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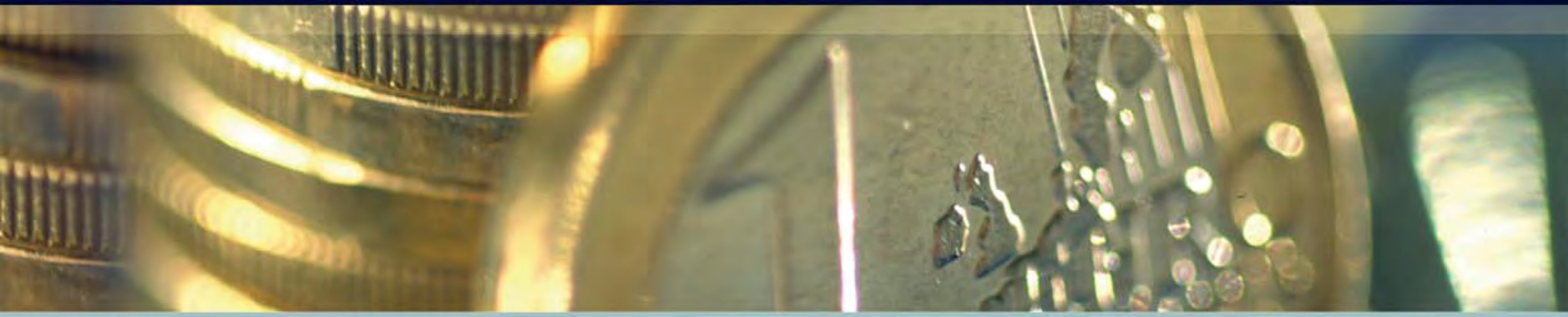

What is the growth potential of green innovation? An assessment of EU climate policy options

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What is the growth potential of green innovation? An assessment of EU climate policy options

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ABSTRACT

This paper provides a model-based analysis of the cost-efficiency of different EU climate policy options that could direct innovation in the private sector towards an environmentally sustainable growth path. Our objective is to assess different policy options in order to identify an appropriate policy-mix of environmental and innovation market instruments in terms of their cost-effectiveness. For this purpose, we develop a fully-dynamic, multisectoral DSGE model with endogenous technological change where we specifically identify its environmental content and we calibrate the model for the EU and the rest of the world. Our results suggest that an appropriate policy mix should intensively stimulate R&D in the green sectors in the short-run and phase-it out by spreading the R&D support to all sectors of the economy in the medium-term. Although intuitive, the orders of magnitude presented in this paper should be interpreted with caution by taking into account the underlying assumptions of the model and identification of green innovation data.

JEL no. C63, H23, O30, O41

Keywords: Carbon revenue recycling, climate change, directed technical change, double dividend, dynamic general equilibrium model, endogenous growth, R&D

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CONTENTS

1 INTRODUCTION

Economic development relying on intensive depletion of natural resources over the long run cannot be considered sustainable neither from an environmental nor an economic point of view. But market forces do not appear automatically to induce transition of economies towards a more environmentally friendly development path. Lately, carbon price is at an all-time low as a result of excess supply of emission allowances reflecting the effect of the crisis on demand for energy. Together with tight credit markets, the sole mechanism of weak carbon market price does not provide a sufficiently strong signal for stimulating private investments in clean production methods. In this paper, we investigate what type of government intervention would be needed to direct technological change towards low-emission technologies without limiting the prospects for future growth. In our analysis we consider that government intervention could somewhat remedy the initial productivity disadvantage of clean technologies and shelter companies from losing their competitive edge. Once new technologies are sufficiently advanced to become commercially viable, transparent market-based signals will be sufficient to facilitate further research in sustainable production methods (see Acemoglu et al., 2009 and Aghion et al., 2009).

A certain degree of government intervention is initially needed because of two market failures occurring simultaneously. First, there is little spontaneous demand for emission-reducing technologies, which chokes the supply of commercially viable non-polluting goods and services. Since a stable climate is a public good, the social benefits of climate action are not fully captured by those incurring the mitigation costs and autonomous climate change mitigation actions remain below the social optimum. Second, companies lack incentives to invest in clean technologies, because of the so-called appropriability effect associated with the expected post-innovation rents (Aghion et al., 2005). Given society preferences, there could be pressure to widely disseminate outputs of green innovation. So, companies anticipate they will not be able to capture fully the market value of their investments in green R&D and therefore downplay their contribution to green innovation (Jaffe et al., 2005; Newell, 2009). By contrast, mutually supportive environmental and innovation policies could stimulate markets to deliver a wider portfolio of green technologies. These technologies would enable climate change mitigation at commercially reasonable costs and even provide opportunities for growth (see e.g. Popp et al., 2009, Aghion et al., 2009).

This paper assesses the theoretical potential of different EU climate and innovation policy options for directing innovation in the private sector towards an environmentally sustainable growth path. The focus is on those policy options that previous literature highlighted as the most cost-efficient (Acemoglu et al., 2009; Aghion et al., 2009; Newell, 2009; Popp et al., 2009) and which are relevant for current EU policy making. To evaluate the growth potential of different policy options, we use a fully dynamic stochastic general equilibrium (DSGE) model with endogenous technological change developed by Roeger et al. (2009). In addition to the existing model, following Varga (2010), we include the environmental content in a multisectoral setting by building upon the theoretical model of Acemoglu et al. (2009). The essential contribution of our approach is to consider that green innovation occurs along the supply chain and is not necessarily bounded within a single sector. The introduction of an exhaustive sectoral input-output matrix allows us to capture the development and use of environmentally-friendly products substituting dirty products across different sectors of the economy. Such "green" multi-sectoral version of the model allows us to evaluate the marginal economic effects of sector-wide measures compared to economy-wide policy intervention in the environmental and innovation markets. In applied terms, this model is calibrated on our newly constructed dataset that includes green R&D and CO_2 emissions for five sectors with a distinctive potential for nesting green activities.

The policy simulation scenarios are built upon the notion that an appropriate policy mix has to jointly tackle the double market failure (as motivated by Newell, 2009). Building upon the previous literature, we consider that an appropriate policy set from a macro-economic perspective should combine instruments that tackle (i) environmental problems by emission pricing and (ii) innovation market problems by appropriate R&D support instruments.[1] Our working hypothesis is twofold. First, an appropriate combination of environmental and innovation policies is desirable in order to address the combination of negative environmental and knowledge externalities. Second, the appropriate set of policies should address the sectoral linkages of the economy. Our policy scenarios differ one from another with respect to the following distinctive elements (i) whether they address the double market failure nature of climate change or exclusively the environmental externality, and (ii) whether they account for the sectoral linkages of the economy or concentrate on certain sectors only. These elements are gradually introduced in the model-based analysis, which allows us to trace back the contribution of each element to economic growth and to identify the scope of potential synergy or trade-off effects of a policy-mix on economic growth and key macro-economic variables relative to individually implemented policies.

The simulation results highlight important aspects of recycling the revenues generated by the carbon market. In general, the main result implies that intelligent intervention aimed at sustainable economic growth should address jointly the double-market failure and consider the sector-wide spillovers. The key simulation results suggest that the most cost-efficient policy mix could take the form of a front-loaded R&D support. While one part of carbon market revenues would enhance fiscal consolidation through labour-market support, the other part would be used to intensively stimulate green-targeted R&D along the supply chain in the short run and phase it out by spreading non-targeted R&D support to all sectors of the economy. The appropriate combination and staging of policies suggested above is supported by the theoretical literature and verified by our further simulations of alternative policy options.

In particular, recycling of carbon revenues with a non-distortionary lump-sum tax reduction leads to a permanent loss of gross domestic product (GDP), while all other policy options considered in the analysis deliver at least weak double dividend in the short run and stronger double dividend after ten years.[2] As demonstrated in our analysis, the R&D support exhibits decreasing returns. Therefore, shifting the direction of R&D from green sectors to all sectors reduces the bottleneck problem of front-loaded R&D targeted to green technologies in the short run by facilitating dissemination of knowledge to other sectors through non-targeted R&D support to all sectors in the long run.[3] The results indicate some reallocation of resources from material inputs towards greater employment and use of knowledge. This substitution mechanism is directly linked to choosing to recycle carbon revenue recycling to support labour tax reduction and to support R&D in sustainable technologies. To assess the growth potential of alternative policy options, detailed results are presented in relative terms rather than in absolute terms. The orders of magnitude presented in this paper illustrate the growth potential of different policy options, but should be interpreted with caution taking into account the underlying assumptions adopted in the analysis.

Section 2 presents the extensions of the forward-looking dynamic general equilibrium model, which captures the link between CO_2 emissions associated with dirty energy use and endogenous directed technical change for each sector. Section 3 describes the dataset used to calibrate the model to the economies of the EU and of the rest of the world. This section documents how we selected disaggregated sectors to identify green production areas of the economy. Section 4 refers to the literature findings and the policy background to define the policy options assessed with the model. Section 5 discusses the simulation results and section 6 provides conclusions for policy consideration and suggests issues for future quantitative assessments of green growth policies.

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[1] We hereby follow the path highlighted in the most recent and prominent academic literature by Popp et al. (2009), Newell (2009), Aghion et al. (2009).

[2] The so-called double dividend (Bovenberg, 1999) occurs if an environmental tax reform yields not only environmental but also non-environmental benefits from returning of carbon tax revenues through less distortionary labour taxes rather than in a lump-sum way.

[3] The bottleneck problem may arise due to insufficient capacity of other sectors to benefit from green-targeted R&D support, unless it is eventually applied to the rest of economy. Although green R&D is needed to induce substitution of final and intermediate sectors away from the more expensive dirty sector (if taking life-cycle costs into account), positive spillover effects may not occur with low knowledge absorption capacity of other sector due to lack of R&D investments.

2 THE MODEL

2.1 Building on QUEST, a fully forward-looking multi-sector model

The analysis uses the QUEST III model, which is a semi-endogenous dynamic stochastic general equilibrium (DSGE) model developed by Roeger et al. (2009)[4]. This model is extended in Varga (2010) by considering the environmental policy elements in a multisectoral-multiregional model to investigate the interaction between the environmental and innovation policy instruments. The practical value of the analysis is to assess the cost-efficiency and growth potential of policies that EU policy makers could consider to address the so-called double market failure of climate change and innovation.

Since the choice of policies depends crucially on the ex-ante perception of the future behaviour of market agents, we derive behavioural equations from the inter-temporal optimization problem under the technological, institutional and budgetary constraints subjected to nominal, real and financial market frictions. This section describes the modelling developments needed for better understanding of our policy-oriented analysis, while further details are provided in the appendix. A comprehensive representation of the model is given by Varga (2010).

Climate change policies inherently constitute a dynamic optimization problem, which is comprehensively addressed by our model and rarely in other applied climate policy models.[5] First, we acknowledge that market agents anticipate rationally the long-term effects of dangerous levels of climate change to decide their current economic activities (as in Sterner and Persson, 2008; Acemoglu et al., 2009). Moreover, the fully dynamic forward-looking model captures the endogenous responses of technology to policy changes. We consider technological change as semi-endogenous by using the knowledge function of Jones (1995) with the R&D investment resulting from the inter-temporal optimization decisions of economic agents. This characteristic is particularly suitable for our modelling objective in line with the Europe 2020 strategy, which, for the EU, sets the goals of bringing about smart, sustainable and inclusive growth so that the EU might emerge stronger from of the crisis. To inform policy making, we provide model-based evidence on how to effectively influence current and future investment decisions in physical capital and R&D aimed at strengthening the prospects for dynamic growth in a way that limits the amount of emissions in the future.

The previous literature motivates that technological change is the key component of long-term reduction in greenhouse gas emissions at a global level, while models without endogenous technological change in sectors typically overestimate the cost of climate change policies (e.g. as suggested by Pizer and Popp, 2008). Hence, we describe the economy in the model with sufficiently disaggregated information about the sectors. The multi-regional setup of the model allows the assessment of potential international spillover effects, but we leave this analysis out of the scope of this paper due to a lack of consistent extra-EU27 data.

The model represents two regions, the EU and the rest of the world. In each region, the model economy is populated by non-liquidity constrained households of Ricardian type and liquidity

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[4] The core of QUEST III model was estimated by Ratto et al. (2008), a calibrated semi-endogenous version of the model for individual member states is presented in D'Auria et al. (2009).

[5] With respect to investment in new technologies, agents try to account for the future expected benefits of investing in R&D. Although majority of the models identify themselves as "dynamic", a closer look at the model-description reveals that surprisingly small fraction of the current models account with some form of forward looking dynamic. Bergman (2005) distinguishes between "fully dynamic" and "quasi-dynamic" models. Fully dynamic models assume forward looking behaviour on the part of households and/or firms. The economic agents have some information about future development, which they consider in contemporary actions as e.g. to maximize the utility or profit over a certain time horizon. Several general equilibrium models in the literature miss this feature. Instead the CGE models are applied for multi-period analysis in a way that for each consecutive years t and $t+1$, the solution for year t is used to update the level of stock variables. In the CGE models, the agents have myopic and not rational expectations as they base their decisions on the current conditions without taking into account the expectations on future developments of their current actions. Bergman (2005) denotes these models as "quasi-dynamic", while our model is fully dynamic assuming rational expectations.

constrained households, companies producing in five sectors, a monetary authority and a fiscal authority. Labour supply is endogenous and households offer high-skilled, medium-skilled and low-skilled labour services, where high-skilled employees are either employed in the R&D activities or traditional production activities. The fiscal authority receives the revenues from excise duties and labour income taxes. On the expenditure side, the government can use its revenue to support R&D activities through wage-subsidies to decrease income taxes, consumption taxes or give transfers to households. The monetary authority follows a standard Taylor-rule in each region and interest rates are also endogenous.

2.2 Accounting for production, consumption and innovation in green technologies

Production in a multisectoral setting

Each firm in each sector produces differentiated goods, which are imperfect substitutes for domestic and foreign goods. Firms use a capital and labour composite (*VA*) and an energy and non-energy composite of intermediate goods (*M*), where energy (*EN*) itself is composed of dirty (*D*) and green (*G*) sources. We distinguish two non-energy sectors, an energy-intensive (*I*) and a non-energy intensive sector (*S*), where the energy-intensive sector is subject to an emission-cap scheme. The energy composite is produced by a dirty sector which exploits an exhaustible polluting resource (sector *D*) and a "green" sector (*G*) which provides machines that can be used to substitute away from the "dirty" sector's product in any production process. For simplicity, we assume that one unit of the exhaustible resource is transformed into one unit of "dirty" energy output. The production function for a firm in sector *i* is defined as:

$$
\begin{aligned}
Y_{n,t}(i) &= F_n\left(VA_{n,t}(A), M_{n,t}(i)\right) \\
&= A_n \cdot \left(sva_n^{\frac{1}{\sigma_{vam,n}}} \cdot VA_{n,t}^{\frac{\sigma_{vam,n-1}}{\sigma_{vam,n}}} + sm_n^{\frac{1}{\sigma_{vam,n}}} \cdot M_{n,t}^{\frac{\sigma_{vam,n-1}}{\sigma_{vam,n}}} \right)^{\frac{\sigma_{vam,nn}}{\sigma_{vam,n-1}}},
\end{aligned}
\tag{1}
$$

where $\sigma_{vam,n}$ is the sectoral elasticity of substitution between the value added and the intermediates, and sva_n and sm_n are the corresponding weights.

Endogenous technological change

An investment in knowledge capital is an endogenous process. In each period the firms hire labour to perform R&D activities in order to increase the productivity on the firm's value-added term (*VA*). We augment Jones's (1995) semi-endogenous knowledge production function by accounting for spillovers from domestic and foreign stock of knowledge. Formally we assume that

$$VA_{n,t}(i) = f_n\left(A_{n,t}^{va}(i), K_{n,t}(i), U_{n,t}(i), L_{n,t}(i)\right) \tag{2}$$

where the productivity term, $A_{n,t}^{va}(i)$ is interpreted as the accumulated sectoral stock of knowledge. Knowledge production is a function of already accumulated knowledge and research labour employment ($RL_t(i)$): $A_{n,t+1}^{va}(i) - A_{n,t}^{va}(i) = RD(RL_t(i), A_{n,t}^{va}(i))$.

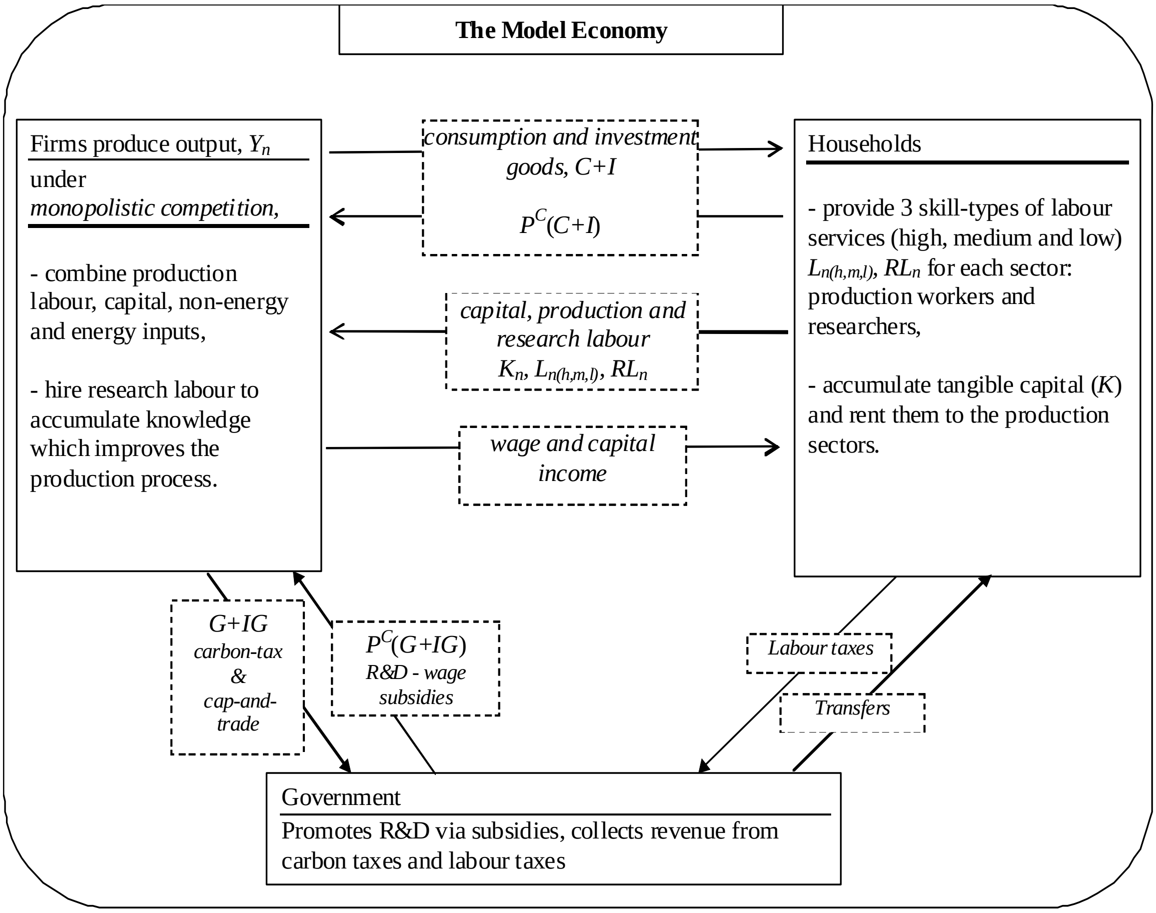
Endogenous labour supply decision

We suppose that labour is mobile within the respective skill-category across sectors but subject to certain adjustment costs. There is a unique wage across sectors for each skill group and the government can use wage subsidies to support certain sectors or R&D activities. Note that high-skilled labour can be employed in production or in research activities but low and medium-skilled can work only in the traditional production process.[6] We distinguish between labour skills and we specify that research activities can only be performed by high-skilled workers, who are also needed for final goods production. This gives an additional strength for the model to explore potential crowding out effects between sectors of research and also between traditional production and research activities. Indeed, the literature has highlighted that these effects could be a cause for concern when introducing the policy mix which interests us.

2.3 Green variant of QUEST

Figure 1 presents schematically the flow chart of the green variant of QUEST model together with the nested CES production structure. The model is sufficiently flexible that the value-added part of production output can appropriate different shares of knowledge stock and capital-labour inputs according to the underlying substitution parameters.

Figure 1. Presentation of the model



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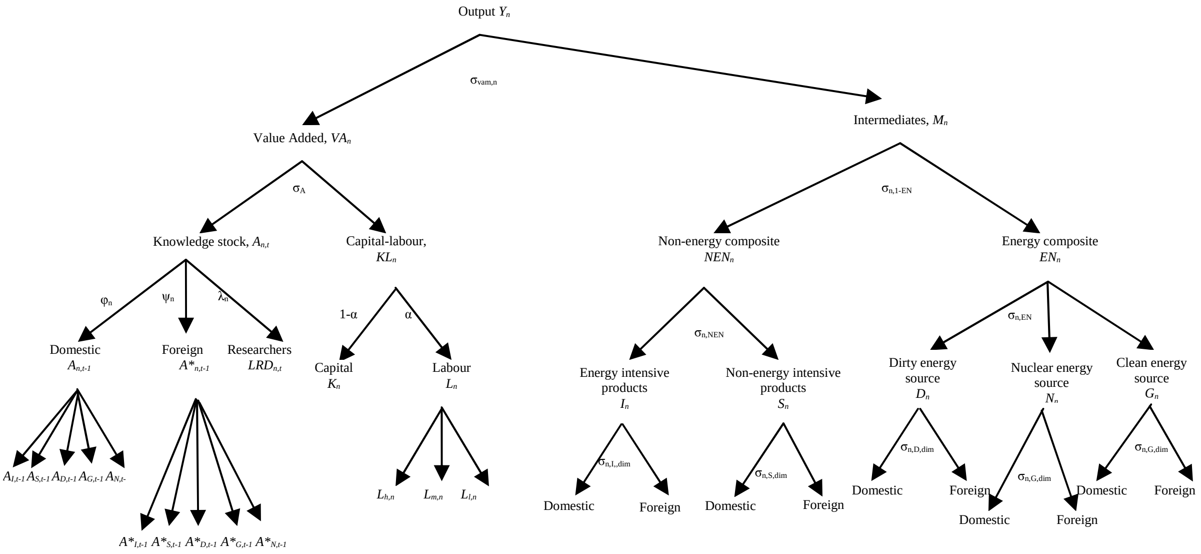
[6] We define high-skilled workers as the segment of labour force that can potentially be employed in the R&D sector, i. e. engineers and natural scientists and we take the high-skilled wages in the education sector as a proxy for the wage level of the R&D labour. Low-skilled workers are those whose highest level of education corresponds to the ISCED 0-2 categories and the remaining share of the working age population is classified as medium-skilled.



It is important to note that the components within the energy composite enter into the production function in an imperfect substitutability fashion while the energy and non-energy composites imperfectly complement each other. One of the most important parameters for the analysis of energy and oil price shocks is the elasticity of substitution between energy and other inputs in production and goods. We follow Bodenstein et al. (2007) in line with other empirical studies and assume the same elasticities for households and firms of 0.5 in the long run. Also in line with their estimates, we assume that adjustment costs imply a half life of the response of fossil fuel demand to a permanent increase in their prices of seven years; therefore the elasticity of substitution is smaller in the short run. Adjustment costs are specified in terms of energy intensity shares and are assumed to have the quadratic form for each energy source, e.g. for dirty energy use:

$$(3) \qquad \Gamma_{D,m} = \frac{\gamma_D}{2}\left(\frac{M_{D,m,t}/M_{EN,m,t}}{M_{D,m,t-1}/M_{EN,m,t-1}} - 1\right)^2$$

and the corresponding energy composite ($M_{EN,m}$) for sector m is:

$$(4) \qquad M_{EN,m,t} = \left(\sum_{e\in\{D,G,N\}} smen_e^{\frac{1}{sigm_{EN,m}}}\left(M_{e,m,t}(1-\Gamma_{e,m})\right)^{\frac{sigm_{EN,m}-1}{sigm_{EN,m}}}\right)^{\frac{sigm_{EN,m}}{sigm_{EN,m}-1}}$$

2.4 Acknowledging costs and benefits of climate action

Climate change impacts

Typically the literature equates the overall impact of climate change based upon the relationship between environmental changes and agricultural-related productivity, tourism, water supply, coastal zones, and mortality from climate-related diseases.[7] Dangerous levels of climate change would impair physical and human capital leading to a reduction in production capacity.

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[7] The current estimates of the impact of doubling GHG emissions, which is believed to increase global temperature by 2.5^{0}C, ranges from 0.2 % (Tol, 2002a and 2002b) and 1.5% (Nordhaus and Boyer, 2000) to 5.3% (Stern, 2006). It seems that overshooting the two degree limit for global warming would also lead to net damages in the EU. For instance, a recent attempt to quantify climate change impacts within the EU region indicate a risk for most Member States to experience at least 0.1% to 0.5% losses in their GDP by the end of the century (Aaheim et al., 2009).

Following the approach by Acemoglu et al. (2009), we construct an environmental quality variable as a function of total CO_2 emissions which enters into the utility function of households instead of directly affecting productivity (see e.g. Nordhaus and Boyer, 2000). However, we alter from Acemoglu et al. (2009) by assuming that environmental quality affects the quality of households' leisure time instead of consumption (see Appendix A for more detail). It should be emphasized in advance that since we consider the same EU27 emission reduction efforts along our counterfactual scenarios; they lead to about the same global environmental improvements without further assumptions for the rest of the world. Therefore it is not the environmental quality variable but the recycling options and the substitution possibilities which drive the differences between our simulation results for climate change mitigation policies.

The feedback of climate change damages on growth is likely to be downward biased because we cannot apply probabilistic risk assessment methods, which would balance the mitigation cost with benefits of avoiding negative environmental outcomes of human-induced interference with climate change systems. This is motivated by the literature documenting that climate change mitigation creates benefits by reducing the risk premium associated with dangerous climate change (Yohe and Tol, 2009). It is worth bearing in mind when interpreting the results that we do not account for air pollution reductions in climate change mitigation despite the potential benefits documented by the IIASA GAINS model results (Amann et al., 2009). Our analysis does not capture the impacts of climate change on the well-being of a population, which could arise from their preference shift towards low-carbon goods. Finally, the model does not capture any damage associated with the unsustainable use of the elements forming the natural capital stock, e.g. biodiversity and ecosystem services.

Climate change policy through market-based instruments

The model is suitable for representing price and quantity based environmental instruments. Firms in the energy intensive (*I*) and dirty (*D*) sectors are required to hold emission certificates based on the emission content of their (dirty) energy consumption. Emissions trading allows for banking following the Cronshaw and Kruse (1996) model of pollution permit trading. Additional to the emission trading system, the government can apply quantity or *ad valorem* taxes on dirty energy use. At the beginning of each period the government issues emissions allowances reflecting its own emissions target for that period. One part of these emission allowances is allocated without any charge to energy-intensive sectors, while the other part is auctioned by polluting energy producers. Firms in the energy intensive and dirty sectors are allowed to purchase or sell the obtained emission allowances. The emission content of their production process is calculated as the CO_2 equivalent ratio denoted by co_n of their total dirty input use, captured by $M_{D,n,t}(i)$.[8] Let $CS_{n,t}(i)$ be the stock of emission allowances held by the firm at the beginning of period t, $\omega_{n,t}(i)$ be the free allowances received, and $s_{n,t}(i)$ be the additional purchase or sale of emission allowances (positive or negative respectively). Then the stock of emission allowances evolves over time according to:

$$CS_{n,t}(i) = CS_{n,t-1}(i) + \omega_{n,t}(i) + s_{n,t}(i) - co_n \cdot M_{D,n,t}(i) \qquad (5)$$

3 DATA DESCRIPTION

We construct a comprehensive dataset to calibrate the model parameters on economic activity, R&D investments and environmental data at the sector-level. The rationale behind the sectoral choice is that policy shocks correcting market failures are likely to induce sector-specific responses, which might not be accounted for in the analysis considering a uniform policy shock for the entire economy. We built representative sectors according to three key characteristics of the QUEST model. First, the

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[8] Note, that we do not model any technological advances in the CO_2 emission equivalent ratio.

model allows the use of detailed national accounts at the sector level including input-output tables and trade linkages between sectors of different regions in the world. Our green version of QUEST defines sectors according to their potential for nesting green activities. Second, the QUEST model uses a social accounting matrix, which is now extended to capture the relationship between economic activity and emissions. Third, the green version of the model takes into account private and public R&D investments in all sectors of an economy. Given the lack of readily available green R&D and innovation indicators, we carefully map the R&D data with other sector-wide and economy-wide data, as explained in the appendix. The following sub-sections explain the structure of our datasets and the technical approach behind their consolidation.

3.1 Green sectors and CO_2 emissions in the input-output matrix

The social accounting matrix is the backbone of the model. This square matrix represents each region's economy by depicting inter-industry relations and incorporating activities by consumers, government, and foreign suppliers in an accounting framework. Our model economy contains two regions, i.e. the EU27 and the rest of the world. This choice is based on the following reasoning: first, the focus of our analysis directly concerns EU environmental policy choices by investigating the potential benefits of green innovation for sustainable growth. Second, the rest of world's regions are represented as an aggregate for which comprehensive data on national accounts and emissions could be obtained. As described in the appendix, the conventional matrix has been extended to consider direct linkages between economic activity and emissions by simply adding an additional row to the supply side block once the standard national accounts flows have been defined. The main source is the 7th version of the GTAP database (Narayanan and Walmsley, 2008), which determines 2004 as the starting year of analysis.

Table 1. Definition of sectors used in the model

Code	Description	Composition
REN	Renewable energy sector	Hydro energy production New renewable production (new power plants, non IGGC, etc.) Biomass and waste fuels
NUCL	Nuclear-plant based electricity production	Nuclear electricity generation facilities
FOEN	Fossil fuel based energy production inputs	Oil, gas extraction and coal mining Refining activities Non-renewable energy utilities (coal, oil, gas)
EII	Energy intensive manufacturing	Iron and steel Other metals and minerals Chemicals Pulp and paper
OTHER	All transport (household, public, freight)	Road transport Air transport Maritime transport Transport equipment manufacturing
	All final energy users (households, services)	Residential buildings Commercial buildings Construction Energy using equipment manufacturing
	Agriculture, forestry, fishing	Food, beverages, tobacco industry Wood and wood products
	All other industries and services	Textile industry Plastics and rubber industry Insurance and financial services Tourism and other household services

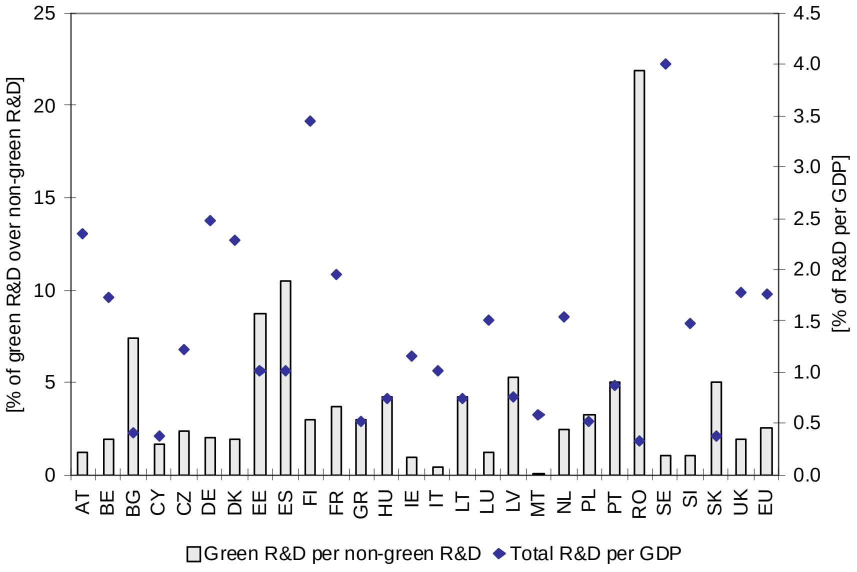
Source: Authors' own classification based upon the technical procedure explained in Appendix B.

The supply side of economy is represented by five distinctive sectors, which are defined by Table 1. The choice of sectors is based upon differences in their potential for development and use of environmentally-friendly technologies, i.e. green technologies with negligible emission content. The sectors labelled as "REN" and "NUCL" comprise the renewable energy sector and the nuclear energy sector with negligible emissions. The next two sectors in Table 1 roughly correspond to the set of industrial sectors defined within the current EU Emissions Trading Scheme. These sectors are divided in two distinctive groups, which are fossil fuel based energy inputs (FOEN) and energy intensive manufacturing industry (EII). The emission content of the latter sectors is determined by the inter-industry relations on the production side, i.e. referring to "domestic supply" for "intermediate uses" in the upper rows of the matrix in Appendix B. Total emissions from production process are denoted by $\sum_s M_{d,s}^{emis}$ in the matrix, which covers all three sectors and a fraction of the fourth sector called "Other" in Table 1. Apart from these three categories, the "Other" category also covers the emissions from the final use of industrial outputs, which are associated with investment ($\sum_s I_{d,s}^{emis}$), household consumption (G^{emis}) and government consumption (G^{emis}).

3.2 Identifying green innovation

An identification of "green" or "environmentally-friendly" data on R&D and innovation is a challenging endeavour because of the analytical and empirical shortcomings. On the one hand, there is no clear methodology helping us to define the concept of "green" R&D, that is, the extent to which the R&D activities in different sectors set the environmental-related objectives as their main priorities. On the other hand, there is a lack of comparable cross-country data on investments in environmental-friendly technologies. Therefore, we have to complement available environmental data with other non-environmental data sources of R&D investments. Considering these shortcomings, our paper contributes analytically to this stream of literature by constructing a unique dataset including comparable R&D investments in green technologies across EU27 countries.

Figure 2. Investments in green R&D compared to total R&D investments, 2004



Source: Authors; computations based on the latest Eurostat, GBOARD and IEA data.

For the purpose of our model calibration, the primary data source is the EUROSTAT Science and Technology Indicators (STI) that entails the most detailed R&D data available for sufficiently disaggregated levels of industrial activity for all EU Member States. For the reasons explained above, we complement these data with the data from the EUROSTAT Government Budget Appropriations or Outlays on R&D (GBAORD) and the International Energy Agency (IEA). The final dataset includes both private and public R&D appropriated to the green sector - labelled REN - in Table 1. The methodology used for the decomposition of R&D figures into a green and non-green component is explained in more detail in Appendix.

Table 2. Intensity of public support to total R&D and green R&D

	Euro per capita			Share in GBOARD	
	Energy	Environment	Total R&D	Energy	Environment
EU27	6.30	5.30	180.40	3.49%	2.94%
Non-EU average	12.70	4.38	271.58	4.68%	1.61%
Norway	13.70	9.10	474.90	2.88%	1.92%
Japan	25.20	1.70	183.40	13.74%	0.93%
South Korea	6.40	5.10	109.90	5.82%	4.64%
US	5.50	1.60	318.10	1.73%	0.50%
Highest and lowest level of public support to R&D, by category					
Finland	16.60				
Lithuania	0.20				
Spain		11.60			
Bulgaria		0.10			
Denmark			363.10		
Bulgaria			14.20		

Source: Authors' computations from statistics on total Government budget appropriations or outlays on R&D (GBAORD) by NABS 2007: energy (NABS 2005), environment (NABS 2007) and total R&D appropriations (NABS 1999).

Figure 2 shows that R&D investments targeted exclusively to environmentally-friendly technologies are rather low – out of 100 Euros in non-targeted R&D investments in the EU27, only 2.5 Euros go into environmentally-friendly R&D investments. Figure 2 does not show any systematic pattern on the link between green R&D investments and a country's total R&D investments relative to the size of its economy in terms of GDP. However, countries with higher shares of green vs. non green R&D are also countries with lower R&D intensities and new Member States (with the exception of Spain). This may indirectly indicate that new waves of R&D investments – such as those witnessed in these countries – are increasingly directed towards green sectors. Public support to R&D for environmental and energy objectives was around €12 p.c. in the EU27 in 2008, up from €8 p.c. in 2004-2005. This is more than 50% higher than the equivalent figure for the US, but less than the figure for Norway and, especially, Japan (see Table 2).

4 POLICY SHOCKS

4.1 Starting points from the literature

The policy options are built to test if a policy mix can jointly tackle the double market failure and what would be the benefits of such intervention. We start from recognising the public good nature of a stable climate and we assume households and firms will keep polluting in the absence of a correction mechanism, taking a form of the emission price or shift in preferences towards a lower environmental degradation in view of better quality of life. In a response to low demand for emission reductions, the firms will under-invest in mitigation technology research. From the perspective of innovation markets, knowledge also has public good characteristics resulting in sub-optimal private incentives for R&D. Due to a potentially wide dissemination of private firms' innovations, the individual firms are not able to capture fully the market value of investments in green research and development, which tends to spill over to other users and potential competitors (Goulder, 1997; Jaffe et al., 2005; Newell, 2009).

Popp et al. (2009), Newell (2009) and Aghion et al. (2009) motivate us to consider that an appropriate policy set from a macro-economic perspective would combine instruments that tackle (i) environmental problems by emission pricing and (ii) innovation market problems by appropriate R&D support instruments. On that basis, our working hypothesis is twofold. First, an appropriate combination of environmental and innovation policies is desirable in order to address the combination of negative environmental and knowledge externalities. Second, an appropriate set of both policies will achieve largest emission reductions at minimal fiscal burden. To test these assertions, we consider policy scenarios differing from one another in their treatment of three elements: (i) the negative externalities of climate change, (ii) the specific problems concerning the market for innovations, and (iii) the contribution of public finances to the growth enhancing policy-mix. Importantly, all our scenarios assume balanced fiscal accounts with no additional financial resources used for tackling the double-market failure, but instead recycling the carbon market revenues for financing the innovation market policies. These elements are gradually introduced in the model-based analysis, which allows us to trace back the contribution of each element to growth and to identify the scope of potential synergy or trade-off effects of a policy-mix relative to individually implemented policies.

A theoretical model by Fischer (2008) shows that government support for emission-abating R&D is only effective if there is at least moderate environmental policy in place to stimulate adoption of new technologies by putting higher cost on dirty technologies. In a similar vein, Bosetti et al. (2009) find that a stand-alone innovation policy is insufficient to stabilize CO_2 levels without an accompanying carbon tax. Popp (2006) also strongly argues for a combination of optimally designed emission tax and R&D subsidies for environmentally friendly technologies. Finally, Golombek (2010) shows that to stabilise greenhouse gas emissions, the first-best outcome can be reached through a technology subsidy and carbon taxes, whereas announcing drastic emission reductions for the future has a less positive effect on growth.

4.2 Assumptions about the climate change policy applicable to all scenarios

We considered six counterfactual policy scenarios. We built these scenarios as different and comparable to our benchmark case, while bearing in mind an overarching principle of fiscal consolidation. In particular, the policy scenarios distribute public expenditures coming solely from the new financial flows generated by the revenue-raising instrument we simulate in the model.[9] The benchmark case refers to a steady-state of an economy presented by descriptive statistics in Table 3.[10] The steady-state benchmark scenario differs from counterfactual scenarios as it does not consider any specific policy initiatives either in the EU or in the rest of the world to encourage green innovation. While both EU and non-EU economies have set up support to green technologies and green infrastructures within their responses to the crisis, no international agreement was reached in its aftermath. Therefore, countries are not obliged to adopt policies to address the climate change challenge and have not announced any new unilateral actions to date.

The next set of assumptions considered in the steady-state benchmark case applies also to counterfactual policy scenarios. It is considered that regions outside the EU27 do not implement any policy constraining their GHG emissions.[11] Following the outcome of the UNFCCC conference in Copenhagen, the model invokes no specific assumptions about the future international climate regime and international pledges for reduction of emissions.[12] The analysis is based on CO_2 emissions and does not account for REDD and LULUCF as abatement options. No use is made of excess Assigned

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[9] The additional revenues are policy-driven and not technology-driven, i.e. by the carbon price mechanism, because new technological breakthroughs can occur only exogenously in the model. Also for the sake of simplicity, we do not project specific improvements to the state of public finances in the aftermath of the crisis.

[10] For example, the emissions are evenly distributed between the ETS and non-ETS sectors and amount to 12% in the energy intensive industries denoted by EII (13% at global level) and 38% in the fossil fuel based power sector denoted by FOEN (43% at the global level), while 50% of emissions occur in the sector labelled as "Other" in Table 1 (44% at the global level).

[11] This assumption could be relaxed in future. For example, one could explore the outcomes of a coordinated intervention towards green growth by considering a policy mix similar to the EU also in the rest of the world. Such coordinated intervention could eventually result from the follow up of Copenhagen negotiations.

[12] The European Council has reiterated the EU objective to stay below the science-based limit for global warming (Commission, 2009), after calling other countries to agree to reduce global emissions of at least 50% by 2050 compared to 1990 levels (Presidency, 2009a). Also the EU Environment Council confirmed the EU aspires to reduce global emissions by 50% by 2050, as it see this level of ambition would enable a limit global warming of well below 2°C (Presidency, 2009b).

Amount Units (AAUs) from the first commitment period of the Kyoto Protocol to meet the 2020 emission reduction targets.

Table 3. Descriptive statistics of the steady state in 2004

	EU27	*ETS*	*Non-ETS*	Rest of World
Macroeconomic indicators (Bill € at 2004 prices; ETS as % of total)				
GDP	10 316	10%	90%	22 460
Domestic private consumption	6 148	7%	93%	13 992
Extra-EU27 exports	1 162	24%	76%	3 632
Extra-EU27 imports	1 251	29%	71%	1 992
Environmental indicator				
CO2 emissions (Mt; ETS as % of total)	4 264	50%	50%	22 800
Innovation indicators				
R&D investments (% of GDP)	1.86%	0.31%	1.55%	1.86%
Share of skilled labour (% of labour)	42%	30%	43%	39%
Production input shares (as % of inputs)				
Labour input (%)	26%	15%	28%	29%
Capital input (%)	18%	11%	20%	19%
Intermediate input (%)	55%	70%	52%	50%
Fossil fuel input	3%	11%	2%	5%

Note: Baseline is not dynamic, but refers to the steady state of the economy described by the GTAP data available for 2004. Due to lack of comparable data on R&D intensity of the regions outside the EU-27, we apply the same rate as for the EU-27 to avoid any pre-determined judgements of innovation efforts in the rest of the world. For illustration purposes, we report CO2 emission statistics that are consistent with GTAP data. As explained in appendix, we had to map the CO2 emissions statistics with GTAP data because there is no readily available input-output table extended with environmental information.

Source: The descriptive statistics present the values of the input-output matrix, which uses the GTAP 7 data in 2004 and CO2 emissions data reported to UNFCCC and IEA.

The ETS sectors described by energy intensive industries and the fossil fuel driven power sector, which jointly account for about half of emissions (Table 3), will have to cap and trade their emissions under the EU Emission Trading Scheme (ETS). We consider a theoretical case with all carbon revenues auctioned and with no grandfathering of emission allowances. The rest of non-ETS sectors of the economy have to deliver emission reductions compatible with the overall EU binding emission target, whereby the European Council encourages Member States to rely upon the cost-effective economic instruments.[13] While the focus lies on the carbon price mechanism, the other elements of EU climate and energy policy are not explicitly considered, for example the obligation to achieve 20% of energy production from renewable sources in the EU in 2020. Nonetheless, the benchmark case captures key features of the ETS directive by letting the sectors bank their allowances over forthcoming periods.

Last, we realistically assume the EU action against climate change will not be discontinued after 2020 given that the European Council has already said that the EU aspires to limit global warming well below 2^0C compared to pre-industrial levels. We take that the EU-wide quantity of allowances decreases in a linear manner over time, so that the Community scheme contributes to achieving the commitment of the EU to an overall reduction in emissions of at least 20% by 2020 as specified in the Directive 2009/29/EC of 23 April 2009 (European Union, 2009). We extrapolate a not-so-ambitious emissions reduction path for the EU, as presented in Figure 3, corresponding to roughly 20% of EU reductions are achieved in 2020 and 50% in 2050 relative to 1990 levels.

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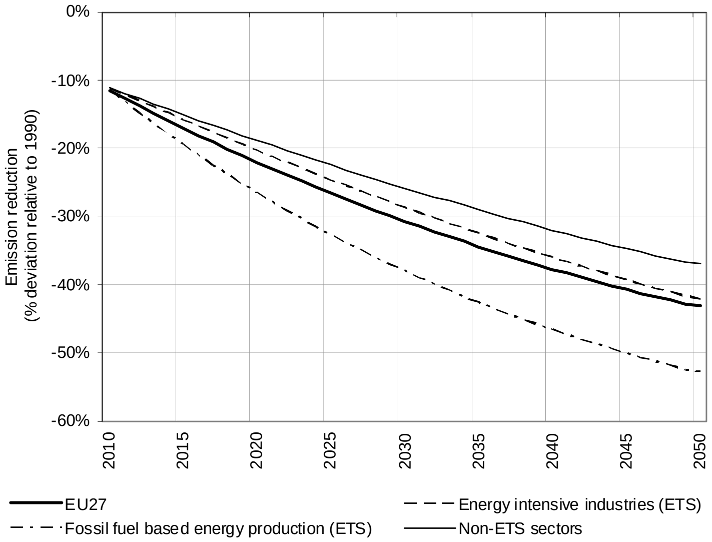
[13] Note that we suppose full auctioning from the beginning of the simulations, but no specific emission policies are considered for the non-ETS sectors. It is the pass-through of allowances prices from ETS to non-ETS sectors via intermediate consumption which leads to emission reductions outside the cap-and-trade scheme.

Figure 3. Path of emissions reduction in all scenarios



Note: The path of emission reductions is determined in the model by the allowance reduction targets. There are no significant differences in emission reductions across scenarios, which facilitates their comparison in terms of cost efficiency. The latest official estimate at the writing of this paper is available for 2008 only which is equivalent to 10.7% reduction of EU27 GHG emissions relative to the 1990 level (EEA, 2009). We consider this emission level as our starting point in 2010, although it possibly exceeds the current level. The baseline scenario implicitly assumes that the current caps and the explicitly not modeled vintage effects keep the emissions at their 2008 level. That requires an additional 10% point decline in emissions relative to 1990 in order to reach the 2020 target.

Source: QUEST simulation results.

4.3 Counterfactual policy scenarios

Green growth policy options to recycle carbon market revenues

We considered that any new fiscal revenues serve for a reduction in labour taxes, unless a rule to earmark resources for environment or innovation policy is specified. General labour tax reductions have a number of positive effects on growth because they encourage entry in the labour market, increase real wages and enhance labour productivity. Among the policy instruments using public revenues, the labour tax cuts have typically larger effects on growth than e.g. the lump-sum transfers to households.

Taking a closer look at our scenarios, the policy options differ with respect to specific environmental and innovation measures added to the policy-mix. In general, the mechanism for recycling the revenues generated by the carbon price determines the outcomes of scenarios, which differ with respect to how these new revenues are used in the economy. The importance of these revenues for the R&D support is gradually increased from the first to the last scenario. To design the recycling features of our scenarios, we took inspiration from the existing regulatory and policy environment. First, we strictly implement a constraint to use new fiscal revenues for growth enhancing purposes, as required by the Stability and Growth Pact, and as the Europe 2020 strategy put in place conditions to tap new sources of growth while ensuring a sound use of public finances (Commission, 2009). Second, the Directive on the EU Emission Trading Scheme ensures auctioning of carbon emission allowances will be generalised throughout the EU after 2013, and its Article 10.3 makes it compulsory to use at least 50% of auctioning revenues for financing EU climate action (Parliament, 2009). The directive stipulates that this earmarked revenue can be allocated to measures encouraging the take-up of existing green technologies or financing research in clean technologies, among other fiscal or financial support policies.

Last, we also stylised the features of this regulatory and policy environment to be able to interpret our scenarios in the light of the current state of art. Indeed, while the academic literature is consistent on the potential benefits of jointly implemented policies, it is far less clear on the appropriate combination of individual policies. Ulph (1997) finds that the ranking is ambiguous largely because of two competing effects of an environmental policy. First, there is a direct effect of increasing costs that stimulates investments in R&D to develop cost-saving pollution abatement technologies. Second, there is an indirect effect of reducing output that reduces the incentives for R&D investments. Fischer and Newell (2008) show that carbon price is the first choice on the list of environmental policy instruments and demonstrate that an optimal portfolio of policies including emission pricing and R&D support achieves emission reductions at substantially lower costs than any single policy. Our initial policy scenario is extended to demonstrate the role of crowding-out and efficiency of R&D support conditional on the sectoral coverage in the support scheme. Schneider and Goulder (1997) demonstrate that policies addressing knowledge spillovers are more effective if applied simultaneously to all sectors rather than exclusively to alternative energy choices within the renewable energy sector. Moreover, Schneider and Goulder (1997) find that the R&D policy is less effective and less efficient in absence of an appropriate environmental policy.

Gerlagh et al. (2007) study the role of technology subsidies in a simple dynamic equilibrium model with learning by doing. The authors find that the optimal subsidy rate of a carbon-free technology is high when the technology is first adopted, but falls significantly over the next decades. Supporting only the existing energy technologies or "picking the winners" could lead to lock-in of the wrong technology and the negative impacts of lock-in increase with the learning potential of new advanced technologies. Otto et al. (2008) compute an optimal policy mix in a calibrated dynamic CGE model for the Dutch economy. The authors find that the most cost effective set of instruments comprises differentiated and non-zero R&D subsidies to CO_2 intensive and non intensive sectors with somewhat higher subsidy rates for CO_2 intensive industries, combined with more stringent taxes on their production.

Another issue addressed in our scenarios is the necessity to coordinate R&D support and other policy stimulus that are provided across different sectors in the view of potential crowding-out effects. The literature reviewed by Newell (2009) tends towards generally applied R&D support to all sectors of an economy. The main reason is that the occurrence of market failures is generally not sector-specific but prevalent across different technologies, so that the R&D support directed to one sector might not be sufficient to sustain R&D growth. There are two reasons why growth effects may be lower if the R&D support is directed only to one sector instead of being spread across the whole supply chain. First, Popp (2002) attributes the gradual decrease in innovation over time to diminishing returns on R&D investments because of the concavity of the knowledge production function. The investments in green R&D will limit the overall growth potential with an increasing amount of resources directed to this R&D activity. Second, Jones (2009) uses a multi-sector model to demonstrate the so-called weak link effect. In short, he argues that each chain of economic process is as strong as the weakest part of it and problems at any point in the production chain can reduce the output substantially if inputs are used the production process in a complementary way.

Description of counterfactual policy scenarios

The baseline assumes that the pre-2010 emission trading scheme is in place and caps the current emission allowances on the ETS sectors. In the counterfactual scenarios we simulate a 1.74% decrease in allowances in each year starting from 2010 over a 40 year horizon and the amount of allowances are fixed after that period. In our hypothetical counterfactual scenarios, the climate change policy interventions are simulated through negative shocks given to the sectoral emission allowances variables (ω_t).[14] Since the EU accounts for about one tenth of world emissions, the net contribution of

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[14] There is no official data available on the 2010 level of GHG emissions. The latest official estimate at the writing of this paper is available for 2008 only which is equivalent to 10.7% reduction of EU27 GHG emissions relative to the 1990 level (EEA 2009). We consider this emission level as our starting point in 2010, although it is likely to overestimate the current level of emissions given that EU27 GDP dropped by about 4% in 2009 which probably further decreased the European GHG emissions. The baseline scenario implicitly assumes that the current caps and the explicitly not modeled vintage effects keep the GHG emission at their 2008 level. That requires an additional 10% point decline in emissions relative to 1990 in order to reach the 2020 target. In our counterfactual scenarios we reach this target by imposing the 1.74% decline per annum in the emission allowances without grandfathering. (The current EU law allows for a gradual phasing out of free allowances.) The counterfactual scenarios should be considered as comparisons of cost-effective recycling alternatives.

EU climate change policies to GDP and wealth depends on the future climate policy of other countries, which we do not simulate here. The results should therefore be interpreted in relative rather than absolute terms when assessing the performance of different recycling options in view of their cost-efficiency.

We construct the policy scenarios in the context of the new Europe 2020 strategy and therefore consider that interventions by the EU and Member States prioritise cost-effective instruments.[15] Hence we give preference to market-based instruments and pre-selecting policy mix with a large potential to be cost-effective in tackling the climate change and inducing green innovation. Table 4 summarizes our policy scenarios which take into account the issues raised above. Scenario S0 considers that the EU recycles all fiscal revenues generated by the carbon price for reduction of a lump-sum tax. Scenario S1 considers that all carbon-price revenues are recycled for a reduction of the labour tax. Scenario S2 considers that 10% of revenues are used to subsidise the purchase of green products supplied by the renewable energy sector (REN) by lowering the pertinent sales tax, and 90% for the reduction of labour tax. Scenario S3 considers that 10% of revenues are directed to green R&D support in green sector and 90% of revenues to labour tax reduction.[16] Scenario S4 considers that 10% of revenues are directed to general R&D support for all sectors and 90% for reduction of labour tax.

Table 4. Simulation scenarios

	Recycling options for carbon tax revenues (% of total revenues in terms of present value added over 50 years)				
	Lump-sum taxes	Labour taxes	Renewable s. sales subsidy	Green R&D subsidy	General R&D subsidy
S0: Lump-sum tax	100%				
S1: Labour-tax		100%			
S2: Renewable sector sales subsidy		90%	10%		
S3: Green R&D subsidy		90%		10%	
S4: Not-targeted R&D subsidy to all sectors		90%			10%
S5: Front-loaded green R&D subsidy		80% (2010-2020) 90.5% (2021-2050)		20% (2010-2020)	9.5% (2021-2050)

Note: Green R&D subsidy in scenarios S3 and S5 refers to R&D investments in the renewable energy sector and R&D investments for green purposes in the rest of economy, which accounts for rough 8% of the total R&D investments in the rest of economy.

Scenario S5 considers a front-loaded green R&D support, which is phased out through a general R&D support. In the first 10 years 20% of revenues are used explicitly for green R&D and 80% for labour tax reduction. After 2020, roughly 10% of revenues are directed to the green R&D support of green sector and roughly 90% of revenues to the labour tax reduction. Revenue recycling in the form of decreased indirect labour costs operates through lowering the rate of employers' social security contribution. Apart from accounting for the bottleneck problem, the purpose of the front-loaded scenario (S5) is to assess the impact of different staging of policy intervention. Hence, the choice of an economy-wide labour tax reduction parameter has to be based upon the neutrality condition, which implies that the amount of R&D support is comparable across all policy scenarios over the entire period.[17] This approach ensures that the effects of the front-loaded scenario (S5) are neither driven by

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[15] The Competitiveness Council (Council, 2009) stressed the intentions of the EU to assign predictable price for carbon emissions and to fulfil Member States' greenhouse gases emission reduction obligations in a cost-effective way.

[16] The green R&D in scenarios S3 and S5 refers henceforth in the text to the R&D by the renewable energy sector and R&D for green purposes in all other sectors of the economy. These two components represent jointly about 10% of total R&D in the EU-27.

[17] In other words, to ensure the final scenario is comparable with previous scenarios S3 and S4, the volume of ETS revenues recycled to reduce labour tax is kept constant over the entire period during which the policy mix is implemented. For example, providing a larger support in the first years and decreasing the support in the later years of the period in S5 is comparable to the equally spread R&D support over time in scenarios S3 and S4.

different policy staging over time nor potential differences in the amount of R&D support considered in scenarios. This constraint is in line with the stated priority of the EU for fiscal consolidation advocating the use of all available options including new revenues from environmental policy to alleviate the tax burden and make tax schemes less distortive.

5 SIMULATION RESULTS

5.1 Cost-efficiency of policy options

There is a clear ranking of cost-efficiency for different policy options in terms of GDP per capita at comparable levels of effectiveness to comply with the 20% reduction by 2020 (Table 5).[18] First, the results show that climate change mitigation is costly at least in the short-run. As long as it is difficult to substitute away from the dirty sources of energy, the providers of dirty energy pass the carbon price costs on the energy users. A policy mix represented by front-loaded green R&D subsidy (S5) is the least costly of all policy options considered in our analysis. Following an initial loss of economic growth in the short run (-0.07% GDP in 2014 and -0.02% GDP in 2017 relative to baseline), the economy recovers by 2020 exhibiting a slight improvement of 0.05% GDP relative to the benchmark case.

The least cost-efficient policy option is recycling carbon revenues through lump-sum tax reductions (S0), which does not stimulate long-term economic activity (-0.51% GDP in 2020). This economic effect is comparable to the findings of the impact assessment Climate and Energy package. It was then established that by excluding the benefits from the recycling of new revenues, the cost of EU environmental constraints was in the order of -0.54% to -0.35% GDP (European Commission, 2008). While recycling of carbon revenues for lowering labour taxes (S1) and increasing green sales subsidies (S2) appears to be less costly than the lump-sum case (S0), these policy options do not address adequately the environmental and innovation market failures and hence do not stimulate sufficiently the future economic growth.

Table 5. Potential economic costs and environmental benefits

	GDP of EU27				ETS revenues (% GDP)			
	2014	2017	2020	2030	2014	2017	2020	2030
Lump-sum scenario [S0]	-0.20	-0.35	-0.51	-1.11	0.10	0.20	0.30	0.56
Labour-tax scenario [S1]	-0.03	-0.06	-0.10	-0.31	0.12	0.22	0.31	0.57
Green sales subsidy scenario [S2]	-0.04	-0.07	-0.11	-0.35	0.12	0.21	0.30	0.55
Green R&D subsidy scenario [S3]	-0.03	-0.01	0.03	0.17	0.12	0.22	0.31	0.56
Not-targeted R&D subsidy to all sectors [S4]	-0.07	-0.04	0.02	0.38	0.09	0.19	0.29	0.55
Front-loaded green R&D subsidy [S5]	-0.07	-0.02	0.05	0.37	0.10	0.19	0.29	0.55

Note: GDP values are expressed as % deviation from baseline.
Source: Authors' computations using the climate version of QUEST.

The potential ETS revenues are comparable across different policy scenarios by construction of our scenarios with a pre-determined cap on emissions (Table 5bis). Consequently, new fiscal resources increase over time from about 0.1% in 2014 to 0.3% of GDP in 2020. An important assumption is that fiscal accounts are balanced with no additional financial resources required, so that policy objectives

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[18] The complete set of economy-wide and sector-wide simulation results is presented in Annex C.

are financed exclusively from carbon market revenues. This assumption implies that revenues from carbon markets help to ease the pressure on budgets by generating substantial fiscal revenues. This is particularly the case for the policy mix with the best potential to stimulate economic activity, as shown in Table 5.

Table 5bis. Fiscal resources involved with recycling

Macro-economic indicator	S0: Lump-sum tax		S1: Labour tax		S2: Green sales subsidy		S3: Green R&D subsidy		S4: General R&D subsidy		S5: Front-loaded green	
	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020
GDP	-0,20	-0,51	-0,03	-0,10	-0,04	-0,11	-0,03	0,03	-0,07	0,02	-0,07	0,05
ETS revenues (% GDP)	0,10	0,30	0,12	0,31	0,12	0,30	0,12	0,31	0,09	0,29	0,10	0,29
Recycling to lump-sum tax	0,10	0,30	0	0	0	0	0	0	0	0	0	0
Recycling to labour tax	0	0	0,12	0,31	0,11	0,27	0,11	0,28	0,08	0,26	0,08	0,23
Recycling to green sales subsidy	0	0	0	0	0,01	0,03	0	0	0	0	0	0
Recycling to green R&D subsidy	0	0	0	0	0	0	0,01	0,03	0	0	0,02	0,06
Recycling to general R&D subsidy	0	0	0	0	0	0	0	0	0,01	0,03	0	0

Note: The values refer to % deviations in 2020 relative to baseline.
Source: QUEST simulation results.

An introduction of a carbon tax with non-distortionary lump-sum tax reduction leads to a permanent loss in GDP while all other recycling options deliver at least a weak double dividend in the short run during the first ten years.[19] The simulations demonstrate that in order to mitigate the cost of carbon tax, policy makers can either decrease the current distortionary forms of taxation or they can address the knowledge externality involved in the double market failure behind the climate change problem. Although a difference between recycling rules is sometimes very small (e.g. in the order of 0.01% to 0.03% of GDP in scenarios S2, S3 and S4 in Table 5bis), it is still possible to distinguish between scenarios in terms of potential costs. An important policy message is that the choice of the recycling rule influences the size of associated economic benefits; moreover, the details in these rules should not be neglected as they could magnify the associated economic benefits.

5.2 Opportunities for new sources of growth

Figures 4 and 5 below depict GDP deviations from baseline across different scenarios. A graphical presentation of results vividly shows that it takes several years of adjustment before any visible gains in economic activity are realized. An appropriate policy-mix has a potential for growth, provided that it assigns part of carbon revenues to green R&D for providing the basis for future economic developments.

Confirming our discussion in the previous section, a clear ranking of policy options is observed from figures 4 and 5 with regard to their ability for compensating adverse effects of emission targets on growth. The front-loaded scenario (S5) has the largest potential for stimulating future economic growth, because it supports the development of green technologies by addressing the double-market failure and facilitates dissemination of knowledge along the supply chain. The initial costs of this policy option appear to be manageable in the short-term as the front-loaded scenario (S5) is only slightly more costly than the non-targeted R&D scenario (S4).

Our preferred scenario (S5) promises growth over a longer time horizon than recycling of carbon revenues to labour taxes (S1), green sales subsidies (S2) or lump-sum taxes (S0). The lump-sum case (S0) holds no prospects for boosting growth. Among scenarios with at least some content of green technology support (i.e. S2 to S5), the recycling of revenues to green sales subsidies (S2) appears to be the worst choice in terms of costs, except for a tiny advantage in the first few years. A possible interpretation of this under-performance can be drawn by comparing this scenario with the green subsidy scenario (S3) in which we substitute the 10% green sales subsidy by the 10% green R&D

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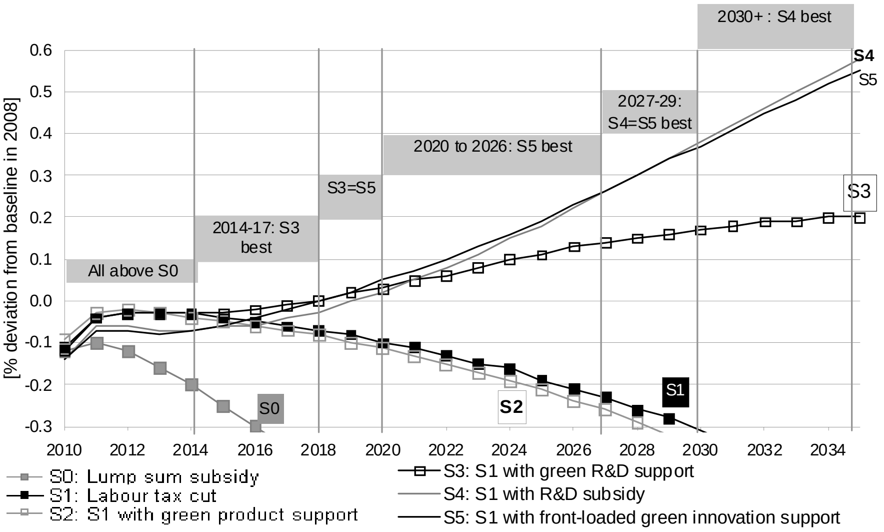
[19] Generalizing Goulder (1995) we refer to weak double dividend when the emission reduction measure creates a net loss to the economy, but this loss is partially mitigated by a revenue recycling instrument (i.e. tax or subsidy). We use the strong double dividend term when the emission reduction measure and recycling instrument result in an overall net gain to the economic welfare. The literature originally used these terms only for distortionary tax reductions as recycling instruments.

subsidy. Green sales subsidies neither increase the investment returns on development of green technologies nor tackle the "knowledge" part of the double market failure.

The price signal through sales subsidy taxes is not sufficient for intermediate and final consumers to substitute environmentally less friendly products by environmentally friendly products. Shortage in demand for green products hampers future investments in green R&D, because innovating firms do not expect sufficiently high post-innovation rents.[20] Without tackling the innovation market failure, the green-sales subsidy scenario (S2) is persistently more costly than R&D subsidy scenarios (S3 to S5).

Figure 4. The mid-term economic impact of recycling

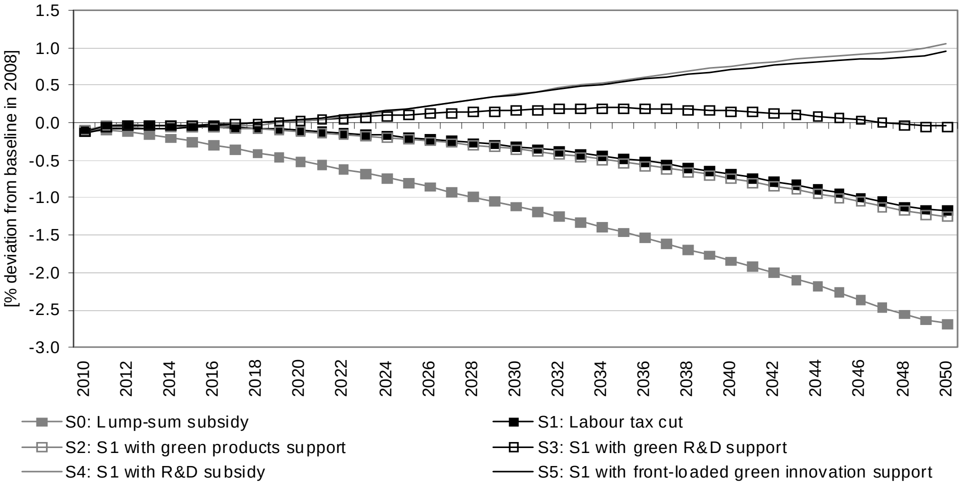
(% deviation in GDP from the baseline)



Source: QUEST simulation results

Figure 5. The long-term economic impact of recycling

(% deviation in GDP from the baseline)



Source: QUEST simulation results

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[20] The so-called appropriability effect refers to the insufficient level of post-innovation rents expected by innovating companies (Aghion and Howitt, 1992). The innovation rents in the climate change setup can be rather low because of potentially wide dissemination of green technologies across sectors.

Among scenarios that address the under-investment in "knowledge" (i.e. S3, S4 and S5), the recycling of carbon revenues for general R&D support (S4) is only marginally more cost-efficient in the short run, if it includes a targeted R&D support to green technologies in the first ten years (S5). The long-term growth prospects of a stand-alone targeted R&D support to green sector (S3) are limited because of the so-called bottleneck problem resulting in little green technology spill-over to the entire economy. Eventually with (S5), R&D subsidies support a gradual development of "green" technologies, which in turn helps to reduce the relative price advantage of dirty goods over clean goods in the long-run by subsidizing the initial costs of technological change.

The simulation results are broadly consistent with the literature (e.g. Newell, 2009) showing that carbon revenue recycling by labour taxes is less harmful for the economic activity than recycling through lump-sum taxes.[21] An important message of our analysis is that non-distortionary labour taxes should not be considered in isolation from R&D support because they do not address the underlying source of climate change mitigation costs, which is the lack of investment incentives for development and use of green technologies. The relative benefits in terms of the long-run GDP intensify from the policy scenario including only labour tax reduction (S1) to policy scenario including also different forms of R&D support. A "green policy" mix is growth-enhancing as it directly improves the incentives for private innovation in green technologies due to inter-temporal knowledge spillovers from current to future R&D (Golombek et al., 2010).

5.3 Transition to a low-emission economy

Scope for reallocation of resources

Our model mimics reality showing action against climate change comes at a cost on growth as long as there is limited possibility to substitute away from the dirty source of energy. Indeed, we see in the simulations how the environmental constraint burdens intermediate and final consumption. Any policy facilitating cheaper substitution can relieve the cost of climate change mitigation in the economy. And indeed we see also that policy mix fostering research activities require time to accumulate knowledge capital, but eventually release green technologies enabling to address climate change at lower costs.

Still, short-run costs of environmental action are unavoidable even under the most beneficial R&D scenarios. The reason is that these policies attract more researchers from high-skilled jobs from energy intensive manufacturing sectors into research activities, while the benefits of accumulated knowledge can only be appropriated at later points in time. Unless the pool of high-skilled workers is increasing over time, the traditional production parts of firms suffer from the loss of high-skilled workers, which firms substitute by less efficient low-skilled and medium-skilled workers.

Table 6 compares different policy scenarios with respect to the opportunities for job creation and relocation of human resources. The aggregate effect of labour tax scenario (S1) has the strongest impact on aggregate job creation (0.27% of baseline in 2020), while recycling through lump-sum tax has the opposite effect (-0.29% of baseline in 2020). Table 6 indicates that the aggregate employment effect decreases with the increased orientation of policy towards the R&D support. Hence, the general subsidy and front-loaded scenarios (S4 and S5) improve the aggregate employment by about 0.10% points less than the purely labour tax orientated scenario (S1).

The detailed results on the skill-based and sector-wide decomposition of labour effects reveal further insights into green policy-driven job relocation. Table 6 indicates that a reduction of non-wage labour costs has the strongest positive effect on employment of low-skilled labour (0.53%, S1); however, this result should be interpreted with caution as the employment rate on the baseline is highest for the high-skilled group and lowest for low-skilled. High-skilled labour gains relatively more in the front-loaded scenario (S5) compared to other skill groups across scenarios. While there is an 11% increase in employment of high-skilled (relative to the 0.53% increase of low-skilled) in labour tax scenario (S1), the gap between the gains in high-skill and low-skill groups narrows with additional R&D

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[21] In the next subsection, we trace back the relative benefit of labour tax reduction to its positive effect on employment as shown by Table 6.

support. Table 6 indicates that R&D support of clean technologies stimulates demand for high-skilled labour resulting in a relatively higher real wage premium for the high-skilled group compared to the low-skilled group. This attracts proportionally more high-skilled than low-skilled workers from energy-intensive and fossil-fuel sectors to low-carbon sectors.

Table 6. Potential employment effects and allocation of ressources in the EU-27 in 2020

	Lump-sum tax	Labour tax	Renewable s. sales subsidy	Green R&D subsidy scenario	General R&D subsidy	Front-loaded green R&D subsidy
	(S0)	(S1)	(S2)	(S3)	(S4)	(S5)
EMPLOYMENT						
All sectors	-0.29	0.27	0.23	0.21	0.17	0.18
Low-skill employment	-0.57	0.53	0.47	0.42	0.37	0.37
Medium-skill employment	-0.21	0.19	0.16	0.14	0.11	0.11
High-skill employment	-0.11	0.11	0.10	0.10	0.08	0.08
EII employment	-1.01	-0.55	-0.54	-0.65	-0.69	-0.67
OTHERS employment	-0.57	-0.02	-0.01	-0.14	-0.18	-0.17
REN employment	7.04	7.72	6.83	7.78	7.74	7.79
FOEN employment	-7.07	-6.76	-6.84	-6.93	-7.03	-7.04
NUCL employment	7.89	8.64	7.97	8.28	8.71	8.60
High-skill gross real wage	-0.44	-0.53	-0.54	0.01	0.01	0.01
Medium-skill gross real w.	-0.55	-0.69	-0.68	-0.48	-0.43	-0.41
Low-skill gross real wage	-0.37	-0.86	-0.84	-0.62	-0.57	-0.55
KNOWLEDGE INPUT						
EII	-0.03	-0.06	-0.07	0.07	0.12	0.13
OTHERS	0.16	0.14	0.12	0.33	0.39	0.40
REN	0.44	0.44	0.39	1.88	0.53	1.04
FOEN	-1.70	-1.75	-1.74	-1.62	-1.62	-1.60
NUCL	0.61	0.61	0.56	0.68	0.73	0.73
INTERMEDIATES INPUT						
EII	-2.59	-2.30	-2.22	-2.18	-2.13	-2.10
OTHERS	-0.98	-0.58	-0.54	-0.44	-0.44	-0.42
REN	8.38	9.03	8.02	10.25	9.29	9.72
FOEN	-17.60	-17.61	-17.56	-17.60	-17.62	-17.61
NUCL	9.13	9.81	9.10	9.62	10.14	10.04

Note: The values refer to % deviations in 2020 relative to baseline.
Source: QUEST simulation results.

Since the R&D support of clean technologies creates opportunities for economic growth (see Table 5), the relative wage decline is less harsh for low-skill labour in S5 than S1 despite severe downsizing in energy-intensive manufacturing and fossil-fuel energy sectors. Comparing the labour tax scenario (S1) with the front-loaded scenario (S5), the relatively higher employment gains of 0.10% points in S1 cannot outweigh the larger decline in real wage (-0.86% in S1 relative to -0.55% in S5) in the low-skilled labour group. There is a clear ranking of scenarios from S1 to S5 in terms of improvements in real-wage depreciation at considerable positive employment effects. Looking at the sector-wide disaggregation of employment and knowledge capital impacts, it comes clear that in presence of recycling through labour taxes and R&D subsidies, the capital and material production factors become relatively more expensive, and a downsizing of energy intensive and fossil-fuel intensive sectors occurs, activities in low-emission sectors is boosted, and the situation remains rather stable in other sector categories.

Our results suggests that green policy mixes may induce substitution from material towards labour and knowledge production inputs and a restructuring of the industrial base away from energy-intensive manufacturing and fossil-fuel sectors, and towards high-skilled and knowledge-intensive sectors.

Transformation of sector-wide output orientation

Advancing towards environmental objectives entails substantial transformation of industrial structure of the economy. Our results show that emission caps lead to substantial re-orientation of production towards cleaner technology options away from energy-intensive and fossil-fuel sectors. As indicated in Table 7, the output shifts are foremost driven by climate change policy and to a lesser degree by explicit recycling rules involving the R&D support. This implication is suggested by low variation in output impacts found in non-ETS sectors grouped under the category "Others" (the last column, Table 7). The value-added of fossil-fuel energy sector is down by about -12.66% on average over the different scenarios in 2020 relative to the baseline. There is little deviation from these figures across scenarios with only marginally lower values in the front-loaded scenario (i.e. -12.77 in 2020, S5).

Table 7. Potential sector-wide value-added effects in the EU-27

Variable: Value-added	Energy-intensive industries			Fossil-fuel energy sector			Renewable energy sector			Nuclear energy sector			Others		
	2010	2020	2030	2010	2020	2030	2010	2020	2030	2010	2020	2030	2010	2020	2030
Lump-sum [S0]	-0.24	-1.17	-2.61	-1.30	-12.70	-24.02	0.22	8.77	17.94	0.24	9.54	20.17	-0.09	-0.46	-0.98
Labour-tax [S1]	-0.27	-0.78	-1.83	-1.39	-12.50	-23.73	0.18	9.51	19.56	0.22	10.29	21.88	-0.07	-0.05	-0.19
Renewable s. sales subsidy [S2]	-0.23	-0.77	-1.81	-1.18	-12.62	-23.88	0.32	8.42	17.46	0.31	9.49	20.24	-0.06	-0.06	-0.20
Green R&D subsidy [S3]	-0.29	-0.71	-1.48	-1.47	-12.59	-23.82	0.15	11.38	26.26	0.18	9.99	21.04	-0.08	0.07	0.28
Not-targeted R&D subsidy to all [S4]	-0.34	-0.71	-1.28	-1.70	-12.77	-23.86	0.12	9.66	20.48	0.16	10.53	23.12	-0.09	0.07	0.53
Front-loaded green R&D subsidy [S5]	-0.34	-0.69	-1.28	-1.68	-12.77	-23.86	0.10	10.35	20.96	0.15	10.41	22.96	-0.09	0.09	0.52

Note: The values refer to % deviations in 2020 relative to baseline.
Source: QUEST simulation results.

To a certain degree, policy scenarios help to mitigate the variable cost associated with the carbon cap. The magnitude of the impact depends on their capacity to stimulate higher growth in green sectors and facilitate substitution away from dirty energy carriers. Table 7 shows that green-targeted R&D particularly stimulates the output in the renewable sector (comparing S3 to other scenarios), while the nuclear sector gains more from widely spread R&D support (comparing S5 to other scenarios). This suggests a bottleneck effect that prevents other sectors from benefitting from green-targeted R&D support, unless it is eventually applied to the rest of economy. The growth of green output somewhat compensates for the loss of dirty output, whereas restricting R&D subsidies to the renewable sector is inferior to non-targeted R&D subsidy scenario.

Consumption and investment effects

Table 8 presents the consumption and investment effects of different policy scenarios. The front-loaded scenario (S5) has the largest positive effect on households' consumption which is mainly driven by the higher consumption of non-liquidity constrained households due to the increase in their permanent income. Note that non-liquidity constrained households include the scarce supply of high-skilled workers who benefit the most from R&D promoting policies because these policies put upward pressure on their wages and increase their disposable income. Looking at the sector-wide pattern of intermediate consumption, there is an expected shift towards cleaner products supplied by green sectors at a loss of carbon-intensive sectors.

Referring to investment figures, the sector-wide results indicate a substantial disinvestment in the fossil-fuel energy sector and to a lesser extent in the energy-intensive sector on account of increased investments in low-carbon sectors. The overall decline in total investment is driven by the disinvestment in the "Others" non-ETS sector which also have to bear the burden of climate change mitigation via the carbon price pass-through from the ETS-sectors, especially from the dirty energy sector whose products are hard to substitute at the beginning of the time-profile.

The investment effects reported in Table 8 are also consistent with the intuition that carbon recycling to lower labour tax induces some reallocation of resources from material, energy and capital to labour and knowledge production factor. Government consumption and investment are linked to nominal GDP and thus remain neutral in the scenarios (see the detailed tables of results in the Appendix).

Table 8. Consumption and investment effects in the EU-27 in 2020

	Lump-sum tax	Labour tax	Renewable sector sales subsidy	Green R&D subsidy scenario	General R&D subsidy	Front-loaded green R&D subsidy
	(S0)	(S1)	(S2)	(S3)	(S4)	(S5)
CONSUMPTION						
Household consumption	-0.54	-0.01	0.06	0.20	0.32	0.33
Liquidity-cstr. households	-0.41	-0.22	-0.29	-0.03	-0.11	-0.08
Non-liquidity-cstr. households	-0.58	0.05	0.16	0.27	0.45	0.45
Intermediate consumption						
EII	1.14	1.62	1.72	1.90	2.10	2.08
Other	-0.02	0.42	0.56	0.69	0.95	0.93
REN	11.33	11.98	11.33	12.53	12.89	12.92
FOEN	3.93	4.53	4.05	4.57	4.88	4.77
NUCL	10.85	11.61	10.97	11.70	12.54	12.39
DISCOUNTED TOTAL UTILITY						
Wealth	-0.93	-0.44	-0.39	-0.06	0.24	0.22
INVESTMENT						
Total investment	-1.18	-0.99	-0.96	-0.96	-1.14	-1.09
EII	-1.56	-1.58	-1.54	-1.57	-1.75	-1.71
Other	-1.35	-1.13	-1.07	-1.09	-1.29	-1.24
REN	11.99	12.46	11.02	12.98	12.77	12.87
FOEN	-24.69	-25.31	-25.52	-25.92	-26.61	-26.50
NUCL	14.36	14.96	13.81	14.42	15.38	15.29

Note: The values refer to % deviations in 2020 relative to baseline.

Source: QUEST simulation results.

Implications for international trade

The model-based analysis assumes no carbon caps in the rest of the world. Under our assumption that only the EU has a cap on emissions, we find there is a potential for the EU to reap gains from its unilateral environmental policy through trade. A possible reason for countries without emission targets to demand green products of the EU could be that they could use the knowledge embodied for development of technologies in other sectors of economy. However, to analyse potential displacement of carbon-intensive industries to countries with lenient climate change policies, a better representation of the rest of the world situation than what we implemented so far is essential. Therefore, the results in Table 9 should be interpreted with caution and bearing in mind they relate to a simplistic representation of emissions patterns and green policies in the rest of the world.

Table 9 indicates a negative trade balance particularly in scenarios with some form of R&D support due to the terms of trade effect. Notably, as EU27 emissions are capped and other regions' emission constraints are not, some additional trade in carbon-intensive goods is taking place: there is an increase in imports of relatively cheaper output from the fossil-fuel sector (FOEN) on account of falling domestic output. By contrast, the EU27 advance its relative competitive position in green sectors, increasing its exports of goods produced by renewable, nuclear and even energy-intensive sectors. The reason for the latter could be that R&D support in the last two scenarios (S4 and S5) particularly stimulates dynamic productivity of firms by more than the labour-tax stimulus of scenarios S1. Note still that the relatively strong response of clean energy imports could also be due to their small initial share within the total imports on the baseline.

Table 9. Trade balance effects of the EU-27 in 2020

	Sector trade share (%)	Lump-sum tax (S0)	Labour tax (S1)	Renewable sector sales subsidy (S2)	Green R&D subsidy scenario (S3)	General R&D subsidy (S4)	Front-loaded green R&D subsidy (S5)
Trade balance (% GDP)	100%	0.02	-0.02	-0.03	-0.06	-0.10	-0.09
EXTRA-EU27 EXPORTS							
EII	22.7%	-2.50	-2.44	-2.44	-2.51	-2.61	-2.58
Other	75.2%	-0.77	-0.66	-0.74	-0.73	-0.91	-0.89
REN	0.1%	1.12	1.30	1.20	2.47	1.12	1.62
FOEN	1.8%	-15.85	-15.99	-15.72	-16.01	-16.33	-16.27
NUCL	0.2%	1.81	1.95	1.84	1.76	1.83	1.84
EXTRA-EU27 IMPORTS							
EII	15.8%	0.28	0.61	0.68	0.82	0.92	0.92
Other	70.9%	-0.38	-0.06	0.05	0.14	0.28	0.28
REN	0.0%	7.75	8.15	6.74	8.29	8.74	8.69
FOEN	13.2%	-7.64	-7.45	-7.68	-7.46	-7.37	-7.41
NUCL	0.1%	8.96	9.57	8.92	9.59	10.34	10.21

Note: The values refer to % deviations in 2020 relative to baseline. The percentage sector share in economy is calculated by using the percentage share of sector-specific output traded with the rest of the world in 2004.

Source: QUEST simulation results.

5.4 Economic effects of an "intelligent" policy-mix

Restricting R&D subsidies only to the green sector is inferior to our non-targeted R&D subsidy scenario. In sum, the following explanations intuitively support the results. First, there is potential crowding out effect of green R&D subsidies due to scarce supply of skilled labour. Higher levels of R&D support could lead to costly adjustments because skills to use green technologies are relatively scarce. For instance, heavily subsidising the diffusion of recent outputs of green innovation would require opening the scope of support to green technologies upgrading the built infrastructure. Such pressure could push up the wages of workers if the labour market was not ready to provide more green skills across the economy and in all segments of the workforce.

Second, one should take into account the lost positive spillover effects in the absence of co-ordinated R&D support across all sectors. Although green R&D is crucial to induce technological change, the pace of replacing carbon-intensive with green product depends on the positive spillover effects from R&D investments in other sectors of the economy. For example, it is well known that advances in solar panel development depend on innovations in the semi-conductor industry.

Third, the knowledge production takes a semi-endogenous form in the model. This means that its concavity implies decreasing returns on R&D investments. Hence, the investments targeted exclusively in green R&D limit the overall growth potential as more and more resources are directed to this particular R&D activity. This slows down the growth of knowledge stock over time.

Finally, referring to the multisectoral growth model with intermediate inputs by Jones (2008), there is a certain weak-link effect involved in targeting only one industry. In terms of our multisectoral endogenous technological change model, subsidizing only one industry can leave others weaker, which ultimately hinders overall economic growth. Other industries cannot grow as fast as the green sector and its products cannot substitute for products of all other sectors because these are interlinked in the production function via complementarities with the energy intensive and the non-energy intensive sectors. As Jones (2008) argues, each chain of economic process is as strong as the weakest part of it, if all parts complement each other. Therefore we see that the relatively smaller growth of other industries holds back the overall growth of the economy.

6 SENSITIVITY OF RESULTS

6.1 Elasticity of substitution between green and dirty inputs

We perform several robustness checks with respect to the substitution elasticities under the same environmental target. Our sensitivity analysis confirms and extends the Goulder (1995) and Bovenberg (1999) findings that carbon-tax revenue recycling through cuts in distortionary taxes and increasing R&D subsidies results in at least weak double dividends (i.e. cost savings relative to the case where revenues are returned in the lump-sum fashion).

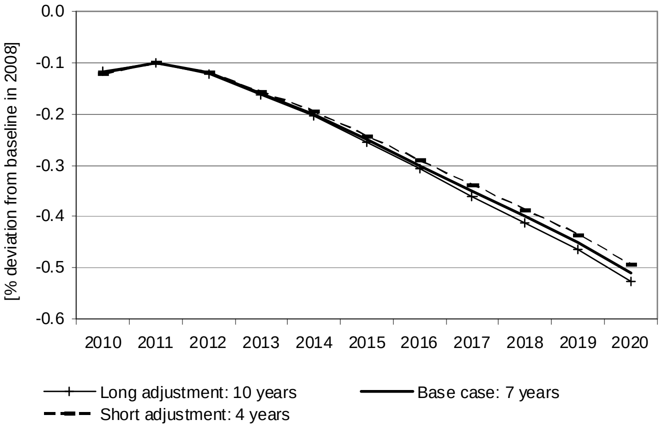
Theoretical analyses and numerical evidence are mixed on the strong double dividend case, which states that the revenue-neutral change of environmental taxes to cut distortive taxes should result in zero or negative gross costs. We also find that the evidence for strong double dividend is mixed in the case of recycling through labour tax cuts. Nevertheless, most importantly the ranking of our recycling instruments remains robust to the substitution elasticities. Intuitively, we found that with high substitution elasticities between dirty and green products, all scenarios can result in strong double dividend even in the short-run but with small substitution elasticities, more and more of the recycling instruments give only weak double dividend in the short and in the long-run.

6.2 Calibration of adjustment costs

As explained in Section 2, the components within the energy composite enter into the production function in an imperfect substitutability fashion. Thus, the elasticity of substitution between energy and other inputs in production and goods is an important parameter for our analysis of environmental policies which basically introduce an energy price shocks. In line with other empirical studies we assume the same elasticities for households and firms of 0.5 in the long run. As motivated by Bodenstein et al. (2007) we assume that adjustment costs imply a half-life of the response of fossil fuel demand to a permanent increase in their prices of 7 years. The value of this parameter implies that the elasticity of substitution is smaller in the short run since the adjustment costs are specified in terms of energy intensity shares and are assumed to have the quadratic form for each energy source. A detailed analysis of the role of adjustment costs lies out of this paper's scope. This sensitivity check solely aims at throwing some light on this issue by considering different values of adjustment costs in the case of lump-sum scenario.

Figure 6 illustrates the potential impact of different adjustment costs for the case of our lump-sum tax scenario (S0), which should not be generalized to other scenarios and interpreted with caution. The orders of magnitude are influenced by the fact that our analysis does not consider a large sudden change of policy but rather assumes a linear climate policy shock of 1.74% emission reduction occurring gradually over a long time horizon. Figure 6 presents deviations when taking alternative assumptions. We observe a low degree of sensitivity of GDP effects with respect to adjustment costs, but we reckon that it is difficult to draw conclusions as alternative values of the parameters may not necessarily reflect the real economy patterns. At the same time, these simulations are in line with intuition as they suggest that lower adjustment costs are associated with more favourable effects on economic activity. We can also conclude that smaller adjustment costs increase the speed at which certain recycling policies reach strong double dividend due to the easier short-run substitution between dirty and green energy.

Figure 6. Sensitivity to adjustment costs:
The lump-sum tax scenario (S0)



Source: QUEST simulation results.

6.3 The scale of R&D support

Another set of sensitivity analysis was carried out to explore the plausible adequate upper bound for R&D subsidies. The currently applied 10%/90% division reported in Table 4 is a result of these experiments. In order to reach ambitious emission targets, strong price-signals are needed to be introduced, which translates into large carbon revenues compared to the current size of green R&D investments. In the absence of more capacity to absorb larger subsidies, a further increase of R&D support exerts an upward pressure on the wage of high-skilled workers in production and research in all sectors. Goolsbee (1998) and Wolff and Reinthaler (2008) argue that in the case of government funded R&D, a significant fraction of the increased spending goes directly to higher wages because the labour supply of high skilled workers is rather inelastic. This effect is captured in our model in a multisectoral environment. In particular, we observe that due to the "weak-link" effect, productivity in other sectors cannot increase so much, because other sectors cannot afford such high wages to their own high-skilled workers. Since these sectors cannot perfectly substitute away from high-skilled whom they need for production and research, the development of these sectors suffers even more. This suggest that to consider scaling up support to R&D, there is a need to consistently increase the high-skilled labour supply of the economy, e.g. by increasing higher education expenditures already in the very short-run because it takes time until the new high-skilled cohorts become operational and decrease the upward pressure on wages.

7 CONCLUSION

In this paper we investigate what could be the appropriate policy-mix of environmental and innovation market instruments in terms of their cost-effectiveness. For this purpose, we develop a fully-dynamic, multisectoral DSGE model with endogenous technological change by including the environmental content and we calibrate it for the EU and the rest of the world in a two region setting.

The key finding is that an appropriate policy mix could be to intensively stimulate R&D in the green sectors in the short run and phase it out by spreading R&D support to all sectors of the economy in the medium term. Among different policy scenarios considered in this paper, the latter option appears to be the most efficient in terms of economic costs. To demonstrate the importance of the choice of recycling rules that could be considered by policy-makers, we provide a clear ranking of different recycling options in view of their potential for future economic development. The results are presented in relative terms to facilitate the comparisons among scenarios and should be interpreted with caution by taking into account the underlying assumptions and identification of green innovation.[22]

The advantage of our analysis is that the composition of recycling measures in the policy mix can be traced back to two main sources: (i) whether they address the double market failure of climate change or solely the environmental externality, and (ii) whether they account for the sectoral linkages of the economy or the economy as a whole.

Overall, the simulations show that fighting climate change is not costless but clever recycling policies which take into account the double market failure property of climate change and account for sectoral spill-overs can reduce the costs of climate change mitigation. In the context of our multi-sectoral model the cap on carbon emissions creates a burden for growth due to higher costs of intermediate and final consumption as long as there is limited possibility to substitute away from dirty sources of energy. By the same token, any policy which tackles this problem and encourages faster and cheaper substitution can relieve the cost of climate change mitigation on the economy.

Recognising that fighting climate change is not costless, clever recycling policies which take into account the double market failure property of climate change and account for sectoral spill-overs can alleviate substantially these costs. The first key message to take from the model-based analysis is that the most cost-efficient policy mix comes from a well-designed recycling of carbon market revenues: to reap benefits for growth, the policy mix could enhance fiscal consolidation through recycling carbon revenues to labour market support, and it should also stimulate green-targeted R&D along the supply chain in the short-run, then spread its support to R&D in all sectors of the economy. Such an intelligent policy mix combining environmental and innovation polices would effectively address the double market failure behind the climate change problem.

The second key message of this model-based analysis encourages recycling carbon revenues in a timely manner. To cope with the necessary costs of climate action, GHG emissions externalities should be internalized gradually. But it won't be possible to tighten the environmental constraint without impinging significantly on growth, if green technologies are not available. As research activities need sufficient time to accumulate knowledge capital and deliver green technologies, in the short term, new sources of fiscal revenues could be directed to support green innovation.

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[22] As explained in the paper, the dataset has been carefully constructed to identify systematically the share of green R&D in country's total R&D. The appropriation of cross-sectoral participation of firms in green R&D activities is not straightforward and by construction of our dataset we assume an upper bound estimate of private green R&D funds.

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9 ANNEX A: MAIN ENVIRONMENTAL ELEMENTS OF THE MODEL

This appendix provides an algebraic summary of the model. In the following description we omit the country indices and present the elements of the model relevant for description of the environmental policy.

9.1 Firms

Sectors of the economy sectors are indexed by $n \in \{I,S,G,N,D\}$. The total production of each firm, $Y_{n,t}(i)$ is a CES of its value-added, $VA_n(i)$ and the aggregate inputs from intermediate goods, $M_n(i)$ according to

$$Y_{n,t}(i) = F_n\left(VA_{n,t}, M_{n,t}(i)\right) =$$

$$= A_n \cdot \left(sva_n^{\frac{1}{\sigma_{vam,n}}} \cdot VA_{n,t}^{\frac{\sigma_{vam,n}-1}{\sigma_{vam,n}}} + sm_n^{\frac{1}{\sigma_{vam,n}}} \cdot M_{n,t}^{\frac{\sigma_{vam,n}-1}{\sigma_{vam,n}}} \right)^{\frac{\sigma_{vam,nn}}{\sigma_{vam,n}-1}},$$

where $\sigma_{vam,n}$ is the sectoral elasticity of substitution between the value added and the intermediates, and sva_n and sm_n are the corresponding weights.

Value added is in given by a Cobb-Douglas production function of capital, ($K_n(i)$) with a degree of capacity utilization, labour input ($L_n(i)$) and the endogenous technological progress term, A_n^{va} which we interpret as the stock of knowledge in the production process.

$$VA_{n,t}(i) = f_n\left(A_n^{va}(i), K_{n,t}(i), U_{n,t}(i), L_{n,t}(i)\right) =$$

$$= \left(K_{n,t}(i) \cdot U_{n,t}(i)\right)^{1-\alpha_n} \cdot \left(A_{n,t}^{va}(i) \cdot \left(L_{n,t}(i) - FC_{L,n}\right)\right)^{\alpha_n} - FC_{Y,n}$$

The production of final goods is subject to overhead labour and additional fixed costs ($FC_{L,n}$, $FC_{Y,n}$). In each sector firms face monopolistic competition with aggregate demand of

$$Y_{n,t} = \left[\int_0^1 Y_{n,t}(i)^{\frac{1}{1+\tau_n}} di\right]^{1+\tau_n},$$

where $1 + \frac{1}{\tau_n}$ is the elasticity of substitution.

Firms rent capital services at rate $i_{n,t}^K$, production and research labour services (L and RL). Firms employing RL_t research labour in period t accumulate their stock of knowledge (or productivity index) A_n^{va} according to a knowledge production function $A_{n,t+1}^{va}(i) = RD(RL_t(i), A_{n,t}^{va}(i)) + A_{n,t}^{va}(i)$ for the next period. In the current exercise, we will use the Jones-type semi-endogenous knowledge production function (Jones, 2005). The functional form of $RD(RL_t, A_{n,t}^{va}(i))$ will be $A_{n,t+1}^{va}(i) = \nu RL_t(i)^{\lambda} A_{n,t}^{va}(i)^{\phi} + A_{n,t}^{va}(i)$.

9.2 Firms not directly covered by emission trading

The profit maximization problem yields the following Lagrange function for the non-energy intensive and "green" firms which are not subject to any emission constraints, $n \in \{S, G, N\}$:

$$\max_{\substack{Y_{n,t}(i), A^{va}_{n,t}(i), K_{n,t}(i) \\ U_{n,t}(i), L^{S}_{n,t}(i), M_{n,t}(i)}} L = E_0 \sum_{t=0}^{\infty} d_t \frac{1}{PY_{n,t}} \left(\begin{array}{c} PY_{n,t}(i) \\ - \left(\begin{array}{c} i^K_{n,t} P^I_{n,t} \cdot K_{n,t}(i) + \sum_S w_t \cdot L^S_{n,t}(i) + w_t \cdot RL_{n,t}(i) \\ + PM_{n,t} \cdot M_{n,t}(i) \\ + \Gamma_{P,t} + \Gamma_{L,t} + \Gamma_{RL,t} + \Gamma_{U,t} \end{array} \right) \end{array} \right)$$
$$- \sum_{t=0}^{\infty} d_t \eta_{n,t} \left(Y_{n,t}(i) - F_n \left(f_n \left(A^{va}_{n,t}(i), U_{n,t}, K_{n,t}(i), L^H_{n,t}(i), L^M_{n,t}(i), L^L_{n,t}(i) \right), M_{n,t}(i) \right) \right)$$
$$- \sum_{t=0}^{\infty} d_t \psi_{n,t} \left(\left(A^i_{n,t} - J^{Ai}_{n,t} \left(RL^i_{n,t}, A^i_{n,t-1} \right) - (1 - \delta^A_n) A^i_{n,t-1} \right) \right)$$

with adjustment costs of $\Gamma_{P,t}, \Gamma_{L,t}, \Gamma_{RL,t}, \Gamma_{U,t}$ on prices ($PY_{n,t}(i)$), production and research labour ($L_{n,t}(i), RL_{n,t}(i)$) and capacity utilization:

$$\Gamma_{P,t} = \frac{\gamma_P}{2} \frac{\Delta PY_{n,t}(i)^2}{PY_{n,t-1}(i)} Y_{n,t}(i)$$
$$\Gamma_{L,t} = \frac{\gamma_L}{2} w_t \Delta L_{n,t}(i)^2$$
$$\Gamma_{RL,t} = \frac{\gamma_{RL}}{2} w_t \Delta RL_{n,t}(i)^2$$
$$\Gamma_{U,t} = P^I_{n,t} K_{n,t}(i) \left(\gamma_{U1} (U_{n,t} - 1) + \frac{\gamma_{U2}}{2} (U_{n,t} - 1)^2 \right)$$

where d_t is the discount term. Labour input in the production process is a composite of three different types, high-, medium- and low-skilled:

$$L_{n,t} = \left(s_{n,L}^{\frac{1}{\sigma_L}} \left(ef_{n,L} L^L_{n,t} \right)^{\frac{\sigma_L - 1}{\sigma_L}} + s_{n,M}^{\frac{1}{\sigma_L}} \left(ef_{n,M} L^M_{n,t} \right)^{\frac{\sigma_L - 1}{\sigma_L}} + s_{n,H,Y}^{\frac{1}{\sigma_L}} \left(ef_{n,H} L^{HY}_{n,t} \right)^{\frac{\sigma_L - 1}{\sigma_L}} \right)^{\frac{\sigma_L}{\sigma_L - 1}}.$$

Parameter $s_{n,s}$ is the share of labour-force in subgroup s (low-, medium- and high-skilled), L^s_n denotes the employment rate of skill-type s, $ef_{n,s}$ is the corresponding efficiency unit, and σ_L is the elasticity of substitution between different labour types. Note that high-skilled labour, can be employed in production or in research activities but low- and medium-skilled can work only in the traditional production process[1].

9.3 Firms subject to emission trading

Energy intensive and polluting energy provider firms face restrictions from emission trading. Firms in the energy intensive sector receive $\omega_{n,t}(i)$ free emission allowances from the government but they are required to hold emission certificates based on the emission content of their (dirty) energy consumption. The emission content of their production process is calculated as the CO_2 equivalent

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[1] We define high skilled workers as that segment of the labour force that can potentially be employed in the R&D sector, i. e. engineers and natural scientists and we take the high-skilled wages in the education sector as proxy for the wage level of the R&D labour. Low-skilled are those whose highest-level of education corresponds to the ISCED 0-2 categories and the remaining share of working age population is classified as medium-skilled.

ratio, - denoted by co_n of their total dirty input use: $M_{D,n,t}(i)$ [2]. Firms can trade or save their emission allowances following the banking model of emission trading by Cronshaw and Kruse (1996). Let $CS_{n,t}(i)$ be the stock of emission allowances held by the firm at the beginning of period t, $\omega_{n,t}(i)$ be the free allowances received, and $s_{n,t}(i)$ be the additional purchase or sale of emission allowances (positive or negative respectively). Then the stock of emission allowances evolves over time according to

$$CS_{n,t}(i) = CS_{n,t-1}(i) + \omega_{n,t}(i) + s_{n,t}(i) - co_n \cdot M_{D,n,t}(i)$$

which modifies the relevant profit-maximization for these firms as ($n = \{I\}$)

$$\max_{\substack{Y_{n,t}(i), A^{va}_{n,t}(i), K_{n,t}(i) \\ U_{n,t}(i), L_{n,t}(i), M_{n,t}(i) \\ s_{n,t}(i), CS_{n,t}(i)}} \quad L = E_0 \sum_{t=0}^{\infty} d_t \frac{1}{PY_{n,t}} \begin{pmatrix} PY_{n,t}(i) Y_{n,t}(i) \\ - \begin{pmatrix} i^K_{n,t} P^I_{n,t} \cdot K_{n,t}(i) + w_t \cdot L_{n,t}(i) \\ + PM_{n,t} \cdot M_{n,t}(i) + i^A_{n,t} P^A_{n,t} \cdot A_{n,t}(i) \\ + \Gamma_{P,t} + \Gamma_{L,t} + \Gamma_{U,t} \end{pmatrix} \\ - ps_t s_{n,t}(i) \end{pmatrix}$$

$$-E_0 \sum_{t=0}^{\infty} d_t \eta_{n,t} \left(Y_{n,t}(i) - F_n \left(f_n \left(A^{va}_{n,t}(i), U_{n,t}, K_{n,t}(i), L_{n,t}(i) \right), M_{n,t}(i) \right) \right)$$

$$-E_0 \sum_{t=0}^{\infty} d_t \rho_{n,t} \left(CS_{n,t}(i) - CS_{n,t-1}(i) - \omega_{n,t}(i) - s_{n,t}(i) + co_n \cdot M_{D,n,t}(i) \right)$$

Note that intermediate input use (M_n) is a nested composite of energy and non-energy inputs $M_n = \left(sm_{NEN,n}^{\frac{1}{sigm_n}} \left(M_{NEN,n,t} \right)^{\frac{sigm_{,n}-1}{sigm_{,n}}} + sm_{EN,n}^{\frac{1}{sigm_{,n}}} \left(M_{EN,n,t} \right)^{\frac{sigm_{,n}-1}{sigm_{,n}}} \right)^{\frac{sigm_{,n}}{sigm_{,n}-1}}$. Adjustment costs are specified in terms of energy intensity shares and are assumed to have the quadratic form for each energy source, eg. for dirty energy-use: $\Gamma_{D,m,t} = \frac{\gamma_D}{2} \left(\frac{M_{D,m,t} / M_{EN,m,t}}{M_{D,m,t-1} / M_{EN,m,t-1}} - 1 \right)^2$ and the corresponding energy composite (M_{EN}) for sector *m* is: $M_{EN,m,t} = (\sum_{e \in \{D,G,N\}} smen_e^{\frac{1}{sigm_{EN,m}}} M_{e,m,t} (1 - \Gamma_{e,m})^{\frac{sigm_{EN,m}-1}{sigm_{EN,m}}})^{\frac{sigm_{EN,m}}{sigm_{EN,m}-1}}$.

The demand for dirty energy input in terms of intermediate consumption can be expressed as[3]:

$$M_{EN,n,t} = sm_{EN,n} \left(\frac{PM_n}{P^M_{ENn,t}} \right)^{sigm_n} M_n, M_{D,n,t} = smen_{D,n} \left(\frac{P^M_{ENn,t}}{P_{D,n,t}} \right)^{sigm_{EN,n}}$$

and

$$M_{EN,n,t} \rightarrow M_{D,n,t} = smen_{D,n} \left(\frac{P^M_{ENn,t}}{P_{D,n,t}} \right)^{sigm_{EN,m}} sm_{EN,n} \left(\frac{PM_n}{P^M_{ENn,t}} \right)^{sigm_n} M_n$$

$$\frac{\partial M_{D,n,t}}{\partial M_{n,t}} = smen_{D,n} \left(\frac{P^M_{ENn,t}}{P_{D,n,t}} \right)^{sigm_{EN,n}} sm_{EN,n} \left(\frac{PM_n}{P^M_{ENn,t}} \right)^{sigm_n}$$

Therefore in the optimal use of intermediate inputs firms take into account the marginal costs plus the proportionate costs of emission allowances from using intermediate inputs.

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[2] Note, that we do not model any technological advances in the CO_2 emission equivalent ratio.

[3] Without the adjustment costs to simplify the algebra.

9.4 Dirty energy sector: Firms subject to emission trading and exhaustible resource

The polluting firms of sector D face two additional constraints compared to non-energy intensive sectors. First, they exploit an exhaustible resource; second they must also hold one emission permit for each unit of emission. Unused emission allowances may be banked but dirty energy sector does not have free allocated emission allowances $\omega_{n,t}(i)$ in contrast with the energy-intensive sector. For simplicity, we assume that one unit of the exhaustible resource is transformed into one unit of "dirty" energy output, therefore in each period a $Y_{D,t}(i)$ quantity of the exhaustible resource is extracted by firm i which will be the input for the energy composites[4]. We assume that exhaustible resource has a currently known size $S_{t-1}(i)$ for each firm and there is an exogenous detection rate g. Therefore the stock of exhaustible resource evolves according to

$$S_t(i) = (1+g)S_{t-1}(i) - Y_{D,t}(i).$$

In this case the maximum profit condition changes as follows ($n = \{D\}$):

$$\max_{\substack{Y_{n,t}(i), A^{va}_{n,t}(i), K_{n,t}(i) \\ U_{n,t}(i), L_{n,t}(i), M_{n,t}(i) \\ s_{n,t}(i), CS_{n,t}(i) \\ S_t(i)}} L = E_0 \sum_{t=0}^{\infty} d_t \frac{1}{PY_{n,t}} \begin{pmatrix} PY_{n,t}(i) Y_{n,t}(i) \\ -\begin{pmatrix} i^K_{n,t} P^I_{n,t} \cdot K_{n,t}(i) + w_t \cdot L_{n,t}(i) \\ + PM_{n,t} \cdot M_{n,t}(i) + i^A_{n,t} P^A_{n,t} \cdot A_{n,t}(i) \\ + \Gamma_{P,t} + \Gamma_{L,t} + \Gamma_{U,t} \end{pmatrix} \\ - ps_t s_{n,t}(i) \end{pmatrix}$$

$$-E_0 \sum_{t=0}^{\infty} d_t \eta_{n,t} \left(Y_{n,t}(i) - F_n\left(f_n\left(A^{va}_{n,t}(i), U_{n,t,} K_{n,t}(i), L_{n,t}(i) \right), M_{n,t}(i) \right) \right)$$

$$-E_0 \sum_{t=0}^{\infty} d_t \rho_{n,t} \left(CS_{n,t}(i) - CS_{n,t-1}(i) - s_{n,t}(i) + co \cdot M_{D,n,t}(i) \right)$$

$$-E_0 \sum_{t=0}^{\infty} d_t \varphi_t \left(S_t(i) - (1+g)S_{t-1}(i) + Y_{D,t}(i) \right)$$

9.5 Environmental regulations, environmental quality and human wealth

The government each year allocates Ω_t emission allowances, part of them $\omega_{I,t}$ is free and the rest is auctioned. Therefore the total sale/purchase of emission certificates should satisfy: $s_{I,t} + s_{D,t} = \Omega_t - \omega_{I,t} - \Delta CS_{I,t} - \Delta CS_{D,t}$ condition, i.e. the sum of net purchases equals to the sum of government auctioned allowances and the decrease of accumulated emission permit stocks.

In order to trace the environmental impact of the economic development and the economic impact of environmental change, we follow the approach by Acemoglu et al. (2009) (AABH) and construct an environmental quality variable env_t as a decreasing function of temperature increase compared to preindustrial times:

$$env_t = 280 \cdot 2^{\Delta_{\max}/3} - \max\{C_{CO_2}, 280\}$$

where C_{CO_2} is the atmospheric concentration of CO_2 in ppm, $\Delta_{\max}$ is the "disaster temperature". The current atmospheric concentration of CO_2 is set to 379 ppm, the preindustrial atmospheric

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[4] Formally the production function for the dirty sector can be written as: $Y_D = \min\{a \cdot F_D(VA_D, M_D), b \cdot R_D\}$ where R_D is the quantity of extracted exhaustible resource and $a = b = 1$. $F_D(VA_D, M_D)$ captures the production process necessary for extraction and transformation of the exhaustible resource into "dirty" energy.

concentration is 280 ppm, while the "disaster temperature" is chosen as $\Delta_{\max} = 9.2$ in AABH. We also use the common approximation of the relationship between temperature increase since preindustrial times (Δ) and the atmospheric concentration of carbon dioxide:

$$\Delta \approx 3\log_2(C_{CO_2} / 280)$$

Environmental quality evolves according to the following difference equation:

$$env_{t+1} = -\xi(C^E_{CO_2} + C^R_{CO_2}) + (1+\varepsilon)env_t$$

where ξ measures the rate of environmental degradation resulting from the global use of dirty inputs which increases the emissions of carbon-dioxide by $C^E_{CO_2}$ and $C^R_{CO_2}$ respectively for the EU and the Rest of the World, and ε is the rate of environmental regeneration. Note that the regional emission contribution in terms of atmospheric CO_2 concentration is

$$\sum_m co_m X_{D,m,t} / 2.13$$

for all use of dirty inputs, i.e. in intermediate and final use: $X \in \{C, I, IG, M_n\}, n \in \{I, S, G, N, D\}$) where $\sum_m co_m X_{D,m,t}$ is the total emission in Gt of CO_2 equivalent and 1 ppm atmospheric concentration increase is equal to 2.13 Gt CO_2 emission.[5]

The existing literature typically follows the practice to directly put the environmental quality into the production of final output. AABH "mimics" this structure by inserting the environmental quality into constant relative risk aversion (CRRA) utility function. Following the approach by Acemoglu et al. (2009), we construct an environmental quality variable as a function of total CO_2 emissions which enters into the utility function of households instead of directly affecting productivity (see e.g. Nordhaus and Boyer, 2000). However, we alter from Acemoglu et al. (2009) by assuming that environmental quality affects the quality of households' leisure time instead of consumption. We calibrate our baseline scenario so that we reproduce the Nordhaus and Boyer (2000) result of around 1 % GDP cost of climate change from a temperature increase of 2.5 C relative to the preindustrial level.

$$U(env_t, C^i_t, 1-L^i_t) = (1-habc)\log\left(C^i_t - habcC_{t-1}\right) + \frac{\omega}{1-\kappa}\left(\phi(env_t)(1-L^i_t)\right)^{1-\kappa}.$$

where $\phi(env_t) = \phi(\Delta(env_t)) = \frac{(\Delta_{\max}-\Delta(env_t))^{\lambda} - \lambda\Delta^{\lambda-1}_{\max}(\Delta_{\max}-\Delta(env_t))}{(1-\lambda)\Delta^{\lambda-1}_{\max}}$. Following AABH we set $\lambda = 0.3501$ in order to match our $\phi(env_t)$ function with the direct environmental damage function on production applied in [NordhausBoyer00] over the range of temperature increases up to 3.5 ^{0}C. This parameter choice generates the effects that are very close to the one obtained in Nordhaus calibration exercises for temperature increase of 2.5 ^{0}C (around 1% of GDP).

10 ANNEX B: CALIBRATION OF THE MODEL AND DATA DESCRIPTION

Our model economy contains 2 regions, namely the EU27 and the rest of the world. In the current version we consider five sectors for our modelling purposes, which represent the renewable energy

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[5] The stock of CO_2 in atmosphere is calculated using $5.137 \cdot 10^{18}$ kg as mass of the atmosphere, which is equivalent to 1 ppm of CO2 = 2.13 Gt of carbon (Sinn, 2008).

sector (REN), nuclear (NUCL) and fossil-based energy production inputs (FOEN), energy intensive manufacturing (EII) and the rest of economy (Other).

10.1 Input-output matrix

The calibration of the model starts by normalizing the total value-added for each country to 1 ($VA=1$), i.e. we divide all entries of the input-output matrix by VA. In the following we suppose that $VA=1$, therefore most of the entries from the table can be directly introduced into the model. The only exceptions are the sector-specific investment demands for which we do not have data. Our input-output matrix has data only for the sectoral investment supplies (domestic, $\mathbf{I}^{S}_{s.}$ and imported, $\mathbf{I}^{S,IM}_{s.}$). To determine the distribution of investment demand across all sectors we assume that investment spending is proportional to value-added in each sector:

$$\frac{\mathbf{I}^{D}_{.d}+\mathbf{I}^{IM}_{.d}}{\mathbf{I}}=\frac{\mathbf{VA}_{d}}{\mathbf{VA}}$$

and that the way the investment supply of sector s is distributed across the individual sectors corresponds to the aggregate distribution:

$$I^{D}_{s,d}=\mathbf{I}^{S}_{s.}\cdot\frac{\mathbf{VA}_{d}}{\mathbf{VA}}$$

$$I^{IM}_{s,d}=\mathbf{I}^{S,IM}_{s.}\cdot\frac{\mathbf{VA}_{d}}{\mathbf{VA}}.$$

In the model we distinguish between government consumption and investment but the input-output table provides us only with the total final goods use of the government. To determine $\mathbf{IG}_{s.}$ we assume that the same share of public final goods use takes the form of public investment (around 11% for each sector). All price indices are normalized to 1 and the corresponding share-parameters can be easily obtained from the actual (or calibrated) input-output ratios:

$$sZd_{s,d}=\frac{Z^{D}_{s,d}}{Z^{D}_{s,d}+Z^{IM}_{s,d}},\quad sZ_{s,d}=\frac{Z^{D}_{s,d}+Z^{IM}_{s,d}}{\mathbf{Z}^{D}_{.d}+\mathbf{Z}^{IM}_{.d}}\ \text{ for } Z\in\{I,M\}$$

$$sXd_{s}=\frac{X^{D}_{s.}}{X^{D}_{s.}+X^{IM}_{s.}}\ \text{ for } X\in\{C,G,IG\}\ \text{ and}$$

$$sim^{c'\to c}_{s}=\frac{IM^{c'\to c}_{s}}{\mathbf{IM}_{s}}.$$

We can determine the steady state foreign debt from equation fdebt by fixing the same foreign benchmark interest rate r^{F}_{t} (this will be the US interest rate in our region model):

$$B^{F}_{t}=-\frac{\sum_{n=1}^{N}\left(P^{Y}_{n,t}EX_{n,t}-P^{IM}_{n,t}IM_{n,t}\right)}{E_{t}r^{F}_{t}}$$

Note that by construction a positive trade-balance is always coupled with foreign debt stock. The interest-rate is obtained from the interest parity condition and the risk premium on capital assets is the difference between the region's interest rate and the US interest-rate. The next step is the calibration of the intermediate and factor demand equations. First note that the sectoral capital stock can be obtained from the sectoral capital accumulation equation in the steady state: $K_{n,t}=I_{n,t}/\delta^{K}_{n}$ and we assume that labour is distributed according to the value-added shares across sectors. Wages are assumed to be equal for each sector. The rental rate of capital can be solved from the Q-equations. For given substitution elasticities ($\sigma_{vam,n}$) we can divide the first order conditions for labour and capital and solve for α_n. For given fixed costs (distributed according to the value added shares) we can obtain A_n^{va} from the value-added term. Parameters sva_n and sm_n are jointly determined by the first order conditions for intermediates and labour and A_n can be calculated from the final production function. Finally, the inverse mark-up comes from the first order conditions for labour (capital or intermediates). With respect to taxes and duties, the import duties are included in the import values but domestic excise duties are part of domestic taxes which should be taken into account in the calibration. The research production function parameters are calibrated by using Pessoa (2005) results obtained for λ and ϕ for selected OECD countries. We apply the same parameters for each sector, however the knowledge production inputs are calibrated on the basis of our collected R&D data.

10.2 Compilation of the input-output matrix

Obtaining a consistent and complete input-output matrix with environmental information is a challenging endeavour. First, the sectors of the GTAP data have been mapped to five sectors according to the definition of groups in Table 1. Second, the UNFCCC ver. 10 (UNFCCC, 2009) data have been used for the EU27 to extend the matrix by emissions from fossil fuel combustion. The data include all emission categories together with energy carriers, but exclude the emissions associated with the land use and international bunkers. We build a convergence key to appropriate the UNFCCC sectors to our four categories. Most of UNFCCC sectors could be directly mapped to our four categories; however we had to split a couple of UNFCC sectors between our four categories. This difficulty is approached by combining various databases and generating estimates where applicable. For that purpose we calculate the weights based on emissions reported by the NAMEA database, which represents sectoral emissions in more detail than the UNFCCC data.[6] Finally, the UNFCCC includes comprehensive sectoral data only for the EU27 but not for the rest of the world. To obtain the emissions data for the rest of the world, we combine this source with the statistics on CO_2 emissions from fuel combustion by the International Energy Agency (IEA, 2006).[7] The comprehensive description of sector allocations by the IEA (2006 Edition, Ch. 1.8) is used to map the emission data into our five categories in order to generate a square input-output matrix for all regions.

10.3 Compilation of R&D data

A construction of a country's aggregate share of green R&D investments involves the identification of green R&D investments in both the public and the private sector. First, private R&D investments are computed by using sector-level data. In particular, the information on sector-specific business R&D spending (BERD) and business R&D personnel is obtained from Eurostat Structural business statistics (SBS) at the NACE rev.1 two-digit sector level for all EU27 Member States. The data coverage at the sector-level is only available for one or a few years across countries. It is not possible, therefore, to perform a robust temporal analysis of sector-level R&D figures for all EU27 countries. A comparison is limited to differences across countries by the means of data from the last available year (i.e. 2006 or 2007 for most countries; 2005 for Germany, Ireland, Luxembourg and Portugal; 2003 for Belgium). Values are expressed in millions of Euros in real terms by using the EUROSTAT GDP deflator.

Moreover, the coverage at the NACE two-digit level is not complete for every country and hence the available 2-digit data do not perfectly correspond to the country totals (available from Eurostat STI). To obtain a representative set of sector-level data, we adopt the following procedure. In the first step,

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[6] Keuning (1993) was among the first to propose an extended SAM including environmental accounts provided by NAMEA. In the NAMEA database, pollution emissions from production, consumption, and imports are presented in a pollution emission account and allocated into a set of environmental themes. We prefer the UNFCCC to NAMEA database for a simple reason that it covers not only EU27 but also the rest of the world. Comparing both data sources, the emissions are about 5% higher in NAMEA than in UNFCCC database.

[7] For the case of EU27, the UNFCCC data reports on average 6% higher total emissions than the IEA data. We make an assumption that emissions data are under-represented also for the rest of the world by 6% and adjust them accordingly to this figure.

a relative sector-specific share of total R&D (spending and personnel) is computed for all available two-digit sectors and countries. In the next step, we compute the average of that share individually for the EU-15 and EU-12 countries. Finally, we calculate the difference between the country's total and sectoral data. This difference is then appropriated to the sectors with missing information by using the GDP weights on their relative importance in the economy.

Second, business R&D investments at the sector-level are aggregated in five sectors following our classification presented in Table 1. For those few sectors for which no straightforward correspondence is possible (e.g. "Electricity, gas and water supply"), the closest possible appropriation is made. The weights are based on energy-specific R&D data from the International Energy Agency, which report individual R&D data for different energy carriers (i.e. renewable energy sources, fossil fuels, nuclear fission and fusion, hydrogen and fuel cells).[8]

Third, data on public R&D referring to environment-related and energy-related government R&D support are retrieved from the EUROSTAT Government Budget Appropriations or Outlays on R&D (GBAORD) and add to private R&D figures across the macro sectors identified in Table 1.[9] Public R&D data are allocated across these sector categories by using these weights based on the share of R&D activity in each individual energy carrier reported by the IEA dataset.

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[8] The total business R&D in each EU country is allocated across our sectors without double counting.

[9] GBAORD data are built up using the guidelines laid out in the OECD's Frascati Manual (2002). Data are broken down in accordance to the Nomenclature for the analysis and comparison of scientific programmes and budgets (NABS) at chapter or subchapter level. NABS 02 refers to environment-related public R&D while NABS 05 indicates energy-related public R&D spending. The latest version of the nomenclature (NABS 2007) is applicable since reference year 2007, before that its earlier version (NABS 1992) was used.

11 ANNEX C: DETAILED OVERVIEW OF SIMULATION RESULTS

Table A1. Potential medium-term macro-economic effects in the EU-27

Macro-economic indicator	S0: Lump-sum tax			S1: Labour tax			S2: Green sales subsidy			S3: Green R&D subsidy			S4: General R&D subsidy			S5: Front-loaded green R&D subsidy		
	2014	2017	2020	2014	2017	2020	2014	2017	2020	2014	2017	2020	2014	2017	2020	2014	2017	2020
GDP	-0.20	-0.35	-0.51	-0.03	-0.06	-0.10	-0.04	-0.07	-0.11	-0.03	-0.01	0.03	-0.07	-0.04	0.02	-0.07	-0.02	0.05
Employment	-0.12	-0.21	-0.29	0.12	0.20	0.27	0.11	0.17	0.23	0.10	0.16	0.21	0.07	0.12	0.17	0.06	0.12	0.18
Low-skill employment	-0.22	-0.40	-0.57	0.26	0.40	0.53	0.24	0.36	0.47	0.23	0.33	0.42	0.18	0.29	0.37	0.16	0.28	0.37
Medium-skill employment	-0.09	-0.15	-0.21	0.08	0.14	0.19	0.06	0.11	0.16	0.06	0.10	0.14	0.03	0.07	0.11	0.02	0.07	0.11
High-skill employment	-0.05	-0.08	-0.11	0.05	0.08	0.11	0.04	0.07	0.10	0.04	0.07	0.10	0.02	0.05	0.08	0.03	0.05	0.08
Real wage	-0.17	-0.30	-0.45	-0.29	-0.49	-0.69	-0.29	-0.48	-0.69	-0.20	-0.29	-0.36	-0.20	-0.28	-0.33	-0.14	-0.26	-0.32
Low-skill real wage	-0.15	-0.25	-0.37	-0.38	-0.62	-0.86	-0.37	-0.60	-0.84	-0.34	-0.49	-0.62	-0.32	-0.46	-0.57	-0.28	-0.44	-0.55
Medium-skill real wage	-0.21	-0.37	-0.55	-0.28	-0.49	-0.69	-0.28	-0.48	-0.68	-0.25	-0.37	-0.48	-0.23	-0.35	-0.43	-0.21	-0.33	-0.41
High-skill real wage	-0.15	-0.28	-0.44	-0.21	-0.36	-0.53	-0.21	-0.37	-0.54	-0.02	-0.01	0.01	-0.05	-0.03	0.01	0.08	0.00	0.01
Consumption	-0.16	-0.35	-0.54	0.21	0.10	-0.01	0.27	0.17	0.06	0.33	0.26	0.20	0.43	0.36	0.32	0.42	0.37	0.33
Liquidity constraint households	-0.31	-0.34	-0.41	-0.12	-0.15	-0.22	-0.11	-0.18	-0.29	-0.08	-0.05	-0.03	-0.11	-0.12	-0.11	-0.09	-0.08	-0.08
Non-liq. constraint households	-0.12	-0.35	-0.58	0.31	0.18	0.05	0.39	0.27	0.16	0.44	0.35	0.27	0.58	0.50	0.45	0.57	0.50	0.45
Government consumption	-0.20	-0.35	-0.51	-0.03	-0.06	-0.10	-0.04	-0.07	-0.11	-0.03	-0.01	0.03	-0.07	-0.04	0.02	-0.07	-0.02	0.05
Investment	-0.49	-0.84	-1.18	-0.55	-0.77	-0.99	-0.55	-0.75	-0.96	-0.64	-0.82	-0.96	-0.77	-0.99	-1.14	-0.78	-0.95	-1.09
Government investment	-0.20	-0.35	-0.51	-0.03	-0.06	-0.10	-0.04	-0.07	-0.11	-0.03	-0.01	0.03	-0.07	-0.04	0.02	-0.07	-0.02	0.05
Nominal interest rate	-0.21	-0.21	-0.20	-0.13	-0.13	-0.13	-0.11	-0.11	-0.12	-0.09	-0.08	-0.07	-0.07	-0.05	-0.03	-0.06	-0.05	-0.04
Real interest rate	-0.05	-0.05	-0.05	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.01	0.01	0.01	0.02	0.03	0.01	0.02	0.03
Consumer price level	-0.79	-1.18	-1.56	-0.49	-0.74	-0.99	-0.43	-0.65	-0.88	-0.39	-0.55	-0.70	-0.34	-0.43	-0.51	-0.31	-0.41	-0.50
Inflation	-0.14	-0.13	-0.12	-0.09	-0.09	-0.09	-0.07	-0.08	-0.08	-0.06	-0.05	-0.05	-0.04	-0.03	-0.02	-0.03	-0.03	-0.03
Government debt (% GDP)	0.04	0.01	0.01	0.03	0.03	0.05	0.04	0.05	0.08	0.02	0.01	0.01	0.04	0.04	0.03	0.03	0.02	0.03
Government balance (% GDP)	0.18	0.16	0.14	0.10	0.09	0.08	0.08	0.07	0.07	0.08	0.07	0.06	0.06	0.05	0.04	0.08	0.04	0.04
Trade balance (% GDP)	-0.02	0.00	0.02	-0.08	-0.05	-0.02	-0.10	-0.06	-0.03	-0.12	-0.09	-0.06	-0.17	-0.13	-0.10	-0.17	-0.13	-0.09
Global environmental quality	0.56	1.17	1.86	0.53	1.13	1.81	0.54	1.15	1.83	0.54	1.15	1.84	0.61	1.25	1.97	0.60	1.25	1.96
ETS revenues (% GDP)	0.10	0.20	0.30	0.12	0.22	0.31	0.12	0.21	0.30	0.12	0.22	0.31	0.09	0.19	0.29	0.10	0.19	0.29
Recycling to lump-sum tax	0.10	0.20	0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recycling to labour tax	0	0	0	0.12	0.22	0.31	0.11	0.19	0.27	0.11	0.20	0.28	0.08	0.17	0.26	0.08	0.15	0.23
Recycling to green sales subsidy	0	0	0	0	0	0	0.01	0.02	0.03	0	0	0	0	0	0	0	0	0
Recycling to green R&D subsidy	0	0	0	0	0	0	0	0	0	0.01	0.02	0.03	0	0	0	0.02	0.04	0.06
Recycling to general R&D subsidy	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.03	0	0	0

Note: The values refer to % deviations in 2020 relative to baseline.

Source: QUEST simulation results.

Table A2. Sectoral presentation of potential medium-term macro-economic effects in the EU-27

Macro-economic indicator	S0: Lump-sum tax			S1: Labour tax			S2: Green sales subsidy			S3: Renewables R&D subsidy			S4: General R&D subsidy			S5: Front-loaded green R&D subsidy		
	2014	2017	2020	2014	2017	2020	2014	2017	2020	2014	2017	2020	2014	2017	2020	2014	2017	2020
Value added																		
EII	-0.44	-0.79	-1.17	-0.31	-0.53	-0.78	-0.31	-0.53	-0.77	-0.34	-0.52	-0.71	-0.38	-0.55	-0.71	-0.39	-0.53	-0.69
OTHERS	-0.19	-0.32	-0.46	-0.02	-0.03	-0.05	-0.01	-0.03	-0.06	-0.02	0.02	0.07	-0.05	-0.01	0.07	-0.06	0.01	0.09
REN	3.64	6.17	8.77	3.86	6.64	9.51	3.43	5.88	8.42	4.13	7.55	11.38	3.84	6.67	9.66	4.16	7.35	10.35
FOEN	-5.57	-9.15	-12.70	-5.46	-8.99	-12.50	-5.53	-9.09	-12.62	-5.54	-9.07	-12.59	-5.77	-9.29	-12.77	-5.78	-9.29	-12.77
NUCL	3.87	6.63	9.54	4.10	7.11	10.29	3.79	6.56	9.49	3.99	6.92	9.99	4.10	7.20	10.53	4.01	7.09	10.41
Knowledge.capital																		
EII	0.00	-0.01	-0.03	-0.01	-0.03	-0.06	-0.01	-0.04	-0.07	0.01	0.04	0.07	0.01	0.06	0.12	0.02	0.07	0.13
OTHERS	0.04	0.09	0.16	0.03	0.08	0.14	0.03	0.07	0.12	0.07	0.19	0.33	0.07	0.20	0.39	0.08	0.22	0.40
REN	0.10	0.24	0.44	0.09	0.24	0.44	0.08	0.21	0.39	0.35	0.98	1.88	0.11	0.28	0.53	0.39	0.82	1.04
FOEN	-0.40	-0.96	-1.70	-0.40	-0.98	-1.75	-0.41	-0.98	-1.74	-0.38	-0.91	-1.62	-0.40	-0.93	-1.62	-0.39	-0.91	-1.60
NUCL	0.13	0.33	0.61	0.13	0.33	0.61	0.12	0.30	0.56	0.14	0.37	0.68	0.14	0.38	0.73	0.15	0.39	0.73
Employment,capital																		
EII	-0.42	-0.71	-1.01	-0.25	-0.39	-0.55	-0.25	-0.39	-0.54	-0.31	-0.47	-0.65	-0.34	-0.51	-0.69	-0.36	-0.50	-0.67
OTHERS	-0.24	-0.41	-0.57	0.01	0.00	-0.02	0.01	0.00	-0.01	-0.04	-0.08	-0.14	-0.06	-0.11	-0.18	-0.09	-0.11	-0.17
REN	3.05	5.04	7.04	3.26	5.49	7.72	2.90	4.86	6.83	3.23	5.49	7.78	3.22	5.47	7.74	3.21	5.49	7.79
FOEN	-3.53	-5.40	-7.07	-3.38	-5.17	-6.76	-3.42	-5.23	-6.84	-3.45	-5.28	-6.93	-3.59	-5.40	-7.03	-3.61	-5.42	-7.04
NUCL	3.38	5.62	7.89	3.63	6.12	8.64	3.36	5.65	7.97	3.51	5.90	8.28	3.61	6.13	8.71	3.52	6.02	8.60
Consumption																		
EII	0.50	0.80	1.14	1.07	1.33	1.62	1.19	1.44	1.72	1.34	1.61	1.90	1.58	1.82	2.10	1.57	1.80	2.08
OTHERS	0.15	0.07	-0.02	0.70	0.56	0.42	0.84	0.70	0.56	0.98	0.84	0.69	1.29	1.12	0.95	1.28	1.11	0.93
REN	5.03	8.19	11.33	5.60	8.80	11.98	5.42	8.38	11.33	5.91	9.21	12.53	6.30	9.59	12.89	6.31	9.62	12.92
FOEN	1.62	2.80	3.93	2.25	3.41	4.53	2.11	3.10	4.05	2.44	3.55	4.57	2.57	3.73	4.88	2.52	3.63	4.77
NUCL	4.68	7.76	10.85	5.27	8.43	11.61	5.09	8.01	10.97	5.48	8.59	11.70	5.88	9.17	12.54	5.81	9.03	12.39
Investment																		
EII	-0.65	-1.10	-1.56	-0.85	-1.21	-1.58	-0.85	-1.19	-1.54	-0.94	-1.27	-1.57	-1.06	-1.43	-1.75	-1.06	-1.39	-1.71
OTHERS	-0.57	-0.97	-1.35	-0.62	-0.88	-1.13	-0.59	-0.83	-1.07	-0.70	-0.92	-1.09	-0.83	-1.10	-1.29	-0.84	-1.05	-1.24
REN	7.81	9.94	11.99	7.83	10.19	12.46	6.90	8.99	11.02	7.91	10.46	12.98	7.80	10.29	12.77	7.82	10.39	12.87
FOEN	-21.23	-23.33	-24.69	-22.55	-24.26	-25.31	-22.84	-24.50	-25.52	-23.32	-24.98	-25.92	-24.15	-25.75	-26.61	-24.23	-25.65	-26.50
NUCL	9.41	11.92	14.36	9.49	12.27	14.96	8.74	11.31	13.81	9.14	11.83	14.42	9.51	12.44	15.38	9.35	12.33	15.29
Exports																		
EII	-1.02	-1.73	-2.50	-1.21	-1.80	-2.44	-1.26	-1.82	-2.44	-1.37	-1.92	-2.51	-1.52	-2.05	-2.61	-1.52	-2.02	-2.58
OTHERS	-0.47	-0.62	-0.77	-0.66	-0.66	-0.66	-0.74	-0.74	-0.74	-0.84	-0.79	-0.73	-1.11	-1.03	-0.91	-1.10	-1.00	-0.89
REN	0.49	0.78	1.12	0.31	0.78	1.30	0.24	0.70	1.20	0.39	1.30	2.47	0.05	0.55	1.12	0.30	1.05	1.62
FOEN	-7.15	-11.62	-15.85	-7.35	-11.79	-15.99	-7.26	-11.60	-15.72	-7.46	-11.86	-16.01	-7.68	-12.12	-16.33	-7.65	-12.05	-16.27
NUCL	0.72	1.21	1.81	0.50	1.17	1.95	0.42	1.08	1.84	0.30	0.97	1.76	0.25	0.98	1.83	0.24	0.99	1.84
Imports																		
EII	0.14	0.20	0.28	0.50	0.54	0.61	0.58	0.62	0.68	0.67	0.73	0.82	0.81	0.84	0.92	0.81	0.85	0.92
OTHERS	-0.03	-0.21	-0.38	0.34	0.14	-0.06	0.44	0.24	0.05	0.53	0.33	0.14	0.74	0.51	0.28	0.74	0.51	0.28
REN	3.48	5.63	7.75	3.80	5.99	8.15	3.25	4.99	6.74	3.94	6.13	8.29	4.23	6.48	8.74	4.18	6.42	8.69
FOEN	-3.40	-5.56	-7.64	-3.19	-5.36	-7.45	-3.26	-5.51	-7.68	-3.13	-5.33	-7.46	-3.10	-5.28	-7.37	-3.12	-5.32	-7.41
NUCL	3.89	6.42	8.96	4.32	6.94	9.57	4.11	6.51	8.92	4.45	7.03	9.59	4.79	7.54	10.34	4.72	7.41	10.21

Note: The values refer to % deviations in 2020 relative to baseline.

Source: QUEST simulation results.