Technological Forecasting & Social Change 90 (2015) 166–177

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

The implications of initiating immediate climate change mitigation — A potential for co-benefits?

Valeria Jana Schwanitz [a,*], Thomas Longden [b], Brigitte Knopf [a], Pantelis Capros [c]

[a] Potsdam Institute for Climate Impact Research, Telegraphenberg A 31, Postfach 60 12 03, 14412 Potsdam, Germany
[b] Fondazione Eni Enrico Mattei (FEEM), Euro-Mediterranean Centre for Climate Change (CMCC), Palazzo Delle Stelline, Corso Magenta 63, 20123 Milan, Italy
[c] National Technical University of Athens, 42 Patission Str., 106 82 Athens, Greece

ARTICLE INFO

Article history:
Received 1 February 2013
Received in revised form 3 December 2013
Accepted 7 January 2014
Available online 1 February 2014

Keywords:
Climate policy
Energy modeling
Integrated assessment
Fragmented climate action
European Union Roadmap
Co-benefits

ABSTRACT

Fragmented climate policies across parties of the United Nations Framework on Climate Change have led to the question of whether initiating significant and immediate climate change mitigation can support the achievement of other non-climate objectives. We analyze such potential co-benefits in connection with a range of mitigation efforts using results from eleven integrated assessment models. These model results suggest that an immediate mitigation of climate change coincide for Europe with an increase in energy security and a higher utilization of non-biomass renewable energy technologies. In addition, the importance of phasing out coal is highlighted with external cost estimates showing substantial health benefits consistent with the range of mitigation efforts.

1. Introduction

Within documents related to the Doha Climate Change Conference in November 2012, "grave concern" was noted as there is still a "significant gap between the aggregate effect of Parties' mitigation pledges … and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2 °C" (UNFCCC, 2012a [27,13]). Fragmentation is a suitable description of global climate policy action as countries follow their own policy agendas. On the other hand, a topical case of a region leading the way by initiating more stringent climate action is the European Union and the implementation of the "Roadmap for moving to a competitive low-carbon economy in 2050" (short: EU Roadmap). Within this Roadmap both immediate mitigation efforts and large-scale reductions of emissions by 80–95% below emissions in 1990 have been proposed, refer to [9]. Alas, pioneering with mitigation efforts in a world of fragmented climate policies leads to a question of whether initiating significant and immediate climate change mitigation can support the achievement of other non-climate objectives. More specifically, we ask whether such co-benefits exist regardless of how the rest of the world responds to Europe's pioneering action.

Using the results from eleven global integrated assessment models (IAMs), we focus our analysis on potential co-benefits connected with energy security and air pollution. With respect to energy security, we study the development of import dependence on fossil fuels as well as the impact on Europe's bill for oil and gas. We also review energy diversity indicators (Section 3.1). Regarding, the side-effects of climate change mitigation efforts on air pollution (Section 3.2), we review whether external costs avoided in the electricity sector are sizable in comparison to the overall policy cost. In addition, we highlight the sources of the greatest potential co-benefits which underlie the sectoral estimates with a focus on eight different energy sources (including nuclear, a range of renewable energies (RE), coal, oil, and gas).

To test the robustness of co-benefits across varying mitigation efforts in a fragmented world, we analyze different climate

---

* Corresponding author.
E-mail address: schwanitz@pik-potsdam.de (V.J. Schwanitz).

http://dx.doi.org/10.1016/j.techfore.2014.01.003

policies which have been implemented by eleven IAMs, refer to Kriegler et al. of this issue [20]. In particular, we look at the following subset of scenarios with a focus on the European Union:

- *Fragmentation — RefPol*: Countries have their own agenda and follow more or less stringent climate policies. This scenario is an extrapolation of unconditional climate policies that are currently in place based on the Copenhagen Pledges.
- *Concerted action — CF450*: The world jointly commits to a 450 ppm target with flexibility allowed in the models' response to the target in terms of the timing of emission reductions.
- *Inspiration — 450P-EU*: The European Union pioneers with more stringent climate policies as foreseen in the EU Roadmap 2050. Inspired by this early action, the world makes a transition to a global emission reduction path consistent with a 450 ppm target.
- *Disillusion — RefP-EUback*: The European Union pioneers with its Roadmap 2050 but does not succeed in inspiring the world to follow, the EU then returns to the less stringent climate policies of the fragmented world from 2030.
- *No policy case — Base*: Countries do not follow any climate policies, and hence, the shadow price of greenhouse gas (GHG) emissions is zero.

Studies related to ours are [4,11,12,18]. Knopf et al. [18] is a model inter-comparison exercise of the energy modeling forum, EMF 28, focused on EU 2020 and 2050 climate targets with a review of different technological futures. Their analysis of the EU Roadmap strategy suggests that a reduction of GHGs by 80% in 2050 is possible but challenging as strong cost increases take place from 2040. The authors also conclude that it is necessary to start the transformation of the energy system before 2030. References [11,12] are the official assessments carried out for the development of the EU Roadmap 2050. Capros et al. [4] discusses related energy projections of the scenarios used for the EU Roadmap 2050. Both studies are based on the model PRIMES.

In this paper we define co-benefits as a positive physical side effect of one policy (here climate policy) for another public policy objective (see also [8]). The following papers take up a similar discussion of climatic co-benefits as we do: in a single-model study McCollum et al. [23] find co-benefits in an increasing renewable energy (RE) deployment in terms of energy security and air pollution. Borenstein [2] discusses potential co-benefits of RE such as their contributions to alleviating externalities from fossil fuel burning, energy security improvements, reducing the vulnerability of energy market prices, and the creation of jobs. Due to various methodological shortcomings (e.g. the market value of electricity depends on time and location, the problem of how to account for variability) the author concludes that environmental co-benefits may be more important. Similarly, Edenhofer et al. [7] argue that a possible benefit of RE (as a decentralized energy option) is that they can play an important role in improving access to energy in rural areas. A note of caution should be raised as co-benefits should also be assessed in a more complex framework, i.e. taking account of competing public policy objectives, which to the authors' knowledge have not been completed to this date.

The paper is structured the following way. In Section 2, we introduce details of the scenario design and briefly review participating models. We also compare GHG emission reductions in these scenarios with those defined in the EU Roadmap 2050. In Section 3, we analyze co-benefit candidates as they were described above. The concluding section summarizes our findings on possible sources of co-benefits.

2. Europe's early action in a world of fragmented climate policies

In this section we provide details on the scenario framework and on participating models. We then study the consequences for the development of GHG emissions across the different scenarios. As expected the EU Roadmap 2050 implies more stringent climate policies in comparison to the unconditional Copenhagen Pledges which are the basis of the fragmented regional action scenario.

2.1. Scenario design

The current world with fragmented climate policies is characterized by diverse levels of ambition with respect to mitigating climate change. These are expressed in our scenarios with different targets across the globe for GHG emission caps and intensities, shares of RE in electricity production or final energy, and capacity targets for low carbon technologies (wind, solar, geothermal, and nuclear energy). Apart from these targets, which are based on a review of current climate policies, the development of GHG intensity rates from 2020 was projected reflecting current trends and planned policies.[1]

More specifically, the scenario 'Fragmentation' (short: RefPol) is an extrapolation of climate policies that are currently in place based on the unconditional Copenhagen Commitments and national/regional low carbon technology targets (if these exist). The European Union has a moderate GHG reduction target of 15% in 2020 with the aim of achieving a 20% share of RE in final energy by 2020. After 2020, we assume that the GHG intensity falls at least at 3% p.a. in the European Union. Fig. 1 also provides an overview of emission caps and constraints on the development of GHG intensities as imposed in other world regions. Assumptions in these regions concerning technology targets for RE shares and/or capacities for low carbon technologies are provided in [20]. Note, that neither emission trading between regions nor banking and borrowing are allowed.

As opposed to the fragmented climate policy action in different world regions, we also study scenarios of immediate 'Concerted action' where the world aims to stabilize atmospheric GHG concentrations at 450 ppm CO_2se. These constraints on GHG emissions are imposed for all sectors, incl. land-use change (short scenario name: CF450). The full basket of GHGs includes CO_2, CH_4 (GWP 25), N_2O (GWP 298), and F-gasses. Note however, that the model IMACLIM reports only CO_2 and the model POLES does not report N_2O and CH_4. To harmonize targets between models capturing different baskets of GHGs, models were provided with a cumulative carbon dioxide budget for the period 2000–2100 (1500 $GtCO_2$ and 2400 $GtCO_2$ for 450 and 550 ppm CO2e targets, respectively).

In scenarios 'Inspiration' (short: 450P-EU) and 'Disillusion' (short: RefP-EUback) the EU pioneers with more stringent

---

[1] Note that all climate policies have been implemented by means of equivalent regional taxes on GHG emissions' running auxiliary scenarios. These taxes represent the shadow price of the quantity instruments.

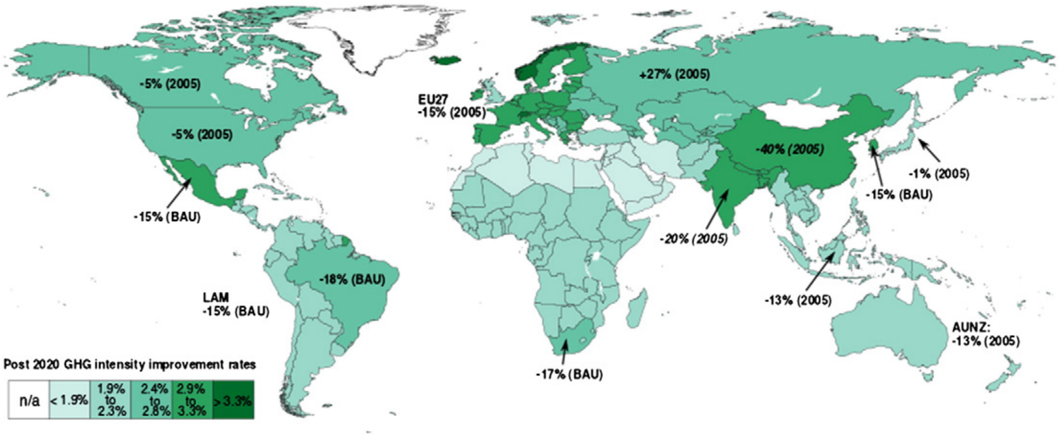

Fig. 1. Climate policies in the fragmentation scenario (RefPol) include caps for 2020 greenhouse gas emission/intensities for selected regions, targets for renewable shares, capacity targets for low carbon technologies, and projections of post-2020 greenhouse gas intensity improvement rates (see legend).

climate policies as foreseen in the EU Roadmap 2050 by targeting in GHGs a reduction of 20% in 2020 and 80% in 2050, with respect to 1990 levels. Note that land-use, land-use change and forestry sectors have been included in our study whereas they are not in the EU Roadmap. Regional carbon trajectories following from this design are used as an input for the period 2011–2030 in 450P-EU and RefP-EUback. Therefore, decisions under both scenarios are identical until 2030. From 2030 both scenarios, however, depart. In 450P-EU, inspired by the early action of the EU, the world makes a transition to a global 450 ppm path from 2030 onward. This is implemented in the models by a linear transformation of regional carbon taxes obtained in 2030 to carbon prices that are consistent with a global 450 ppm trajectory in 2050 (note that technology targets are included). Utilizing this scenario design means that foresight models can implement the scenario in a way where there is no anticipation of the transition to a concerted action. In the RefP-EUback scenario, the EU pioneering with its Roadmap 2050 does not succeed in inspiring the world to follow. The EU then returns to the less stringent climate policies of the RefPol from 2030. This is implemented by relaxing the EU carbon price to the carbon price of RefPol over the period 2030–2050. Again, the foresight models can implement the scenarios so that foreseeing the fallback of carbon prices is not possible.

Finally, we include a ‘no policy case’ in our scenario framework (short: Base). In this scenario, countries do not follow any climate policies, and hence, the shadow price of GHG emissions is zero. This acts as a baseline when reviewing co-benefits in Section 3.1 and calculating policy costs as well as external costs avoided within Section 3.2.

2.2. Overview on participating models

The scenario framework has been implemented by eleven global IAMs: four inter-temporal general equilibrium models (MESSAGE, MERGE-ETL, REMIND, and WITCH), three computational general equilibrium models (GEM-E3, IMACLIM, and WorldScan), and four partial equilibrium models (DNE21+, IMAGE, GCAM, and POLES). Differences across the models w.r.t. their economic coverage, assumptions on technologies and technical change as well as trade are provided in the Appendix, Table 5. A discussion of these differences is taken up in the following analysis. Models also differ in their regional resolution. The mapping of native model regions to the 27 EU member states is not exact for the following models: GCAM additionally includes EFTA and Turkey, while for IMACLIM and MESSAGE they are EFTA, Turkey, and former Yugoslavia. IMAGE as well as MERGE-ETL additionally includes EFTA and former Yugoslavia. DNE21+ does not include the Baltic States. These differences should be kept in mind throughout the paper.

Furthermore, as part of the AMPERE study, all models have harmonized their long-term population and GDP trajectories. Input for all models is based on the medium-fertility variant of the UN World Population Prospects Revision 2010 [29]. Regarding the development of economic growth, a medium growth scenario has been computed for GDP utilizing the method developed in [21] and also documented in [19]. In this scenario, technology leaders are assumed to grow at a medium rate and countries catch-up to their level of development at a medium speed of convergence. The assumptions on economic and population growth translate to a global GDP growth of about 3.5% in the period 2005–2050. It slows down at the EU-27 level from 1.7% growth to 1.5% by 2100. Scenario assumptions for the development in the EU are comparable to projections used by the European Commission.

Note that throughout Sections 2.3 to 3.1 we define that a cross-model result x is robust if

$$x = \frac{Q_3 - Q_1}{Q_2}, \quad \text{with} \begin{cases} x < 0.2 & \text{robust}, \\ 0.2 < x < 0.3 & \text{less robust}, \\ 0.3 < x & \text{mixed}, \end{cases}$$

where Q_3 is the upper quartile, Q_1 is the lower quartile, and Q_2 is the median. The ratio is also known as the robust coefficient of variation. Our choice in the definition of ‘robust’, ‘less robust’, and ‘mixed’ is somewhat arbitrary. It is, however, motivated by the numerical values obtained for harmonized population and GDP developments. Note that despite the harmonization, we see some variations across the models in these variables (0.07–0.12 and 0.03–0.07, respectively). This is caused by small differences in implementing the population and GDP growth scenarios (e.g. conversion of purchasing power parities to monetary exchange rates) and the aggregation of native model regions to the region that results in the best mapping to EU27. Thus, due to this inevitable spread, we define 0.2 as the threshold for robustness.

2.3. Emission reductions compared to EU Roadmap 2050

Having defined the scenarios, we first compare the RefPol and 450P-EU scenarios to the more common 450 ppm scenario at both, the global and EU levels. Across all models, RefPol shows higher GHG emissions at the global level in comparison to CF450. Regarding 450P-EU, one model (IMACLIM) did not find a feasible solution. For the other models 450P-EU is close to a 450 ppm path at a global level. In the case of Europe most models have GHG emissions in RefPol below Europe's path that would be consistent with a global 550 ppm regime in the first half of this century but above the 450P-EU and 450 ppm paths (CF-450). Therefore, we relate RefPol with 'moderate action' and 450P-EU with 'stringent action' (which is also the case for RefP-EUback for the period 2011–2030).

Next we turn to the question of how GHG reductions in IAMs compare to the EU Roadmap targets. According to this policy study, cost-effective milestones along this path are the achievement of GHG reductions by about 40% and 60% below 1990 levels by 2030 and 2040, respectively.[2] Note again, that we include emissions from land-use, land-use change and forestry. For the comparison, we take 1990 emission levels from the UNFCCC reporting (taking account for the definition of Europe in each model) [28].,

Roadmap targets (incl. indicative sectoral reductions) and model means (incl. coefficient of variation in brackets) are shown in Table 1. The reduction of GHG emissions tend to be robust or less robust across all scenarios. At the lower range are GCAM and MESSAGE. Results are far less robust for non-CO_2 emissions. This is due to larger uncertainties connected with non-CO_2 data and due to different model strategies to comply with targets which are imposed on the full GHG basket. For example, WITCH reduces Non-CO_2 in 2050 by 63% whereas GCAM shows a reduction of only 8% (450P-EU). CO_2-reductions realized for fossil fuels & industries (FF&I) show a smaller spread ranging from less robust to robust. Though, not shown in Table 1, data for 450P-EU and CF-450 are very close to each other. These scenarios are – as expected – those closest to the EU Roadmap targets. A reason for this lies in the scenario design in that from 2030 onward models follow a 450 ppm path. This means that models do not necessarily meet later reduction targets as long as they do not overshoot the carbon budget. In case Europe rolls back its Roadmap in 2030 (RefP-EUback), we find that emission levels are almost back to those in the RefPol by 2050.

3. Identifying co-benefits

In this section we take a closer look at potential co-benefits of climate change mitigation and we focus on those connected with energy security (Section 3.1) and air pollution (Section 3.2). We define co-benefits as a positive physical side effect of one policy (here climate policy) for another public policy objective (see also [8]). Note that, Borenstein [2] and others are skeptical about the possibility to calculate such co-benefits as there are large uncertainties connected with the methods to compare costs (e.g. how to separate between private and public benefits or how to monetarize environmental externalities). Edenhofer et al. [7] add that as policies typically target multiple objectives, an assessment of co-benefits would need to account for this. They argue that additional welfare effects of co-benefits can conceptually only occur when these other objectives have not been addressed by appropriate policy instruments. In addition to the difficulty around cost calculation methods, there are also large uncertainties connected with our knowledge about the fundamental processes that govern the complex human–environment system in its past, present, and future. These uncertainties translate into different modeling approaches, input assumptions, and choices in the level of details.

Table 1
Comparing EU Roadmap targets (rel. to 1990) with the median of emissions in % across scenarios and models (coefficient of variation in brackets; land-use, land-use change and forestry sectors are included) in the EU. IMACLIM and POLES are not included for GHG and Non-CO2 results as these models do not comprise the full basket of Kyoto gasses. Abbreviation: FF&I refers to fossil fuels and industryrefers to fossil fuels and industry.

Reduction	Scenario	2030	2040	2050	2100
GHG	Roadmap	40–44%	60%	79–82%	N/A
	RefPol	24 (0.30)	34 (0.21)	44 (0.16)	72 (0.04)
	450P-EU	34 (0.18)	51 (0.19)	67 (0.35)	96 (0.14)
	RefP-EUback	34 (0.21)	41 (0.17)	48 (0.18)	74 (0.10)
Non-CO_2	Roadmap	72–73%	N/A	70–78%	N/A
	RefPol	32 (0.82)	39 (0.61)	41 (0.60)	44 (0.90)
	450P-EU	38 (0.49)	45 (0.30)	49 (0.15)	59 (0.39)
	RefP-EUback	38 (0.49)	40 (0.59)	40 (0.61)	47 (0.88)
FF&I CO_2	Roadmap, Power	54–68%	N/A	93–99%	N/A
	Roadmap, Industry	34–40%	N/A	83–87%	N/A
	RefPol	24 (0.34)	37 (0.20)	45 (0.18)	80 (0.12)
	450P-EU	38 (0.21)	57 (0.37)	73 (0.26)	107 (0.12)
	RefP-EUback	38 (0.23)	45 (0.13)	51 (0.14)	82 (0.07)

Given these large methodological and model uncertainties, we keep our analysis at the level of a qualitative discussion with regard to energy security and trade expenditures. In the case of external costs avoided, we provide rough estimations comparing the costs and benefits of and from EU's pioneering action.

3.1. Improving energy security and reducing trade expenditures

With respect to energy security, a region benefits when its self-sufficiency ratio in supplying energies can be increased or when the resilience of the energy system against uncertain risks can be improved, as for example achieved by diversifying energy sources, refer to [1,5] for a detailed review. Upon exploring pathways for a sustainable energy transition, Riahi et al. [25] find that energy efficiency and RE have the potential to double the share of domestic energy supply. Borenstein [2] and Edenhofer et al. [7] however point out that the contribution of RE to energy security is likely to be small once the variability of RE is taken into account. According to the authors, advantages of higher RE shares tend to be associated with environmental

---

[2] Note, Knopf et al. [18] find that the 20% reduction target in 2020 is not consistent with the cost-effective milestones set in the EU Roadmap. General conclusions made in the EU Roadmap and related documents are, however, supported by their study.

benefits, [2,7], or access to energy for less developed regions, [7], rather than energy security.

For our analysis, we follow Riahi et al. [25]. and McCollum et al. [23] who calculate a compound energy security indicator applicable to the IAMs participating in our study. It accounts for a region's self-sufficiency in energy supply as well as for its resilience strength. The former is represented by the share of traded energy at the primary level, whereas the latter measures the diversity of energy supply (at primary level and for electricity generation) based on the Shannon–Wiener index. While our choice of this indicator is motivated by a desire for the analysis to not become too complicated and is dependent on the coverage of all possibilities to, e.g., generate electricity, the compound energy security indicator offers an opportunity to produce results comparable to the literature. There are other energy security indicators and for a review of their pros and cons refer to [1,5,21].

The portfolio of possible supply resources we account for at the primary energy level includes biomass, coal, gas, geothermal, hydro, nuclear, ocean, oil, solar, and wind. Potential sources for generating electricity are biomass, coal, gas, geothermal, hydro, nuclear, ocean, oil, solar, and wind. We use the same definition of the indicator, *DI*, and its compound, *CDI*, as in [16] and calculate

$$DI = -\sum_i (p_i * ln(p_i)), CDI = -\sum_i (1-m_i) * (p_i \ln(p_i)),$$

with p_i as the share of primary energy (PE) type (or the share of a power generation technology) i in total supply, and m_i as the share of PE resource i supplied by net imports. The classification of *CDI* is the same as for *DI*. Note that decarbonization can also decrease the indices.

Table 2 shows the index for the diversity of PE supply and electricity generation across different scenarios as model means (with the coefficient of variance given in brackets). Across all scenarios with climate policies, the diversity of PE supply increases by 2030. Differences between these scenarios are small as they are almost independent of early action, concerted action, or levels of stringency. For the no policy baseline, however, comparatively high values are only reached at the end of the century, which makes the diversification of primary energy a co-benefit of climate change mitigation. Note that the findings are robust for all models and scenarios.

The diversity indicator of electricity supply is already above 1.5 for all scenarios from 2005 onward, although the coefficient of variation increases in some scenarios and leads to less robust findings. The development of the compound index, which also incorporates import dependencies, is again robust for all models and scenarios (this is of course also due to the high aggregation level of the index which blurs differences in model strategies). For scenarios fostering climate policies, the category tends to reach around 1.5 already by 2030. This is only achieved in the no policy base by 2100. This suggests a co-benefit exists with respect to energy security in general, as it can be enhanced relative to Base in climate policy scenarios regardless of the level of stringency or its timing.

Table 2
Trends of energy diversity indicators. Abbr.: PE — primary energy. Numbers in brackets give the coefficient of variation across models.

Index for Europe	Scenario	2005	2030	2050
Diversity of PE supply	Base	1.43 (0.03)	1.43 (0.09)	1.52 (0.19)
	RefPol	1.43 (0.03)	1.64 (0.08)	1.72 (0.11)
	450P-EU	1.44 (0.02)	1.69 (0.10)	1.72 (0.12)
	RefP-EUback	1.43 (0.03)	1.67 (0.09)	1.71 (0.10)
	CF-450	1.43 (0.03)	1.54 (0.14)	1.72 (0.16)
Diversity of electricity	Base	1.54 (0.08)	1.55 (0.24)	1.56 (0.38)
	RefPol	1.54 (0.08)	1.79 (0.12)	1.73 (0.27)
	450P-EU	1.54 (0.05)	1.83 (0.10)	1.74 (0.16)
	RefP-EUback	1.54 (0.08)	1.82 (0.12)	1.73 (0.30)
	CF-450	1.54 (0.08)	1.70 (0.12)	1.73 (0.07)
Compound index	Base	1.26 (0.06)	1.22 (0.16)	1.36 (0.23)
	RefPol	1.26 (0.06)	1.45 (0.14)	1.60 (0.21)
	450P-EU	1.27 (0.02)	1.53 (0.17)	1.64 (0.18)
	RefP-EUback	1.27 (0.06)	1.51 (0.16)	1.63 (0.18)
	CF-450	1.26 (0.06)	1.41 (0.22)	1.61 (0.22)

In the following we examine the development of import dependency on fossil resources (coal, gas, and oil) since co-benefits are connected with lower or less vulnerable trade expenditures for importing fossil fuels in case of increasing or instable price developments at global fossil fuel markets. Table 3 presents an import dependency indicator that calculates the share of fossil energy resources traded at the primary energy level. This indicator has also been used in [16]. We find that by 2050 Europe's import dependency could be reduced below today's level in scenarios with climate policies, although the spread across models is large. Note that the indicator only increases until 2030 in Base and RefPol. Note that trends are consistent with results found in [12], where in 2050 decarbonization scenarios range between 35 and 45% compared to 58% for both, the reference and current policies scenarios. As in our scenarios, the import dependency is affected only in later decades, driven by installed capacities of RE and a decline in domestic consumption. While these trends differ across the decarbonization scenarios in [12], resulting indicators show a spread of 10%.

The large spread in the indicator across models in this study is due to different strategies across models regarding decarbonization options and due to differences in a model's input assumptions. For example, DNE21 + builds its emission reduction strategy on strongly reducing CO_2 emissions from the residential and commercial sectors and by completely capturing carbon dioxide emissions of electricity supply, which is most pronounced in 450P-EU. Also, DNE21 + is a model with a high variety of energy supply technologies and CCS plays a large role as well as the transition to a hydrogen based society. On the other hand, the highest shares of RE in primary energy are seen in 450P-EU for the models IMAGE, MERGE-ETL, and REMIND ranging from 43 to 53% by 2050. Only these models in the corresponding scenario are in the range of RE shares seen in decarbonization scenarios within the EU Roadmap [12], i.e. 41–59% by 2050. A reason for a high

Table 3
Indicator on import dependency of Europe on fossil resources (coal, gas, and oil). Numbers in brackets give the coefficient of variation across models.

Scenario	2010	2030	2050
Base	48% (0.15)	49% (0.24)	46% (0.36)
RefPol	49% (0.19)	50% (0.41)	38% (0.88)
450P-EU	48% (0.13)	45% (0.30)	25% (1.17)
RefP-EUback	48% (0.12)	43% (0.33)	29% (1.17)
CF-450	48% (0.13)	47% (0.42)	33% (0.73)

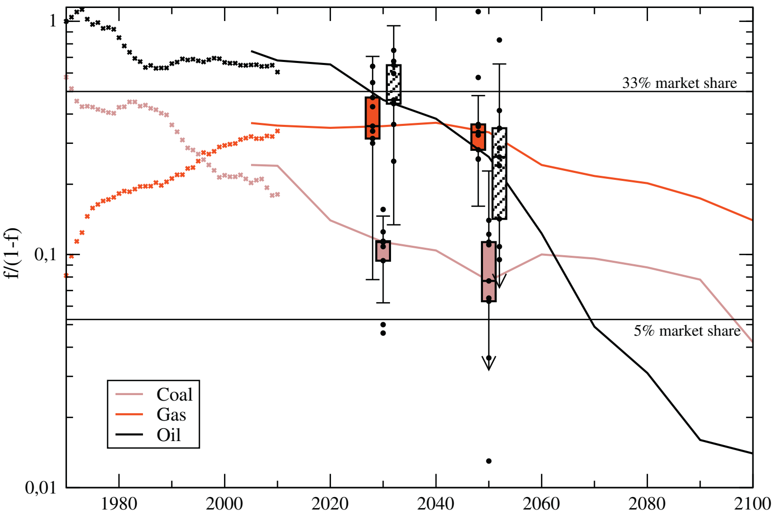

Fig. 2. Fisher–Pry plot (upper panel).

RE share in, e.g., IMAGE, is that on-shore wind is a particular low-cost option (measured by levelized cost of electricity — LCOE). A second pillar in the RE mix of IMAGE is biomass in combination with CCS.

In all models, the import of oil is being reduced strongly in upcoming decades across all climate policy scenarios. Compared to 2010, oil imports in 2050 decrease between 46% (0.71) and 54% (0.54) in climate policy scenarios and 29% (0.51) in the Base. Since oil prices are increasing during the same time (most pronounced in climate policy scenarios), this is combined with a lower bill for oil. The reduction potential compared to the Base in 2050 is up to 40–50% (with mixed robustness). How coal and gas bills are affected is even more diverse across models since models opt for different roles of coal and gas in future markets. For example, some models see a renaissance of coal possible as CCS technologies mature. Others, see gas to take a bridging role before renewable energies have the lion's share in the markets. This is also underlined in Figs. 2–4 showing the market ratio of fossil primary energy carriers f (as $f/(1-f)$) over time in a semi-logarithmic plot (Fisher–Pry graph) for 450P-EU, RefP-EUback, and RefPol (upper panel, middle panel, and lower panel, resp.). Historical data are also included and shown as crosses.[3] Lines show the development of model means, the range of models is indicated for 2030 and 2050 using standard box plots.[4] Furthermore, the two black lines indicate market shares of 5% and 33%.

Concluding, the analysis in this section leads to the identification of co-benefits connected with energy security and trade expenditures. However, the spread across models is large as multiple pathways are available to decarbonize the energy system — especially with regard to CCS linked to gas and/or coal.

3.2. External costs avoided within the electricity sector

Ever since the ExternE project was commissioned by the European Commission in 1995, cross-benefits of major policies have increasingly been reviewed. While doubts may persist in the validity of externality estimates, especially in terms of climate change damages, other key metrics such as health related damage costs from air pollution have been acknowledged to give a good approximation of the order of magnitude of the associated external cost [18]. This consideration is an important one as external costs in terms of monetary valuations tend to be heavily driven by respiratory effects. The EXIOPOL project estimated that for the EU in 2000 67.2% of the total external cost was attributed to air pollution and that this is consistent with a 369 billion Euro valuation [26]. With a heavy focus on the EU, EXIOPOL assessed the damages from the emissions of pollutants and applied these estimates to an evaluation of EU Directive 2009/28/EC, [10], which focuses on a 20% share of RE in gross energy consumption and a 10% share of biofuels within transport. Focusing on GHGs, airborne pollutants, particulate matter and sulfur dioxide, the EXIOPOL project estimates that a decrease in CO_2 emissions of almost 150 Mt in 2020 leads to 11.6 billion Euros of benefits for the EU-27 [14].

Utilizing external cost estimates for electricity generation in 2020 sourced from the CASES (Cost Assessment of Sustainable Energy Systems) project, [3], we conduct a similar calculation for a range of models and a range of climate policies. Using estimates for the external cost of electricity generation for a range of energy types and a range of factors, such as human health, loss of biodiversity, and other various impacts from non-CO_2 gasses (including nitrogen oxides, particulates, and sulfur dioxide), we compare the implied external cost to the range of policy costs sourced from the models participating in the AMPERE project. Table 4 reviews the range of external cost estimates sourced from CASES that will be applied to the changes in electricity produced within the model results. For oil, solar PV, hydro, and biomass we have utilized an average of a range of specific technologies types provided within CASES to couple these with the broader categories reported by the

---

[3] Note, smaller deviation in 2005 from historical and model data are due to different regional definitions and differences in accounting methods.

[4] To avoid overlapping boxes, they are not exactly located at 2030 and 2050.

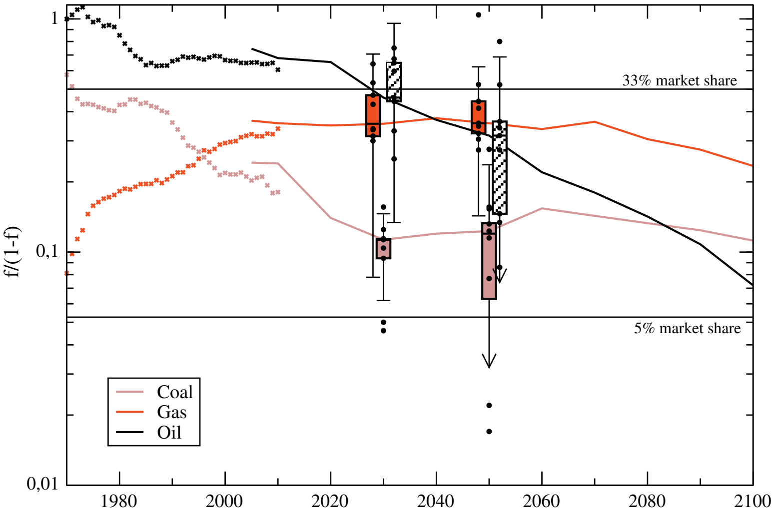

Fig. 3. Fisher–Pry plot (middle panel).

modeling teams within the AMPERE project. While this adds some uncertainty into the analysis, the discussion surrounding Fig. 6 will address the impact of the most notable source of potential bias this being differences in the source of biomass used for electricity production. CASES provides external cost estimates for both biomass from straw and biomass from woodchips with a differential in the external cost estimates of almost 3:1. Within this analysis, we have applied the average of these two costs and hence assume a 50–50 split between straw and woodchip based biomass. Fig. 6 shows the potential improvement if only woodchip based biomass were to be utilized, however it should be acknowledged that even with this allowance made the external cost associated with woodchip based biomass electricity production remains higher than that of gas without CCS.

Consistent with larger emission decreases and higher RE shares than in EU Directive 2009/28/EC and reviewed in the EXIOPOL project, Fig. 5 reviews the issue of whether there are co-benefits of following a range of climate policies. Fig. 5 shows that in 2020 the external costs avoided from electricity generation that can be associated with following different climate policies rival the total cost of following that policy. Shading within Figs. 5 and 6 represent the area between the 25th and 75th percentiles and highlight the clustering of individual model observations (marked as white rectangles). It should be noted that these estimates for external costs avoided are only for electricity production and are likely to increase as other sectors are added to these numbers. It is important to note that external costs are calculated using the CASE estimates (Euro cents per kWh) for each fuel type and the levels of energy in each scenario separately. These

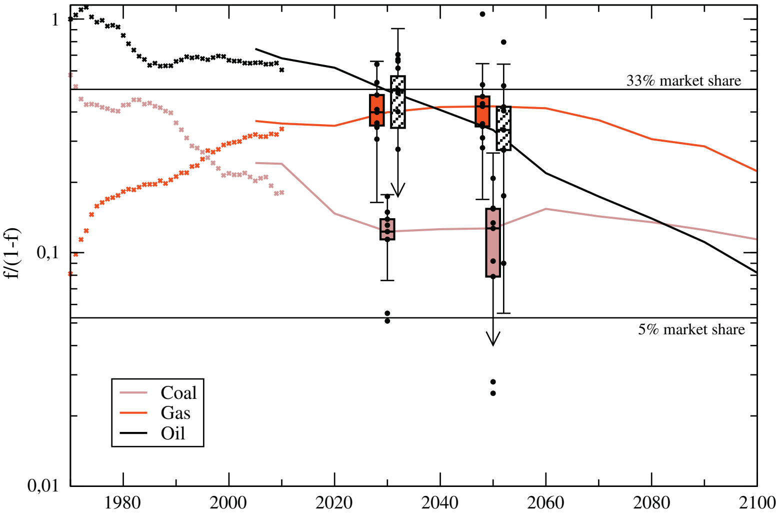

Fig. 4. Fisher–Pry plot (lower panel) showing the development of market shares f for fossil energy technologies at primary energy level. The upper panel shows 450P-EU, the middle panel RefP-EUback, and the lower panel shows RefPol. Historical data are indicated by crosses, source of data: ENERDATA.

Table 4
External costs of energy produced by impact category (2005 Euro cents per kWh). Abbr.: SO_2 — sulfur dioxide, NO_x — nitrogen oxides.

	Nuclear	Oil	Gas	Coal
			wo CCS	wo CCS
Human health	0.090	2.035	0.519	0.855
Loss of biodiversity	0.006	0.133	0.060	0.078
Crop N deposition & crops O3	0.001	0.028	0.016	0.017
Crops SO2	−0.0001	−0.0016	−0.0002	−0.0005
Materials: SO2 & NO_x	0.001	0.040	0.007	0.014
Other pollutants — h. health	0.020	0.050	0.023	0.055
Radionuclides generic	0.0020	0.0002	≈0	0.0001
	Wind	Solar PV	Hydro	Biomass
Human health	0.041	0.546	0.050	0.981
Loss of biodiversity	0.003	0.030	0.002	0.202
Crop N deposition & crops O3	0.001	0.006	0.001	0.016
Crops SO2	≈0	−0.0003	≈0	−0.0003
Materials: SO2 & NOx	≈0	0.008	≈0	0.009
Other pollutants — h. health	0.014	0.086	0.003	0.161
Radionuclides generic	≈0	0.0003	≈0	0.0003

are then aggregated so that they can be compared to the Base scenario, resulting in external costs avoided. While some of these externalities may be accounted for in reality through non-climate based policy making and regulations, IAMs usually start from a no policy baseline and this is how we approach this analysis with respect to the differences between the Base and the climate policy scenarios.

Note that the mitigation/policy costs included in Fig. 5 are not fully comparable; however they nevertheless show that the external costs avoided from electricity alone tend to rival the aggregate cost of the climate policies reviewed. Mitigation costs from the general equilibrium models (Table 5) are given in terms of GDP losses (GEM-E3, MERGE-ETL, MESSAGE, REMIND, WITCH, and WorldScan). The mitigation costs for the partial equilibrium models are given in terms of the dead-weight loss area under the MAC curve (GCAM, IMAGE, and POLES) or in terms of additional energy system costs (DNE21+). WITCH has also reported the additional energy system cost and these estimates are included in Fig. 5. Upon reviewing these results, the differences between these mitigation cost concepts need to be kept in mind. Nevertheless, Fig. 5 includes lines which link the estimates of external costs avoided with the policy costs in terms of GDP loss for the five models which utilize the GDP loss policy cost metric. Of the five models, three show policy cost levels which are already below the estimates of external costs avoided for the electricity sector when the CASES generic climate change costs are accounted for in the RefPol and 450P-EU scenarios. Two models (MESSAGE and REMIND) show higher policy costs of approximately 15 billion Euros and 50 billion Euros, respectively, for the RefPol scenario. In the case of the 450P-EU scenario this differential is approximately 12 billion Euros and 43 billion Euros for these same models.

Irrespective of these differentials, the overall amount of emission reductions in comparison to the Base scenarios, the amount of emission reductions in other sectors, and the associated benefits of these reductions from these additional sectors are all issues which need to be considered. In the case of the CF450 scenario, all five models show benefits from following the policy based on external costs avoided in the electricity sector alone. As there is uncertainty concerning the cost of climate change damages, Fig. 5 shows external costs avoided with and without climate impacts. Introducing these climate change related costs inflate the estimates differently across the models, however four of the five models which report GDP loss based policy cost show relatively stable increases.

All of the models have a notable share of RE within Base and while the energy mixes to meet the different policies do differ, the one constant is that decarbonization in all models is associated with the decrease of coal without CCS technologies within electricity. A common trend across most models is the immediate decrease in the use of traditional coal-fired power stations, unless notable and rapid land-use changes are possible. Global concerted effort that coincides with the cost-effective solution for each model (CF-450) results in lower policy costs within the EU and less aggressive reductions than those shown in the policies where the EU pioneers with immediate action. Fig. 5 shows that the gain of co-benefits through external costs avoided is possible, even upon reviewing the reduction of externalities from electricity alone, with and without the impact of climate damages. Additional external costs avoided should be added to these estimates to account

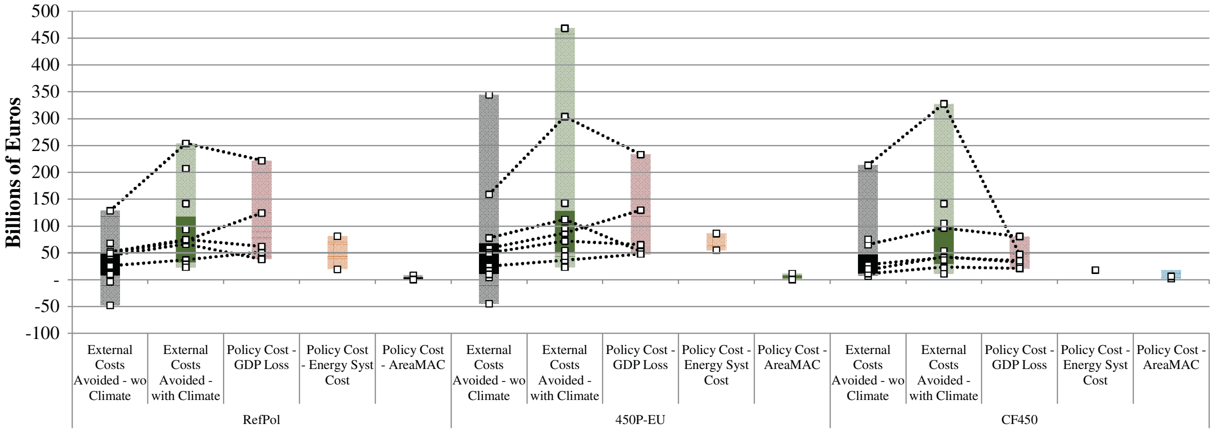

Fig. 5. External costs avoided from changes to electricity production in 2020 costs avoided calculated using Base scenario (billions 2005 Euros).

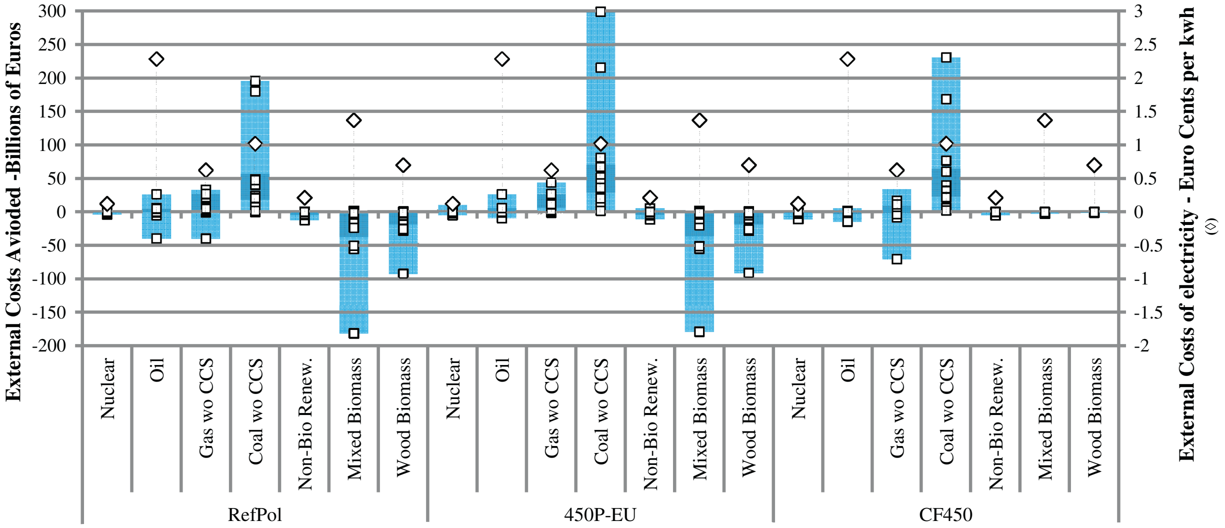

Fig. 6. External costs avoided from changes to electricity production in 2020 calculated using Base scenario (billions 2005 Euros).

for changes in transportation and other sectors. For example, within the EXIOPOL project a 10% biofuel share consistent with meeting EU Directive 2009/28/EC and achieving an 8% decrease in total emissions was attributed to a benefit of 4 billion Euros [14]. The issue of energy security and RE energy has also been reviewed with respect to co-benefits in Section 3.2; [7,15,22] should also be considered in addition to the analysis within this section.

Fig. 6 presents the range of external costs avoided across technology types (without climate impacts). Reducing traditional coal-fired power plants provides the greatest co-benefit due to the amount of external costs associated with this technology. Note that coal without CCS has the third highest external cost per kWh as denoted by the height of the diamonds in Fig. 6 and across the categories in Table 4. The cost of coal without CCS is lower than the external cost for oil and mixed biomass in terms of Euro cents per kWh, upon using the assumed 50–50 split between straw and woodchip based biomass. The benefits of a greater share of non-biomass RE than in the no policy scenario Base assist decarbonization aimed at meeting the climate policy target without a significant increase in external costs. The impact of biomass is an important issue as the CASES estimates show that the source of the biomass will have a notable impact upon the external costs estimates. Uncertainties concerning the impact of biomass are present within this analysis due to the likelihood of different mixes of biomass sources in each model and/or scenario. The potential impact of this is shown within Fig. 6 with the external costs defined for woodchip based biomass alone being almost half of that associated with the mixed biomass case. Human health and biodiversity loss are where noticeable differences in the costs between straw and wood chip based biomass occur.

Indeed, the source of biomass is important within IAM studies as while providing notable emission reduction potential, these models also may not fully capture the negative externalities of this fuel source. Creutzig et al. [6] note that while IAMs tend to notably rely upon bio-energy, life-cycle emissions of these fuel sources are highly uncertain overall and IAMs tend to insufficiently account for induced land-use changes. Upon directly incorporating external cost estimates into the MARKAL model, Rafaj and Kypreos [24] found large reductions in coal use which were heightened when both local and global externalities were accounted for. While Klaassen and Riahi [17] found that accounting for externalities within the MESSAGE-MACRO model resulted in little reduction in carbon dioxide emissions (due to carbon leakage), significant decreases in sulfur emissions did occur irrespective of the existence of DESOX technologies within their baseline. With co-benefits acknowledged, Klaassen and Riahi [17] conclude with the acknowledgment that damage costs for SO_2 and NO_x are underestimated due to the exemption of damages to sensitive ecosystems and historical buildings, as well as the valuation of mortality impacts. These limitations are also valid for the external cost estimates utilized within this paper.

To conclude the discussion, we now focus on a comparison of the external costs avoided in comparison to the CF450 scenario using the RefPol and 450P-EU scenarios. In doing so, we are able to review how these interim policy measures differ in comparison to a fully flexible global climate policy. The majority of observations in Fig. 7 show the expected relationship between higher abatement/emissions and higher external costs avoided/suffered. With respect to external costs avoided in comparison to CF450, the MERGE model stands out with similar emission reductions and less external costs avoided in comparison to other models due to either more coal w/o CCS and/or biomass prevailing in these MERGE results. Four models (DNE21, GEM-E3, MESSAGE, and REMIND) cluster together with a range of relative abatement of 10–15% more CO_2 emission reductions compared to the 1990 level. GCAM has strong CO_2 emission reductions in both RefPol and 450P-EU as the model has a relatively low decrease in energy demand with respect to other models, while IMACLIM also does strong CO_2 abatement in the RefPol scenario. Two models (WITCH and WorldScan) have fewer emission abatement in the 450P-EU scenario with respect to the CF450 scenario which reflect how much abatement is conducted outside the EU or in other GHGs.

Across the scenarios reviewed (RefPol and 450P-EU), the consideration of external costs from the electricity sector

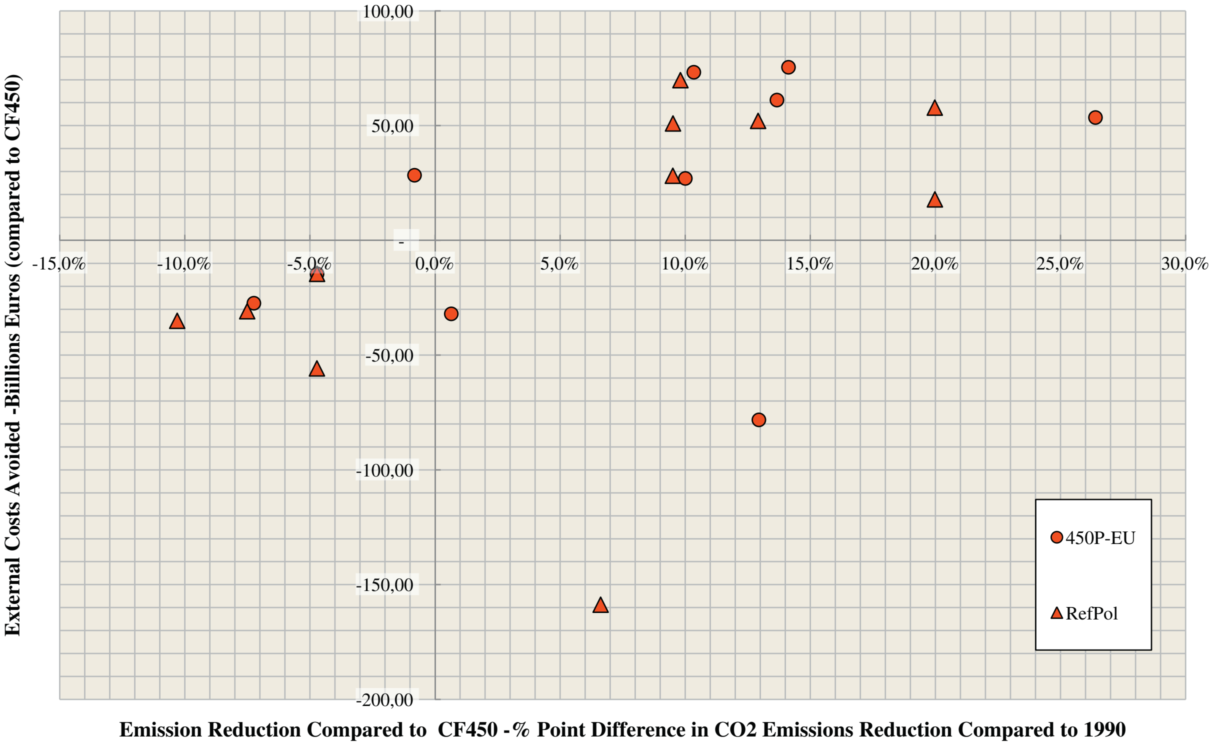

Fig. 7. External costs avoided and CO_2 emission reductions in comparison to CF450 scenario.

leads to evidence that non-climate co-benefits are likely to include the reduction of coal without CCS and the promotion of non-biomass RE. It is acknowledged that a definitive choice between the policy scenarios within this analysis would need a broader range of benefits and a more direct comparison to the costs of these policies. As such, these results on external costs avoided should be treated as being indicative of the potential co-benefits of climate policies (with sizable external costs avoided related to the electricity sector), while identifying reduced coal and increased RE as reasonable co-benefits related to a range of targets for CO_2 abatement — subject to caveats, such as caution based on the source of biomass.

4. Conclusions

Within this paper, we study co-benefits of climate change mitigation for the EU across eleven different IAMs and a range of decarbonization scenarios. We review non-climate synergies related to energy security and lower trade expenditures. In addition, we analyze external costs avoided in the electricity sector and identify those technologies with the greatest potential benefit in terms of externalities reduced. Our assessment yields the following results:

- *Improving energy security and reducing trade expenditures*: We find a tendency for the oil bill to be lower under climate policies and a reduction of import dependencies on fossil resources. But results show a large spread across models since decarbonization pathways vary. At the same time the diversity of PE supply improves in all climate policy scenarios across the models and it has been identified as being robust. Thus, the diversity of energy supply constitutes a co-benefit. Models are, however, mixed regarding the relative flexibility in the electricity sector.
- *External costs avoided within the electricity sector*: We find that in 2020 the co-benefit of decarbonizing the electricity sector tends to result in potential benefits which rival the total cost of the policy. These benefits are related to the reduction of coal without CCS in favor of non-biomass RE. An important issue to consider w.r.t. externalities is the source of biomass, which can lead to notably different estimates of external costs avoided. For example, in this analysis we have looked at costs associated with wood based biomass in comparison to a mixed source which includes 50% straw. However, IAMs will likely have different sources utilized across models and/or scenarios. Note that we have been conservative in applying the mixed sources external costs estimates within the sectoral calculations.

As a general result we furthermore find that the spread across models is larger than across climate policy scenarios, suggesting that a multi-model analysis is necessary to identify robust results given the large uncertainties surrounding climate change causes and impacts. In light of this, the analysis has focused upon identifying results which are robust and consistent across models.

Acknowledgment

The research leading to these results has received funding from the European Union's Seventh Framework Program [FP7/2007–2013] under grant agreement no 265139 (AMPERE).

Appendix A

Table 5
Overview on model characteristics. Abbr.: agri — agriculture, aggr. — aggregated, LU — land-use, regional mapping: + if a native model region is larger than EU27 and − if smaller, U uranium, C coal, O oil, G gas, TC — technological change, exTC exogenous TC, enTC endogenous TC, AEEI autonomous energy efficiency improvements, agro — agro-products, elec — electricity, o — other.

Model	Economic coverage	Regional resolution	Technology and TC	Trade
DNE21+	energy	19 regions, EU27−	exTC	C, O, G, LNG, bio fuel, elec
GCAM	economy, energy, LU	14 regions, EU27+	exTC	C, O, G, U, agro
GEM-E3	economy, energy, agri	9 regions, EU27	exTC	agro, C, O, G, power, o. goods
IMACLIM	economy, energy, agri	12 regions, EU27+	enTC, LBD	all sector products
IMAGE	energy, agri	26 regions, EU27+		
MERGE-ETL	aggr. economy, energy	8 regions, EU27+	exTC, LBD	C, O, G, U, biomass, capital & energy-intensive good
MESSAGE	aggr. economy, energy, LU	11 regions, EU27+	exogenous for energy	C, O, G, U, LNG, elec, other energy
POLES	economy, energy, agri	21 regions, EU27	exTC, enTC	C, O, G, U, biomass
REMIND	aggr. economy, energy	11 regions, EU27		C, O, G, U, capital good
WITCH	aggr. economy, energy	13 regions, EU27	exTC, enTC	C, O, G
WorldScan	aggr., energy, economy	5 regions, EU27	exTC	C, G, O

References

[1] H. Blum, L.F.L. Legey, The challenging economics of energy security: ensuring energy benefits in support to sustainable development, Energy Econ. 34 (2012) 1982–1989.

[2] S. Borenstein, The private and public economics of renewable electricity generation, J. Econ. Perspect. 26 (2012) 67–92.

[3] CASES, Cost Assessment for Sustainable Energy Systems, 2008–2010. Available: http://www.feem-project.net/cases/.

[4] P. Capros, N. Tasios, A. De Vita, L. Mantzos, L. Paroussos, Transformations of the energy system in the context of the decarbonsation of the EU economy in the time horizon to 2050, Energy Strategy Rev. 1 (2012) 85–96.

[5] A. Cherp, A. Adenikinju, A. Goldthau, F. Hernandez, L. Hughes, J. Jansen, J. Jewell, M. Olshanskaya, R. Soares de Oliveira, B. Sovacool and S. Vakulenko, Chapter 5 — Energy and Security, in: Global Energy Assessment — Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA, and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012, pp. 325–384.

[6] F. Creutzig, A. Popp, R. Plevin, G. Luderer, J. Minx, O. Edenhofer, Reconciling top-down and bottom-up modelling on future bioenergy deployment, Nat. Clim. Chang. 2 (2012) 320–327.

[7] O. Edenhofer, L. Hirth, B. Knopf, M. Pahle, S. Schlömer, E. Schmid, F. Ueckerdt, On the economics of renewable energy sources, Energy Econ. 40 (2013) 12–23.

[8] O. Edenhofer, B. Knopf, G. Luderer, Reaping the benefits of renewables in a nonoptimal world, Proc. Natl. Acad. Sci. U. S. A. 110 (2013) 11666–11667.

[9] European Commission, A Roadmap for moving to a competitive low carbon economy in 2050, COM (2011) 112 final, (Available:) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF2011.

[10] European Commission, On the promotion of the use of energy from renewable sources and amending and subsequently, Directive 2009/28/EC, (Available:) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF2009.

[11] European Commission, Impact assessment to “A Roadmap for moving to a competitive low carbon economy in 2050”. SEC (2011) 288 final, (Available:) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SEC:2011:0288:FIN:EN:PDF2011.

[12] European Commission, Impact assessment to “Energy Roadmap 2050”. SEC (2011) 1565/2, (Available:) http://ec.europa.eu/energy/energy2020/roadmap/doc/sec_2011_1565_part1.pdf2011.

[13] 18th session of the Conference of the Parties to the UNFCCC and 8th session of the Conference of the Parties to the Kyoto Protocol, Doha, Qatar, November/December 2012, (Available:) http://unfccc.int/2860.php2011.

[14] Exiopol, A new environmental accounting framework using externality data and input–output for policy analysis, bottom-up approach, Technical report to the European Commission, contract no 037033-2, 2011, (Available: http://www.feem-project.net/exiopol/).

[15] GEA, Summary for policymakers, in: T.B. Johansson, N. Nakicenovic, A. Patwardhan, L. Gomez-Echeverri (Eds.), Global Energy Assessment — Toward a Sustainable Future, Cambridge University Press, Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, So Paulo, Delhi, Mexico City, 2012.

[16] T.B. Johansson, N. Nakicenovic, A. Patwardhan, L. Gomez-Echeverri (Eds.), Global Energy Assessment — Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA, and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012.

[17] G. Klaassen, K. Riahi, Internalizing externalities of electricity generation: an analysis with MESSAGE-MACRO, Energy Policy 35 (2007) 815–827.

[18] B. Knopf, H. Chen, E. De Cian, H. Förster, A. Kanudia, I. Karkatsouli, I. Keppo, T. Koljonen, K. Schumacher, D.P. van Vuuren, Beyond 2020 — strategies and costs for transforming the European energy system, Clim. Chang. Econ. 4 (4) (2013).

[19] W. Krewitt, External costs of energy — do the answers match the questions?: looking back at 10 years of ExternE, Energy Policy 30 (2002) 839–848.

[20] E. Kriegler, K. Riahi, N. Bauer, V.J. Schwanitz, N. Petermann, et al., Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy, Technol. Forecast. Soc. Chang. 90 (2015) 24–44(in this issue).

[21] B. Kruyt, D.P. van Vuuren, H.J.M. de Vries, H. Groenenberg, Indicators for energy security, Energy Policy 37 (2009) 2166–2181.

[22] M. Leimbach, E. Kriegler, N. Roming, V.J. Schwanitz, Future growth pattern of world regions — divergence or convergence? Glob. Environ. Chang. (2014)(submitted for publication).

[23] D.L. McCollum, V. Krey, K. Riahi, P. Kolp, A. Grubler, M. Makowski, N. Nakicenovic, Climate policies can help resolve energy security and air pollution challenges, Clim. Chang. 119 (2013) 479–494.

[24] P. Rafaj, S. Kypreos, Internalisation of external costs in the power generation sector: analysis with global multi-regional MARKAL model, Energy Policy 35 (2007) 824–843.

[25] K. Riahi, F. Dentener, D. Gielen, A. Grubler, J. Jewell, Z. Klimont, V. Krey, D. McCollum, S. Pachauri, S. Rao, B. van Ruijven, D. P. van Vuuren and C. Wilson, Chapter 17 — Energy Pathways for Sustainable Development, in: T. B. Johansson, N. Nakicenovic, A. Patwardhan, L. Gomez-Echeverri (Eds.), Global Energy Assessment — Toward a Sustainable Future, Cambridge, University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012, pp. 1203–1306.

[26] A. Tukker, M. Bouwmeester, J. Oosterhaven, A. de Koning, R. Heijungs, Policy impact assessment — resources, products and imports and exports, Technical report to the European Commission, contract no 037033-2, 2011, (Available: http://www.feem-project.net/exiopol/M54/WPIV.2.b_Final.pdf).

[27] UNFCCC, Advancing the Durban Platform, Draft decision-/CP.18, Available: http://unfccc.int/files/meetings/doha_nov_2012/decisions/application/pdf/cop_advanc_durban.pdf2012(Accessed: January 31, 2013).

[28] UNFCCC, Data on greenhouse gas emissions and removals, sent by countries to UNFCCC and the EU Greenhouse Gas Monitoring Mechanism (EU Member States), (Available:) http://www.eea.europa.eu/data-and-maps/2012.

[29] United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section. The World Population Prospects: The 2010 Revision, (Available:) http://esa.un.org/unpd/wpp/Documentation/WPP%202010%20publications.htm.

Valeria Jana Schwanitz is a researcher at the Potsdam Institute of Climate Impact Research (PIK) in Germany. She is a member of the Global Energy Systems and Macroeconomic Modeling research groups.

Thomas Longden is a researcher at Fondazione Eni Enrico Mattei (FEEM) and the Euro-Mediterranean Centre for Climate Change (CMCC) in Italy.

Brigitte Knopf is a Researcher at the Potsdam Institute of Climate Impact Research (PIK) in Germany. She is head of the group Energy Strategies Europe and Germany.

Pantelis Capros is a professor of Energy Economics and Operation Research at the Department of Electrical and Computer Engineering of National Technical University of Athens. He is leading the E3M-Lab/ICCS laboratory.