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European green bonds, carbon tax and crowding-out: The economic, social and environmental impacts of the EU's green investments under different financing scenarios

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ABSTRACT

This study provides novel insights into the economic, social and environmental impacts of green energy investments in the European Union using MAGNET, a computable general equilibrium model of the world economy. MAGNET was extended to include sector-specific investment allocation, investment risk premiums adjustment, and technology learning effects to endogenize productivity growth in renewable and bioenergy sectors. In line with the proposals on climate neutrality and the Green Deal, the study simulates an increase in investments in renewable energy and bioeconomy sectors (additional 15 % increase in capital stock) starting in 2025. Three alternative financing scenarios are compared; the European Green Bonds scenario, carbon tax scenario and the crowding-out scenario (assuming green investments are financed from existing resources). It is found that additional green energy investments bring generally positive GDP, social and emission-saving effects. In the case of GDP, the deviation from the baseline reaches +0.9 % in 2050 for the EU if financed from the Green Bond. The other scenarios show that when green investments are not crowding-out other investments in the EU, the economic impacts at EU level are still positive. It is also shown that, on average, the investment policy would increase the size of bioeconomy sector by between 3.2 % and 4.2 % in 2050. However, the impacts across particular countries and industries are very heterogenous.

1. Introduction

The Paris Agreement, adopted by 196 Parties, aims to limit global warming to well below 2 °C, preferably to 1.5 °C. According to Ref. [1], the global warming dramatically affects natural and human systems. [1] also states that "human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming". The latest Conferences of Parties (COP26 and COP27) and the United Nations Framework Convention on Climate Change (UNFCCC) summits, therefore stressed the importance of finance in delivering the goals of the Paris Agreement. The focus in this context has been the support to developing countries, but also richer regions such as the United States with its Inflation Reduction Act mobilizing over $360 billion by 2030, Japan with its green transformation plans of $140 billion, and the European Union (EU) have ambitious plans to invest in a low-carbon economy. Examples of the EU plans can be found in the European Green Deal [2], the "Fit for 55 delivering the EU's 2030 Climate Target" [3], the "Sustainable Carbon Cycles" [4], and the progress report on the "European bioeconomy policy" [5]. The EU has also set up the Recovery and Resilience Plans (RRPs) as a response to the COVID-19 pandemic, a large part of the budget of which is allocated to green public investments (GPIs). Lately, the Green Deal Industrial Plan for the Net-Zero Age [6] provides further elements to speed up net-zero industrial transformation. The comprehensive research and innovation agenda of the European Union, including its key funding programme Horizon Europe with a budget of more than €95 billion, plays an important role in fostering technical progress and tackling climate change while boosting

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Nomenclature

Abbreviations

Act	Activities
AGRI_PRIM	Primary Agriculture
AGRI_PROC	Processed Agriculture
c_oil	Crude Oil
CGE	Computable General Equilibrium
CO2 eq	CO2 equivalent
coa	Coal
ESP	Spain
EU	European Union
€	Euro
FOSSIL	sectors producing fossil energy
FRA	France
gas_dist	gas distribution
GDP	Gross Domestic Product
GINV	Green Investment Scenario
GINV-FF	Green Investment Scenario with learning rates in fossil sectors
GINV-noTL	Green Investment Scenario without technology learning
GPI	Green public investment
greensec	Renewable energy and bioenergy sectors
GTAP	Global Trade Analysis Project
IPCC	Intergovernmental Panel for Climate Change
ISG	Investments for sustainable growth (ISGs)"
ITA	Italy
MAGNET	Modular Applied General Equilibrium Tool
MW	Megawatt
NorthAme	North America
NUTS	Nomenclature of Territorial Units for Statistics
OTHER_PRIM	Other primary sectors
petro	Petrochemical sector
POL	Poland
R&D	Research and Development
ReEU13	Rest EU13 (EU countries of Central and Eastern Europe)
ReEU14	Rest EU14 (EU countries of Northern, Western and South Europe)
ROW	Rest of the world (Rest Europe, Asia and Oceania)
RRP	Recovery and Resilience Plans
SouCenAme	South and Central America
SSP2	Shared Socioeconomic Pathways
UNFCCC	United Nations Framework Convention on Climate Change
$	United States Dollar
$VKBa_{(a,r)}$	Value of beginning capital stock

Notations

a	unit cost
$aoall1$	productivity parameter
b	rate of cost reduction
$bLBD$	rate of cost reduction from learning by doing
$bLBR$	rate of cost reduction from learning by research
$I^P_{i,r}$	private investments allocated to sector i and region r
$K^P_{i,r}$	sector capital stock
$kba_{i,r}$	sector-specific growth of capital stock
LR	learning curve
p^I_{EU}	investment price index at the EU level
$pes_{capital,i,r}$	price of capital per sector
$qinvza_{i,r}$	investment allocation per sector from Tobin-Q function
$pinv_r$	investment price
r	interest rate
$\dot{R}$	knowledge stock
$rentala_{i,r}$	rental rate of capital
$riskp_{i,r}$	risk premium
$rk_{i,r}$	rate of return to capital
rp_r	exogenous risk premiumΔ
$tkba$	installed capital stock
uck_r	user costs of capital (RHOMOLO)
$usc_{i,r}$	sector-specific user costs of capital (MAGNET)
x	cumulative experience
$\dot{x}$	cumulative installed capacity in MW
Y	cost of technology
$\dot{y}$	reduction in unit cost
δ_r	depreciation rate
σinv	elasticity of investment allocation with respect to the "Q" ratio
Δ	change

the EU's competitiveness and growth. However, the recent adoption of the European Green Bonds Regulation [7] should probably be considered as the most important step undertaken by the EU to ensure the funding for green investments in the next decades.

Green investments, or so-called "investments for sustainable growth (ISGs)", are primarily meant to achieve the transformation to a climate neutral European economy [8]. Aligning green energy investments with policy objectives creates both opportunities and challenges for governments. In the case of investment-driven economic development, special insights into investment allocation per sector, their financing, and productivity effects are required. In addition, supplied funding has to be in line with the sustainability agenda [9], particularly when it comes from a public body. It is therefore necessary to investigate the economic, social, and environmental impacts of investments.

The available empirical literature, though scarce, points to the positive role of publicly funded green energy investments in the economy. Financial-oriented modelling approaches [10,11] have shown the importance of debt-financed investment policies as a means of de-risking private green investments and reducing potential transition costs. The role of green bonds in stimulating green transition is also thoroughly discussed by Ref. [12]. On the empirical side, [13–15] found statistically significant fiscal multipliers of green investments, with long-term positive effects on the economy, providing further justification for debt-finance green policies. These studies follow an indirect approach based on estimating a relationship between past investments in assumed green sectors and GDP, given that the identification of the proportion of capital stock formation per sector that is attributed to green energy investments in the national accounts is currently not possible. However, they do not take into account the intersectoral linkages of the green sectors in the economy (in the supply chain, on the markets of production factors), the delayed character of building capital stocks, and the role of technology learning (the impacts are long-run and not easily captured in annual or quarterly time series). Furthermore, the impact on emissions, which is a very important performance criterion for green energy investments, is omitted in these studies.

Addressing the questions raised and considering that green investments are designed to have a medium-term to long-term impact, requires a modelling approach that depicts the more sustainable, including bio-based, alternatives for relevant products, account for market interlinkages, competition for production factors (labour, capital), and repercussions at the global scale and quantify the impact on economic as well as environmental indicators over a long-term horizon. Economy-wide simulation models such as Computable General Equilibrium (CGE) models with broad coverage of sectors, production factors, actors, regions, and indicators can fill the gap in the literature. For instance, in the study of [16], global aggregated investment in 2030 grows under climate change mitigation scenarios with sectors related to clean power technologies standing out as the prime driver of this transition. However, in light of recent policy ambitions towards a more sustainable growth model and the economic recovery from the COVID-19 pandemic, it became apparent that existing CGE models with broad sector and sustainability indicator coverage are not yet sufficiently equipped to assess the impact of green energy investments. This is because many of the existing CGE approaches impose climate change mitigation by adjusting to the expected emission decline without explicit linking to the investment needs of such a policy (e.g. Refs. [17,18]). This is related to the common problem in the CGE models, as underlined by Ref. [19], that technological change for economic growth is surprisingly often assumed as "manna from heaven" in modelling exercises. This study makes three contributions to the literature: Firstly, from the policy perspective, it evaluates the economic, environmental, and social impacts of green investments under three alternative financing scenarios. The first one aligns with the concept of the European Green Bond Regulation. Two remaining scenarios assess the impacts of green investments under more restrictive sources of financing. The novelty of this is study lies not only in its explicit costing of the green transition (as opposed to studies where green transition is assumed to happen automatically) but also in its evaluation of the impacts in line with the recent financing framework, which, to the authors' knowledge, has not been done before.

- Secondly, from a methodological perspective, this study applies and extends a CGE model called MAGNET (Modular Applied General Equilibrium Tool), which is widely used in the context of the energy-water-food-land-climate nexus [20], mitigation policies [21,22], the bioeconomy [23] and global economic energy transition pathways [24]. The study incorporates new modelling extensions in MAGNET, including sector-specific investment allocation capabilities to simulate changes in the investment mix, and technology learning effects that capture the long-term productivity effects of capital. These extensions are crucial for evaluating the economic impacts of green energy investments, and their incorporation in MAGNET allows for a more comprehensive analysis of the transition to a low-carbon economy.
- Thirdly, this study takes a holistic approach to assessing the impacts of green investments, considering all three sustainability dimensions: economic (measured by GDP and sectoral GVA), environmental (measured by total and sectoral emissions) and social (measured by real wages, food and energy security). Unlike other studies, this research does not focus solely on aggregated industries but instead uses a highly granular representation of bioeconomy sectors in MAGNET, which includes established forward and backward linkages in the economy [23,24]. This is particularly relevant given the EU's focus on developing the bioeconomy, as expressed in the EU Bioeconomy Strategy [26,27]. The bioeconomy encompasses all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles [26]. By considering the bioeconomy in its analysis, this study provides a comprehensive assessment of the impacts of green investments on the economy, environment, and society.

The European Union (EU) is the focus of this study, building on the recent adoption of the European Green Bonds Regulation that can be considered as an additional source of funding for green investments. As such, it provides valuable insights into assessing the ex-ante impacts of policies related to the green transition, such as the Green Deal. The approach presented in this study can also be applied to evaluate other policies or instruments related to investments, such as Research and Development Policies (RPPs) or the Common Agricultural Policy. Additionally, this work provides strong economic justification for financial market actors to design financial instruments that stimulate a green transition.

The article proceeds as follows. In section 2, the methodological approach is outlined, including the description of the MAGNET CGE model and the novel features for investment modelling. In section 3, the results of the scenario analysis are presented, including a sensitivity analysis. Section 4 provides discussion and section 5 concludes.

2. Methodology

2.1. Description of the MAGNET model

The Modular Applied GeNeral Equilibrium Tool (MAGNET) is a recursive dynamic, multi-regional, multi-commodity CGE model that covers the entire global economy [28]. It is similar to other CGE models as it explicitly represents the economic linkages across the sectors within each regional economy. This is particularly important when analysing policy effects in sectors that are vertically linked with each other, such as bioeconomy sectors [23,24]. MAGNET is built upon the GTAP (Global Trade Analysis Project) model [29] and has been widely used for policy analysis [30–35]. MAGNET model is modular in nature and extends the GTAP model through the addition of a number of policy-relevant modules.

MAGNET uses version 10.1 of the GTAP database, which covers 140 regions, 57 sectors and 8 production factors including natural resources, oil and gas. The original GTAP database, was further disaggregated to include additional agricultural and bioeconomy sectors (residue sector, biodiesel, biogasoline, Fischer–Tropsch 2nd generation biofuel, ethanol 2nd generation biofuels, Bioelectricity 2nd generation, polylactic acid bioplastics, polyethylene bioplastics, traditional bioplastics, Ligno sugar). As a result, a complete MAGNET database contains the total of 113 sectors and 127 commodities. The database includes detailed information on production, gross bilateral trade flows, transport costs and trade protection data for a 2014 benchmark year.

Table 1 lists all the commodity groups aggregated for this version of the MAGNET model. The commodity groups are defined in line with the focus of the study: individual sectors closely related to energy transition are disaggregated, while the other less relevant sectors are more aggregated.

Fig. 1 shows the regional aggregation used in the simulations. As in the commodity aggregation, individual GTAP countries were aggregated into 10 regional blocks. With a focus on the EU, representative member states in terms of size, geography and planned investments, as well as aggregates for the remaining "old" and "new" member states were selected. Other regions were kept more aggregated. MAGNET contains a broad set of sustainability indicators (environmental, economic, social) covering a large number of Sustainable Development Goals [36,37].

2.2. Modelling of green energy investments

Fostering the green energy transition in Europe requires significant stimulation of green investments directed towards the renewable energy and bioeconomy sectors [38]. Green public investments should be concentrated in various areas, including green mobility, infrastructure, R&D, energy systems, sustainable food production, and in line with the EU Taxonomy [39]. Following [6], "the greater part of investment needed for the net-zero transition will have to come from private funding". Still, the EU is assumed to mobilize hundreds of billions of euros in public investments to ensure the participation of private sector in the next decades. The idea is, however, to finance the increased borrowing needs through long-term bonds rather than immediate rises in taxes. That is precisely where the European Green Bonds Regulation comes into the scene. It allows both public and private investors to issue long-term bonds with the EU Green Bond label once they apply the standards specified in the regulation. Such bonds are considered as a means of attracting new investors globally and mobilizing liquidity for green investments [40]. Still, given that it is not certain that the green

Table 1
Aggregate commodity groups in the MAGNET model.

Order	Group	Desc	Order	Group	Desc
1	pdr	Paddy rice	**33**	res	Residue sector
2	wht	Wheat	**34**	biod	Biodiesel
3	grain	Cereal grains nec	**35**	biog	Biogasoline
4	oils	Oil seeds	**36**	ftfuel	Fisher-Tropsch 2nd gen biofuel
5	sug	Sugar cane, sugar beet	**37**	eth	Ethanol 2nd gen biofuels
6	hort	Vegetables, fruit, nuts	**38**	gas	Gas
7	crops	Crops nec	**39**	coa	Coal
8	oagr	Other agriculture	**40**	ely	Electricity
9	cattle	Cattle sector	**41**	ely_c	Electricity from coal
10	othctl	Sheep, goats, horses	**42**	ely_g	Electricity from gas
11	pltry	Poultry sector	**43**	ely_n	Electricty from nuclear
12	wol	Wool, silk-worm cocoons	**44**	ely_h	Electricty from hydro
13	pigpls	Pig and other animal product	**45**	ely_w	Electricty from wind and solar
14	milk	Raw milk	**46**	bioe	Bioelectricity 2nd gen
15	bfmt	Beef meat	**47**	pla	Polylactic acid bioplastics
16	othcmt	Meat: other cattle, sheep, goats, horses	**48**	pe	Polyethylene bioplastics
17	pulmt	Poultry meat	**49**	bfchem	Traditional bioplastics
18	othmt	Other meat product nec	**50**	lsug	Ligno sugar
19	dairy	Dairy products	**51**	othcrp	Chemical, rubber, plastic products
20	sugar	Sugar and molasses	**52**	fert	Fertilizer
21	cvol	Crude vegetable oil	**53**	f_chem	Mixed fossil biochemical sector
22	vol	Vegetable oils and fats	**54**	mvh	Motor vehicles and parts
23	pcr	Processed rice	**55**	cons	Construction
24	ofd	Processed food	**56**	othind	Other industry
25	feed	Animal feed	**57**	pel	Pellet sector
26	wfish	Wild fish	**58**	gas_dist	Gas manufacture, distribution
27	aqcltr	Aquaculture	**59**	trans	Transport sector
28	fishp	Fish processing	**60**	pubedu	Public service & education
29	frs	Forestry	**61**	ser	Services
30	plan	Plantation	**62**	ddgs	Biogasoline byproduct
31	c_oil	Crude oil	**63**	oilcake	Oil cake byproduct of cvol
32	petro	Petroleum, coal products	**64**	fishm	fish meal

Source: authors

bonds will provide all necessary funding, this study also considers two alternative financing scenarios. The first one assumes an increase in a carbon tax and the second one considers a change in investment patterns without any increase in overall investment spending (crowding-out scenario).

With increased interest in green public investments, there is also a growing attention to evaluate the impact of such investments, requiring EU Member states to supplement their requests for funds by sound ex-ante analysis, partly based on CGE models [41]. The strength of MAGNET model lies in the inclusion of detailed bioeconomy sectors, modules and the insights into the Sustainable Development Goals that allow for a holistic assessment of green energy investments [25]. Fig. 2 provides a scheme of individual bio-based sectors and their linkages incorporated in MAGNET. This makes the model suitable for the analysis of green transitions] [23,42–44].

Using MAGNET for investment impact analysis requires investment behaviour to be guided by a proper sector investment allocation mechanism. This allows steering investments into the sectors that are "green" or aligned with the EU taxonomy. To achieve this, various modelling extensions were incorporated using a step-by-step approach:

- Conversion to a recursively dynamic model with sector-specific investment allocation - > introduction of sector-specific capital markets.
- Introduction of exogenous sector-specific investments - > steering the investment mix to renewable energy and bioeconomy sectors (green energy sectors).
- Implementation of technology learning effects in the energy sectors - > stimulation of green transition.

2.2.1. Implementation of sector-specific investment allocation

Different investment allocations per sector result in different capital stock growth rates with repercussions for a sector's productivity. In the global GTAP model, investments are usually not sector-specific but determined on a regional level (this holds also for the dynamic GTAP extensions). Therefore, implementing the investment allocation mechanism on the sectoral level is crucial. A central element in the GTAP model is the representation of a global bank that collects savings from individual countries and redistributes them in the form of investments based on equalization of returns (or by a fixed proportion). It is possible to apply this principle on the sectoral level – i.e. assuming that expected rates of return equalize both across the regions and across the sectors. However, this assumption is very constraining, particularly in model settings with a high number of individual sectors and is also not in line with empirical observations.

The investment allocation per sector implemented in MAGNET follows the Uzawa specification (Tobin's Q) approach [45], which allocates investments according to the ratio of return to investment and user costs [37]. [46] found that Tobin's Q explains the largest share of investment variability, confirming the empirical base of this approach. Tobin's Q theory has been commonly used in various CGE models [47–51]. For instance, in RHOMOLO, the Tobin's Q specification is as follows:

$$I_{i,r}^{P} = \delta_r . K_{i,r}^{P} . \left(\frac{rk_{i,r}}{uck_r}\right)^{\nu} \tag{1}$$

where $I_{i,r}^{P}$ refers to private investments allocated to sector i and region r, $K_{i,r}^{P}$ is sector capital stock, δ_r is a depreciation rate (note that it is not sector-specific). The variables $rk_{i,r}$ and uck_r are rates of return to capital and user costs of capital respectively, parameter ν indicates the elasticity of investment change with respect to change in the Q ratio. In RHOMOLO, the rates of return to capital correspond to the sector-specific price of capital. User costs are defined as:

$$uck_r = (i + \delta_r) \bullet p_{EU}^{I} + \Delta p_{EU}^{I} + rp_r \tag{2}$$

where i is an interest rate, p_{EU}^{I} is an investment price index at the EU level and rp_r is an exogenous risk premium. Note that RHOMOLO is a regional CGE model where index r ranges over NUTS2 level EU regions, plus a Rest of the World region. The user costs are defined over a particular region, but they are mostly driven by an EU-wide investment price.

In MAGNET, a linearized Tobin's-Q investment function is applied where variables are expressed as percentage change growth rates. It is assumed that depreciation rate is constant over time and the interest rate is excluded, therefore the equation is reduced to the following expression (equation (3)).

$$qinvza_{i,r} - kba_{i,r} = \sigma inv \bullet (rentala_{i,r} - usc_{i,r}) \tag{3}$$

where $qinvza_{i,r}$ is the growth of investment per sector from Tobin's-Q function, $kba_{i,r}$ is growth of capital stock per sector and parameter σinv

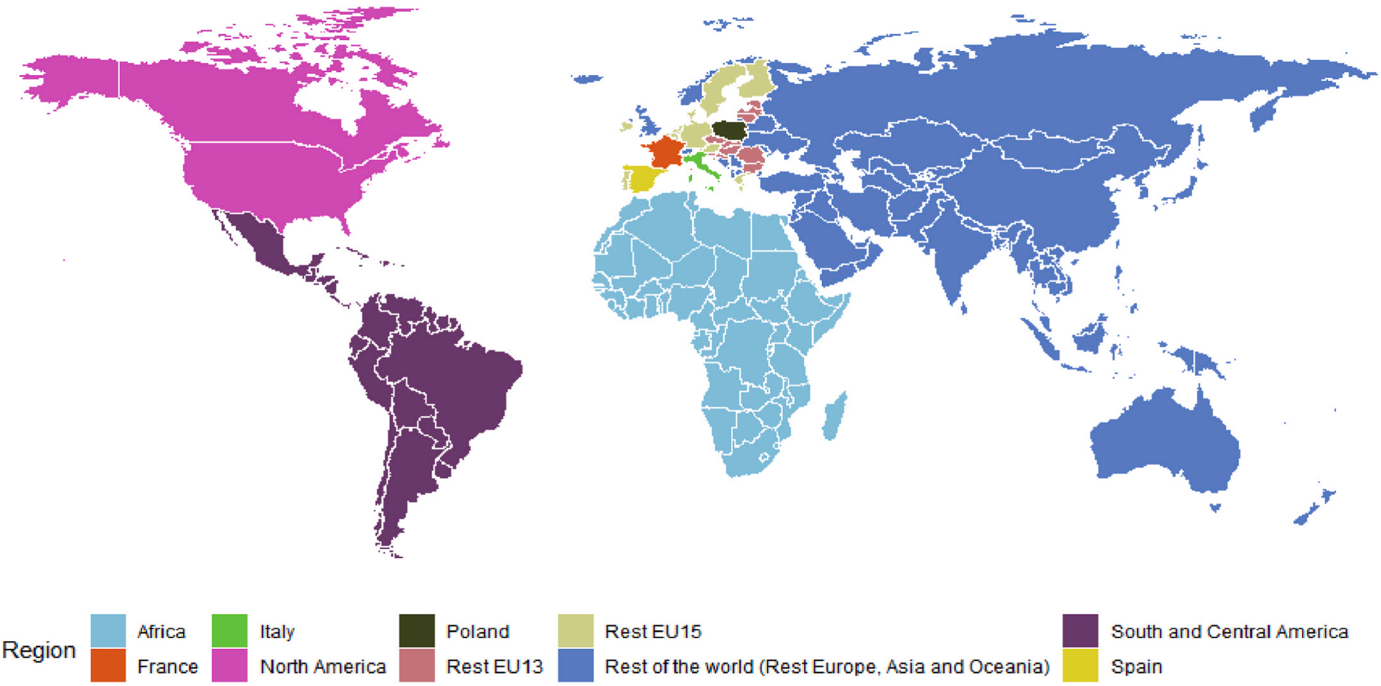

Fig. 1. Aggregated regions in the MAGNET model.
Source: authors

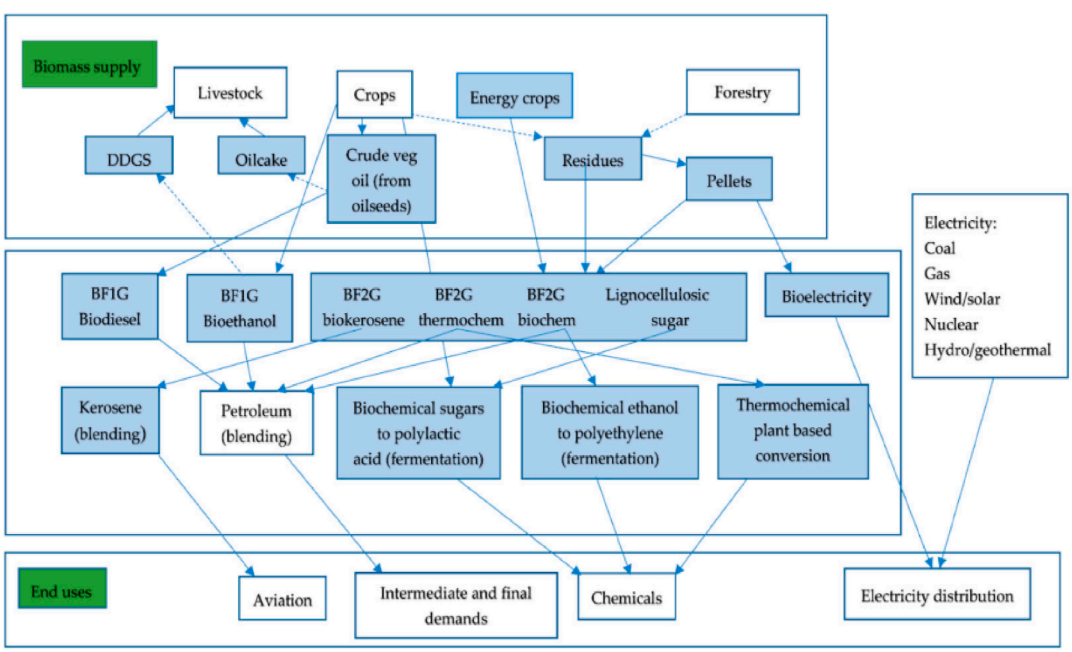

Fig. 2. Overview of bio-based sectors and linkages in MAGNET.
Source [32].

indicates the elasticity of investment allocation with respect to the "Q" ratio (parameter v in the Tobin's Q function (equation (1)). Growth of rental rate of capital $rentala_{i,r}$ is defined from the growth of sectoral price of capital $pes_{\text{capital},i,r}$ (equation (4)). Capital price is determined as an equilibrating price that clears the capital markets, i.e. assures that demand for capital obtained from CES production function and capital supply, obtained from recursively dynamic specification of capital stock on sector level.

$$rentala_{i,r} = pes_{\text{capital},i,r} \tag{4}$$

Growth of user costs of capital $usc_{i,r}$ per sector consist of investment price growth rate $pinv_r$, which is defined at regional level and a sector-specific risk premium growth rate $riskp_{i,r}$, which is normally set to zero but can be used in scenarios to target desired growth rates of sectoral investments (equation (5)).

$$usc_{i,r} = pinv_r + riskp_{i,r} \tag{5}$$

2.2.2. Introduction of exogenous green energy investments

The next step in modifying investment behaviour in MAGNET is to include an exogenous component corresponding to the green investment budget (Fig. 3). A certain part of investments is determined exogenously $GINV_{t,r,a}$ (for period t, region r and activity a) and the remaining part of investments $REGINV_{t,r,a}$ is still allocated according to the private returns. The total amount of investments (summing green and other) $REGINV_{t,r}$ creates a demand for total investment goods in the economy $VDI_{t,r}$. Both green and other investments are accumulated to form green $VGKB_{t+1,r,a}$ and other capital stock $VKB_{t+1,r,a}$. The total amount of capital stock $TKB_{t+1,r,a}$ consequently enters the production function and leads to a higher volume of production. This is further reflected in income of the regional household (*REGHOUS*). Income not spent on household $PRIVEXP_{t,r}$ and governmental consumption $PRIVEXP_{t,r}$ represents savings $SAVE_{t,r}$ collected by the Global Bank.

2.2.3. Implementation of technology learning effects

Thus far, the MAGNET model enables the relocation of investments between the sectors to achieve a productivity effect called capital deepening. Additionally, MAGNET already incorporates another source of investment driven productivity improvement which is linked to Rural Development CAP Payments [52,53]. Consequently, the sectors receiving green energy investments may grow quicker because of their faster capital stock accumulation. If the green energy investments are allocated to sectors with a lower carbon footprint, this already partially contributes to the green transition.

New investments lead also to productivity gains from technology learning which stimulates the green transition. Technology growth models are in line with the endogenous growth theory of [54], which contrasted the original assumptions of technological change as an exogenous source of productivity growth. The most common model used in the energy literature to forecast changes in technology cost is the "one-factor learning curve" or "experience curve" [55]. The one-factor learning curve is derived from empirical observations across a variety of energy technologies based on a log-linear relationship between the unit cost of technology and its cumulative output or installed capacity:

$$Y = a \bullet x^{b} \tag{6}$$

where Y is the unit cost of the technology and x is cumulative experience. The cumulative experience can be measured either in cumulative installed capacity expressed in Megawatts (MW) or in energy produced. The constant a represents the unit cost of the first unit and b is the rate of cost reduction (constrained to be negative). The reduction in cost associated with a doubling of experience, referred to as learning curve (LR):

$$LR = \frac{Y(2 \bullet x) - Y(x)}{Y(x)} = -\frac{a \bullet 2^{b} \bullet x^{b} - a \bullet x^{b}}{a \bullet x^{b}} = 1 - 2^{b} \tag{7}$$

When learning rates are provided, the rate of cost reduction is derived from equation (8) as:

$$b = \frac{\ln(1 - LR)}{\ln(2)} \tag{8}$$

Multi-factor models for energy technologies employ different cost reduction factors. The most commonly used factors are learning-by-doing and learning by research:

$$Y = a \bullet x^{bLBD} \bullet R^{bLBR} \tag{9}$$

where R represents cumulative R&D investments and parameters *bLBD* and *bLBR* are rates of cost reduction from learning by doing and learning by research respectively. The implementation of technology learning in MAGNET requires converting equation (6) in growth rates:

$$\dot{y} = b_{LBD} \bullet \dot{x} + b_{LBR} \bullet \dot{R} \tag{10}$$

where a reduction in unit costs $\dot{y}$ is approximated by productivity parameter; cumulative installed capacity in MW $\dot{x}$ is approximated by installed capital stock and knowledge stock $\dot{R}$ is calculated from annual R&D investments in energy technology.

Still, in all simulations only the technological progress resulting from learning by doing part of equation (10) is considered. This is mainly due to the lack of data on learning by research for several sectors. In MAGNET, learning-by-doing parameters for green energy were obtained from the GEM-E3 model [56] (Table 2). These learning rates assume that doubling of installation capacity reduces unit costs by 10 % for most green energy sectors, for residues it is 32 %. Given that the technology applied in the fossil fuels sectors is rather mature [55], learning rates in the fossil fuel sectors are omitted in the benchmark scenario.

Fig. 4 demonstrates the productivity linkages of technology learning in MAGNET. Renewable energy sectors achieve productivity gains from learning-by-doing by investments in capital stock. Here, production costs decline, and the clean energy sectors become more competitive compared to fossil sectors. Consequently, clean energy inputs substitute fossil energy inputs in the energy mix. At the end of this chain, there is a decrease in total emissions. For learning-by-doing, this process is fully endogenized, as it depends on the accumulation of capital stock in the renewable energy sectors. Even without additional increases in "green" investments, productivity of these sectors grows because of their usual investments. The additional investment boost increases their advantage further. As for the learning-by-research, this process can be either endogenous or exogenous, depending on how R&D investments are determined – either exogenously by following a given governmental R&D budget plan, or targeted to a constant R&D intensity, in which case they are endogenous.

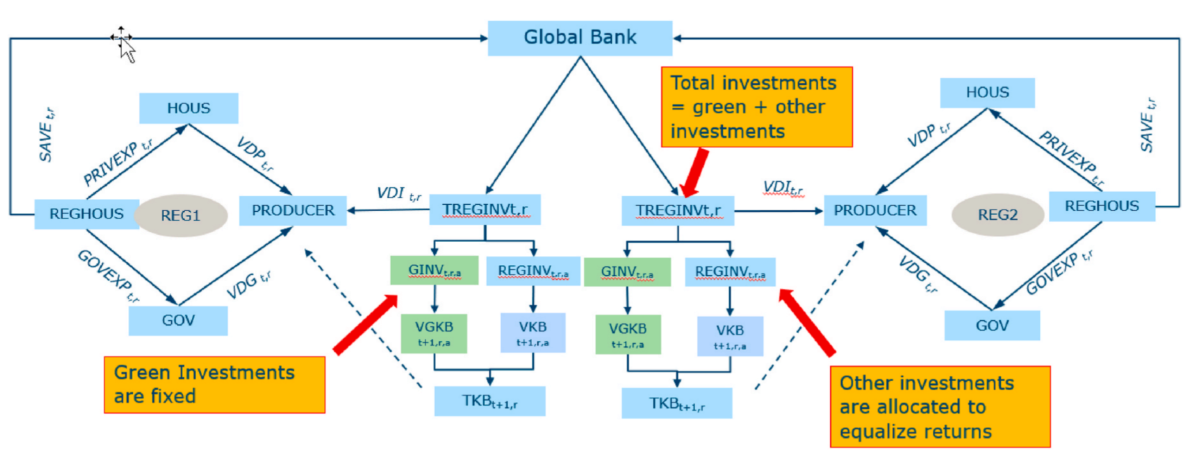

Fig. 3. Schematic representation of green investment mechanism in a recursively dynamic version (case of two regions) Source: authors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Learning rates and productivity coefficient.

	Learning rates (LR)	Productivity coefficient (b) (see equation (8))
residues	0.32	−0.56
biodiesel	0.10	−0.15
biogas	0.10	−0.15
2nd generation biofuel	0.10	−0.15
2nd generation ethanol	0.10	−0.15
hydroelectricity	0.10	−0.15
wind and solar electricity	0.10	−0.15
bioenergy	0.11	−0.17
pellets	0.32	−0.56

Source: authors based on [47].

2.3. Set-up of baseline and green investment scenarios

2.3.1. Baseline assumptions

The MAGNET baseline is characterized by the SSP2 trajectory, a middle-of-the-road assumption for shared socio-economic pathways [57–59]. Under this trajectory, GDP growth and population growth in the world are facing medium-level challenges and the growth varies quite significantly across regions. GDP growth and population growth from 2014 to 2040 in the EU are moderate compared to the rest of the world. Within the EU, GDP growth is expected to be stronger in the EU13 countries, constituted by Central and Eastern European member states + Malta and Cyprus, than in the EU14 countries (or so-called old member states). This GDP growth trend contrasts with the assumed population growth trend, as population growth, on average, is anticipated to be positive in the EU14 and slightly negative in the EU13. As will be shown later, these structural differences in socio-economic drivers would affect the projected results accordingly.

Concerning the investment modelling, the initial capital stock values per sector were calibrated from shares in capital income obtained by GTAP. This corresponds well to the decomposition of capital stock per sector obtained by EU KLEMS Productivity and Growth Accounts [60]. KLEMS is based on the NACE 2 industry classification and the new European System of National Accounts ESA 2010. The baseline and scenarios are produced for simulation horizon from 2014 to 2050 in 5-year loops. As for the first period, capital stocks in 2020 are calculated from annual solutions over the period 2014–2020 to obtain the most precise update of capital stock. All baseline features are summarized in Table 3.

2.3.2. Scenario definition

Various sources discuss the required size of the investment budget to achieve climate neutrality in the EU. For instance Ref. [61], estimates that about €28 trillion would be needed in the next 30 years in the EU, from which 8.4 trillion would be required in the next decade. Out of this amount, investments in energy represent about 7 %, which is about €58 billion, i.e. $70 billion of investments annually. This compares well with the investment gap of €84 billion estimated by Ref. [13] and the investment gap of €80 billion in the power sector presented by the European Commission [62] as part of the European Green Deal plan (and an additional €30 billion in the electricity grid).

The translation of the estimated investment gaps in the renewable energy sector to MAGNET requires assumptions on the allocation of the budget across the focus EU member states and the green energy sectors. This study follows the approach of [13], who estimate the investment gap by increasing the investment-capital ratio in each of the sectors. An increase in investments of about $80 billion annually in the period 2020–2030 (including the investments in grid), corresponds to an additional 15 % capital stock increase in the green energy sectors and an additional 5 % increase in the electricity grid sector on the top of the existing investments. The analysis focuses on the second-generation biofuel sectors, bioelectricity and renewable energy sectors which play an important role in energy transition. Although the energy transition is largely based on electrification and a switch to renewable sources of electricity, the second-generation biofuels can also play a role if stimulated by additional capital investments [63]. For the subsequent decades, the green energy investments are further increased following the growth rate expected by Ref. [61]. This represents additional investments of $121 billion in the 2030–2040 decade and $170 billion in 2040–2050. Table 4 summarizes the investments that are implemented in addition to the normal baseline investments that would occur irrespective of climate-neutral policy.

Table 5 provides an overview of the relative importance of the implemented shocks expressed as a proportion of additional green investments to baseline investments per sector. For the green energy

Table 3
Description of baseline assumptions.

Baseline components	Assumptions
Time periods	2014–2020, 2020–2050 in 5-year periods
Exogenous drivers	Population, GDP growth and land-augmenting technical change [58]
Sector-specific investment allocation	Region level - GTAP, sector level -follows Tobin's Q (investment allocation based on rates of return)
Calibration of capital stock ($VKBa_{(a,r)}$) per sector	$VKBa_{(a,r)}$ for 2014 based on initial capital income distribution from GTAP, $VKBa_{(a,r)}$ updated based on simulated annual growth 2014–2020.
Learning-by-doing	Implemented in 9 green energy sectors and 3 fossil fuels sectors, learning rates from 0.05 to 0.32 based on [55,56]

Source: authors

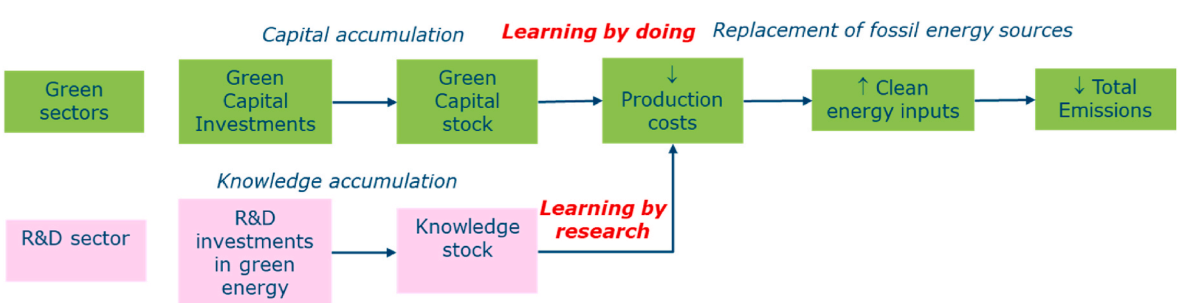

Fig. 4. Introducing productivity effects of green energy investments in MAGNET. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: authors

Table 4
Assumptions on annual additional EU green energy investments (million US$).

	2020–2030	2030–2040	2040–2050
Residues	2470	3360	4738
Ethanol	6	9	12
Hydroelectricity	14,052	19,118	26,956
Wind-Solar Electricity	35,356	48,103	67,826
Bioelectricity	4105	5584	7874
Pellets	87	119	168
Electricity distribution	32,963	44,848	63,236
Total “green energy” sectors	**56,076**	**76,294**	**107,574**
Total “green energy” sectors + electricity	**89,039**	**121,142**	**170,810**

Source: authors

sectors, the investment boost is considerable – on the aggregate EU level, additional investments in green energy sectors are 137 % of the original level. Note, however, that the relative value of investment shocks in Poland (71 %) and the ReEU13 countries (85 %) is considerably lower as compared to the old member states of the EU (the values up to 161 % in France). Here, due to the approach by Ref. [13], the lower value of existing capital stock in the former states negatively influences the amount of additional green energy investments (expressed in relative terms, their investment -capital ratio increases proportionally).

From the sector perspective, the growth rates are mostly above 200 % of the original baseline investments. However, in terms of the relative importance of the green energy sectors, the shocks are rather moderate. On average, the share of the green economy in total investments would increase from less than 2 %–5 %. The highest share would be in Spain (7 %) and the lowest in Poland (3 %).

An important aspect of green investments is the source of financing. As stated by Ref. [13], “the private sector’s poor performance in providing green infrastructure in the past casts doubt on whether this is the most effective way towards carbon neutrality”. The Authors consequently call for a large-scale publicly funded investment initiative to speed up the process of energy transition. The recent developments in the European Green Bond legislation are likely to assure the necessary funding in the next decades. Therefore, in the first scenario (GREEN BOND scenario) the green investments are funded through the issuing of green bonds. Under this scenario, an increase in green energy investments is possible without the crowding-out effect on the non-green investments, leading to an increase in total investments in the EU. Considering the long maturity time of the issued bonds which goes beyond the simulation horizon, the scenario does not account for the repayment of the funding costs over the simulation periods, i.e. by assuming that this debt will be paid by future generations [64]. On the other hand, it is supposed that the necessary private funds would come either from multinational energy companies willing to invest in the European market and/or global investors willing to buy European green bonds issued by private companies already operating on European market. In this sense, the vast majority of investment should be financed from abroad. Not surprisingly, the latter assumption implies a positive demand shock for European economy that may lead to “rosy” results. However, less favourable scenarios are also possible. Consequently, the study further explores two alternative scenarios, the CROWD-OUT scenario and the SAVE + CO2 scenario, where the financing costs are explicitly modelled. These alternative scenarios provide insight into how different financing sources may alter the impact of the green investments.

In the CROWD-OUT scenario, the additional investments in green sectors are possible as a result of a decrease in investment in all remaining sectors of the EU economy. This is an extreme negative scenario from a growth perspective as green investments fully crowd out other investment. In the SAVE + CO2 scenario, it is assumed that the green investments are partly funded from the existing national income (reflected through higher savings and lower government and household expenditures) and partly from additional CO2 taxes. The experiment is designed such that about 50 % of the green investment expenditures are covered by additional CO2 tax collections. The imposed CO2 tax, which is uniformly applied within the EU, is set to $30 per tonne of CO2eq in the period 2020–2025 and increases gradually to $90 per tonne of CO2eq in the last period (2040–2050). The CO2 tax is based on fossil fuel industries to (partly) address the negative externalities related to CO2 (polluters pay principle). This effectively means that the fossil fuel industries address part of their societal costs and partially finance the green transition. At this stage, revenues from the EU’s Carbon Border Adjustment Mechanism are not considered, but could be also included as an additional source of financing.

3. Results

3.1. Economic impacts of green energy investments and cross-sectoral spillovers

This section begins with the evaluation of the macroeconomic impacts of additional green energy investments considering three alternative sources of financing. Fig. 5 shows the impact on GDP growth rate, represented as % deviation from the baseline (blue dot), and GDP gains per dollar of green energy investment (green bar). Here, both the baseline and the policy scenario assume the existence of learning-by-doing in the green energy sectors only, learning-by-doing in the fossil sectors is considered as negligible.

The simulation results show positive impacts of green energy investments on GDP (right axis) under the GREEN BOND scenario, although there exist significant differences across the EU Member States.

Table 5
Relative importance of the green energy investments shocks in 2020 (%).

	ITA	ESP	FRA	POL	ReEU14	ReEU13	EU
Residues	235	198	256	170	270	170	**253**
Ethanol	237	199	255	171	269	172	**242**
Electricity Distribution	79	67	85	58	90	58	**151**
Hydroelectricity	237	200	258	171	272	174	**247**
Solar and Wind	237	200	258	172	271	174	**239**
Bioelectricity	238	202	260	175	273	178	**255**
Pellets	273	299	128	15	103	10	**86**
Total	**135**	**126**	**161**	**71**	**154**	**85**	**137**

Source: authors

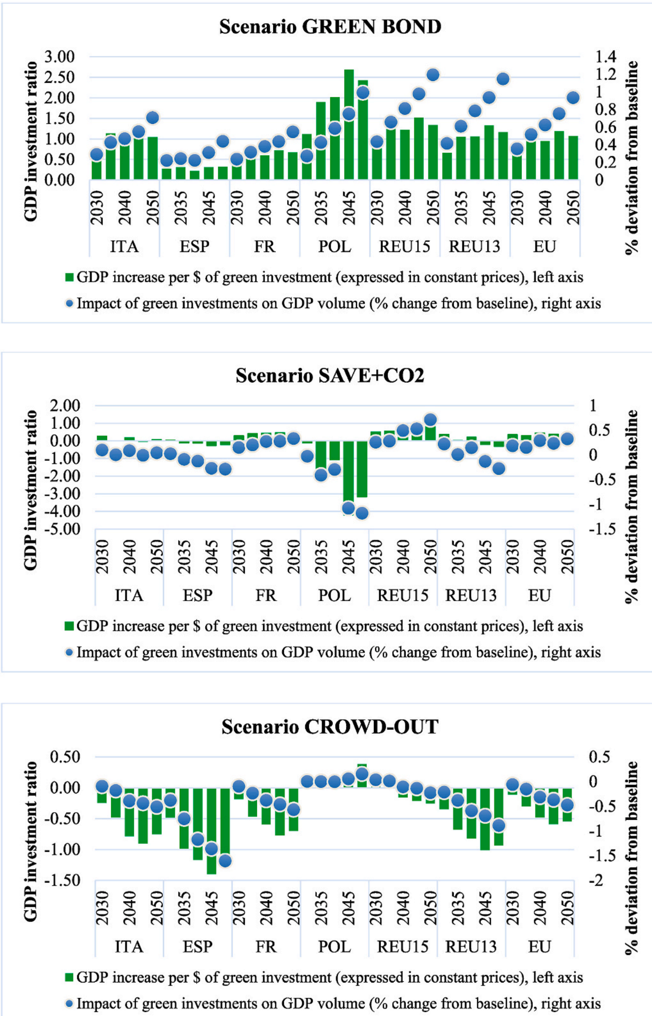

Fig. 5. (a,b,c): Impact of green energy investments on GDP (green investments are financed from extra investment budget). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Note: GDP/investment ratio was calculated as a ratio of absolute increase in GDP to an increase in investment volume in the previous period (as a difference from baseline).
Source: MAGNET results

The highest impacts are found for Poland and the rest of the EU (over 0.9 % and 1.2 % increase in GDP in 2050 as compared to the baseline, respectively). At the same time, the resulting GDP effects in France and Spain are much weaker (slightly over 0.5 % in 2050). Small deviation from baseline indicates low efficiency of green energy investments. Indeed, Spain experiences the lowest GDP/investment ratio that tops 0.32 in 2050 (left axis on Fig. 5). The highest efficiency is found in ReEU15 and Poland, with the GDP/investment ratio around 2.1 and 1.3 in 2050 respectively. Note that the GDP/investment ratios in France and Spain are below the EU average, most likely due to the relatively high share of green sectors in these countries. This, in turn, may suggest that the allocation of additional investment in green energy sectors based on the estimated investment gap would not be economically efficient [13].

In the SAVE + CO2 tax scenario, it is apparent that the economic benefits of green investments are reduced for Poland due to high burden of CO2 taxation on its energy sector. Contrary to that, France and the rest of the EU13 countries would still experience positive impact on GDP as their economies are less emission intensive.

In the least likely CROWD-OUT scenario, the impact of green investments on GDP volume is clearly negative, although limited at the aggregate EU level. The deviation from the baseline scenario does not exceed −0.5 % in 2050. There is some variation at the member state level, with Spain as the most negative one (with deviation from the baseline exceeding −1%) and Poland as the only big member state improving its situation as compared to the baseline (by less than 0.3 %). This suggests that in Poland, shifting the investment mix in favour of the green energy sectors can be economically beneficial even without additional funding sources, provided that fossil fuel sectors are not charged for the green transition.

Table 6 shows the impacts on gross value added (GVA) in the key sectors of the economy. The impact of green energy investment on different sectors is very heterogeneous across countries. As expected, green energy sectors increase their GVA notably across all scenarios. The scenario with additional CO2 taxes would lead to a faster green transition, with fossil fuel sectors' GVA falling by 33 % in 2050 and green energy sectors increasing by 212 %, compared to about 14 % and 145 % respectively in the scenarios without CO2 taxes. It is also found that the remaining sectors of the economy are better-off as well. This can be interpreted as a positive multiplier effect of green energy investments on the rest of the economy, particularly industry and services. However, if green investments are not funded from additional sources, the positive spillover effects are not realized as value added in industry and services is expected to decline at the expense of green sectors' expansion. The reduction is nevertheless rather marginal (about 1 % decline compared to baseline).

Table 7 shows the impact of green energy investments on the growth of GVA in particular bioeconomy sectors in 2050. It is observed that the bioeconomy as a whole is growing faster, showing that an increase in investment in green energy sectors would have a positive impact on the EU's bioeconomy. For the EU as a whole, the aggregate deviation from the baseline in 2050 is 3.2 % (up to 4 % under additional CO2 taxes). The main exceptions are some of the meat sectors (e.g., poultry sector, pig and other animal products or beef meat), vegetable oils and fats, plantation, and biogasoline. In general, the increased demand for bioeconomy sectors raised demand for resources such as the specific production factor land and therefore raises land prices and this induces some sectors decline as their output prices becomes higher. In the case of bio gasoline, its relative decline is due to the increased competition from the green energy sectors and brings along a reduced demand for primary agricultural resources such as wheat. Concerning plantations, under the increased productivity of bioelectricity, residues and pellets sectors the demand for plantations is reduced and this is reflected in the significant drop of their production. Still, on average, the difference between the baseline and the policy scenario in the agri-food sectors is on average rather small.

3.2. Emission-saving impacts of green energy investments

The emission-saving effects of green energy investments measured as a percentage difference from the baseline scenario increase over time. While the results for the CROWD-OUT and the GREEN BOND scenario project a reduction of emissions of about 8 %, for the SAVE + CO2 tax scenario, emission savings are much more substantial, with projected decline of −22 % and for Poland up to −37 % (Fig. 6a). The CO2 taxation seems thus an effective instrument to significantly speed-up the energy transition, with some accompanying worsening economic impacts in countries like Poland. Evaluating the emission reduction with respect to the required green investment provides a measure of abatement cost, i.e. the cost of green investment required per one tonne of emission reduction. The average abatement costs per 1 tonne of reduced CO_2eq top about $400 but are considerably lower with additional CO2 taxes ($160). Still, there exist significant differences between countries. In Poland abatement costs per tonne of CO_2 are around $100 and decline sharply (about $70 in 2050), whereas in France they are more than forty times higher and exceed $3200 by 2050. This is due to the differences in

Table 6
Impact of alternative scenarios on value added (% changes compared to baseline).

% Change in GVA in Selected EU MSs and regional aggregates in 2050							
	ITA	ESP	FRA	POL	ReEU15	ReEU13	EU
Scenario GREEN BOND							
AGRI_PRIM	0.2	-0.3	-0.3	0.1	0.0	0.1	-0.1
AGRI_PROC	0.0	-1.3	-1.5	0.0	-0.3	0.1	-0.6
OTHER_PRIM	0.0	-0.6	-0.7	0.2	0.6	0.1	0.2
GREEN ENERGY SECTORS	143.0	103.7	169.5	143.0	161.6	141.4	145.4
FOSSIL	-12.7	-38.5	-23.4	-8.4	-11.4	-16.7	-14.3
INDUSTRY	0.4	2.9	0.9	0.5	0.5	0.7	0.8
SERVICES	0.7	0.1	0.2	0.6	0.7	1.3	0.6
TOTAL	1.3	1.3	0.7	0.8	1.2	2.0	1.2
Scenario SAVE+CO2							
AGRI_PRIM	0.5	0.2	0.3	0.4	0.3	0.5	0.4
AGRI_PROC	0.6	0.4	0.3	0.8	0.5	-0.3	0.4
OTHER_PRIM	0.3	1.1	0.5	-0.3	0.9	0.1	0.6
GREEN ENERGY SECTORS	225	163.3	178.7	255.6	256.7	176.3	212
FOSSIL	-29.6	-63.5	-24.4	-49	-22.2	-51	-33.8
INDUSTRY	1.2	3.6	2.3	0.9	0.9	0.9	1.3
SERVICES	0.6	-0.1	0	0.2	0.7	0.5	0.4
TOTAL	1.6	1.9	0.9	0.2	1.5	1.3	1.4
Scenario CROWD-OUT							
AGRI_PRIM	0.1	-0.5	-0.3	-0.1	-0.2	-0.4	-0.2
AGRI_PROC	0.0	-1.7	-0.8	-0.4	-0.3	-0.5	-0.6
OTHER_PRIM	-0.6	-1.2	-0.9	0.3	-0.8	-1.1	-0.8
GREEN ENERGY SECTORS	135.1	100.2	171.6	144.5	159.9	141.1	143.3
FOSSIL	-12.9	-39.9	-24.7	-8.7	-12.7	-17.9	-15.4
INDUSTRY	-1.1	-0.8	-0.7	-0.4	-1.2	-1.7	-1.1
SERVICES	-0.4	-1.6	-0.8	0.1	-0.5	-0.4	-0.6
TOTAL	0.1	-0.6	-0.3	0.1	-0.1	0.2	-0.1

the structure of energy sectors in both countries and initial emissions level. In fact, France has currently the lowest level of emissions with over 70 % of electricity generated from nuclear power in 2020 (followed by hydropower with more than 11 % share). Therefore, the potential for emission savings via a decarbonizing energy sector is lower. At the same time, Poland still relies on energy generated from coal power plants (over 70 % in 2020). From this point of view, the emission saving efficiency of green energy investments in country such as France is more than doubtful.

The breakdown of emission saving per sector (Table 8) provides further insights. It is found that the decarbonisation effect of green investments is not only resulting from the reduction of fossil sectors but also by reducing carbon footprint in industry, which is more pronounced with the CO2 tax scenario.

The largest emission reduction is produced by the decline of coal (−30.6 %), followed by gas (−16.5 %) and gas distribution. From the sector perspective, the fossil sectors contribute the most to emission saving from fuel use, followed by industry. In relative terms, the largest emission saving is expected in the countries of EU-13 and Spain, with additional CO2 taxes, the reduction is also noticeable in Poland. These countries thus exhibit both high economic and emission efficiency of green investments. Not surprisingly, in the case of France, additional green energy investments contribute comparatively less to emission saving. This is mainly due to the high share of nuclear power and hydropower in energy generation. The role of coal power plants is marginal compared to, for instance, Poland which despite low amount of additional investment experiences relatively high emissions reduction (up to −36 % in the SAVE + CO2 scenario).

3.3. *Social impacts of green energy investments*

The MAGNET model provides several indicators that can be used to verify the social impacts of investment policies. The results are mostly positive as real wages, food and energy security improve. If financed from the Green Bond, green energy investment would lead to an increase in real wages in the EU, for both unskilled (2.3 %) and skilled (1.6 %) workers. This is a result of an interplay of several factors, from the output side, capital stock deepening leads to a higher marginal product of labour and thus higher returns to labour. From the demand side, the investment boost stimulates the demand for domestically produced investment goods which are labour-intensive (such as construction and services sectors). As shown in Table 9, the highest rise in salaries is expected in Spain, the lowest in Poland and France. Because wages of unskilled labour would grow faster, the wage disparity between skilled and unskilled professions is reduced. This, in turn, should lead to a decrease in overall income inequality.

The social impacts of green energy investments are even more pronounced when looking at energy security and poverty. Table 9 shows that energy prices would decline notably (more than 10 %) compared to the baseline, which leads to a decrease in expenditures on energy. This is mostly driven by cheaper electricity. Expressed relatively, the ratio of unskilled wage in agriculture (taken as proxy to the lowest household income group) to the energy price index would increase by about 14 % on average). However, in specific cases, particularly when CO2 taxes are applied, countries such as Poland or the Rest of EU 13 would see negative impacts due to a reduction in real wages as well as worsening access to energy compared to the baseline. It is also interesting to note that even under the crowding-out scenario, the social effects of green

Table 7
Impact of alternative scenarios on value added of bioeconomy sectors (% deviation from baseline).

	GREEN BOND	SAVE + CO2	CROWD-OUT
Bioelectricity 2nd gen	257.7	272.1	258.4
Residue sector	256.0	261.8	257.5
Ethanol 2nd gen biofuels	101.4	103.6	101.1
Pellet sector	45.4	48.2	45.5
Polyethylene bioplastics	17.1	16.4	14.2
Fisher-Tropsch 2nd gen biofuel	10.8	10.8	9.2
Processed rice	5.8	26.4	−13.0
Traditional bioplastics	5.7	3.5	3.2
Paddy rice	1.7	6.9	−3.7
Ligno sugar	1.3	−2.0	−2.2
Polylactic acid bioplastics	0.8	0.1	−1.7
Beef meat	0.8	−1.1	1.5
Aquaculture	0.8	0.3	−0.2
Forestry	0.5	0.8	−0.7
Wheat	0.3	0.1	0.2
Cereal grains nec	0.2	0.6	0.0
Raw milk	0.1	1.0	0.0
Cattle sector	0.0	0.3	0.1
Crops nec	0.0	0.0	0.0
Other agriculture	0.0	−1.1	0.0
Oil seeds	0.0	0.4	0.0
Vegetables, fruit, nuts	0.0	0.3	0.1
Biodiesel	−0.1	6.5	−3.0
Sugar cane, sugar beet	−0.2	−0.9	−0.4
Dairy products	−0.3	1.5	−0.1
Crude vegetable oil	−0.3	1.1	0.1
Other meat product nec	−0.3	0.1	−1.0
Wool, silk-worm cocoons	−0.4	−0.8	0.0
Poultry sector	−0.4	0.3	−1.1
Pig and other animal product	−0.5	0.2	−1.1
Poultry meat	−0.5	0.3	−1.2
Sheep, goats, horses	−0.5	1.1	−1.2
Sugar and molasses	−0.6	−1.9	−0.5
Wild fish	−0.6	0.3	−1.0
Processed food	−0.7	0.1	−0.5
Meat: other cattle, sheep, goats, horse	−1.2	1.9	−1.6
Animal feed	−1.2	0.5	−1.2
Fish processing	−1.4	0.2	−0.9
Vegetable oils and fats	−1.9	1.8	−1.2
Biogasoline	−4.9	2.2	−6.2
Plantation	−49.8	−48.4	−50.3
Bioeconomy total	**3.2**	**4.2**	**3.1**

Source: MAGNET results

investments are mostly positive as moderate increase in real wages, improvement in food and energy accessibility would be still observed.

3.4. *The role of technology learnings in speeding-up green transition – sensitivity analysis*

The economic and emission-saving effects of green energy investments are also affected by the assumptions concerning technology learning. Note that the three financing scenarios assume the possibility of learning-by-doing in the green energy sectors only (additional simulations were performed where technology learnings were included also in the fossil fuel sectors - the learning rates for fossil sectors were assumed to be 0.06 for coal, 0.10 for natural gas and 0.05 for nuclear energy - but no significant differences in the results were observed).

Fig. 7 compares GDP and emission-saving effects induced by additional green investments with and without technology learnings. It appears that technology learning enhances the positive GDP impacts of green investments in the Green Bond scenario (+0.9 % vs +0.6 % without technology learning), they prevent negative GDP effects in the SAVE + CO2 scenario and mitigate GDP decline under the crowding-out scenario.

Technology learning effects are even more important for emission savings. Here, the scenarios assuming additional green energy investments with technology learning roughly double the speed of the emission reduction in the Green Bond scenario. That confirms that technology learning effects are important enablers of the substitution from fossil to green sources of energy. Without technology learning, the additional capital does not create a similar productivity boost of green energy sectors and slows down the energy transition from fossil to clean energy. Only in the scenario with additional CO2 tax collection the role of technology learning is less significant as the CO2 tax provokes already significant emission saving effect. It is also noted that the effect of technology learnings on emission reduction becomes more pronounced in the longer run while the CO2 taxes achieve a decline in emissions practically immediately.

4. Discussion

The simulated increase in investments in green energy sectors (additional 15 % increase in capital stock since 2025) corresponds roughly to the estimates available in the literature. It is found that additional green energy investments lead to reduced emissions, and these are highest when the investments are partly paid by CO2 taxes. The GDP effects might be positive as in the case of green bonds, small as in the case of SAVE + CO2 and a bit negative in case of the crowding-out scenario. In the case of GDP, cumulative deviation from the baseline reaches 0.9 % in 2050 for the EU as a whole in the Green Bond scenario. Still, there are significant differences across member states. The results are comparable to Ref. [15] but considerably smaller than multipliers estimated by Ref. [14]. The latter study used a time series approach, which did not account for the possibility of substitution between capital

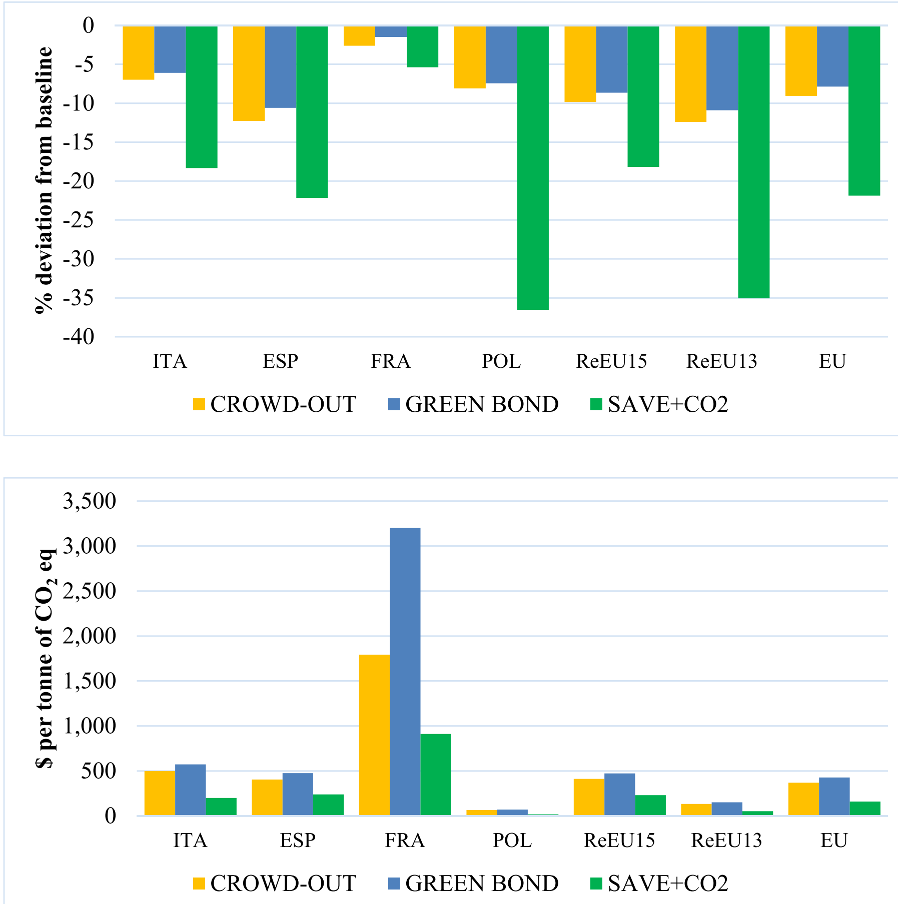

Fig. 6. (a,b): Impact of green investments on total emissions (% diff. from baseline) and costs of green investments per tonne of emission saving. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Note: Abatement cost is measured as a division of emission saving to increase in investment in the previous period (compared to baseline).
Source: MAGNET results

and other production factors. Such an omission most likely leads to an overestimation of multipliers. In fact, it is found that, a 1 % increase in green energy investments results, on average, in a 0.4 % increase in GDP of the targeted energy sectors.

The emission-saving effects of green energy investments measured as a percentage difference from the baseline scenario increase over time. The average abatement costs per tonne of reduced CO_2eq top at almost $350. In the literature, the abatement costs per tonne of reduced CO_2eq are around $100/tonne of CO_2eq and vary per technology [65]. Yet, this study shows that abatement costs in certain countries such as France can be very high due to their initial energy mix. This in turn negatively influences average abatement costs for the entire EU. Furthermore, due to the different energy mixes in EU member states, there are important differences across the EU regions, with Poland and the rest of EU-13 having the highest efficiency of green investments (measured as GDP increase/investment ratio and emission reduction). A sensitivity analysis of varying assumptions on financing and technology learnings shows that if green investments are realized at the expense of the other baseline investments (without additional funding), GDP impacts can be negative although almost negligible. This may suggest that private sector initiatives to stimulate the green transition are not sufficient and additional public spending needs to be promoted to achieve climate neutrality in countries such as France, Spain and ReEU15. This is also in line with the other cited references that highlight the positive role of green investments if they are debt financed. The assumptions on technology learnings have an important impact on the resulting emission savings and substitution of fossil by renewable energy sources. They also influence the competition among the individual bioeconomy sectors and their resource providers, such as plantations and forestry. However, in terms of the magnitude of emission reduction, it is apparent that emission reduction relying solely on technology learning in green energy sectors is less impactful compared to the situation where fossil fuel sectors are directly targeted with CO2 taxes.

5. Conclusion

This study provides novel insights into the economic, social and emission-saving impacts of green energy investments on the EU's economy. Although various policy and scientific references call for an investment-stimulated transition towards climate neutrality, the literature that explains the economic and emission effects of such investments in a holistic framework is still scarce. This research addresses the existing literature gap through extending the general equilibrium model MAGNET with additional features that allow for assessing such multi-dimensional issues. The added features include sector-specific investment allocation, investment risk premiums adjustment to achieve a desired investment mix and technology learning effects to endogenize productivity growth in renewable and bioenergy sectors. Several scenarios that explore the impacts of alternative financing options were analysed to gain insights into different options of the investment-induced multi-dimensional impacts when the financing costs are taken into consideration.

The main findings can be summarized as follows:

Table 8
Emissions in CO_2 Equivalents in 2050 (% diff. from baseline) – EU detail – alternative scenarios.

	Split by selected Member States, Regions						EU	Split by selected Sectors			
	ITA	ESP	FRA	POL	ReEU15	ReEU13		Agri_Prim	FOSSIL	INDUSTRY	SERVICES
Scenario GREEN BOND											
Total	-6.1	-10.6	-1.5	-7.4	-8.7	-10.9	-7.9	-0.1	-31.9	-3.5	-0.3
c_oil	5.5	-1.3	0.3	0.5	0.8	-38.5	-16.2	0.0	-16.7	0.0	0.4
petro	5.1	2.5	0.8	0.4	0.7	1.4	1.4	0.0	-1.4	-5.1	0.4
gas	-18.6	-21.1	-5.4	-6.2	-20.1	-12.1	-16.3	-0.1	-51.4	-6.0	-6.7
coa	-31.3	-55.0	-48.6	-13.6	-46.6	-28.1	-30.9	0.1	-34.9	-6.7	-3.0
gas_dist	-13.9	2.7	2.5	-1.6	-9.1	-3.7	-5.9	0.0	-49.5	-6.0	-5.5
Act	0.2	-0.4	-0.5	-1.9	0.1	-0.2	-0.3	-0.2	-4.0	0.3	0.0
Scenario SAVE+CO2											
Total	-18.3	-22.2	-5.4	-36.5	-18.2	-35.0	-21.9	0.7	-74.6	-16.5	-3.1
c_oil	0.9	-10.9	-5.5	-9.1	-5.2	-41.0	-21.1	0.3	-21.7	-1.5	-12.2
petro	3.5	-3.3	-3.4	-4.8	-2.9	-4.1	-2.7	0.2	-10.9	-22.8	-2.5
gas	-35.1	-34.7	-13.7	2.4	-32.3	-21.9	-28.3	0.2	-72.5	-27.2	-8.7
coa	-92.0	-95.2	-59.2	-61.7	-88.5	-87.2	-79.9	0.6	-89.6	-16.6	4.0
gas_dist	-35.5	-7.2	-3.2	-1.7	-17.6	-15.9	-14.1	0.3	-64.9	-26.7	-4.0
Act	-2.3	-1.8	-0.6	-24.2	-1.1	-7.2	-4.5	0.7	-37.5	-3.4	-3.5
Scenario CROWD-OUT											
Total	-7.0	-12.2	-2.6	-8.1	-9.8	-12.4	-9.1	-0.3	-32.6	-4.9	-1.7
c_oil	4.6	-2.7	-0.7	-0.2	-0.4	-39.7	-17.3	-0.1	-17.8	-1.0	-1.0
petro	3.6	0.5	-0.7	-0.3	-0.7	-0.2	-0.1	-0.1	-2.5	-7.1	-0.9
gas	-18.0	-23.1	-7.2	-7.3	-21.5	-14.0	-17.5	-0.5	-50.8	-7.7	-9.0
coa	-34.1	-56.4	-48.7	-14.2	-47.6	-29.5	-32.0	-0.1	-36.0	-8.1	-4.4
gas_dist	-13.6	0.4	0.4	-3.7	-10.7	-5.7	-7.6	0.0	-49.4	-7.6	-7.2
Act	-0.4	-1.2	-0.6	-1.9	-0.6	-1.4	-0.9	-0.4	-4.1	-0.3	-1.1

- The GDP effects of green energy investments depend on the financing options. They might be positive as in the case of European Green Bonds, small if part of the investments is paid by CO2 taxes and a slightly negative when green investments crowd out other investments.
- Irrespective of the financing option, green energy investments reduce emissions and provide positive social spillovers in terms of higher real wages, improved energy and food security on the aggregate EU level. They also have a positive impact not only on renewable energy sectors but also on the bioeconomy as a whole. They can thus be seen as an attractive investment option with positive sustainability impact. This is an important insight in the context of the European Green Deal's objective of a just transition.
- The main aim of the green investments is the reduction in CO2 emissions. While the results for the CROWD-OUT and the GREEN BOND scenario project a reduction of emissions of about 8 %, emission savings are much more substantial in the SAVE + CO2 tax scenario (−22 %). The CO2 taxation thus seems an effective instrument to significantly speed up the energy transition, with some accompanying worsening economic impacts in countries like Poland. However, CO2 taxes induce higher energy and food prices which might induce some negative social impacts.
- The impacts, including on macroeconomic growth and on emissions reduction, are scenario dependent and vary greatly across the EU's member states. The highest returns on investments are observed in countries with high energy intensity.
- Technology learning is crucial for the emission saving effect of green investments, and also enhances positive GDP effects. Furthermore, it is found that in combination with additional CO2 taxes, emission reduction is much stronger leading to faster green transition.

There are several policy recommendations that can be derived from the above insights from the modelling exercise. Firstly, green investments reduce CO2 emissions at rather low economic costs or even with low economic benefits. Instruments supporting green energy investments should be stimulated to prevent crowding-out effects. In this respect, the Green Bond Regulation is a well targeted instrument to have in place that enables reaching the positive impacts of green investments that are quantified in this study. However, there is a need to identify barriers or potential challenges that are relevant to the implementation of various policies to promote green investment. In addition to the Green Bond Regulation the already existing European Emissions Trading System (ETS) is based on a uniform CO2 price across the EU member states. CO2 taxes can represent an effective policy instrument to stimulate the green transition, but their implementation should be carefully designed to prevent too drastic negative economic and social effects in countries with high emission intensity. As the results showed, the efficiency of green investments in terms of GDP gains per one dollar of investment varies importantly across the EU member states. When allocating the green investments, from a purely economic perspective, priority of funding could be given to locations with the highest expected rate of return, which are countries with higher emission-intensity of their economy. A policy design that equilibrates rates of returns across countries leads to a higher efficiency and lower economic cost per tonne of CO2 reduction.

With a view to "The Future of European Competitiveness" [67] it is in fact recommended to level the energy taxation playing field and the strategic use of taxation measures to reduce the cost of energy. From a fairness point of view, part of the CO2 taxes or other taxes could be used to compensate negative social effects by providing compensation payments. A balanced policy package is needed to achieve a variety of economic, environmental and social targets. Not by chance the above cited so-called Draghi report [67] stresses the need for better coordination between national and EU efforts, combining multiple policies in

Table 9
Impact on social indicators in 2050 (% changes compared to baseline).

	Real wages		Food Security Indicators			Energy Security Indicators		
	Unskilled Labour	Skilled Labour	Food Consumption Volume	Consumer Food Prices	Food Access	Household Energy Expenditures	Consumer energy prices	Energy Access
GREEN BOND								
ITA	2.4	1.7	1.4	0.2	3.9	0.0	-7.4	12.1
ESP	3.1	1.7	1.0	0.3	4.9	-0.8	-7.8	13.6
FRA	2.0	1.2	1.2	0.5	3.8	0.5	-8.0	12.5
POL	2.1	1.8	1.2	0.1	2.4	-2.2	-9.0	12.4
ReEU15	2.1	1.6	1.1	0.1	2.6	-1.0	-14.9	20.5
ReEU13	3.2	2.5	1.1	0.1	3.8	-2.6	-9.3	14.3
EU	2.3	1.6	1.2	0.2	3.4	-0.8	-11.4	16.7
SAVE + CO2								
ITA	1.2	0.5	-0.7	-1.2	2.2	-3.1	-5.2	6.0
ESP	1.0	-0.2	-2.6	-1.2	1.6	-5.5	-3.6	3.4
FRA	0.5	0.0	-1.2	-1.2	0.8	-3.8	-7.3	7.0
POL	-3.1	-2.9	-1.5	-1.4	-1.3	6.9	26.6	-23.3
ReEU15	0.9	0.4	-0.8	-1.2	1.4	-3.9	-11.6	12.9
ReEU13	-0.2	-0.9	-1.6	-1.2	0.4	-3.2	0.0	-1.3
EU	0.6	0.1	-1.2	-1.2	1.1	-3.4	-6.7	6.6
CROWD-OUT								
ITA	0.6	0.4	0.0	0.0	1.3	-1.9	-7.8	9.9
ESP	0.2	-0.3	-0.9	-0.9	1.0	-3.4	-8.3	10.4
FRA	0.1	-0.1	-0.5	-0.5	0.4	-1.9	-8.7	10.1
POL	0.5	0.6	0.1	0.1	0.2	-4.0	-9.8	11.1
ReEU15	0.4	0.3	-0.4	-0.4	0.4	-2.8	-15.2	18.7
ReEU13	0.7	0.6	-0.4	-0.4	0.8	-5.0	-9.7	11.7
EU	0.4	0.2	-0.4	-0.4	0.6	-2.8	-11.9	14.5

Note: *Food Consump*. refers to food consumption volume, *Food access* is calculated as a ratio of wage of unskilled labour to cereal price index and *Energy access* is calculated as unskilled labour wage to energy price index.

an efficient way.

The question of how to finance the green investments is beyond the scope of this article, but it is certainly a major challenge as the investment share in Europe would have to increase by around 5 % of GDP to digitalise and decarbonise the economy [67]. The scaling back of the persistently high fossil fuel subsidies are one potential source for the financing which would not only generate revenue, but also reduce air pollution, and make a major contribution to slowing climate change [68].

With respect to the limitations, the analysis includes a Green Bond scenario where the financing of green energy investments comes from abroad which is broadly in line with the EU's green bond legislation. However, the limitation in this scenario is that it does not account for the repayment of the issued green bonds due to the nature of their long expiry which is beyond our simulation horizon. Also, the scenario does not factor in possible interest payments associated with the bonds issuing. To address the limitations in this scenario, we introduce two additional scenarios, CROWD-OUT and SAVE + CO2, to account for the potentially associated costs in financing green investments. The impacts resulting from these additional scenarios can be interpreted as the lower bounds of the Green Bond scenario since the financing costs in these scenarios are recovered well before the bond matures as required in the Green Bond scenario.

Future research should focus on incorporating the ownership of foreign assets and liabilities to account for foreign capital income gains from green investment financing. The positive result of real wage increase should be further explored in a framework which allows modelling unemployment. More research should be also devoted to the parameters guiding technology learning processes – particularly the impacts of R&D in energy technology should be investigated to help parametrize learning curves in the models. This would also help strengthen the technology learning effects which are relatively moderate in the current model since insufficient evidence in the literature restricts us from including the learning-by-research component.

There appears to be a need for further analysis using an integrated tool-box approach that could provide more insights into the impacts of the green transition on the food system. Extending the investment modelling, as developed in this study, to the analysis of the food system transition can address how private and public investments in innovation, green infrastructure, and knowledge transfer lead to a more

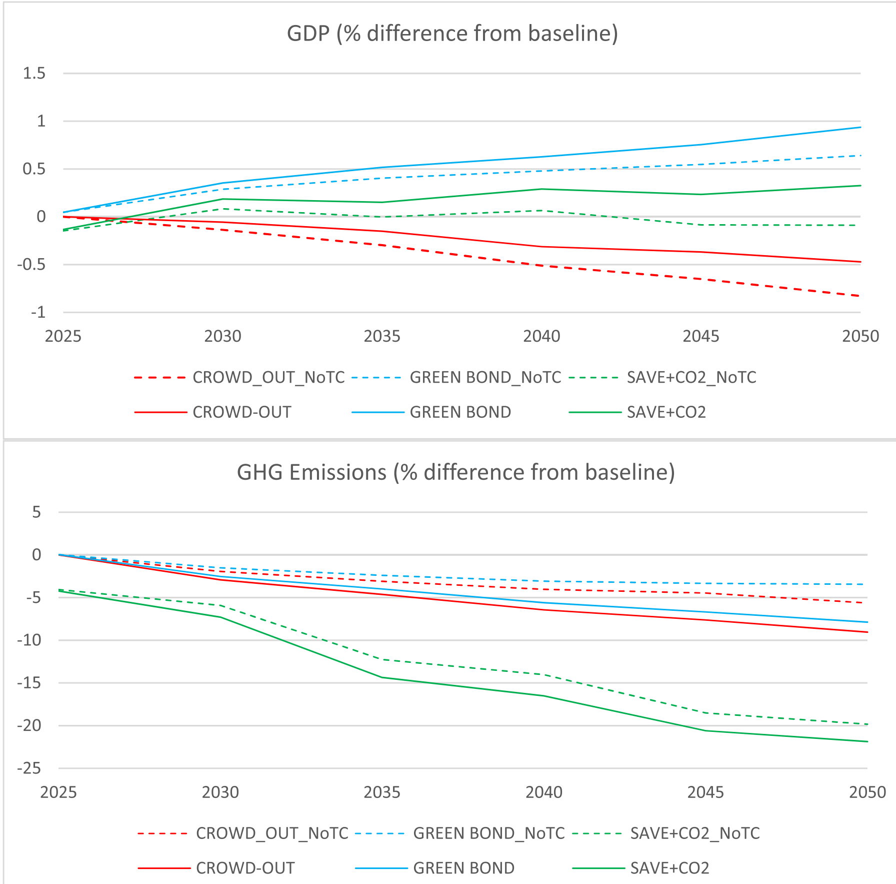

Fig. 7. (a,b): Impact on EU's GDP and GHG emissions under different technology learning assumptions.
Note: Scenarios "No_TC" assume no technology learning (learning rates are set to zero).
Source: MAGNET results.

productive, sustainable, and resilient food systems [66,67].

CRediT authorship contribution statement

Z. Smeets Křístková: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **H.D. Cui:** Methodology, Software, Formal analysis, Writing – review & editing. **B. Rokicki:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **R. M'Barek:** Conceptualization, Writing – original draft, Funding acquisition. **H. van Meijl:** Funding acquisition, Supervision, Writing – Review. **K. Boysen-Urban:** Conceptualization, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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