which disaggregates brown energy output into the domestic and export components, is $\varphi_b = 3$, corresponding to the low elasticity of transformation $\sigma_b = 0,5$.

Once the low elasticity of brown energy transformation is selected, the brown sector's response to the decline in the external price of energy exports involves the producers reducing not only the export but also the domestic component. Such a response may look counterintuitive: if demand or the product price drops in one of the target markets (the export market), the producer could have redirected the goods to the other, domestic, target market. Accordingly, domestic consumption and the external price could be expected to show a negative correlation. However, as statistics show (Figure 3), there is a positive correlation between domestic consumption and the external price.

Figure 3. Consumption of oil and oil products in Russia (seasonally adjusted) and Urals price (right-hand scale).



The second reason why the low elasticity of export transformation is chosen is the scale of export response induced by a change in the external price of exports. As shown in Subsection 7.3 (Figure 15), a 10% drop in the external price of exports with low elasticity of transformation leads to a less than 10% drop in exports – which is a match with reality – and a more than 10% drop when transformation elasticity is high.

That being said, Subsection 7.3 considers the economic response when export transformation is alternatively high. Looking further forward, let us note that given the high elasticity of export transformation, all the scenarios (except the one assuming a decrease in the external price for brown energy) have approximately the same parameters of the energy transition goal (see Table 3). From an economic perspective, the low elasticity of export transformation is interpreted as an economic environment in which an increase in the external price for brown product exports reduces supply in the domestic market, and high elasticity is seen as a reorientation of exports to the domestic market involving a drop in the external price.

5.2. Permanent external price shock to brown energy

This subsection discusses a permanent decrease of 10% in the external price of brown energy exports (Figure 4). This shock is similar to the negative oil price shock explored in *Andreyev and Polbin* (*2019*), *Kreptsev and Seleznev* (*2018*), and *Polbin* (*2014*).

A declining price of brown energy in global markets reduces export revenues and, by extension, its supply. The brown energy producer decides on the volume of total brown energy output and its distribution between the domestic and external markets. The CET function of brown energy disaggregation (26) is such that given the low elasticity of export transformation and a decline in one of the components, the producer will cut back supply in both markets, causing also a drop in the output of the domestic component of brown energy. Since the supply of brown energy in the domestic market shrinks, domestic prices for this type of energy increase against current demand.

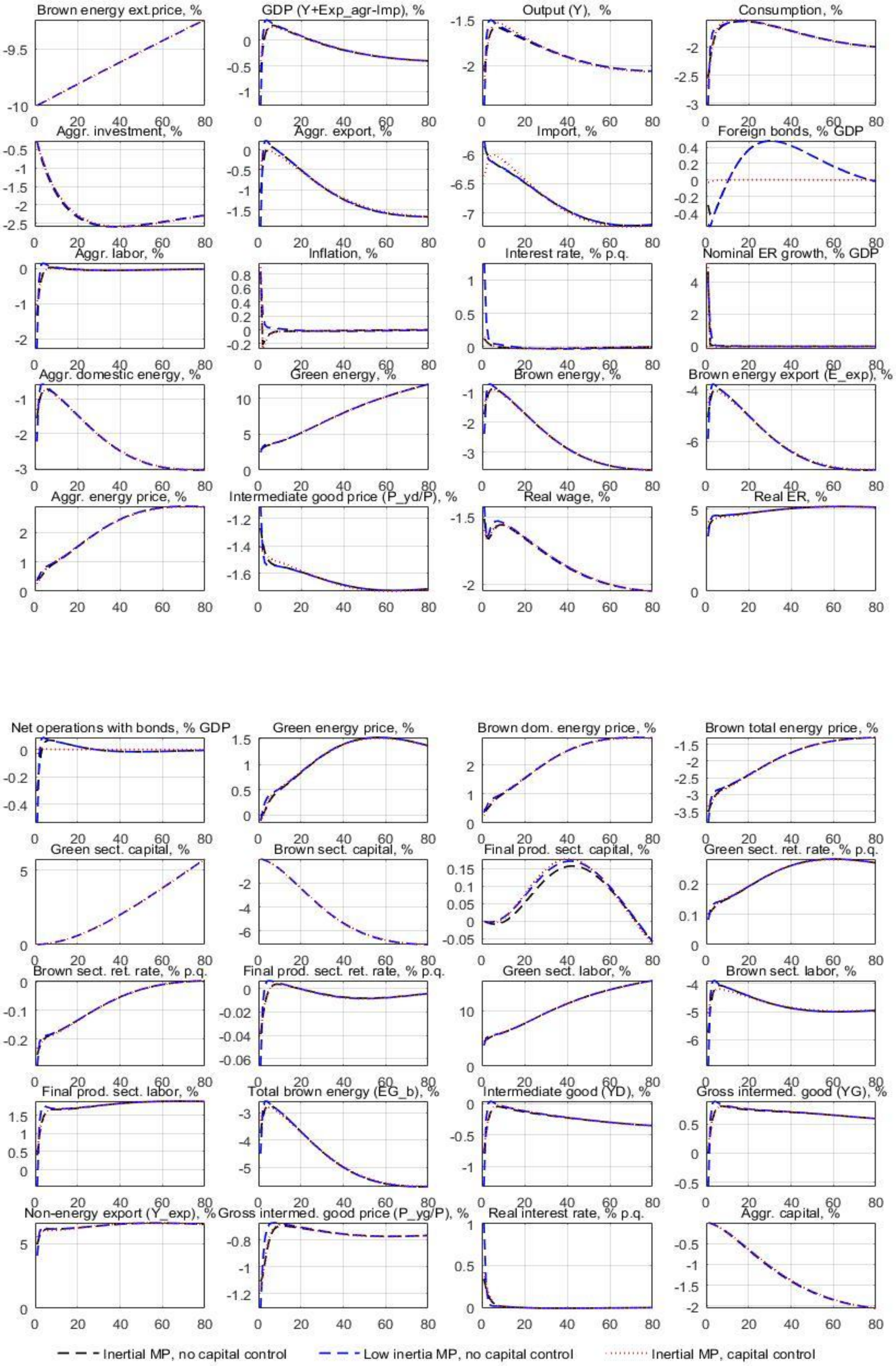
The squeeze in brown energy supply propels the economy to switch to green consumption. At the same time, prices rise as green production expands. Importantly, this process enables the energy transition in the scenario of Subsection 6.2. Otherwise, the energy transition is impossible, as noted in Subsection 7.3.

The decrease in income triggers a drop in consumption and, by extension, in output, aggregate investment, and imports. A decline in demand for final products down demand and the volumes of production factors, namely aggregate energy, aggregate labour and aggregate capital. Growth is seen only in labour in the green energy sector, on the back of cheapening of this factor, its mobility, and the green sector's positive output performance.

A significant contraction in energy exports in the short term triggers domestic currency devaluation. As the domestic currency weakens, non-energy exports expand. Aggregate exports fall over a short term in sync with a fall in energy sales abroad; this is followed by a slight rally on the back of the prevailing effect of expanding non-energy exports.

A weakening in the domestic currency creates inflationary pressures. Consistent with the Taylor rule, monetary policy responds to the deviation of inflation from a steady level, and the regulator increases the rate. Higher rates and lower wages reduce household consumption, output, and imports.

Figure 4. Functions of impulse response of model variables to permanent 10% drop in export price of brown energy



5.3. Permanent domestic tax shock to brown energy

In what follows, we discuss the effect of the permanent imposition of a 10% domestic tax on brown energy production (Figure 5). Both brown energy entering the domestic market and energy sold abroad are taxed. The resulting tax is funnelled to households.

Growth in the tax translates into a rise in brown energy prices. Demand for brown energy drops, causing a decrease in its output. This results in the emergence of incentives for the transition of the economy to green energy as its production is steadily expanding. However, since these products are substitutes and demand easily goes to the green sector, this sector fails to ensure rapid growth in its production capacities, which entails an increase in green energy prices.

The decline in brown energy output for the domestic market also leads to the faltering supply of brown energy in the export market. This is due to the choice of the production function and its parameters, explained in Subsection 5.1: if either domestic or export market is under pressure, the production of brown energy drops in both markets.

The nature of tax effects is distortive and shifts production towards a less efficient[6] distribution of benefits in the economy. Beyond the above mentioned drop in brown energy output and rising costs of aggregate energy, this is indicative of an overall decline in consumption, output, investment, and imports. There is also a decline in the impact of aggregate factors of production, such as labour, capital, and energy. At the sectoral level, both the green sector and final goods producers post positive labour and capital data, accounted for by rising non-energy exports as the domestic currency weakens.

Inflation grows in the short-term as domestic currency weakening effects outweigh the decline in domestic prices triggered by decreasing output. Through the rate hike, monetary policy enables the regulator to quickly bring price growth back to target, and the rate returns to its neutral level.

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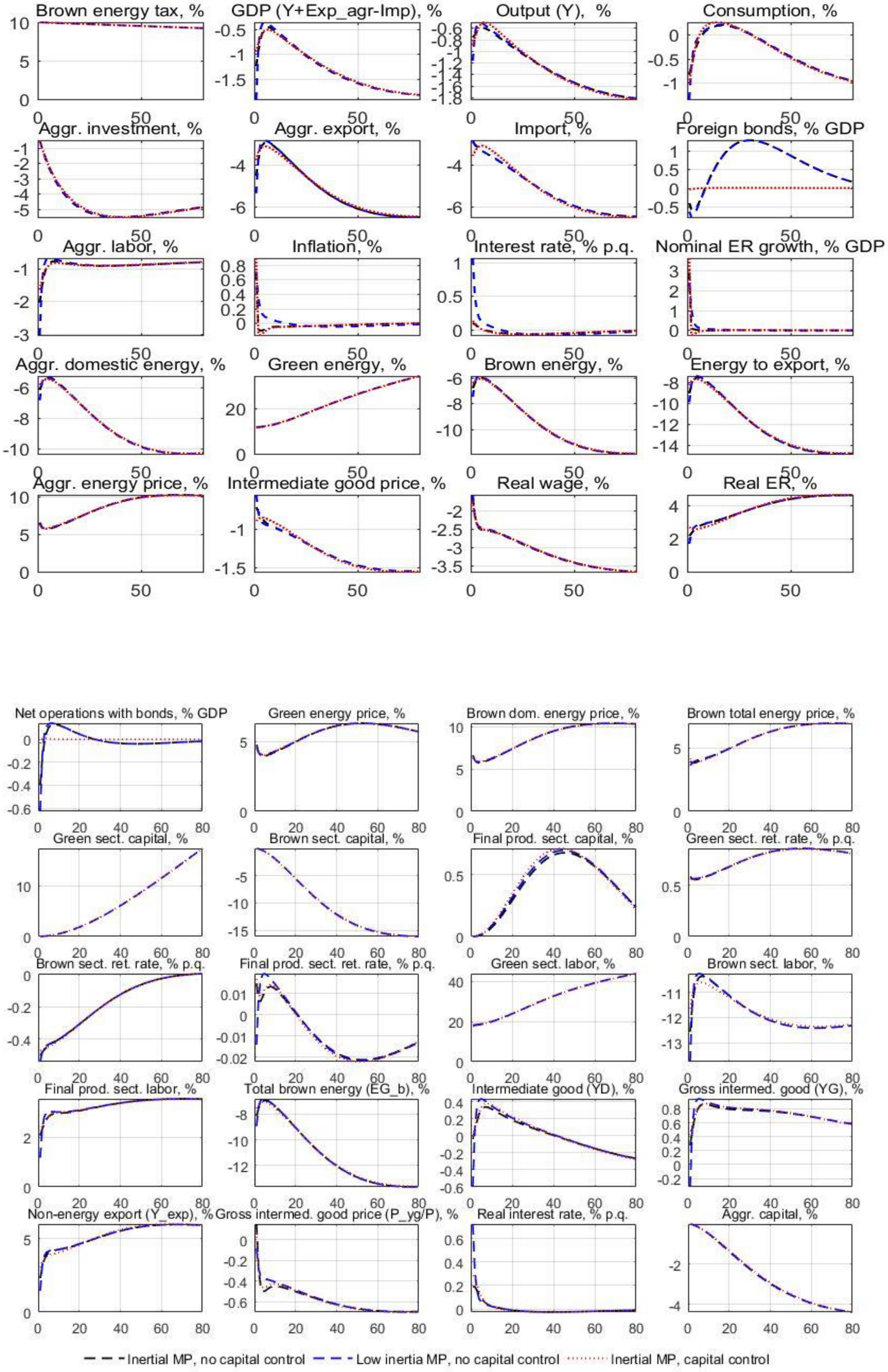
[6] Such a positive effect of energy transition as the elimination of the threat of global warming is not taken into account in this paper. Hence, in the considered scenario we refer to a shift towards a less efficient equilibrium.

Figure 5. Functions of impulse response of model variables to permanent 10% shock of domestic tax on brown energy



5.4. Green sector productivity growth

This subsection looks into permanent growth of 10% of total factor productivity (see equation (20)) in the green energy sector (Figure 6). There is no substantive description of what productivity growth is driven by; it is seen as a random event, the cause of which is unimportant for our calculations.

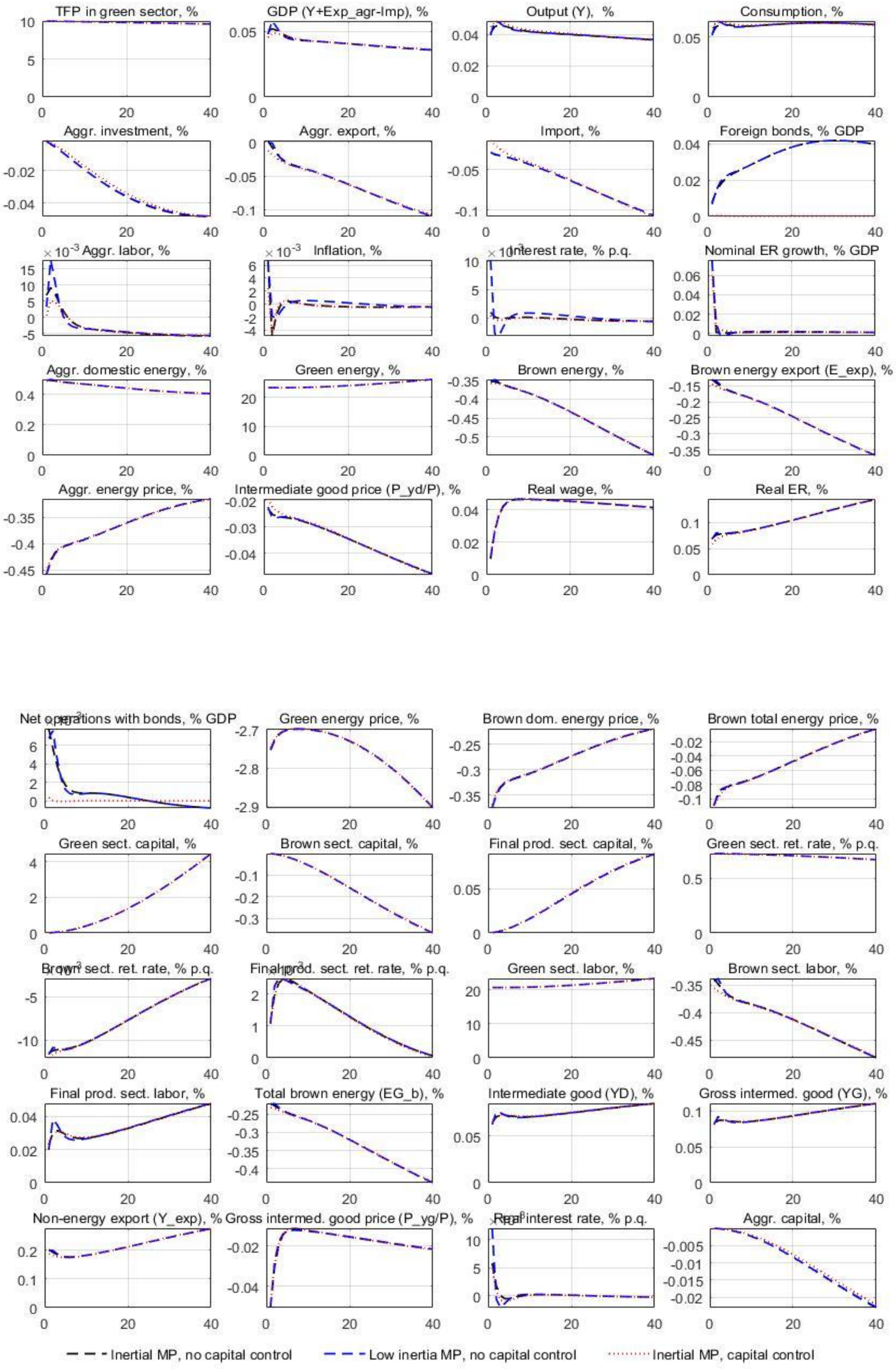
Increased productivity leads to higher green energy output and lowers its price. As brown energy loses competitiveness, its output shrinks. Concurrently, both its domestic consumption and sales abroad are shrinking. The price of brown energy is also decreasing, with producers forced to revise prices downwards to keep at least some of their market share against the background of rising competitiveness of green energy.

The lower prices for energy, which is a factor in the domestic intermediate goods production, entail an increase in the output of intermediate goods and an increase in final output, consumption, GDP, and non-energy exports. Total exports decline on the back of reduced overseas sales of brown energy, while the fall in total exports is partially mitigated by growth in non-energy exports, and there are no green energy exports, as assumed in the model, due to a lack of export infrastructure. The domestic currency depreciates. The economic expansion may generate additional demand for imports, but the downward pressure of weaker exchange rate prevails, causing a drop in imports.

Labour and capital exit the brown sector to the green and final product sectors.

Separately, the response of some variables to the 10% rise in productivity efficiency in the green sector is small since the share of the green sector is assumed to be a mere 2% of the broader energy sector.

Figure 6. Functions of impulse response of model variables to permanent 10% shock of total factor productivity growth in green energy



6. Green energy growth scenarios

6.1. Scenario descriptions

Section 6 discusses scenarios for the effects of macroeconomic instruments that could potentially bring about the energy transition in a hydrocarbon exporting country. The energy transition is understood to be the expansion of green energy from its 1% share of the energy market to 25% (consistent with the narrative of Section 2). It is assumed that the operation of instruments is even for 10 years (40 quarters) and thereafter ceases. The 25% market share target is achieved in long-term equilibrium. To be more precise, green energy may fail to reach the 25% target in 40 quarters but will eventually make it as a result of the progress over the course of these initial 40 quarters.

The calculation of scenarios in the stochastic concept, assuming that all shocks come unexpected to agents, requires the decomposition of the model equations relative to initial equilibrium, which is consistent with the 1% share of green energy. This decomposition is structurally significantly different from a state of the economy in which green energy accounts for 25%. Therefore, scenario calculations based on linearised models and even on higher-order decompositions bring unrealistic results.

This explains the need for the exactly solvable model equations. The deterministic concept makes this possible, with the agents knowing beforehand the change scenarios for the actuating variables. As Section 8 shows, the responses of the most important model variables do not fundamentally differ between the cases of agents being accurately knowledgeable about future scenarios and being unaware of them. This substantiates the calculation of scenarios in line with the deterministic concept.

The following scenarios are considered (see Subsections 6.2–6.5).

Scenario 1. Decrease in external price of brown energy exports. At the root of this process lay the decision by technologically advanced countries importing hydrocarbons to impose a higher tax on products made with hydrocarbon fuel. This includes a cross-border carbon and other taxes. As consumers in the importing countries are confronted with a rise in the cost of one of such products due to the higher tax, they cut back on the consumption of this product, bringing about a decline in the product price less tax. As a result, the product exporter faces a decline in both demand and the price. The model in this work assumes that the exporting country (Russia) is a small country. That is, the assumption is that the whole impact on Russian exports is reflected only in prices: the volume of exports depends on the margins that Russia has at current prices.

Scenario 2. Imposition of (or increase in) domestic brown energy tax. This scenario has already been partially implemented within the Russian Power System. The domestic energy market is governed by a 'two-product model' entitling capacity owners to two types of payments. The first is the charge for energy output, determined by the supply and demand equilibrium. It is the same per 1 kWh for all producers. The second is the capacity charge. Its unit cost differs by producer, with solar and wind power stations charging more due to clean energy surcharges. Therefore, the state of affairs may be viewed as essentially the existence of a domestic intra-Russian-Power-System tax in favour of green and to the detriment of brown energy.

In the Power System, energy producers and major industrial enterprises pay a carbon tax. Carbon tax revenues are not necessarily used to support green energy.

Accordingly, the brown energy sector is taxable in two ways: 1) nationwide, tax revenue is not allocated to green energy; and 2) in the energy system, tax revenue is allocated to green energy. These two ways are described in the dual scenario of 2a and 2b.

Scenario 2a. All brown energy, including exports, is taxable ($P_t^{bg} EG_t^b$, see equation (26)). The tax revenue passes on to households.

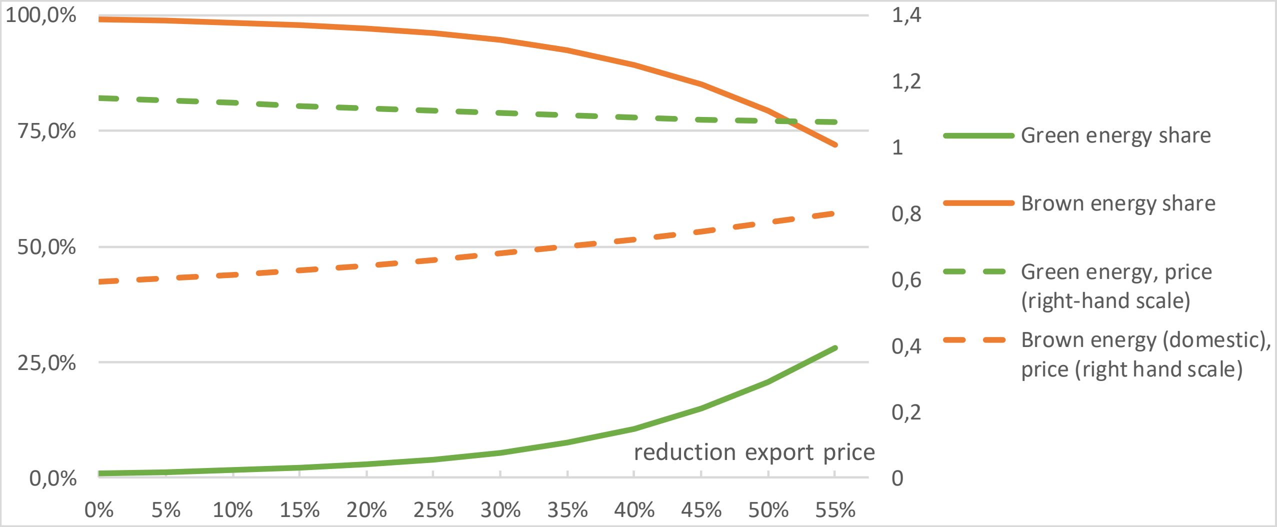
Scenario 2b. Only the cost of brown energy that remains within the country is taxable ($P_t^b E_t^b$, see equation (26)). The tax revenue passes on to green energy producers.

Scenario 3. Growth of total factor productivity in green energy sector. In this scenario, productivity increases in accordance with equation (19). We first consider the case leaving causes of productivity growth unspecified (see Subsection 6.4) and then make calculations for this scenario if productivity growth is down to investments (see Subsection 6.5). Towards this, we introduce investment to productivity transformation ratios, based on comparison with scenario 2a. The inclusion of investment as a cause of productivity growth, apart from being realistic, enables to interpret the scenario in two ways: productivity can grow as a result of the exporting country's efforts to improve production efficiency, or as a result of the exporting country copying imported technologies. The cost of 'copying' technologies is a parameter of the model.

6.2. Scenario 1. Decrease in export price of brown energy

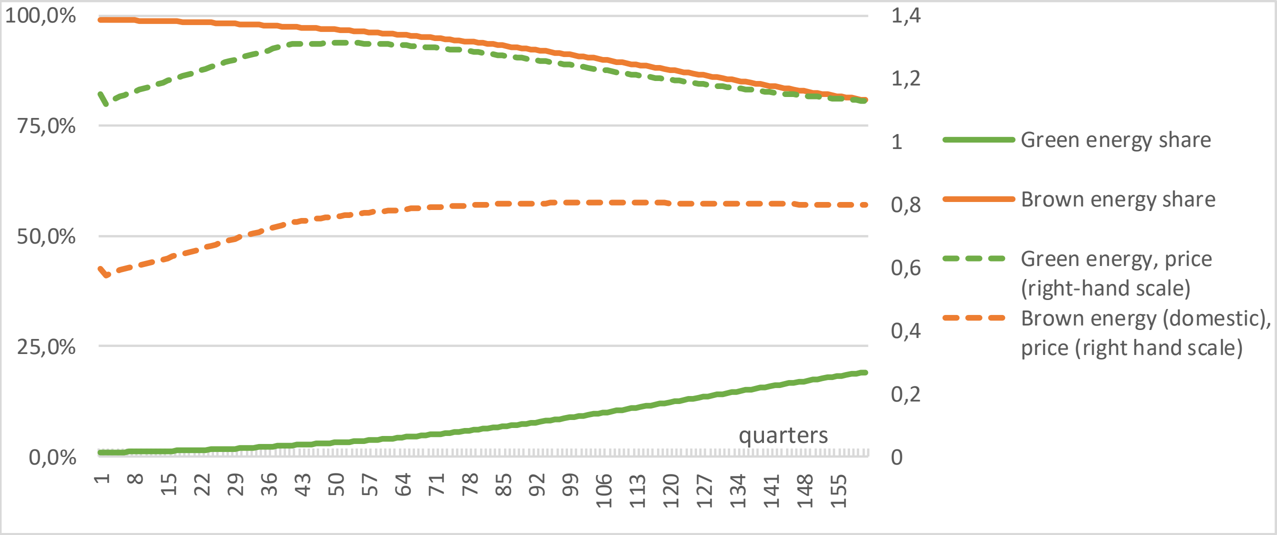
The assumption here is that the export price of brown energy $P_t^{b,\exp}$ decreases at a constant rate for 40 quarters and remains unchanged thereafter. Figure 7 shows the dependence of long-term volumes and prices of energy on the export price decrease. If the decrease is about 53%, the market share of green energy is up to 25%.

Figure 7. Energy volumes and prices in long-term equilibrium subject to scale of decrease in brown energy export price over 40 quarters



The calculated quarterly energy changes in the external price decrease scenario (Figure 8) shows that brown energy volumes are steadily decreasing, while green energy volumes are steadily growing. It takes about 70 years for the indicators to come close to their long-term equilibrium values. After the first ten years and after the decrease in the external price ends, the green sector's share is 2.6%, which is one-tenth of the long-term equilibrium value, suggesting that this is a high inertia scenario. Its inertia is attributable to the slow adjustment of production capital to existing conditions. The other variables change in the direction shown in Subsection 5.2.

Figure 8. Energy volumes and prices when external price for brown energy exports drops 55% over 40 quarters



Note that the result of this scenario is not robust in relation to the assumption of elasticity of transformation φ_b (see Subsection 7.3 and equation (26)) in the brown energy sector. Namely, the higher elasticity of transformation results in producers responding to decrease export prices by increasing, rather than decreasing, sales in the domestic market. Thereby producers prevent the green sector from gaining a significant market share, and the scenario goal falls through.

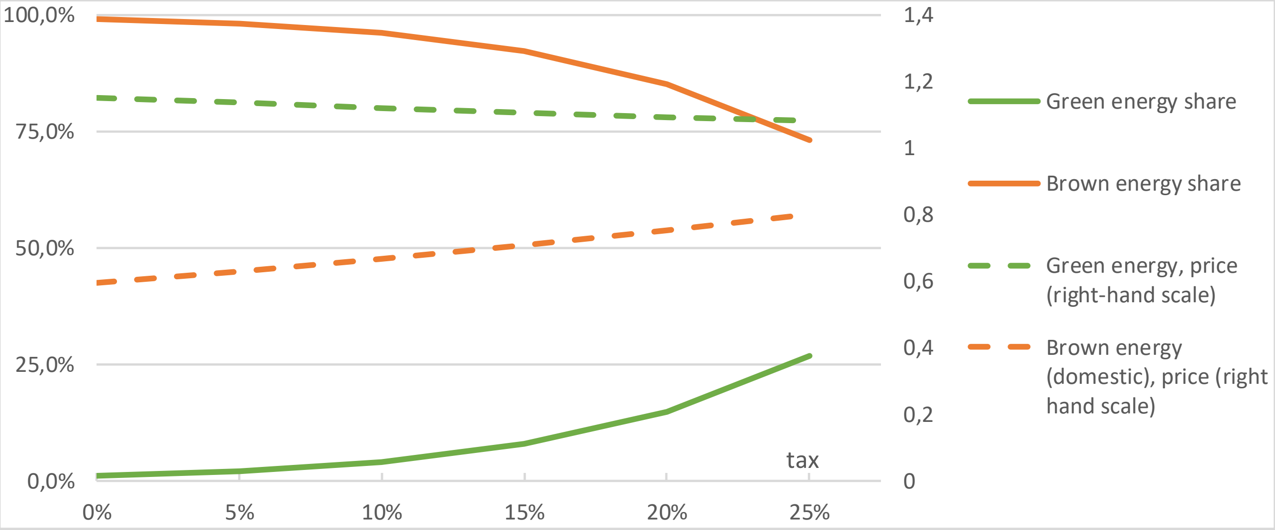
Consequently, the goal can be achieved depending on how aggressive brown energy producers redirect their products to the domestic market as the external price declines.

6.3. Scenarios 2a and 2b. Imposition of domestic brown energy tax

In scenarios 2a and 2b, the tax on brown energy costs rises over 40 quarters at the same rate. In 2a, all brown energy output is taxable and passes to households, while 2b provides for the tax to apply only to domestic brown production and pass on to green energy producers.

The goal is achieved in both scenarios (Figure 9 and Figure 10): the rate is 25%[7] in scenario 2a and 17% in scenario 2b Tax revenues in scenario 2b is about half as large as in scenario 2a since it is based on costs that are half as large as in 2a. However, in scenario 2b, all the tax revenue goes to green energy producers rather than to households. The fact that the required level of tax in scenario 2b turns out to be lower means that incentivising green producers through surcharges is a more effective measure than a tax policy aiming to deteriorate the brown sector’s performance.

Figure 9. Energy volumes and prices in long-term equilibrium subject to scale of increase in domestic tax on total brown energy (scenario 2a) over 40 quarters



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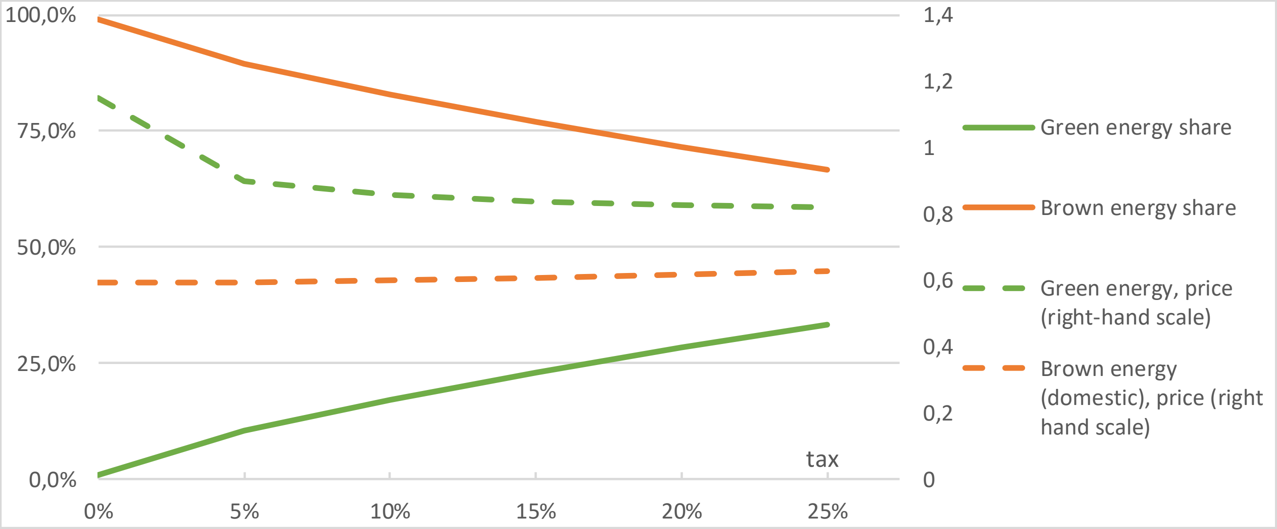
[7] A 25% increase in the electricity tariff corresponds to an emission charge of $10 per 1 tonne of CO_2 for coal-fired sources and $25 per 1 tonne of CO_2 for gas-fired sources (assuming calculation parameters of ₽8 per 1 kWh, the USD/RUB exchange rate of 80, and the carbon intensity of electricity of 1 kg CO_2 / kWh for coal and 0.4 kg CO_2 / kWh for gas).

Figure 10. Energy volumes and prices in long-term equilibrium subject to scale of increase in domestic tax on domestic brown energy (scenario 2b) over 40 quarters



In scenario 2b, the long-term effects of a small tax are also higher than in scenario 2a. In both scenarios, the price of brown energy increases with the rate, while the price of green energy decreases as brown energy producers pass most tax increases on to prices – in contrast to green energy producers, which cut back prices at the expense of revenue.

As changes in energy volumes and prices (Figures 11 and 12) show, the energy transition in scenario 2b is more dynamic: already over a horizon of about 100 quarters green energy is close to the target indicator, whereas these indicators in scenario 2a are only attainable over a period of more than 160 quarters. Greater intensity seen in scenario 2b is explained by the fact that green sector incentives are not only indirect (delivered through pressure on demand for the competing brown energy) but also direct – by way of surcharges. Furthermore, energy costs in scenario 2b are lower than in scenario 2a: surcharges enable green energy producers to reduce prices more aggressively and make it more difficult for brown energy producers to raise prices.

Summing up, we find that low interchangeability between brown and green energy renders energy transition goals unachievable, while with high interchangeability they are achievable. At that, scenario 2b is preferred due to its higher intensity of the energy transition process and lower increase in energy prices. Let us say again (Subsection 6.1) that scenario 2b with surcharges for the green sector is a match with reality, i.e. the practice of the Russian Power System.

Figure 11. Changes in energy volumes and prices when domestic tax on total brown energy increases by 25% (scenario 2a) over 40 quarters

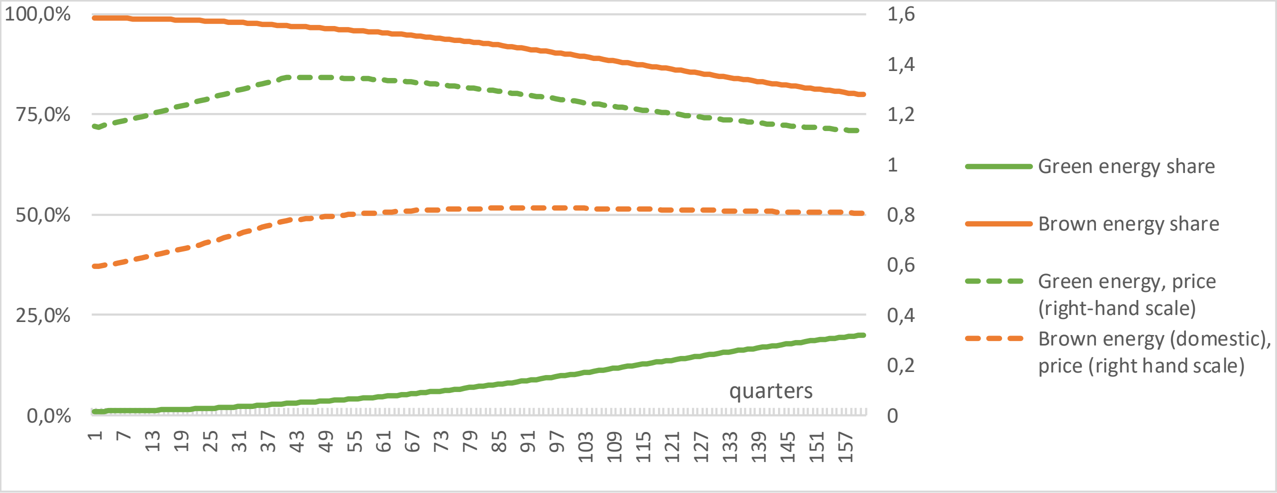
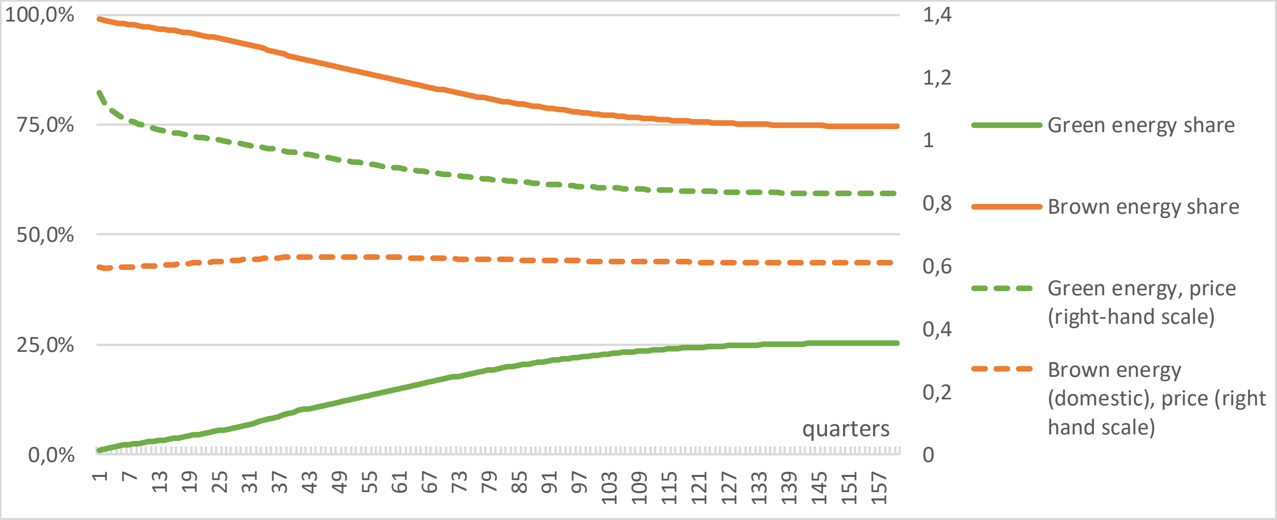


Figure 12. Changes in energy volumes and prices when domestic tax on domestic brown energy increases by 17% (scenario 2b) over 40 quarters



6.4. Scenario 3. Productivity growth in green energy sector without modelling causes of growth

In this scenario, green production efficiency increases for 40 quarters at a constant rate, and it is remains steady once it has achieved this level. The calculations in this subsection do not model a cause of productivity growth (see Subsection 6.5). This is due to the fact that the scenario results are intended only for reference as a benchmark of the highest public wealth achievable in the course of the energy transition on the back of productivity growth. Researchers substantiate such scenarios under the *learning by doing* approach (see, for example, *Thompson*, 2010), i.e. the productivity growth phenomenon based on the production experience that firms accumulate.

In the productivity growth scenario, the energy transition goal is also attainable (Figure 13): if productivity growth is 55%, green energy takes the required market share in long-term equilibrium.

The process dynamics (Figure 14) demonstrate the decline in the cost of green energy driven by higher productivity, as well as the displacement of brown energy by cheaper green energy. Importantly, in this and most previous scenarios, economic changes take much longer than 40 quarters, requiring the adjustment of production capital in the green and brown sectors to new conditions.

Figure 13. Energy volumes and prices in long-term equilibrium depending on productivity growth

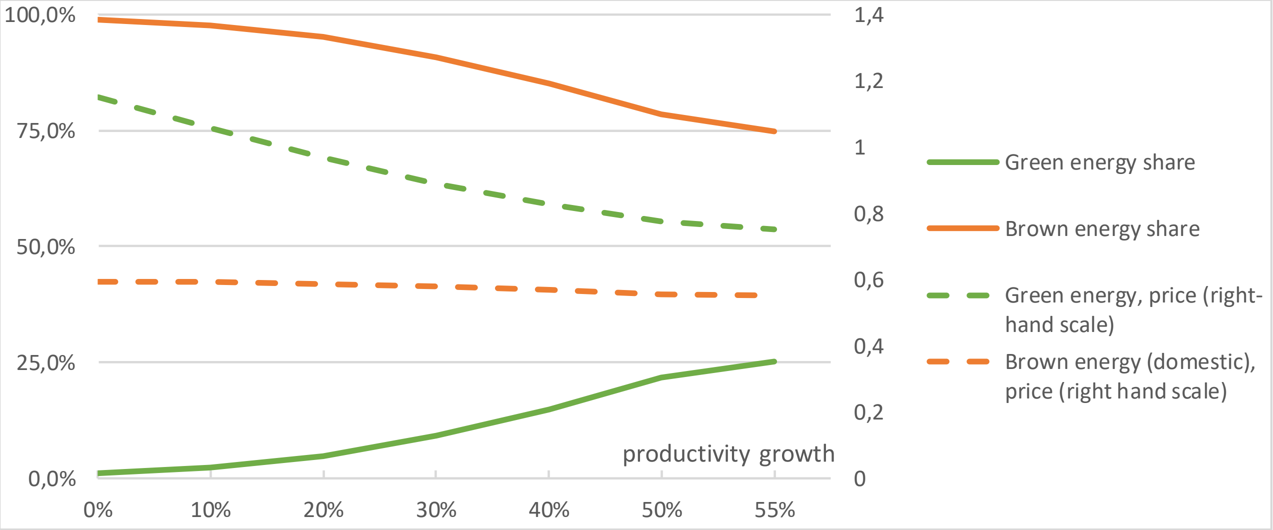
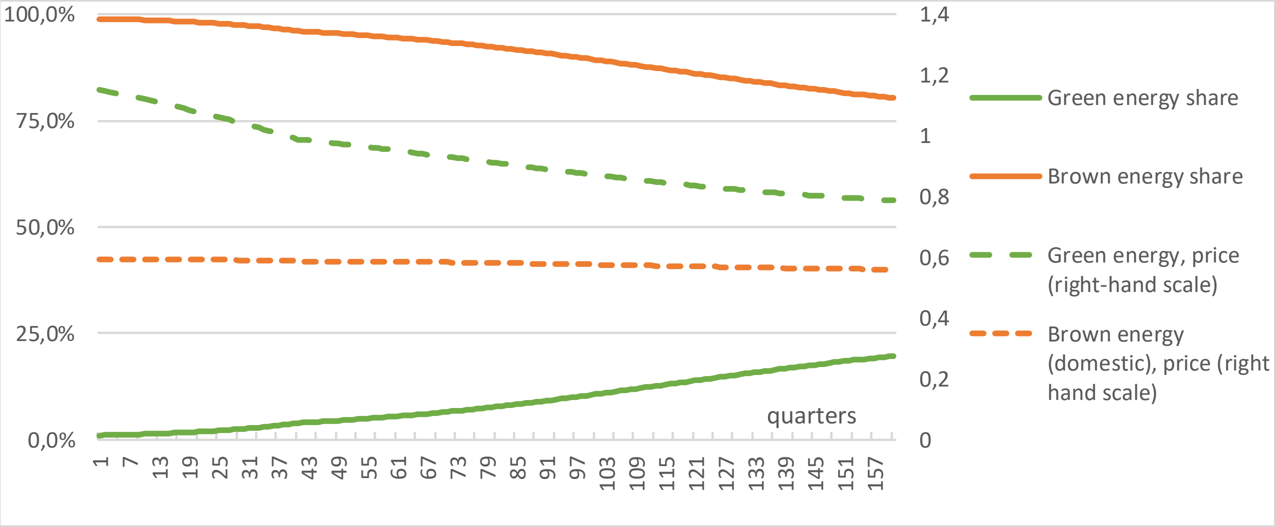


Figure 14. Energy volumes and prices with 55% productivity growth over 40 quarters



6.5. Scenario 3. Productivity growth in green energy sector with consideration for investments in productivity

According to the results of the previous subsections, energy transition is possible in all the scenarios (although the results in the external export price decrease scenario are not robust to the model assumptions). The productivity growth scenario does not describe the cause of productivity growth. For this reason, the scenarios outlined here are not comparable.

They can be compared by describing the cause of productivity growth in scenario 3. Let us assume that green energy production follows the equation:

$$E_t^g = a^g \left(\frac{TFP_{t-1}}{TFP_{ss}} \right)^{\alpha^g} \left(K_{t-1}^g \right)^{\alpha^g} \left(L_t^g \right)^{1-\alpha^g} , \qquad (1)$$

where the dynamics of TFP_t is described by

$$TFP_t = TFP_{t-1} + P_{TFP}\, I_{TFP} . \qquad (2)$$

The value TFP_t characterises the total productivity of two factors, labour and capital. The dynamics of productivity are similar to those of production capital K_{t-1}^g, see equation (5). The difference is that, first, unlike capital, productivity is not affected by depreciation, and second, investments I_{TFP} can boost productivity only with a certain investment transformation ratio P_{TFP}.

Let us assume that the state's volume of real investments is constant at I_{TFP}, made on account of tax collection over the course of 40 quarters; these real investments are purchased in the final product market and enter productivity indicator TFP_t. The problem is the unknown investment transformation ratio P_{TFP}. In this context, the scenarios can only be compared as follows: The amount of investments I_{TFP} and the transformation ratio P_{TFP} are selected so that the domestic tax growth (2a) and productivity growth scenarios (3) are equivalent. The equivalence of scenarios assumes that:

1) the green sector's share in long-term equilibrium totals 25% of the market in both scenarios; and
2) The same change (decrease) in public wealth, which is expressed by ratio (4), in both scenarios.

It turns out that the equivalence of scenarios 2a and 3 requires that the transformation ratio is $P_{TFP} = 0,021$ and that the quarterly investments are $I_{TFP} = 0,057$, i.e. 5.7% of the initial level of GDP.

The investment of 5.7% of GDP in the sector initially producing a mere 1% of energy suggests that the productivity growth scenario is preferred: only if investments are too high, this scenario becomes as ineffective as the domestic tax growth scenario. However, to compare the scenarios, it is more appropriate to characterise the transformation ratio $P_{TFP} = 0,021$ from the investor's perspective. Let us assume that the manufacturing investor chooses between investing a small amount δI in productivity TFP_t or in production capital K_t^g. Both investments result in an increase in green energy output. However, it turns out that at $P_{TFP} = 0,021$ the net present value of output increment when δI is invested in productivity is 13 times lower than when δI is invested production capital. Such a large multiple suggests an unrealistically low transformation ratio P_{TFP}. This again means that productivity growth scenario 3 is preferred to scenario 2a: only the unrealistically low ratio P_{TFP} makes the productivity growth scenario as ineffective as the domestic tax growth scenario. These arguments address the issue of scenario ranking.

To estimate the productivity growth scenario indicators with consideration for the cause of productivity growth, i.e. investment, let us think that the scenario provides for public investment in TFP_t to be less efficient than private investment in production by a factor of 4 (instead of 13). This assumption is substantiated by the view that research projects are generally considered risky for business and are usually funded by the state.

The assumption that public investment is less productive than private investment by a factor of 4 is aligned with $P_{TFP} = 0,0667$. This parameter suggests that a quarterly investment of 1.8% of GDP for 40 quarters is enough for green energy to gain 25%. In this case, the dynamics of prices and volumes of energy are similar to the scenario stripping out investments in productivity (Figure 14).

Total factor productivity $\left(\frac{TFP_{t-1}}{TFP_{ss}}\right)^{\alpha^g}$ for 40 quarters is up 55%. The scenario's other parameters are specified in the subsection below.

6.6. Scenario indicators compared

Table 1 shows changes in the long-term values of the variables across different scenarios and the change in public wealth. For reference, the last column presents the indicators of the productivity growth scenario without modelling causes of productivity growth.

Table 1. Key characteristics of scenarios for green energy sector to achieve 25% market share. Values of new long-term equilibria in % of initial long-term equilibrium (for public wealth values are given in terms of consumption equivalence)[8]

	1	2a	2b	3 With investments	3 Without investments (for reference)
Key scenario indicator	Decrease in external price of brown energy by 55%	Increase in tax on all brown energy by 25%	Increase in tax on domestic brown energy by 17%	Green sector productivity growth by 55% due to investments of 1.8% GDP	Green sector productivity growth by 55%
Public wealth, %	-7.95	-1.92	-1.26	-0.26	0.49
Output (Y), %	-9.8	-6.1	-1.4	1.4	1.5
Consumption (C), %	-9.8	-4.9	-1.4	1.4	1.5
Aggregate investments, %	-9.8	-10.5	-1.4	1.5	1.5
Aggregate labour (L), %	0.0	-1.4	0.0	0.0	0.0
Imports (Imp), %	-32.3	-20.9	-8.6	-4.6	-4.6
Real exchange rate, %	33.3	18.7	7.8	6.3	6.4
Domestic energy (E), %	-18.8	-21.2	3.0	16.7	16.9
Relative price of domestic energy (P_e/P), %	28.8	28.7	-1.4	-11.0	-11.1
Green energy (E_g), %	1,891	1,764	2,200	2,497	2,526
Relative price of green energy (P_g/P), %	-6.5	-6.2	-27.7	-34.7	-34.8
Domestic brown energy, %	-47.9	-48.5	-30.7	-21.4	-21.6
Relative price of domestic brown energy (P_b/P), %	34.6	34.3	2.6	-7.4	-7.4
Energy exports (E_exp), %	-65.2	-51.5	-22.1	-15.8	-16.0
Non-energy exports (Y_exp), %	45.6	25.0	11.7	12.3	12.4
GDP (Y + Y_exp +E_exp - Imp), %	-6.4	-6.1	-1.4	1.4	1.5
Ratio of decrease in brown energy to decrease in public wealth	7.1	26.2	20.1	69.1	-

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[8] In long-term equilibrium, the values of model variables are defined in the distant future, provided there are no economic shocks. In this table, unlike long-term equilibrium, the public wealth indicator, based on equation (4), reflects the change in consumption and labour, which are part of the household utility function, not only in the distant future, but also in the finite period of time.

Is the scenario result robust to the assumption of elasticity of transformation of brown energy exports φ_b ?	No	Yes	Yes	Yes	Yes

While all scenarios considered achieve the energy transition, they reduce the level of public wealth. At that, it should be noted that the positive effect of energy transition, which consists in the elimination of the threat of global warming, is not taken into account in our calculations. This positive effect, if it can be calculated, could have a positive impact on public wealth.

The steepest decline in public wealth occurs in the scenario of a drop in the external price for brown energy (scenario 1): the economy is short of export revenues, with growing non-energy exports failing to offset and just mitigating the drop. The increase in domestic tax (scenarios 2a and 2b) is less burdensome for the economy. Public wealth is negatively affected by the shift from efficient to inefficient production, which is reflected in a trend towards rising energy prices and a drop in total energy volumes. In the scenario of an increasing tax imposed only on domestic brown energy production (scenario 2b), the performance declines more strongly on the back of green sector incentives through surcharges. The smallest loss in public wealth comes from the investment-driven productivity growth scenario (scenario 3), which assumes that public investment in productivity is four times less efficient than private investment in production capital. In this scenario, the decline in public wealth is explained by investment costs, while productivity growth has a positive effect on economic performance, evidenced by growing long-term energy output, consumption and production.

With brown energy production being either adversely affected or gradually losing competition to green energy in all the scenarios, long-term brown energy production, both for domestic consumption and for export, declines in all the scenarios. As a consequence, all the scenarios show a weakening of the national currency, a decline in imports, and an increase in non-energy exports.

The green energy sector grows from 1,891% to 2,497% depending on the scenario, with the share of green energy rising from 1% to 25%. This comes from the fact that brown energy declines in the long term in all the scenarios, allowing green energy to grow by less than 25 times to capture 25% of the market.

For decarbonisation purposes, an important indicator is the ‘cost’ of reducing brown energy output, which can be estimated as the ratio of the decrease in output to the decrease in public wealth. While on this indicator, the ranking of scenarios turns out to be the same except that scenarios 2a and scenario 2b change places: scenario 2a is preferred due to its more substantial reduction in brown exports.

7. Sensitivity of results. Role of individual economic mechanisms

This section explores the model assumptions which determine the findings. Subsection 7.1 states that the type of monetary policy and the extent to which the financial account is closed do not affect the results. As mentioned in Subsection 7.2, the assumption about the degree of interchangeability between brown and green energy is extremely important; in the case of low interchangeability the energy transition goal is not achievable in any scenario. Subsection 7.3 shows that the assumption about the elasticity of export product transformation, which characterises the degree of reorientation of external export flows to the domestic market when external demand falls, may render the energy transition impossible in the declining external export price scenario. Finally, in Subsection 7.4, we discuss the impact of the assumption about the production of non-energy exports on the scale of response of the variables.

7.1. Impact of monetary policy inertia and extent of openness of financial account

The impulse response functions for the cases of inertial and non-inertial monetary policy, as well as the cases of an open and closed financial account are shown in Section 5.

The effect of the inertial monetary policy differs in that the scale of interest rate response to shocks is significantly smaller than in the case of non-inertial monetary policy. In the case of inertial monetary policy, the regulator responds to the shock by promising to hold the rates for an extended period of time. As they heed this message, rational agents take into account future actions of the regulator, changing prices on a smaller scale. As a result, the effects of inertial and non-inertial monetary policies are similar in the form and scale of responses.

The extent to which the financial account is closed also has a weak effect on the impulse response functions and thus the scenario results. When the financial account is closed, agents cannot invest in external financial instruments. This leads to a slightly distorted response of the variables related to the balance of payments (imports and exports).

7.2. Effects of brown and green energy interchangeability degree

It turns out that the scenario results depend in principle on how much the two types of energy – green and brown – can be interchangeable. Section 2 makes the case that interchangeability between the two energy types will decline as the share of green energy in the energy market grows. This may be caused by the uneven generation of green energy and energy storage difficulties.

The model simulates green and brown energy interchangeability through the use of the aggregating CES function (32):

$$E_t = a^e \left(\alpha^e \left(E_t^g \right)^{\varphi_e} + \left(1 - \alpha^e \right) \left(E_t^b \right)^{\varphi_e} \right)^{\frac{1}{\varphi_e}} \tag{3}$$

Clearly, if $\varphi_e = 1$, the two types of energy are perfect substitutes: they substitute one another in a constant proportion. This expression reflects the law of energy conservation and is typical of bottom-up models. Since we use the top-down approach, the elasticity of substitution should be finite, namely $\varphi_e < 1$. In our baseline calculations, we assumed that at least at the initial stage of energy market development, the two types of energy are interchangeable, so we made CES function (3) as close as possible to the case of perfect substitutes by specifying that $\varphi_e = 0,9$. At the same time, it was assumed that the parameter α^e equals $0,55$. The high value of this parameter means that technology (3) does not prevent the market from using green energy in large volumes, and its current market share of 1% is only a consequence of its price, which is 1.9 times the price of brown energy. Given this high price difference and the high degree of competition between brown and green energy (accounted for by the parameter $\varphi_e = 0,9$), producers do not want to use green products extensively.

This assumption of the model's baseline version can be revised in a drastic or moderate way. The moderate way suggests that green and brown energy share the same technologies as any two arbitrary industries do. Then, similar to existing works (e.g. *Klump et al.*, *2007* and *Le´on-Ledesma et al., 2010*), the ratio φ_e should take the value of about $-0,5$. At this parameter value, the dual energy market becomes less competitive, and aggregating technology (3) is less susceptible to the existing price difference between green and brown energy. Then, the price difference of 1.9 times between green and brown energy and the green energy market share of 1% can be explained only by the low value of parameter $\alpha^e = 0,01$. The low value of parameter α^e means that the dual energy aggregator cannot for some reason use a significant volume of green energy in production. That is, green and brown energy are poorly interchangeable. The scenario indicators when the parameters are $\varphi_e = -0,2$ and $\alpha^e = 0,01$ are presented in Table 2.

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Table 2. Scenario indicators: change of long-term equilibria in relation to initial long-term equilibrium. Alternative parameters of the aggregating CES-function ($\varphi_e = -0,2$ and $\alpha^e = 0,01$) are interpreted as low interchangeability of brown and green energy.

Scenario	1		2a		3 Without investments	
Key scenario indicator	External price of brown energy decreases by…		Tax on all brown energy increases by…		Green sector productivity rises by…	
Change in key indicator, %	25	50	25	50	200	1,000
Output (Y), %	-5.4	-9.9	-6.2	-15.3	0.3	0.9
Consumption (C), %	-5.4	-9.9	-4.6	-12.9	0.3	0.9
Aggregate investments, %	-5.4	-9.9	-12.1	-24.0	0.3	0.9
Aggregate labour (L), %	0.0	0.0	-1.9	-3.1	0.0	0.0
Imports (Imp), %	-17.2	-29.5	-16.7	-32.4	0.2	0.6
Real exchange rate, %	14.3	27.7	12.5	25.3	0.1	0.2
Domestic energy (E), %	-9.8	-21.6	-29.2	-58.0	1.6	4.7
Relative price of domestic energy (P_e/P), %	11.2	29.5	39.3	124.4	-1.2	-3.6
Green energy (E_g), %	1.5	2.9	-1.0	-6.0	78.8	588.8
Relative price of green energy (P_g/P), %	-3.5	-6.6	-6.9	-14.6	-49.9	-89.9
Domestic brown energy, %	-10.1	-22.2	-29.8	-58.8	0.2	0.7
Relative price of domestic brown energy (P_b/P), %	11.5	30.6	40.6	129.5	0.4	1.1
Energy exports (E_exp), %	-21.2	-45.6	-37.2	-69.5	0.1	0.2
Non-energy exports (Y_exp), %	18.3	35.4	14.2	23.3	0.4	1.3
GDP (Y + Y_exp +E_exp - Imp), %	-1.8	-5.0	-6.2	-15.3	0.3	0.9

In the scenarios assuming a decrease in the external price for brown energy (scenario 1) and in the tax growth scenario (scenario 2a), the brown energy sector is negatively affected and cuts back its domestic production. However, green energy does not occupy a vacant market: the low value of production parameter $\alpha^e = 0,01$ means that the market technologically does not need green energy. In the green sector productivity growth scenario, even the unthinkable tenfold increase in productivity – entailing a tenfold drop in the price of green energy – results in green energy volumes rising only sixfold, which is below the established goal of energy transition.

Consistent with the drastically reviewed assumption about high interchangeability between green and brown energy, the two energy types become perfect complements instead of almost perfect substitutes. This will happen if the green sector expands and the problem of irregular green power generation persists. Then, the expansion of green energy is possible only with the expansion of total demand, and the two sectors are set to grow in the same proportion. This situation can be modelled by replacing CES production function (3) with the Leontief production function. However, there is no need for a numerical experiment here, in our opinion: clearly, since the brown energy sector declines in all the scenarios (Table 1), a proportional change in the output volumes of the two sectors will cause the green energy sector to fall, not grow, in sync with the brown energy sector.

As a result, if green and brown energy become lowly interchangeable at a certain point, any green policy measures will fall through.

7.3. Role of export transformation elasticity

The elasticity of export transformation (for both energy and non-energy exports) is a factor in the simulated economy described by expressions (26) and (41):

$$EG_t^b = a^{bg}\left(\alpha^{bg}\left(E_t^b\right)^{\varphi_b} + \left(1-\alpha^{bg}\right)\left(E_t^{b,\exp}\right)^{\varphi_b}\right)^{\frac{1}{\varphi_b}}$$

$$YG_t = a^{yd}\left(\alpha^{yd}\left(YD_t\right)^{\varphi_{yd}} + \left(1-\alpha^{yd}\right)\left(Y_t^{\exp}\right)^{\varphi_{yd}}\right)^{\frac{1}{\varphi_{yd}}}$$

The first expression reflects the conversion of all domestically produced brown energy EG_t^b into the domestic E_t^b and export $E_t^{b,\exp}$ components. The second expression reflects the conversion of gross intermediate product YG_t to domestic intermediate product YD_t and non-energy exports $Y_t^{\exp}$.

The elasticity of export transformation is represented by parameters $\sigma_b = \frac{1}{\varphi_b - 1}$ and $\sigma_{yd} = \frac{1}{\varphi_{yd} - 1}$, which take values of $\varphi_b = 3,\ \varphi_{yd} = 2$ at $\sigma_b = 0{,}5,\ \sigma_{yd} = 1$, respectively. Researches usually take the 0–5 range for the elasticity of transformation, and it has a significant regional and sectoral variance.

The elasticity of transformation indicates, specifically, the scale of decline of exports in response to their price reduction, as well as to the response of the second, non-export, component to a decrease in export prices. When the elasticity of transformation is low, a decrease in export prices leads to a smaller decrease in exports and a reaction of the non-export component towards negative values. This is shown in Figure 15, comparing the impulse response functions for the case of low elasticity ($\sigma_b = 0,5,\ \sigma_{yd} = 1$) used in baseline calculations in Sections 5 and 6, and for the case of high elasticity ($\sigma_b = \sigma_{yd} = 5$).

A low degree of elasticity of transformation in response to the permanent shock of the decrease in the export price of brown energy sends down the volume of domestic brown energy. Conversely, high elasticity ensures growth in the volume of domestic brown energy. This difference in response depends exactly on the elasticity of transformation and can be explained by expressions (30) and (31) describing the demand for brown energy.

For the scenarios of this study, the difference in the response of domestic brown energy subject to elasticity is crucially important. High elasticity, associated with the response to a decrease in export prices, leads to growth in domestic brown energy. This results in a more dynamic response of aggregate domestic energy and lower domestic energy prices. As a consequence, green energy fails to take a significant market share, prevented by brown energy flows switching from exports to domestic sales. Ultimately, the energy transition is unachievable in the scenario of a decrease in the export price of brown energy.

In other scenarios, the role of transformation elasticity is insignificant. The table below shows the differences in scenario results.

Figure 15. Functions of impulse response of model variables to permanent 10% shock of decrease in external brown energy price. Cases of low ($\sigma_b = 0,5,\ \sigma_{yd} = 1$) and high ($\sigma_b = \sigma_{yd} = 5$) elasticity of export transformation

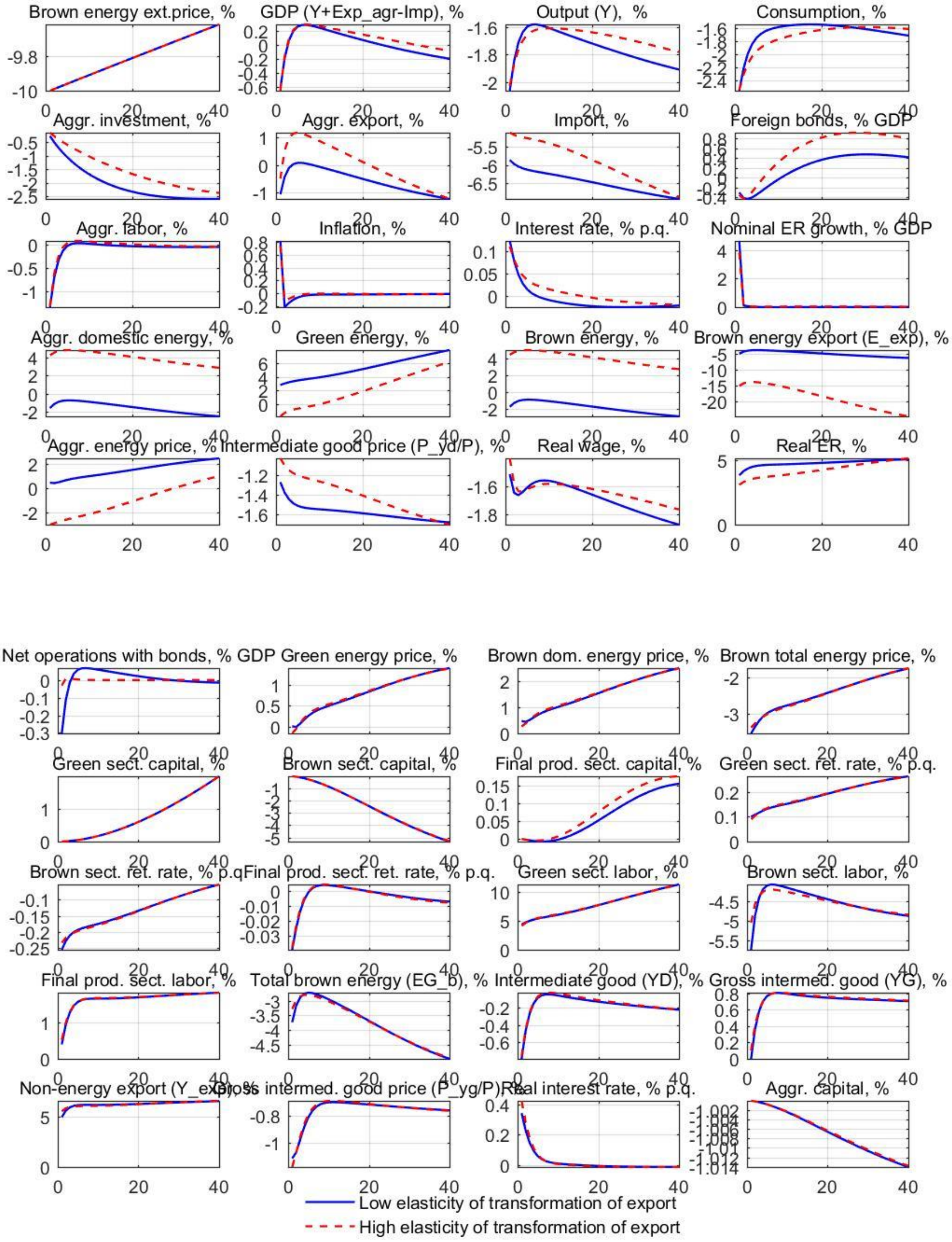

Table 3. Conditions for the feasibility of energy transition scenarios depending on degree of export transformation elasticity

Scenarios and their key energy transition conditions	Low elasticity ($\sigma_b = 0,5,\ \sigma_{yd} = 1$)	High elasticity ($\sigma_b = \sigma_{yd} = 5$)
Scenario 1. External price of brown energy decreases by…	55%	Energy transition goal unachievable[9]
Scenarios 2a. Tax on all brown energy increases by…	25%	25%
Scenario 2b. Tax on domestic energy increases by…	17%	25%
Scenario 3. Productivity in the green energy sector rises by…	55%	55%

In conclusion, our baseline calculations rely on low parameters of transformation elasticity $\sigma_b = 0,5,\ \sigma_{yd} = 1$, since Russian statistics show that changes in external prices come with a weak volume response of domestic consumption of oil, gas, and oil products, which is required by the impulse response function given low elasticity.

7.4. Role of non-energy exports

In the above scenarios, non-energy exports gave an intense response to exchange rate movements. In reality, external demand for non-energy exports may be limited, which is why the scale of response of non-energy exports may be different. In other words, the assumption that the economy under consideration is small and cannot influence supply may be significant for results. To test the importance of the model assumption about non-energy exports changing freely due to the influence of prices, calculations under the following scenario are made.

This scenario, similar to Subsection 5.2, assumes a permanent decrease of 10% in the external price of brown energy (Figure 16). Two cases are compared to understand the economic response: 1) non-energy exports $Y_t^{\exp}$ give a free response to changes in the economy; and 2) non-energy exports are fixed: $Y_t^{\exp} = const$.

In both cases, the direction of response (increase or decrease) of the vast majority of variables remains the same. There are quantitative differences between the cases. When non-energy exports are fixed, the decline in aggregate exports is greater and comes with a stronger response of imports as a result, nudging a sharper currency depreciation. With non-energy exports no longer mitigating the fallout of the shock, the response of the model variables describing the domestic economy becomes more negative. The most significant changes relate to

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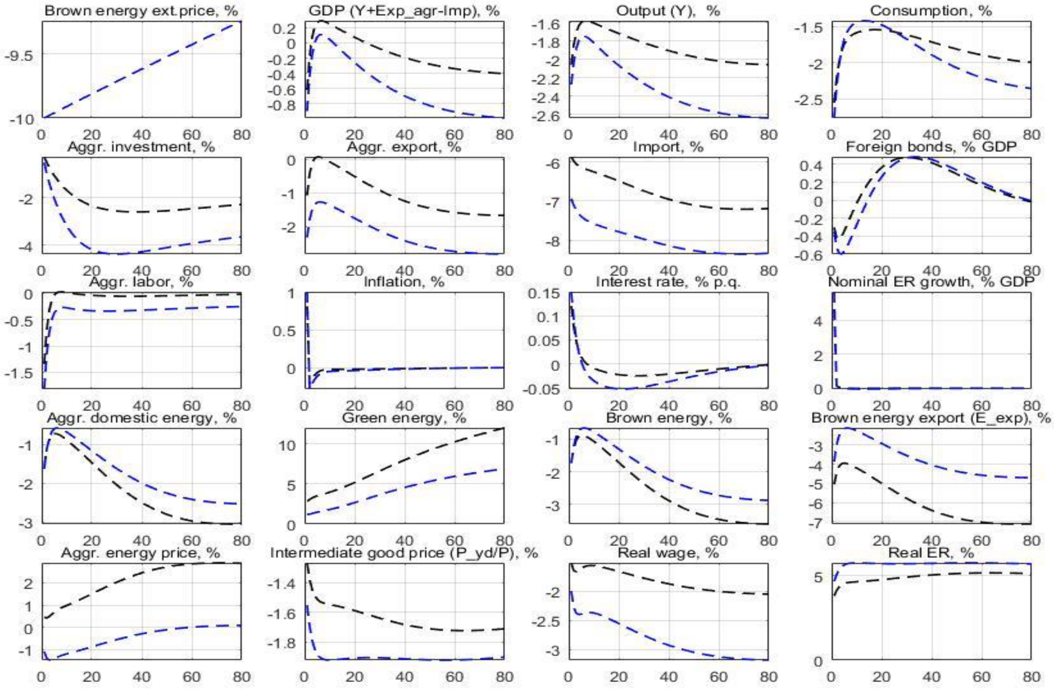
[9] When the external price of brown energy falls 50% or more, the green sector's market share totals 4–5%

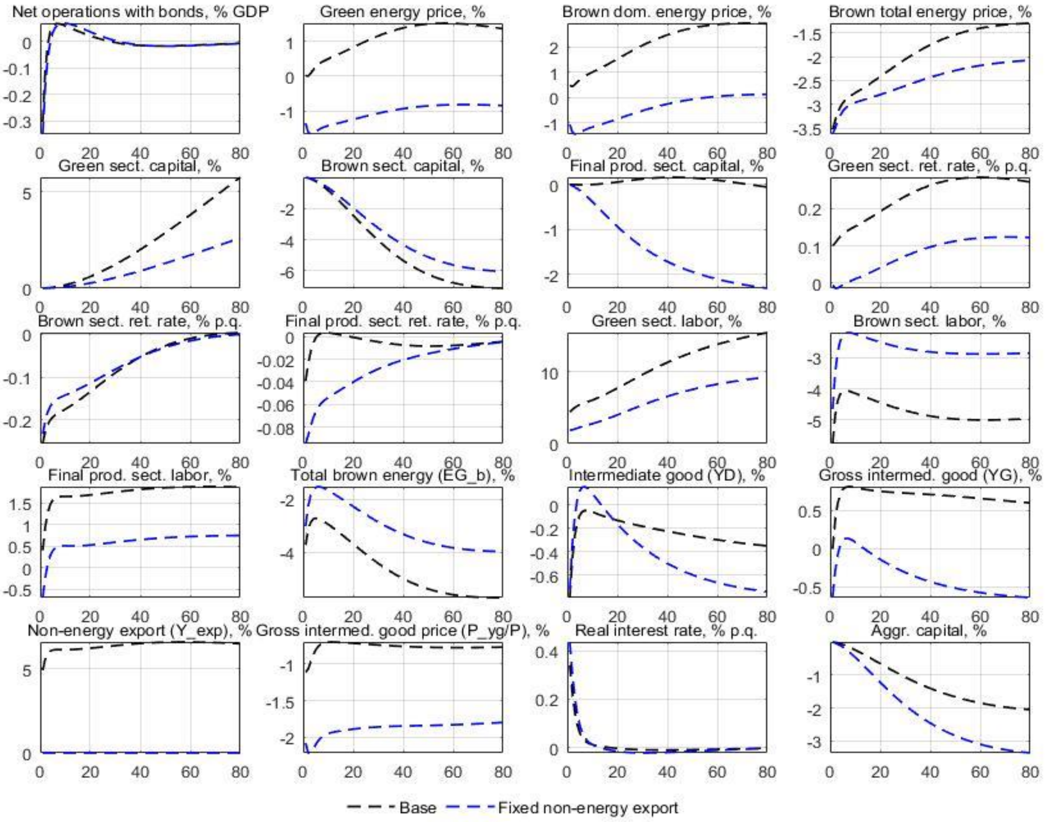
the variables of capital and its price in the final product sector (the response turns negative instead of near-zero): the change in response is explained by the absence of growth in demand from non-energy exports.

Furthermore, over the period under review, domestic energy prices change their sign to the opposite. This result is explained by the fact that domestic demand for energy has decreased more than energy production.

Accordingly, given the shock of the external price of brown energy, the assumption of constant non-energy exports may influence the response of some variables and change the overall scale of response. For other shocks, such as the productivity shock and the domestic brown energy tax shock, the differences in the response of the variables are even smaller.

Figure 16. Functions of impulse response of model variables to permanent 10% shock of decrease in external brown energy price. Cases of constant and variable output of non-energy exports





8. Impact of expectations (news) on energy transition

This section addresses the shock of expectations (news). The assumption is that at the moment the event underlying the news has yet to occur, but the agents have reliable information that the event is set to happen. More specifically, let us assume that economic agents are learning of a planned 10% increase in the domestic brown production tax due in 12 quarters.

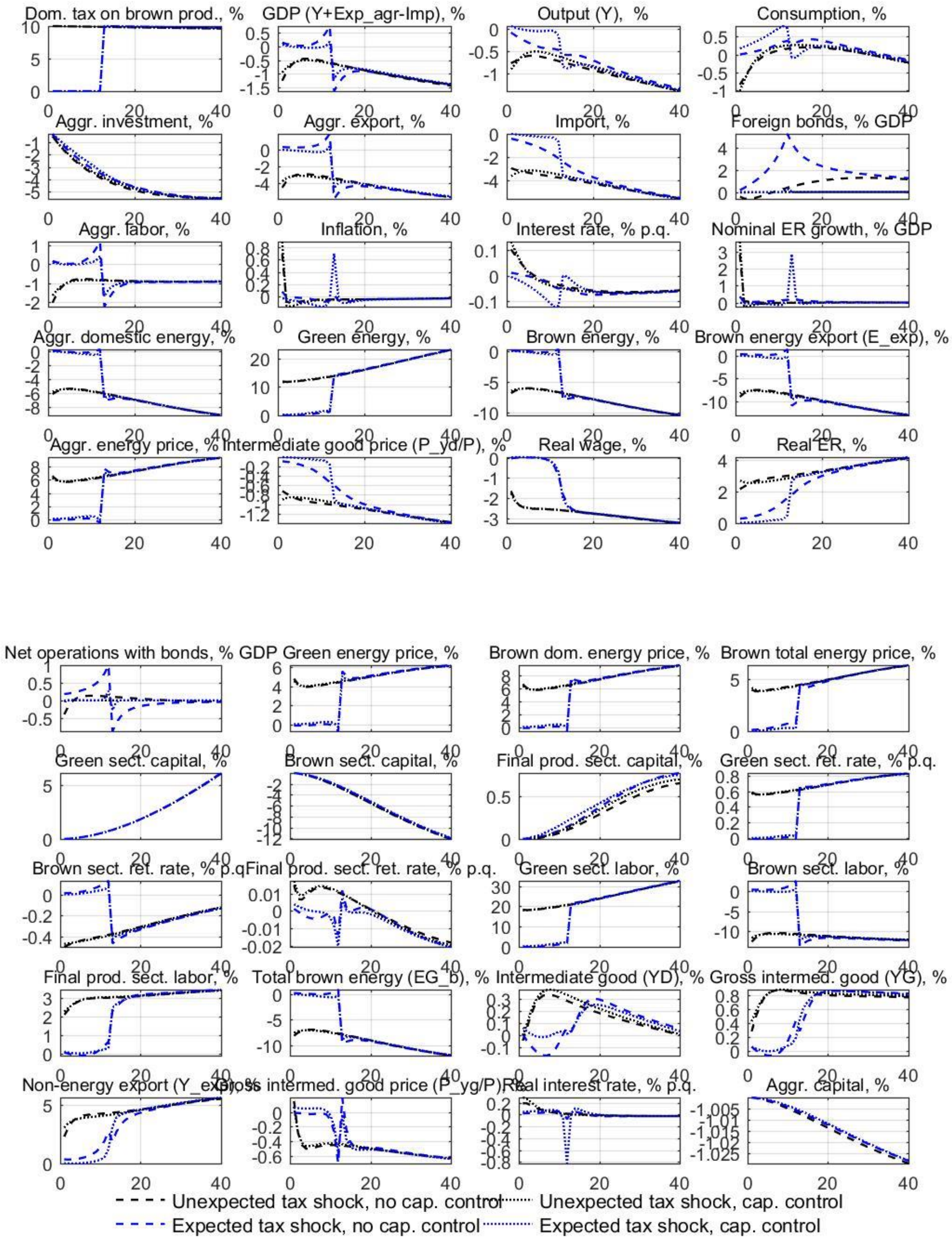
The subject of news and its influence is discussed in multiple works (see, for example, *Mertens and Ravn, 2012*; *Gomes et al., 2017*; and *Andreyev and Polbin, 2023*). In rational expectations models, news effects can be localised in two time intervals. The first impact on the economy may occur at the time of the news, and the second one coincides with the period around the occurrence of the underlying event. The two impacts may differ in magnitude and even direction depending on the model under consideration. Decarbonisation is discussed in findings in *Fried et al.* (*2022*). The researchers make the case for the likelihood of firms making cleaner investments if the country is committed to delivering on climate policy. Thus, agents respond to news even before the underlying event occurs.

As shown below (Figure 17), the news about the brown energy tax increase in 12 quarters has a weak impact on production variables at the onset of the news. The main impact of the shock is localised around the moment the news becomes reality, i.e. in 12 quarters. Only household variables – consumption and foreign bonds – respond in advance. Households, being aware of decreasing consumption in the future, seek to smooth their own consumption. Towards that end, they accumulate financial resources abroad provided that the financial account is open. At the onset of the negative event – the imposition of the tax, accompanied by an early decline in economic indicators, they gradually withdraw foreign bonds. Foreign bond transactions have an effect on imports and exchange rates, smoothing them in advance. If the financial account is assumed to be closed, then households do not have financial assets to save funds, so the responses of consumption, output, imports, and exchange rates are also concentrated at the occurrence of the event.

Another group of variables responding to the news is investment and capital. In fact, capital is the only instrument (following foreign bonds, which may be unavailable) in a model allowing for the redistribution of wealth over time. Information about the imposition of the tax is reflected in advance in changes in the volume of capital accumulation across sectors. It turns out that regardless of whether the tax has been imposed at the current moment or only the intentions to do it in the future have been communicated, the information is immediately and fully reflected on the capital market. Investments in the brown sector are declining and those in the green sector are increasing. At the same time, labour in the green and brown sectors does not grow in advance. This means that production expands only on the back of changes in capital: it does not pay to increase the labour production factor in advance – it can be raised sharply at the time the event materialises.

While on the subject of inflation and interest rates, even before the underlying event, the central bank expects the dominance of deflation risks triggered by plummeting prices of domestically consumed goods. More so, since the domestic currency does not depreciate in the expected tax shock scenario, this proinflationary effect disappears and ultimately there is no need for a short-term tightening of monetary policy, in contrast to the unexpected shock scenario. The drop in the interest rate in this case is stronger and sooner, slightly increasing medium-term consumption.

Figure 17. Functions of impulse response of model variables to permanent 10% shock of decrease in external brown energy price. Expected (in 12 quarters) and unexpected shocks in open and closed financial account



The experiment yields the following conclusions. First, as in *Fried et al.* (*2022*), at the moment of news of coming decarbonisation measures, investment indeed becomes cleaner: green investment rises and brown investment falls. However, surprisingly, the economy is not getting greener: the output of brown energy is decreasing slightly. This is explained by two factors. On the one hand, producers have no reason to change production levels until a tax or other policy measure is introduced – production is optimal at the moment. On the other hand, producers realise that it will be profitable to shift production from brown energy to green energy in the future. If a surge in investment happens in the future, it will lead to higher investment costs and excess spending, which currently encourages agents to make green investments and accumulate green capital in advance. As for the other factor, labour, it is not profitable to make it green early, as it will result in production deviating from the current optimal level, which has not yet been changed by policy measures.

Second, notwithstanding the response of some variables to the news, it can be said that the variables this study focuses on (energy volumes and prices) hardly at all respond to the news.

Both conclusions also hold in the case of other shocks discussed in the paper.

Third, it follows from the second conclusion that the paths of variables in experiments simulating a sequence of shocks will at least coincide in a qualitative sense regardless of which environment, stochastic or deterministic, is assumed for agents. In a deterministic environment, agents have rational expectations in the form of perfect foresight. However, as the experiment shows, their foresight does not have a strong effect on how the variables respond. This substantiates the deterministic approach used in Section 6.

9. Conclusion

In this study, we build a general equilibrium model for a hydrocarbon exporting country. The model provides for two production sectors (brown and green) supplying the ‘energy’ factor of production to the domestic market, while the brown sector also supplies it overseas. We have considered a number of macroeconomic instruments enabling the energy transition, that is a significant expansion in the share of green energy in the domestic energy market.

A reduction in hydrocarbon export revenues can lead to an energy transition in the exporting country only under a certain condition. This condition is a reduction in domestic supply by brown energy producers when external export prices decline, which is the result of modelling brown production using the CES function under standard parameters. This scenario is characterised by a significant and the largest decrease in public wealth[10] among all the scenarios considered. Moreover, we have shown that if brown energy producers do not reduce supply when export prices decrease, but instead actively divert brown production to the domestic market, this prevents the expansion of the green energy sector. In this case, no energy transition occurs.

The scenario of increasing domestic taxes on brown production is more acceptable in terms of public wealth. We have studied two energy transition scenarios driven by tax hikes: the taxation of all brown production combined with a redirection of funds to households, and the taxation of domestic brown production only combined with a redirection of funds to green energy. The scenario involving the redirection of funds to green energy producers proved to be the most beneficial. In this case, the decrease in public wealth is lower, the energy transition is faster, and the rise in energy prices is also lower. In fact, the preferred scenario is in line with the current practices: funds are transferred in favour of renewable energy sources within the Russian Power System. In our view, this result raises the issue of tax strategy in climate policy. We leave this topical issue for future research.

The scenario of stimulating production efficiency in the green energy sector turned out to be the most beneficial. The fair assessment of the scenario depends on knowing / not knowing the degree to which investments are transformed into production efficiency. However, according to our assessment, this scenario provides for the smallest reduction in public wealth. Moreover, unlike the others, this scenario ensures a long-term increase in domestic output, consumption, and energy production, while at the same time the brown sector has the lowest level of decline. This scenario is preferable because it may have a positive impact on the expansion of production capacity. As for the tax approach, it implies a structural shift towards inefficient production.

Thus, according to our calculations, the energy transition is possible and is robust to the assumptions regarding the structure of the economy, if the exporting country applies its own

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[10] In all the scenarios considered, the paper does not take into account the positive effect of energy transition in eliminating the threat of global warming.

incentive instruments: increases the domestic tax on brown production or encourages productivity in the green sector, rather than acknowledging an external impact in the form of declining export revenues.

We have found that the results obtained are sensitive to the model assumptions to varying degrees. On the one hand, the inertia of monetary policy and the openness of the financial account have a minimal impact on the results.

On the other hand, the assumption regarding the technology used to replace brown energy by green energy fundamentally affects the results. Energy transition is feasible as long as green energy freely replaces brown energy. If the substitution is hindered due to, for example, the irregularity of green energy production and the impossibility of storing it, then all the instruments considered are not able to help implement the energy transition. This result is explained by the fact that the brown energy sector experiences a decline in all energy transition scenarios, and the low degree of green and brown energy substitution means that these two types of energy become complements rather than substitutes. Hence any policies that lead to the decline in the brown sector will also lead to the decline in the green sector. We note that the issue of technological replacement of brown energy with green energy is being addressed by the Russian Ministry of Energy, the Russian Power System Operator, the International Energy Agency, and also by a number of researchers. The proposed solution involves the development of green energy storage tools, such as battery systems and hydrogen.

According to calculations, economic agents’ expectations of future implementation of energy transition instruments alone cannot trigger the energy transition process. This is explained by the fact that, on the one hand, when exposed to the news on future climate policy measures, producers seek to maintain their current optimal production level for as long as possible before the policy measures are introduced. On the other hand, producers are interested in making production capital green in advance, as otherwise a sharp and localised growth in investment processes in the future will lead to higher investment costs and unnecessary expenditure. These two factors cause news about future climate measures to make investments and capital green, but production becomes green only to a small extent. To make manufacturing meaningfully green, climate policy measures need to be implemented rather than just announced.

Our findings can help authorities prioritise climate policy measures and deepen understanding of the economic processes that accompany the introduction of climate policies.

The following future research areas are suggested on the basis of our approach: first, the modelling of scenarios of sharp reductions in the cost of brown production caused by climate policy measures and the associated risks; second, the study of more detailed tax incentive arrangements for the energy transition and tax policy in general; and, third, a more granular description of the structure of Russian production.

10. Bibliography

Vedomosti. (26/05/2020). Green energy in Russia may soon become cheaper than conventional energy (in Russian).

Russian Ministry of Energy. (10/11/2020). Installed capacity of renewable energy sources in Russia may reach 97.4 GW by 2050 (in Russian).

Peretok.ru. (13/10/2021). Limitation of solar and wind power generation is normal practice (in Russian).

Power and Industry of Russia. (19/12/2022). Total capacity of renewable energy facilities in Russia reached 5.68 GW as of 1 December (in Russian)

Big Electric Power News. (16/06/2023). Ministry of Energy lowered its forecast of the share of renewable energy sources in Russia's energy balance to 3% by 2035 and to 9% by 2050 (in Russian).

Andreyev M.Yu., Polbin A.V. (2019). Studying the financial accelerator effect in a two-sector DSGE model for an export-oriented economy. *Journal of the New Economic Association*, No. 4 (44), pp. 12–49 (in Russian).

Andreyev M.Yu., Polbin A.V. (2023). Macroeconomic effects of the expected future decline in oil revenues for the Russian economy under capital control. *Voprosy Ekonomiki*, No. 4, pp. 5–28 (in Russian).

Drobyshevsky S.M., Polbin A.V. (2015). Decomposition of the structural shocks contribution to the Russian macroeconomic indicators based on the DSGE model. *Ekonomicheskaya Politika*, Vol. 10, No. 2, pp. 20–42 (in Russian).

Ivashchenko S.M. (2013). Dynamic stochastic general equilibrium model with banks and endogenous defaults of firms. *Journal of the New Economic Association*, No. 3, pp. 27–51 (in Russian).

Kolpakov A.Yu., Yantovskii A.A., Galinger A.A. (2022). Cost of achieving zero CO_2 emissions by mid-century: approach and estimation for the world largest economies. *Journal of the New Economic Association*, No. 3 (55), pp. 139–154 (in Russian).

Kreptsev D.A., Seleznev S.M. (2018). Forecasting for the Russian economy using small-scale DSGE models. *Russian Journal of Money and Finance*, No. 2, pp. 51–67 (in Russian).

Makarov I.A., Chen H., Paltsev S.V. (2018). Impacts of Paris agreement on Russian economy. *Voprosy Ekonomiki*, No. 4, pp. 76–94 (in Russian).

Morozov M., Danilova E., Loginova V., Yudina T. (2020). EU border carbon tax: a challenge for the Russian economy. *Econs.online* (in Russian). https://econs.online/articles/opinions/transgranichnyy-uglerodnyy-nalog-v-es-vyzov-rossiyskoy-economike/

Polbin A.V. (2014). Econometric estimation of a structural macroeconomic model for the Russian economy. *Applied Econometrics*, No. 1 (33), pp. 3–29 (in Russian).

Porfiriev B.N., Shirov A.A., Kolpakov A.Yu., Edinak E.A. (2022). Opportunities and risks of the climate policy in Russia. *Voprosy Ekonomiki*, No. 1, pp. 2–89 (in Russian).

Salikhov M.R. (2022). Scenarios of transformation: Decarbonization of the Russian economy. *Journal of the New Economic Association*, No. 4 (56), pp. 213–219 (in Russian). DOI: 10.31737/2221-2264-2022-56-4-12

Safonov G.V., Potashnikov V.Yu., Safonov M.G. et al. (2022). The prospects for ecological modernization of Russian economy. *Journal of the New Economic Association*, No. 4 (56), pp. 195–201 (in Russian).

Shvarts E.A., Kokorin A.O., Ptichnikov A.V., Krenke A.N. (2022). Cross-border carbon regulation and forests in Russia: from expectations and myth to realization of interests. *Ekonomicheskaya Politika*, Vol. 17, No. 5, pp. 54–77 (in Russian).

Shulgin A.G. (2014). How many monetary policy rules do we need to estimate DSGE model for Russia? *Applied Econometrics*, No. 4, pp. 3–31 (in Russian).

Andreyev M., Polbin A. (2022). Monetary Policy for a Resource-Rich Economy and the Zero Lower Bound. *Ekonomicheskaya politika*, Vol. 17, No. 3, pp. 44–73.

Antosiewicz M., Lewandowski P., Witajewski-Baltvilks J. (2016). Input vs. Output Taxation – A DSGE Approach to Modelling Resource Decoupling. *Sustainability*, No. 8(4). https://doi.org/10.3390/su8040352

Bernanke B.S., Gertler M., Gilchrist S. (1999). The financial accelerator in a quantitative business cycle framework. In Handbook of macroeconomics, Vol. 1. The Netherlands: North-Holland, pp. 1341–1393.

Blazquez J., Galeotti M., Manzano B., Pierru A., Pradhan S. (2021). Effects of Saudi Arabia's Economic Reforms: Insights from a DSGE Model. *Economic Modelling*, No. 95, pp. 145–169.

Burova A., Deryugina E., Ivanova N., Morozov M., Turdyeva N. (2023). Transmission to a low-carbon economy and its implications for financial stability in Russia. *Bank of Russia Working Papers*, No. 109.

Christiano L., Eichenbaum M., Evans C. (2005). Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of Political Economy*, Vol. 113, No. 1, pp. 1–45.

Coenen G., Lozej M., Priftis R. (2023). Macroeconomic effects of carbon transition policies: an assessment based on the ECB's New Area-Wide Model with a disaggregated energy sector. *European Central Bank Working Paper Series*, No. 2819.

Fried S., Novan K., Peterman W. (2022). Climate policy transition risk and the macroeconomy. *European Economic Review*, Vol. 147(C).

Golub A., Lugovoy O., Potashnikov V. (2019). Quantifying barriers to decarbonization of the Russian economy: real options analysis of investment risks in low-carbon technologies. *Climate Policy*, Vol. 19, No. 6, pp. 716–724.

Gomes S., Iskrev N., Mendicino C. (2017). Monetary policy shocks: We got news! *Journal of Economic Dynamics and Control*, Vol. 74(C), pp. 108–128.

Guo X., Xiao B. (2023). Effects of China's low-carbon policy under stochastic shocks – a multi-agent DSGE model analysis. *Environmental Science and Pollution Research*, Vol. 30, pp. 65177–65191.

Gupta S., Thakkar P. (2022). Optimal tax policy to reduce emissions: A DSGE approach. Indira Gandhi Institute of Development Research, Mumbai.

IEA (2023). Electricity Market Report 2023. International Energy Agency. https://iea.blob.core.windows.net/assets/255e9cba-da84-4681-8c1f-458ca1a3d9ca/ElectricityMarketReport2023.pdf

International Panel on Climate Change (IPCC) (1996). Economic and Social Dimensions of Climate Change – Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge.

Kiyotaki N., Moore J. (1997). Credit cycles. *Journal of political economy*, Vol. 105, No. 2, pp. 211–248.

Klump R., McAdam P., Willman A. (2007). The Long-Term SucCESs of the Neo-Classical Growth Model. *Oxford Review of Economic Policy*, Vol. 23, No. 1, pp 94–114.

Kotlikoff L.J., Kubler F., Polbin A., Scheidegger S. (2021). Can Today's and Tomorrow's World Uniformly Gain from Carbon Taxation? *NBER Working Papers*, No. 29224.

Le´on-Ledesma M.A., McAdam P., Willman A. (2010). Identifying the Elasticity of Substitution with Biased Technical Change. *American Economic Review*, Vol. 100, No. 4, pp. 1330–1357.

Li H., Peng W. (2020). Carbon Tax, Subsidy, and Emission Reduction: Analysis Based on DSGE Model. *Complexity*, No. 6.

Lofgren H. et al. A Standard Computable General Equilibrium (CGE) Model in GAMS // Microcomputers in Policy Research. Washington, D.C.: International Food Policy Research Institute, 2002. 79 p.

Martyanova E, Polbin A. (2023). General equilibrium model with the entrepreneurial sector for the Russian economy. *Russian Journal of Economics*, Vol. 2, No. 9, pp. 109–133.

Medina J. P., Soto C. (2007). Copper price, fiscal policy and business cycle in Chile. *Central Bank of Chile Working Papers*, No. 458.

Mertens K., Ravn M.O. (2012). Empirical evidence on the aggregate effects of anticipated and unanticipated US tax policy shocks. *American Economic Journal: Economic Policy*, Vol. 4, No. 2, pp. 145–181.

NGFS (2022). Running the NGFS Scenarios in G-Cubed: A Tale of Two Modelling Frameworks. URL:https://www.ngfs.net/sites/default/files/medias/documents/running_the_ngfs_scenarios_in_g-cubed_a_tale_of_two_modelling_frameworks.pdf

Penikas H. (2022). The Interrelationship of Credit and Climate Risks. *Bank of Russia Working Papers*, No. 100.

Potashnikov V.; Golub A., Brody M., Lugovoy O. (2022) Decarbonizing Russia: Leapfrogging from Fossil Fuel to Hydrogen. *Energies*, Vol. 15, No. 3.

Rotemberg J.J. (1982). Sticky prices in the United States. *Journal of Political Economy*, Vol. 90, No. 6, pp. 1187–1211.

Rutherford T.F., Bohringer C. (2006). Combining Top-down and Bottom-up in Energy Policy Analysis: A Decomposition Approach. ZEW Discussion Papers 06-007.

Smets F., Wouters R. (2003). An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area. *Journal of the European Economic Association*, Vol. 1, No. 5, pp. 1123–1175.

Thompson P. (2010). Learning by Doing, Handbook of the Economics of Innovation. In Bronwyn H. Hall & Nathan Rosenberg (ed.), Handbook of the Economics of Innovation, Vol. 1, Chapter 10, pp. 429–476, Elsevier.

Timilsina G.R., Pang J., Xi Y. (2021). Enhancing the quality of climate policy analysis in China: Linking bottom-up and top-down models. *Renewable and Sustainable Energy Reviews*, Vol. 151(C).

Tuladhar S., Yuan M., Bernstein P., Montgomery D., Smith A. (2009). A top-down bottom-up modeling approach to climate change policy analysis. *Energy Economics*, Vol. 31, Suppl. 2, pp. S223-S234.

11. Appendix. Mathematical description of model

11.1. Households

Each household i in a continuum of households seeks to maximise the utility of consumption C_t^i and minimise displeasure from their labour L_t^i:

$$U_{t_0}^i = E_{t_0} \sum_{t=t_0}^{+\infty} \beta^{t-t_0} \left(\ln C_t^i - \frac{\sigma_L}{1+e} \left(L_t^i \right)^{1+e} \right) \rightarrow \max \tag{4}$$

The operator E_{t_0} denotes the mathematical expectation across all future events starting at time $t_0 + 1$.

Each household i provides labour L_t^i to a perfectly competitive intermediary in the labour market at an individual price W_t^i. Households are assumed to have a monopoly power in the labour services market. As a result, demand arises for an individual household's labour $L_t^i = \left(\frac{W_t^i}{W_t} \right)^{-\eta} L_t$, where L_t is aggregate labour and W_t is the cost of aggregate labour. The type of the labour demand function is a decision-making factor for households. In selecting an individual salary level W_t^i, households, in accordance with the Rotemberg approach (*Rotemberg, 1982*), bear the costs of changing the salary level $\frac{k^w}{2} \left(\frac{W_t^i}{W_{t-1}^i} - 1 \right)^2 W_t L_t$.

In addition to labour and consumption, households choose the volume of investment in foreign bonds $D_t^{i,f}$ yielding income at a fixed external rate r^f. In this case, households incur real costs $\Psi_t^D = \frac{1}{2} d_s \left(D_t^{i,f} S_t / P_t Y_t \right)^2 Y_t S_t \frac{P^f}{P_t}$ paid abroad, where S_t is the exchange rate and P^f is the external fixed price of imports. The costs Ψ_t^D are determined by the ratio of the cost of savings or borrowings $D_t^{i,f} S_t$ to the nominal domestic output $P_t Y_t$. The coefficient d_s reflects the degree of difficulty in using the external debt market. The higher this value, the less readily households respond to changes in the economy by adjusting the level of investment in foreign bonds.

Similar to *Smets and Wouters* (*2003*), households also participate in the mutual lending market by lending loans D_t^i to each other at the interest rate R_t. In equilibrium, aggregate loans are deemed to be zero under the assumption of the homogeneity of households. The domestic money market rate R_t is a money policy tool.

Households choose the volume of production capital $K_t^{i,g}, K_t^{i,b}, K_t^{i,f}$. Capital volumes $K_{t-1}^{i,g}, K_{t-1}^{i,b}, K_{t-1}^{i,f}$ are provided to producers at leasing rates R_t^g, R_t^b, R_t^f. Households also choose the volume of investment in new capital $I_t^{i,g}, I_t^{i,b}, I_t^{i,f}$ purchased at price P_t in the final goods market. When the amount of investment changes, the household incurs a nominal cost in the amount of $\frac{1}{2}k^g\left(\frac{I_t^{i,g}}{I_{t-1}^{i,g}}-1\right)^2 P_t Y_t$, $\frac{1}{2}k^b\left(\frac{I_t^{i,b}}{I_{t-1}^{i,b}}-1\right)^2 P_t Y_t$, $\frac{1}{2}k^f\left(\frac{I_t^{i,f}}{I_{t-1}^{i,f}}-1\right)^2 P_t Y_t$.

Investments and capital movements are related as follows:

$$K_t^{i,g} = (1-\delta)K_{t-1}^{i,g} + I_t^{i,g} \tag{5}$$

$$K_t^{i,b} = (1-\delta)K_{t-1}^{i,b} + I_t^{i,b} \tag{6}$$

$$K_t^{i,f} = (1-\delta)K_{t-1}^{i,f} + I_t^{i,f} \tag{7}$$

Each household is restricted by a budget constraint:

$$\begin{aligned} C_t^i + I_t^{i,g} + I_t^{i,b} + I_t^{i,f} + \frac{D_t^{i,f}S_t}{P_t} \; &= \; \frac{W_t^i L_t^i}{P_t} + r^f\,\frac{D_{t-1}^{i,f}S_t}{P_t} - \Psi_t^D + \frac{D_t^i}{P_t} - R_{t-1}\frac{D_{t-1}^i}{P_t} + \\ &+ \frac{R_t^g}{P_t}K_{t-1}^{i,g} + \frac{R_t^b}{P_t}K_{t-1}^{i,b} + \frac{R_t^f}{P_t}K_{t-1}^{i,f} + \frac{\Pi_t}{P_t} - \\ &- \frac{1}{2}k^g\left(\frac{I_t^{i,g}}{I_{t-1}^{i,g}}-1\right)^2 Y_t - \frac{1}{2}k^b\left(\frac{I_t^{i,b}}{I_{t-1}^{i,b}}-1\right)^2 Y_t - \frac{1}{2}k^f\left(\frac{I_t^{i,f}}{I_{t-1}^{i,f}}-1\right)^2 Y_t - \frac{k^w}{2}\left(\frac{W_t^i}{W_{t-1}^i}-1\right)^2 \frac{W_t}{P_t}L_t \end{aligned} , \tag{8}$$

where Π_t is the profit of the intermediary in the intermediate domestic goods market.

Below we assume that the equilibrium is symmetric: all households are indistinguishable from each other, hence the indices i are discarded. Denoting the Lagrange multipliers under constraints (5)–(8) by $\beta^t\Phi_t^g$, $\beta^t\Phi_t^b$, $\beta^t\Phi_t^f$ and $\beta^t\Lambda_t$, we obtain the following optimisation conditions for consumption, credit, labour, foreign bond investment, total investment, and capital:

$$\Lambda_t = \frac{1}{C_t} \tag{9}$$

$$\Lambda_t = \beta E_t \Lambda_{t+1} \frac{R_t}{\pi_t} \tag{10}$$

$$\sigma_L \eta \frac{(L_t)^e}{W_t / P_t} = (\eta - 1)\Lambda_t + k^w \Lambda_t \frac{W_t}{W_{t-1}}\left(\frac{W_t}{W_{t-1}} - 1\right) - k^w \beta E_t \Lambda_{t+1} \frac{1}{\pi_{t+1}} \frac{L_{t+1}}{L_t}\left(\frac{W_{t+1}}{W_t}\right)^2 \left(\frac{W_{t+1}}{W_t} - 1\right) \tag{11}$$

$$S_t = \beta r^f E_t \frac{\Lambda_{t+1}}{\Lambda_t} \frac{S_{t+1}}{\pi_{t+1}} - d_s \frac{S_t^2 D_t^f}{P_t^2 Y_t} \frac{S_t P^f}{P_t} \tag{12}$$

$$\Phi_t^g = \Lambda_t + k^g \Lambda_t \left(\frac{I_t^g}{I_{t-1}^g} - 1\right)\frac{Y_t}{I_{t-1}^g} - k^g \beta E_t \Lambda_{t+1}\left(\frac{I_{t+1}^g}{I_t^g} - 1\right)\frac{Y_{t+1} I_{t+1}^g}{\left(I_t^g\right)^2} \tag{13}$$

$$\Phi_t^b = \Lambda_t + k^b \Lambda_t \left(\frac{I_t^b}{I_{t-1}^b} - 1\right)\frac{Y_t}{I_{t-1}^b} - k^b \beta E_t \Lambda_{t+1}\left(\frac{I_{t+1}^b}{I_t^b} - 1\right)\frac{Y_{t+1} I_{t+1}^b}{\left(I_t^b\right)^2} \tag{14}$$

$$\Phi_t^f = \Lambda_t + k^f \Lambda_t \left(\frac{I_t^f}{I_{t-1}^f} - 1\right)\frac{Y_t}{I_{t-1}^f} - k^f \beta E_t \Lambda_{t+1}\left(\frac{I_{t+1}^f}{I_t^f} - 1\right)\frac{Y_{t+1} I_{t+1}^f}{\left(I_t^f\right)^2} \tag{15}$$

$$\Phi_t^g = \beta\,(1-\delta)\, E_t \Phi_{t+1}^g + \beta E_t \Lambda_{t+1} R_{t+1}^g \tag{16}$$

$$\Phi_t^b = \beta\,(1-\delta)\, E_t \Phi_{t+1}^b + \beta E_t \Lambda_{t+1} R_{t+1}^b \tag{17}$$

$$\Phi_t^f = \beta\,(1-\delta)\, E_t \Phi_{t+1}^f + \beta E_t \Lambda_{t+1} R_{t+1}^f \quad , \tag{18}$$

where $\pi_t = P_t / P_{t-1}$ is inflation.

Equation (9) relates marginal consumption and the Lagrange multiplier under the budget constraint. Euler's ratio (10) means that the real interest rate in the economy is on average equal to the inverse value of the time preference factor. Equation (11) represents the relationship between the marginal utility of consumption and the marginal displeasure of labour. This equation

(11) realises the mechanism of rigidity of nominal wages: the higher the ratio k^w, the weaker the adjustment of wages to changes in the economy. Equations (10) и (12) collectively enable the condition of parity between the domestic interest rate R_t and the external interest rate r^f, adjusted for the currency appreciation rate and the cost of transactions with foreign bonds. Equations (13)–(15) implicitly link the price P_t of investment I_t^g, I_t^b, I_t^f to shadow prices of capital (these prices are not specified explicitly, but are expressed through Lagrange multipliers). For example, if the cost of capital formation is zero ($k_t^g = k_t^b = k_t^f = 0$), then the price of investment is the same as the price of capital. Expressions (16)–(18) relate capital returns and capital depreciation rates.

11.2. Green energy producer

A green energy producer combines leased labour L_t^g and capital K_{t-1}^g to produce green energy E_t^g according to the Cobb-Douglas production function. This energy is sold only on the domestic market to a green and brown energy aggregator at the price of P_t^g :

$$E_t^g = a^g \left(1+s_t^g\right)\left(K_{t-1}^g\right)^{\alpha^g} \left(L_t^g\right)^{1-\alpha^g} \tag{19}$$

In the above expression, s_t^g is a green energy productivity shock that is zero in the long-term equilibrium and follows an AR(1) process:

$$s_t^g = \rho^g s_{t-1}^g + \varepsilon_t^g \quad , \tag{20}$$

where ε_t^g is a random variable with zero mean, uniformly distributed over time.

The green energy producer seeks to maximise profit, which turns out to be zero in equilibrium:

$$P_t^g E_t^g - R_t^g K_{t-1}^g - W_t L_t^g = 0 \tag{21}$$

The optimisation conditions for maximisation problem (21) given equation (19) are the following:

$$\alpha^g P_t^g E_t^g = R_t^g K_{t-1}^g \tag{22}$$

$$\left(1-\alpha^g\right) P_t^g E_t^g = W_t L_t^g \tag{23}$$

11.3. Brown energy producer

A brown energy producer combines labour L_t^b and capital K_{t-1}^b to produce a gross amount of brown energy EG_t^b according to the Cobb-Douglas production function:

$$EG_t^b = a^b \left(K_{t-1}^b\right)^{\alpha^b} \left(L_t^b\right)^{1-\alpha^b} \tag{24}$$

The gross amount of brown energy produced is accounted for by the producer at the price of P_t^{bg}.

The production of brown energy is subject to a tax τ_t^b, which is transferred to households in full (in scenario 2a). The brown energy producer seeks to maximise profit, which turns out to be zero at the optimum:

$$\left(1-\tau_t^b\right) P_t^{bg} EG_t^b - W_t L_t^b - R_t^b K_{t-1}^b = 0 \tag{25}$$

Once energy EG_t^b is produced, it is disaggregated into two components: the household component E_t^b and the export component $E_t^{b,\exp}$ according to the CET function:

$$EG_t^b = a^{bg} \left(\alpha^{bg} \left(E_t^b\right)^{\varphi_b} + \left(1-\alpha^{bg}\right)\left(E_t^{b,\exp}\right)^{\varphi_b}\right)^{\frac{1}{\varphi_b}} , \tag{26}$$

where $\varphi_b > 1$. The impact of the parameter φ_b on the results is analysed in Subsection 7.3.

The domestic component of brown energy E_t^b is sold to the green and brown energy aggregator at the price of P_t^b, and the export component $E_t^{b,\exp}$ is sold on the foreign market at the external price of $P_t^{b,\exp}$. In scenario 2b, a tax is levied on the value of the domestic brown energy component $P_t^b E_t^b$ and transferred to the brown energy producer. The producer seeks to maximise profit, which turns out to be zero at the optimum:

$$P_t^b E_t^b + S_t P_t^{b,\exp} E_t^{b,\exp} - P_t^{bg} EG_t^b = 0 \tag{27}$$

The conditions for maximising (25) and (27) on labour, capital and energy volumes subject to (24) and (26) are as follows:

$$\left(1-\tau_t^b\right)\alpha^b P_t^{bg} EG_t^b = R_t^b K_{t-1}^b \tag{28}$$

$$\left(1-\tau_t^b\right)\left(1-\alpha^b\right) P_t^{bg} EG_t^b = W_t L_t^b \tag{29}$$

$$P_t^b E_t^b = P_t^{bg} EG_t^b \frac{\alpha^{bg}\left(E_t^b\right)^{\varphi_b}}{\alpha^{bg}\left(E_t^b\right)^{\varphi_b} + \left(1-\alpha^{bg}\right)\left(E_t^{b,\exp}\right)^{\varphi_b}} \tag{30}$$

$$S_t P_t^{b,\exp} E_t^{b,\exp} = P_t^{bg} EG_t^b \frac{\left(1-\alpha^{bg}\right)\left(E_t^{b,\exp}\right)^{\varphi_b}}{\alpha^{bg}\left(E_t^b\right)^{\varphi_b} + \left(1-\alpha^{bg}\right)\left(E_t^{b,\exp}\right)^{\varphi_b}} \tag{31}$$

11.4. Green and brown energy aggregation

We assume that green and brown energy are aggregated in the domestic market according to the CES function:

$$E_t = a^e\left(\alpha^e\left(E_t^g\right)^{\varphi_e} + \left(1-\alpha^e\right)\left(E_t^b\right)^{\varphi_e}\right)^{\frac{1}{\varphi_e}} \quad , \tag{32}$$

where $\varphi_e < 1$. The impact of the parameter φ_e on the results is further specified in Subsection 7.2.

The aggregated energy E_t is sold to the producer of final goods at the price of P_t^e. The objective of the energy aggregator is to maximise its profit, which turns out to be zero in the optimum:

$$P_t^e E_t - P_t^g E_t^g - P_t^b E_t^b = 0 \tag{33}$$

The conditions for maximising profit (33) under technology constraint (32) are as follows:

$$P_t^g E_t^g = P_t^e E_t \frac{\alpha^e \left(E_t^g\right)^{\varphi_e}}{\alpha^e \left(E_t^g\right)^{\varphi_e} + \left(1-\alpha^e\right)\left(E_t^b\right)^{\varphi_e}} \tag{34}$$

$$P_t^b E_t^b = P_t^e E_t \frac{\left(1-\alpha^e\right)\left(E_t^b\right)^{\varphi_e}}{\alpha^e \left(E_t^g\right)^{\varphi_e} + \left(1-\alpha^e\right)\left(E_t^b\right)^{\varphi_e}} \tag{35}$$

11.5. Intermediate domestic and final goods producer

The production of final goods occurs in three stages. The production structure is standard for general equilibrium models (*Lofgren et al., 2002*). In the first stage, the producer combines capital K_{t-1}^f, energy E_t, and labour L_t^f to create a gross intermediate product YG_t according to the Cobb-Douglas function (similar to *Kotlikoff et al., 2021*):

$$YG_t = a^{yg}\left(K_{t-1}^f\right)^{\alpha^f}\left(E_t\right)^{\gamma^f}\left(L_t^f\right)^{1-\alpha^f-\gamma^f} \tag{36}$$

At this point, the producer accounts for the output YG_t at price P_t^{yg} and seeks to maximise the profit from this stage, which turns out to be zero in equilibrium:

$$P_t^{yg}\, YG_t - R_t^f K_{t-1}^f - P_t^e E_t - W_t L_t^f = 0 \tag{37}$$

The optimisation conditions for capital, energy, and labour profit maximisation (37) under constraint (36) are as follows:

$$\alpha^f P_t^{yg}\, YG_t = R_t^f\, K_{t-1}^f \tag{38}$$

$$\gamma^f P_t^{yg}\, YG_t = P_t^e\, E_t \tag{39}$$

$$\left(1-\alpha^f-\gamma^f\right) P_t^{yg}\, YG_t = W_t\, L_t^f \tag{40}$$

In the second stage, the producer disaggregates gross intermediate product YG_t into domestic intermediate product YD_t and non-energy exports $Y_t^{\exp}$ according to the CET function, similar to the approach of CGE models (*Lofgren et al., 2002*) and some DSGE models (*Martyanova E. and Polbin A., 2023*):

$$YG_t = a^{yd}\left(\alpha^{yd}\left(YD_t\right)^{\varphi_{yd}} + \left(1-\alpha^{yd}\right)\left(Y_t^{\exp}\right)^{\varphi_{yd}}\right)^{\frac{1}{\varphi_{yd}}}, \tag{41}$$

where $\varphi_{yd} > 1$.

Non-energy exports are sold on the external market at the external price $P^{\exp}$, which is assumed constant, while the domestic intermediate product YD_t participates in the third stage of production and is accounted for at the price of P_t^{yd}. The objective of the second stage is to maximise profit, which turns out to be zero in equilibrium:

$$P_t^{yd}\,YD_t + S_t\,P^{\exp}\,Y_t^{\exp} - P_t^{yg}YG_t = 0 \tag{42}$$

The first-order conditions for profit maximisation problem (42) under constraint (41) are as follows:

$$P_t^{yd}\,YD_t = P_t^{yg}\,YG_t\,\frac{\alpha^{yd}\left(YD_t\right)^{\varphi_{yd}}}{\alpha^{yd}\left(YD_t\right)^{\varphi_{yd}} + \left(1-\alpha^{yd}\right)\left(Y_t^{\exp}\right)^{\varphi_{yd}}} \tag{43}$$

$$S_t\,P^{\exp}\,Y_t^{\exp} = P_t^{yg}\,YG_t\,\frac{\left(1-\alpha^{yd}\right)\left(Y_t^{\exp}\right)^{\varphi_{yd}}}{\alpha^{yd}\left(YD_t\right)^{\varphi_{yd}} + \left(1-\alpha^{yd}\right)\left(Y_t^{\exp}\right)^{\varphi_{yd}}} \tag{44}$$

In the third stage, the producer first sells the domestic intermediate product YD_t to intermediaries (see Subsection 11.6) at the price of P_t^{yd}, and then buys back the goods in the same volume at the price of P_t^{rig}. Due to the presence of the intermediary, the mechanism of rigidity of internal prices is realised in the model.

The producer then combines the product YD_t with imports Imp_t purchased on the constant price P^{imp} externally, according to the Cobb-Douglas production function. This result in the final product in the economy:

$$Y_t = a^y \left(YD_t\right)^{\omega} \left(Imp_t\right)^{1-\omega} \tag{45}$$

The final product Y_t is traded on the market at the price of P_t. The objective of the third stage is to maximise profit, which turns out to be zero in equilibrium:

$$P_t Y_t - P_t^{rig} YD_t - P^{imp} S_t Imp_t = 0 \tag{46}$$

The first-order conditions for profit maximisation problem (46) under constraint (45) are as follows:

$$\omega P_t Y_t = P_t^{rig} YD_t \tag{47}$$

$$\left(1-\omega\right) P_t Y_t = P^{imp} S_t Imp_t \tag{48}$$

11.6. Intermediaries in domestic intermediate product market (domestic price rigidity)

In the domestic intermediate product, each intermediary j buys a part of the domestic product YD_t^j at a common price of P_t^{yd} and then sells the same product volume to the producer of final goods at a nominal individual price of $P_t^{rig,j}$. In doing so, the intermediary incurs quadratic costs for the change in the individual price level in the amount of $\frac{p^{rig}}{2}\left(\frac{P_t^{rig,j}}{P_{t-1}^{rig,j}}-1\right)^2 P_t^{rig} YD_t$. Here P_t^{rig} is understood to be the price aggregated over all intermediaries' prices $P_t^{rig,j}$. We assume that producers have a monopoly power and know the function of demand for their product: $YD_t^j = YD_t \left(\frac{P_t^{rig,j}}{P_t^{rig}}\right)^{-\varepsilon^p}$.

Intermediaries' profit is determined as follows:

$$\Pi_t^j = P_t^{rig,j} YD_t^j - P_t^{yd} YD_t^j - \frac{p^{rig}}{2}\left(\frac{P_t^{rig,j}}{P_{t-1}^{rig,j}}-1\right)^2 P_t^{rig} YD_t.$$

Each intermediary seeks to maximise the adjusted operating profit: $E_{t_0}\sum_{t=t_0}^{+\infty}\beta^{t-t_0}\Lambda_t\frac{\Pi_t^j}{P_t}$.

Equilibrium is assumed to be symmetric, so individual intermediary indices j will be stripped out in what follows. Then the optimisation condition on the prices $P_t^{rig,j}$ set by intermediaries will be the following:

$$\left(\varepsilon^p-1\right)=\varepsilon^p\frac{P_t^{yd}}{P_t^{rig}}-p^{rig}\frac{P_t^{rig}}{P_{t-1}^{rig}}\left(\frac{P_t^{rig}}{P_{t-1}^{rig}}-1\right)+p^{rig}\beta E_t\frac{\Lambda_{t+1}}{\Lambda_t}\left(\frac{P_{t+1}^{rig}}{P_t^{rig}}\right)^2\left(\frac{P_{t+1}^{rig}}{P_t^{rig}}-1\right)\frac{YD_{t+1}}{YD_t}\frac{P_t}{P_{t+1}} \qquad (49)$$

Condition (49) enables the price rigidity mechanism under the neo-Keynesian approach: the higher the values p^{rig}, the less flexible is the adjustment of prices to ongoing economic changes. If the parameter p^{rig} is equal to zero, the role of intermediaries is limited only to creating a markup of $\frac{1}{\varepsilon^p}$.

11.7. Monetary policy

It is assumed that monetary aims at targeting inflation. In setting the nominal rate, the central bank follows the Taylor rule:

$$R_t-R^{ss}=\rho_r\left(R_{t-1}-R^{ss}\right)+\left(1-\rho_r\right)\rho_{\inf}\left(\pi_t-\pi^{ss}\right), \qquad (50)$$

where R^{ss}, π^{ss} are long-term values of the policy rate and inflation, and the ratio $\pi_t=\frac{P_t}{P_{t-1}}$ is reflective of inflation.

If $\rho_r>0$, monetary policy is inertial: when setting the rate, the regulator focuses not only on current inflation but also on historical values of the rate.

11.8. Equilibrium conditions

The equilibrium conditions in the labour and final goods markets, as well as the equilibrium condition in the foreign exchange market have the following form:

$$L_t^d + L_t^g + L_t^f = L_t \tag{51}$$

$$\begin{aligned} Y_t &= C_t + I_t^d + I_t^g + I_t^f + \frac{1}{2}k^g\left(\frac{I_t^g}{I_{t-1}^g}-1\right)^2 Y_t + \frac{1}{2}k^b\left(\frac{I_t^b}{I_{t-1}^b}-1\right)^2 Y_t + \frac{1}{2}k^f\left(\frac{I_t^f}{I_{t-1}^f}-1\right)^2 Y_t + \\ &+\frac{k^w}{2}\left(\frac{W_t}{W_{t-1}}-1\right)^2\frac{W_t}{P_t}L_t + \frac{p^{rig}}{2}\left(\frac{P_t^{rig,j}}{P_{t-1}^{rig,j}}-1\right)^2\frac{P_t^{rig}}{P_t}YD_t \end{aligned} \tag{52}$$

$$P_t^{b,\exp}E_t^{b,\exp} + P^{\exp}Y_t^{\exp} - P^{imp}\,Imp_t - D_t^f + r^f D_{t-1}^f - \Psi_t^D\frac{P_t}{S_t} = 0 \tag{53}$$

where the real costs of changes in foreign bond investments Ψ_t^D are defined above (see Subsection 11.1).

Conditions (51)–(53) implicitly determine labour costs W_t, the price P_t of final goods, and the nominal exchange rate S_t.

11.9. Shocks

The economic trends in the model under consideration result from several shocks. First, there is an aggregate factor productivity shock in green energy production, as described by equation (20).

Second, there is a domestic tax shock on brown energy production τ_t^b, see (25). We will assume that the dynamics of the tax are determined by the following expression:

$$\tau_t^b = \rho^{\tau^b}\tau_{t-1}^b + \varepsilon_t^{\tau^b}, \tag{54}$$

Third, there is an external brown energy price shock:

$$P_t^{b,\exp} = P_{ss}^{b,\exp} + \rho^{pb}\left(P_{t-1}^{b,\exp} - P_{ss}^{b,\exp}\right) + \varepsilon_t^{pb} \tag{55}$$

In (54) and (55), $\varepsilon_t^{\tau^b}$ and ε_t^{pb} are zero-mean random variables equally distributed at different time periods, and ρ^{τ^b} and ρ^{pb} are autocorrelation coefficients close to 1, as is ρ^g in (20).

The autocorrelation coefficients are almost equal to 1, and agents have rational expectations. Therefore, shocks introduced in this way are permanent: agents believe that if there is a shock and no new shocks occur, then productivity (20), tax rate (54), or external price (55) will remain unchanged for the visible horizon.

The brown energy external price shock introduced by (55) is equivalent to the permanent terms-of-trade shock often assumed in DSGE model for the Russian economy (*Andreyev and Polbin, 2019*; *Ivashchenko, 2013*; *Kreptsev and Seleznev, 2018*; *Polbin, 2014*; and *Shulgin, 2014*).

11.10. Model equations and calculations

The model equations used in the calculations are as follows: (5)–(7), (9)–(20), (22)–(24), (26), (28)–(32), (34)–(36), (38)–(41), (43)–(45), (47)–(55). Household budget constraint (8) does not appear in the calculations as it happens to be linearly dependent with the other equations due to the Walras identity.

Before the calculations, we perform renormalisation of some model variables. Namely, expressions in nominal values (e.g. loans D_t , profits Π_t , wages, and nominal yields) are converted into real values through normalisation by the price of final goods P_t , and nominal prices are converted into relative prices also by dividing by P_t .

The calculations are performed in Matlab using the Dynare add-in.

11.11. Model calibration

The following parameters were chosen for the calibration of the model. The consumer's time preference coefficient was taken to be $\beta = 0.99$, which is standard for dynamic stochastic equilibrium models (*Bernanke et al., 1999*, *Kiyotaki and Moore, 1997*; and *Smets and Wouters, 2003*). This corresponds to a 4% real return on assets per annum. The depreciation parameter of production capital was taken to be $\delta = 0,025$, which corresponds to a 10% annual depreciation rate (*Bernanke et al., 1999* and *Smets and Wouters, 2003*). The elasticity of intermediary product demand in the domestic intermediate market was taken to be $\varepsilon^p = 6$, which means that the intermediary markup was 1/6 in the long term. The chosen value is within the range of values of these parameters found in the literature: from 5 (*Christiano et al., 2005*) to 11 (*Medina and Soto, 2007*) and near to the value used in one of the papers for the Russian economy (7 in *Drobyshevsky and Polbin, 2015*). The labour demand elasticity parameter was set to $\eta = 4$, and the utility function parameter was set to $e = 0,3$ (*Andreyev and Polbin, 2019*). The production function elasticity parameters for green and brown energy sectors were taken in accordance with

Bernanke et al., 1999 and *Polbin, 2014*): $\alpha^g = \alpha^b = 0{,}35$. Regarding the elasticity parameters for the production function of gross intermediate product production, we assumed that the input costs of the factors of production – labour and capital – split in the same proportion as in the other two industries: $\alpha^f \big/ \left(1-\alpha^f-\gamma^f\right) = 0{,}35/0{,}65$.

The parameter φ_e in CES function (32) of aggregation of the two types of energy was set to $0{,}9$, which corresponds to a high elasticity of replacement $\sigma_e = 1\big/\left(1-\varphi_e\right) = 10$. We consider the choice of parameter for the main and alternative calculations in Subsection 7.2. The parameters of disaggregating CET functions (26) and (41) were taken to be $\varphi_b = 3,\ \varphi_{yd} = 2$, which corresponds to low and medium elasticity of transformation $\sigma_b = 0{,}5,\ \sigma_{yd} = 1$. We discuss the level of transformation elasticity in Subsection 7.3.

The rigidity parameters were chosen according to the papers on the Russian economy (*Polbin, 2014* and *Andreyev and Polbin, 2019*): $p^{rig} = 24$, $k^w = 47$, $k^g = k^b = k^f = 4$, $d_s = 0{,}05$. The parameters of Taylor's rule were chosen according to *Andreyev and Polbin* (*2022*), which is an estimate based on Russian data covering the period from 2010 to 2020: $\rho_r = 0{,}9$, $\rho_{\inf} = 1{,}5$. Thus, a highly internal monetary policy was considered. Autocorrelation parameters for random processes were set close to 1: $\rho^g = \rho^{\tau^b} = \rho^{pb} = 0{,}99999$.

The structural parameters of the economy were calibrated as follows. The ratio of imports to GDP was set equal to $0{,}25$ in line with Russian statistical data. Aggregate exports were assumed to be equal to imports in long-term equilibrium and investments in foreign bonds were assumed to be zero. The ratio of (brown) energy exports to aggregate exports was assumed to be $0{,}6$; the ratio of (brown) energy exports to the total value of all brown energy produced (both exported and domestically consumed) was assumed to be the same, which is close to Russian statistical data.

Given the selected parameters of the model, the ratio of domestic prices for green and brown energy P_t^g / P_t^b turned out to be $1{,}9$. With no available official statistics, this figure matches information from the media (*Vedomosti, 26/05/2020*). The fact that there is a difference in prices per 1 kWh of energy in a nominally competitive market is explained by the 'two-product' model of the energy market. Specifically, capacity owners receive two types of payments. The first type the payment per unit of generated energy, which is the same for all owners, and the second type is the payment for installed capacity, which is higher for green energy.[11]

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[11] Russian Federation Government Directive No. 1-r, dated 8 January 2009, 'On the Guidelines for the State Policy for Improving the Energy Efficiency of the Electric Power Industry Based on Renewable Power Sources Through 2035' (as amended on 24 March 2022).