Cost Concepts for Climate Change Mitigation*

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Major cost concepts used for evaluation of carbon policy are considered, including change in GDP, change in consumption, change in welfare, energy system cost, and area under marginal abatement cost (MAC) curve. The issues associated with the use of these concepts are discussed. We use the results from the models that participated in the European Energy Modeling Forum (EMF28) study to illustrate the cost concepts. There is substantial variability in the estimates of costs between the models, with some models showing substantial costs and some models reporting benefits from mitigation in some scenarios. Because impacts of a policy are evaluated as changes from a reference scenario, it is important to define a reference scenario. MAC cost measures tend to exclude existing distortions in the economy, while existing energy taxes and subsidies are substantial in many countries. We discuss that carbon prices are inadequate measures of the policy costs. We conclude that changes in macroeconomic consumption or welfare are the most appropriate measures of policy costs.

Keywords: Emissions mitigation; costs of policy; climate change.

1. Introduction

In the absence of significant reductions in greenhouse gas (GHG) emissions, considerable increases in the average global temperature by the end of the century are projected (IPCC, 2007; Prinn *et al.*, 2011). The resulting changes in climate (e.g., changes in precipitation, sea level rise, etc.) may pose substantial risks to natural and human systems (IPCC, 2007; Reilly *et al.*, 2013). Meaningful emissions reductions require significant changes in the structure of energy use and land-use practices (Reilly *et al.*, 2012; Paltsev *et al.*, 2009). These changes may come at a cost because they require actions that otherwise would not be taken. Numerous studies based on

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individual models and multi-model comparisons have evaluated the costs of mitigation policies aimed at reducing GHG emissions (e.g., Edenhofer *et al.*, 2010; Winchester *et al.*, 2010; Kriegler *et al.*, 2013; Fawcett *et al.*, 2013; Gurgel and Paltsev, 2013). Usually the studies provide certain results for some cost metrics (e.g., change in gross domestic product (GDP), macroeconomic consumption, and marginal abatement cost (MAC)), but do not include a detailed explanation of different cost concepts and nuances in approaches between different categories of models: general equilibrium (GE), partial equilibrium (PE), energy systems, etc.

The goal of this paper is not to focus on the results from a particular model or modeling exercise, but to discuss in detail the economic meaning of the cost concepts used in the economic analyses of mitigation policies by different types of models. This paper is a part of the EU EMF28 exercise (Knopf *et al.*, 2013) that provides a coherent look at achieving the emissions targets in the EU by employing different types of models. The EMF overview paper (Knopf *et al.*, 2013) shows the resulting numbers for several categories of outputs from different models, including GDP costs. We provide some EMF28 results for illustrative purposes and discuss how to interpret mitigation cost estimates and relate to the results from different modeling structures.

There are several reasons why emissions mitigation may by costly for an economy. To support substantial changes in energy mix, large investments in new energy infrastructure would be required (IEA, 2012). Policies to reduce emissions usually lead to a change in energy prices for consumers because carbon taxes, or carbon prices from a cap-and-trade system, add to the price of fossil fuels and make them more expensive to consume and therefore, reducing demand for them. Different studies have looked at the corresponding energy price changes (e.g., Clarke *et al.*, 2007; European Commission, 2011a; Paltsev, 2012). Regulatory policies that promote the use of zero- or low-carbon technologies and/or improved energy efficiency also can add to the cost as they require use of technologies that would not be employed based only on current economic considerations.

Regulations related to emissions reductions may take numerous forms, such as subsidies to electricity generation from renewable sources (like wind or solar), fuel efficiency standards, emissions standards, feed-in tariffs, requirement of a certain share of energy being produced from renewables, etc. With such regulations, additional costs might be less visible to consumers in comparison to carbon taxes or carbon prices (as the full impact of regulations might not be reflected in the price of energy that consumers face). Yet consumers are still affected by such regulations *via* other channels, as the subsidies or feed-in tariffs need to be financed in one way or another, and the related government or industry expenditures will most likely be covered by higher taxes or prices that will be passed on consumers.

In this paper, we focus on the costs of mitigation, i.e., the costs of reaching a certain (explicit or implicit) emission reduction target. We do not consider the corresponding potential benefits of emissions reduction. Because of the complexity of restructuring systems to reduce emissions, researchers have widely used mathematical models to project the required energy transformation and to estimate the associated costs of emission mitigation as compared to a benchmark projection. Following a variety of methodological approaches, they have found rather large variation in cost estimates. Despite numerous published studies (e.g., Creyts *et al.*, 2007; Paltsev *et al.*, 2009; Clarke *et al.*, 2009; Morris *et al.*, 2012; Kesicki and Ekins, 2012; Capros *et al.*, 2012a,b; Capros *et al.*, 2012), there is still lack of consensus not only about the numerical values but also about the core concepts of cost impact assessment.

This paper is organized in the following way. In the next section, we provide a discussion of major cost concepts and issues associated with them. Section 3 then details the issues related to energy system costs. Section 4 provides a discussion of major issues associated with macroeconomic cost concepts. Section 5 offers some illustrative examples of the costs in the EU EMF28 study. Section 6 concludes.

2. Categories of Cost Concepts

Major mitigation cost concepts can be broadly divided into two categories: energy system (or sectoral) costs and economy-wide (or macroeconomic) costs. These categories roughly correspond to the model types that are used for GHG emissions mitigation assessments. The models differ in their coverage: energy system models which perform PE analysis (these models usually treat the rest of the economy as given) and macroeconomic models which represent an energy system as a part of the entire economy.

The cost concepts also differ in their coverage. Energy systems costs can be divided into capital costs, fuel and electricity costs (including taxes), payments for GHG emissions, and disutility costs. Macroeconomic costs are usually reported as a change in GDP, or a change in consumption, or a change in welfare. Two other popular measures in the emission mitigation studies are carbon (or GHG) prices and MAC curves. These measures can be reported both in energy system studies and macroeconomic studies.

Returning to the classification of the models, energy system models can be further classified into system optimization models and energy market simulation models. The former, based on duality between linear programing and perfect competition, calculate energy prices from dual variables. The latter models simulate demand and supply behavior separately and calculate energy prices in an explicit way depending on assumed market competition regimes.

The macroeconomic models can be roughly classified into three categories: computable general equilibrium models (CGE), dynamic growth models, and neo-Keynesian (usually econometric) models. The CGE models calculate commodity prices that support equilibrium between demand and supply in all commodity and factor markets. CGE models can be "recursive-dynamic" and "forward-looking".

In the recursive-dynamic CGE models, decisions about production, consumption, and investment are made only on the basis of prices in the period of the decision, and this is often referred to as "myopic" expectations. Investments (which are converted to capital in the next period) are made as if input costs and output prices will remain unchanged in the future. Usually in the recursive models, savings and total consumption are fixed shares of income and so consumers do not alter their saving and consumption based on expectations of future returns on investment or on expectations of changes in the price of consumption in the future. In forward-looking CGE models, optimization over time means that decisions today about production, consumption, and investment are based on expectations that are realized in the model simulation. Thus, economic actors are characterized as having "perfect" expectations — they know exactly what will happen in the future (including knowing with certainty all future mitigation policies) in all periods of time covered by a modeling exercise.

The neo-Keynesian models tolerate disequilibria in the short term and calculate dynamic market adjustments toward long-term equilibrium. The growth models perform inter-temporal welfare optimization and derive optimal growth (OG). The growth models can be single sector models, where one sector covers the whole economy, while forward-looking CGE usually track multiple sectors of the economy. The methodological differences between the models used for climate change mitigation cost assessment are substantial and therefore, the cost estimations are influenced by the intrinsic model features.

Before going into the details of energy systems costs (Sec. 3) and macroeconomic costs (Sec. 4), we discuss two popular measures that are usually reported in energy system and macroeconomic studies: carbon prices and MACs.

2.1. *Carbon prices*

A popular measure related to mitigation is an emissions price, usually stated in per metric ton of CO_2 or, in case of multiple gases, per metric ton of CO_2-equivalent. Such a price may be established through a market that develops for emissions allowances issued under a cap-and-trade system (the allowance price), or through an emissions tax set directly by a regulating agency. Knopf *et al.* (2013) reports the carbon prices from the model in EMF28 that range from 5 to 40€/tCO_2 in 2020 for the current policy scenario (EU10) rising to 40 to 140€/tCO_2 range by 2050. Mitigation scenarios lead to much higher prices, especially after 2050. For example, a median value of a carbon price in 2050 for the EU6 scenario is 521€/tCO_2. We argue that carbon prices might serve as a very crude indicator of mitigation efforts, however, it is a very poor indicator of the total cost of a policy.

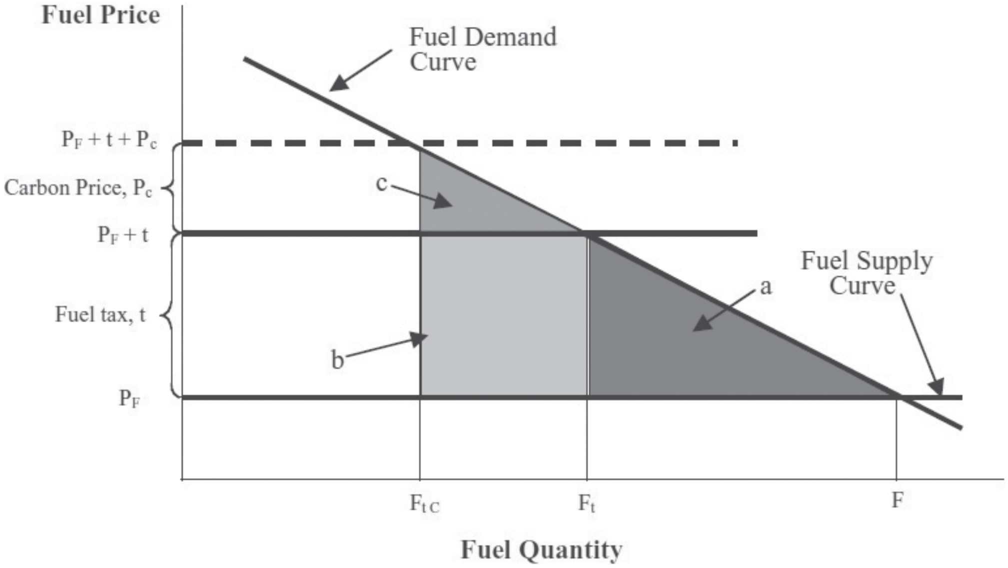
Putting aside the modeling issues in fully representing the market structures and imperfections in order to provide more realistic price changes, emissions prices measure marginal cost, that is, the cost of an additional unit of emissions reduction. Emissions prices are an indicator of the relative scarcity of the allowances compared with the demand for them, but they are not a measure of "total cost" to the economy. Prices convey no information about the physical volumes to which they apply or the magnitude of the cost compared to the level of activity. Prices can also be a misleading indicator of the cost when they interact with other policies and measures — either those directed at GHG reduction (for example, renewable portfolio standards or subsidies to carbon-free technologies) or simply other policy instruments such as other taxes on energy, labor, or capital. Interaction with other policies can reduce the emission prices visible to consumers, but they can increase the overall cost of a policy. Cost analysis refers to the impacts of GHG emissions reduction efforts on consumers and the economy. Consumers and producers react to the prices, but the true measure of the cost of a policy is reflected in the change in their behavior, and this change is captured by a change in welfare or macroeconomic consumption as discussed above.

2.2. *Area under MAC curves*

A MAC curve is a relationship that shows how many tons of emissions can be abated at a certain price. Under highly simplified assumptions, the area under a MAC curve provides an estimate of total abatement cost. If the reduction in emissions is known, then adding all the reductions that would occur before reaching a desired target multiplied by the cost of these reductions (which corresponds to integration under the MAC curve) would lead to the cost estimate of a policy. However, this estimate does not capture some distortion costs related to pre-existing taxes and terms-of-trade effects. Neglecting these distortion effects can lead to substantial underestimation of total policy costs. For example, Paltsev *et al.* (2004) show that distorted costs in the countries with high energy taxes can be 2.5–4.5 times the direct costs measured by the area under the MAC, while in countries with low energy taxes the total costs are close to the area under the MAC.

MAC curves are often used for illustrating economic issues associated with emissions mitigation. The use of the MACs has been popularized by McKinsey & Company (Creyts *et al.*, 2007), especially since their analysis has shown some negative abatement opportunities. Negative parts of MACs have received different interpretations and criticism (see, for example, Kesicki and Ekins, 2012). MACs offer an easy way to understand and visualize how costs depend on the level of abatement. Unfortunately, unless one takes great care in understanding the exact conditions under which MACs are constructed and constructs them for the specific use in mind, it is very easy to misuse them (Morris *et al.*, 2012).

Figure 1 provides a simplified explanation, why the area under MAC may lead to an underestimation of the total cost of the policy. Here, we represent the demand for a carbon-containing fuel, and its supply. We consider a situation with an existing fuel tax that creates a deadweight loss (or excess burden of taxation due to allocative inefficiency) represented by area A in Fig. 1. An introduction of an additional emission constraint leads to an additional increase in fuel price (represented by a movement from $P_F + t$ to $P_F + t + P_c$ in Fig. 1). The area under MAC in PE models usually captures energy system representation, while consumer decisions include consideration of existing taxes in intermediate and final consumption. As mentioned, emission mitigation changes the energy prices and the EU already has high fuel taxes. The models that use area under MAC for their cost measure will consider the direct economic loss associated with the carbon constraint (labeled as area C in Fig. 1).



Source: Paltsev *et al.* (2004).

Figure 1. Effects of existing fuel taxes on the cost of a carbon policy. The economic cost of the fuel tax (t) added to the fuel price (P_F) is given by area a. Adding a carbon constraint, with a price of carbon (P_C), raises the total fuel price, inclusive of the tax and carbon price, to $P_F + t + P_C$. Without the fuel tax, the economic cost of the carbon policy would be just the area labeled c. But, the pre-existing tax means that the cost represented by the area b, in excess of the actual cost of the fuel, is also an added economic cost of the policy. A Marginal Abatement Curve (MAC) for carbon will include only area c.

However, it is only a part of the cost associated with the policy. The full cost will also include an additional deadweight loss associated with the existing fuel tax (labeled as area B in Fig. 1).

Currently, a majority of GHG emissions emanate from fossil fuel combustion for energy purposes (IEA, 2012). Therefore, many studies focus on simulating energy demand and supply restructuring and evaluate cost implications of such restructuring. Such estimations are termed energy system cost implications which usually do not close the loop with the rest of the economy. The next section considers the costs estimated in energy system modeling.

3. Energy System Costs

In an energy system there are demanders and suppliers of energy. For energy system analysis and in order to assess the cost impacts from a macroeconomic perspective, the crucial element is the amount that non-energy sectors (households and firms, both services and industrial) are required to pay in order to get the energy services they need. Energy services are defined by how energy is used, for example, if the energy supports heating, cooling, entertainment, mobility and transportation, industrial production, i.e., uses that enable utility and activity for final energy consumers. Energy services are delivered by using purchased energy commodities, the amounts of which depend on the degree of energy efficiency at the consumption level. Final energy consumers purchase energy commodities from energy producing and trading sectors. Assuming that the energy supplying and trading sectors recover energy production and trading costs through consumer prices, net payment for energy commodities in the whole economy is equal to the cost of purchasing energy only by final energy consumers.

The importance of energy costs for the economy as a whole lies in the fact that energy is a primary production factor which cannot be perfectly substituted when its relative cost increases. As GDP is the sum of value added (remuneration of capital and labor), higher costs of energy imply lower GDP since remuneration of capital and labor will have to reduce to compensate for higher energy costs assuming non-energy output prices are unchanged. If non-energy output prices increase following energy cost increases, demand will be depressed due to lower purchasing power of income and loss of competitiveness in foreign markets. Since household consumption is the largest component of GDP, it decreases when higher energy costs require households to spend less on non-energy goods and services. Therefore, in energy systems analysis the costs which are important to account for are those incurred by final energy consumers. These costs should include all costs related to the provision of energy services, including equipment and energy saving costs and not only energy commodity purchasing costs.

From a final end-user perspective, energy system costs can be divided for each sector into the following categories, for which details are given below: (1) Capital costs; (2) Fuel and electricity costs including taxes; (3) Direct auction payments for CO_2 or other permit systems, where applicable; and (4) Disutility costs.

3.1. *Capital costs*

Capital costs for end-users are the costs which are involved in purchasing energy-using equipment, appliances, as well as the costs related to investments in energy savings. Energy-using equipment also serves non-energy purposes such as entertainment, mobility, or industrial production. Where possible, cost accounting must distinguish between specific energy-related and non-energy-related parts of equipment costs.

Energy systems models implicitly or explicitly involve capital-budgeting decisions of final consumers, for example to determine energy efficiency investment or the choice of more efficient but costlier technologies. The consumer's investment behavior depends on annuity payments for capital compared to variable costs so they depend on present values discounted using an interest rate. Some modeling approaches use different interest rates by demand sector in an attempt to mimic real-life capital budgeting decisions, whereas other approaches use uniform interest rates and often social discount rate values, as opposed to private discount rate values, in an attempt to evaluate the optimum investment from a social welfare perspective (Sanstad and McMahon, 2008; *The Energy Journal*, 2011).

Emissions reduction generally requires higher capital costs for purchasing more efficient equipment and for energy saving purposes, for example in order to increase thermal integrity of buildings. The ensuing energy efficiency progress implies lower demand for energy hence lower variable costs for purchasing fuels and electricity. The net cost of emissions reduction, which compares annuity payments for capital and variable costs, depends on the choice of the interest rate. A low rate may even imply negative net costs under emissions reduction assumptions, compared to a base case.

3.2. *Fuel and electricity costs*

The impacts of emissions reduction on the fuel and electricity costs incurred by final consumers depend on demand volumes, which generally decrease in emission reduction scenarios compared to a base case. The impacts on fuel and electricity costs also depend on the feedback effects of reduced demand on energy commodities prices.

Under emissions reduction assumptions, emissions from electricity generation will also have to be reduced, usually to a larger extent than the rest of the energy system, as suggested by most model results. Decarbonization of power generation implies higher costs per unit of output compared to a base case, as carbon-free generation is more expensive than conventional generation. This implies that electricity prices will tend to increase under emissions reduction assumptions. Most energy models agree that using electricity instead of fossil fuels in final demand facilitates emissions reduction, both in stationary and mobility energy uses, provided that power generation is sufficiently decarbonized. In this context, most models find for example heat pumps (Usher and Strachan, 2010) and electric vehicles (European Commission, 2011a; Capros *et al.*, 2012a; Luderer *et al.*, 2009) as attractive decarbonization options together with energy efficiency improving investment. Electrification of demand combined with increasing electricity generation costs implies increases in electricity bills of end-users, compared to a base case. However, the total end-consumer bill for purchasing fuels and electricity is usually found to be lower in emissions reduction scenarios compared to a base case, because end use of electricity is more efficient than fossil fuels. For example, electric vehicles and heat pumps are much more efficient than internal combustion engines or boilers when accounting only for final energy consumption.

Fossil fuel prices are essentially unaffected by emissions reduction as far as secondary transformation is concerned (e.g., refineries where costs slightly increase under emissions reduction policies). Significant impacts on fossil fuel prices may occur if emissions reduction implies substantial reduction of demand at a global scale so as to influence global or regional fossil fuel markets. It is currently expected that global supply of hydrocarbons will increasingly rely on more expensive resources including unconventional resources, which are more costly than conventional ones. The decrease in global demand for hydrocarbons, as a consequence of global emission reduction, will imply lower production costs, compared to a base case. However, as conventional resources are more concentrated than unconventional ones, oligopoly power in hydrocarbon supply is likely to increase in emission reduction cases. Thus the net impact on world fossil fuel prices depends on whether the effect from demand depression will dominate the effect from market concentration. Most models show decreasing fossil fuel prices in global emissions-reduction scenarios, compared to a base case projection. From an end-use perspective, it is therefore, more likely to see decreasing prices of fossil fuels, due both to demand reduction and to cost reduction, depending on the extent of reduction of global demand for fossil fuels.

Summarizing, emissions reduction implies higher capital costs for energy end-users and more likely lower variable costs, compared to a base case. Whether the net effect on levelized costs is negative or positive depends on the interest rate which is used to annualize capital costs. The net effects on levelized costs are shown by most models to be positive (higher costs) for end users of energy, except when social discount rates are used as interest rates. This may imply even negative net costs in the case of very profitable energy efficiency investment.

The changes in the cost structure for energy of end-users implied by emission reduction are remarkable: final consumers are likely to increasingly spend in their premises or for their vehicles instead of spending money for purchasing commodities from the energy industry. With the probable exception of the electricity industry, all other energy suppliers are likely to see diminishing volume of sales in emission reduction projections compared to a base case. The end-users of energy will be also likely to spend more for capital and less for variable costs, which implies that they will face increasing money borrowing needs. This is important for distributional effects regarding for example income classes or for small and medium enterprises.

3.3. *Auction payments for CO_2*

Emissions reduction is usually driven by pricing carbon emissions. The type of the policy instrument used to enforce/implement emissions reduction affects policy costs, as different instruments imply transfers between different agents. A carbon tax increases the cost of fossil fuels and induces substitution away from fossil fuels, but carbon tax payments imply transfer payments to the state — further implying lower consumer purchasing power and lower expenditures in all types of energy related items. If emissions trading is employed as a means of carbon pricing, the impacts depend on whether emission allowances are allocated to consumers for free (for example according to grandfathering principles) or after auctioning. In the former case, allowance prices represent an opportunity cost for the energy end-user and will stimulate substitution and energy savings, depending on economic conditions, without direct budget implications, contrary to auctioning schemes which imply transfer payments to the state similar to a carbon tax.

Energy end-users bear costs in addition to the consequences of carbon pricing on commodity costs and prices, for example, when electricity generation is also subject to carbon pricing. Electricity producers are likely to pass costs incurred in generation due to carbon pricing through to consumers. In the cases of carbon taxes or the purchasing of allowances in auctions, producers are likely to pass 100% of carbon costs on to consumers. Producers are likely to pass on less than 100% of costs in a case where allowances are allocated for free, depending on the degree of market competition.

From an end-user perspective there are two types of auction payments: direct auction payments and indirect auction payments. The latter, as mentioned above, are passed on to the consumer through the electricity prices and are not recognizable by the end consumer. The amount of payment for carbon pricing, both directly and indirectly, decreases over time in a decarbonization context even in cases where the carbon price increases because energy gradually becomes less carbon intensive.

In terms of cost accounting, auction and carbon tax payments may be excluded from total energy systems costs when they are analyzed from a macroeconomic perspective because the revenues from auction or carbon tax payments may be efficiently recycled in the economy and returned back to final consumers. In this sense, they represent a transfer payment in the economy. However, macroeconomic studies[1] using economy-wide models have shown that different possible schemes of recycling state revenues from carbon taxation or auction back to the economy may have significantly different impacts on GDP and in particular on different sectors and the income of final consumers.

3.4. *Disutility costs*

Accounting for disutility costs in energy systems analysis is essential in impact assessments in order to ensure comparability between different scenarios. Due to higher energy prices, generally driven by higher energy-related costs associated with emissions reduction, consumers may feel the need to reduce their energy requirements beyond the level of energy savings enabled by energy efficiency investment; this implies a reduction in the utility of the consumers. The disutility can be accounted as a cost which can be calculated as income compensating variation. This method monetizes utility loss, due to the increase of a commodity price, by evaluating the amount of income that theoretically should be given to consumers in order to allow them to reach, under increased price conditions, the same utility level as before the price increase. So the additional income compensates consumers for the loss of utility due to the variation of prices.

From a final energy consumer perspective, utility is driven by the amount of comfort and services derived from using energy for useful energy purposes which

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[1] A recent example is the MODELS EU FP6 research project which has used several models to evaluate the impacts of different recycling schemes of carbon auctioning revenues (see http://www.ecmodels.eu/index_files/MODELS_Final%20Publishable%20Report.pdf).

include for example lighting, heating, mobility, industrial production, etc. The tendency over time is to increase utility with increasing income: this leads to higher mobility, higher room temperatures, larger amounts of heated space in dwellings, etc.

A reduction of utility in the energy system can be driven by higher energy prices (e.g., higher taxation, higher oil prices, etc.) and/or higher energy-related costs (costs for purchasing equipment, investment costs in house insulation, etc.). The additional energy cost (either because of higher prices or because of a net cost of efficiency investment) implies reduction of spending for non-energy purposes as consumers' disposable budgets is unchanged. To maximize overall utility, the consumer tends to reduce the part of utility associated with energy and so the consumer reduces luminosity from lighting, decreases thermostat controls for heating, eventually heats only part of the house, reduces mobility or reduces industrial production, etc. All these reductions are utility losses which correspond to a cost for the consumer relative to the case without additional energy costs (Hamamoto, 2013).

When the consumer perceives a benefit from energy efficiency investment, in other words, when there is a net profit, then overall budget increases, and the consumer has the tendency to spend more on energy and non-energy products to get higher levels of utility allowed by the increased disposable budget. In this case, the consumer has a utility benefit which can also be monetized through the income compensation methodology. Either in view of higher energy prices or in view of an obligation to save on energy consumption, the consumer's response is first to improve energy efficiency through investment; if such investment implies net costs, then the consumer also decreases the level of useful energy services and so encounters a disutility loss.

To further explain the importance of disutility costs when comparing two scenario cases, and also for evaluating benefits and costs of policy measures, we take a simple example of a tax imposed equally on all possible fuels consumed by cars; assume that efficiency progress of cars is not possible and also assume that there is no transportation mode other than using a car. In this simple example there is no possibility of responding to higher taxation by substituting between fuel types or between transportation modes. The only possible response is to reduce mobility. The consumer then pays more for energy compared to the case without the additional taxation but less than under unchanged mobility. Obviously to assess total cost of taxation for the consumer, one has to add additional cash flow payments and disutility costs.

Another characteristic example is the assessment of bottom-up control policies. Assume that a rationing type of control applies as a policy to reduce energy consumption, for example smaller fuses do not allow the use of all electric appliances and lighting in a typical house. The consumer is obliged to better manage the use of electricity, which implies also lower overall electricity consumption. So from a cash-flow perspective, the consumer is better-off. But when including disutility costs the consumer obviously bears costs because of the rationing.

There are arguments, however, against including disutility costs in long-term scenarios, in particular regarding energy efficiency improvements in buildings. One type of argument concerns the possible change of utility functions (e.g., different relative weights on the various services enabling utility) over time in the context of decarbonization scenarios compared to a base case. For example, the decarbonization context may also push consumers to attribute higher value to products and consumption conditions that do not exist in business-as-usual (BAU); for example consumers may get utility from soft mobility (walking, bicycles, etc.), from the living conditions in well insulated houses, from new efficient lighting patterns, from flexibility in using small electric cars in city-centers, etc. It is true that the economics do not provide any method for monetizing new utility-enabling conditions. Another type of argument points to secondary benefits provided by improved energy efficiency; for example the value of a house may be higher if well renovated for energy purposes. These ancillary benefits of energy efficiency are not accounted for in energy models and so disutility costs may be over-estimated in some cases.

3.5. *Distributional and investment-related impacts*

The shift toward higher capital costs and the increase of investment which characterize emissions reduction scenarios may raise serious concerns regarding distributional effects on different income classes, industries of different sizes and countries based on their GDP, which are not necessarily analyzed using standard energy system models. The assumption about a single representative consumer per sector and country, which is a common assumption in most energy and economic models, limits the model possibilities for capturing the distributional impacts.

Two main issues may cause problems in this respect: (1) The increasing ratio of energy service costs to income: when energy services do not increase as much as income beyond a certain threshold, i.e., beyond a certain income level the income elasticity is lower than one, energy services cannot be compressed below a certain level, i.e., below a certain income level the income elasticity of energy is above one. This implies that in a situation where energy becomes significantly more expensive the lower income classes may be more strongly affected. This may also be a problem for smaller-sized enterprises or industries with high energy intensity where increasing energy costs may endanger their competitiveness. (2) The increase of capital costs for energy services: In a situation, such as a decarbonization scenario, where capital costs increase significantly compared to variable costs, the problems for low income classes may increase as low income classes have in general less access to capital; in cases such as decarbonization this may imply that some parts of the population may not be able to afford advanced technologies and energy saving investments meaning that they may be entirely cut out from certain technology developments. For industries this may mean that small enterprises are cut out of the business.

In such a context it may be that "energy poverty" occurs. Poverty is generally defined as being below a certain threshold (Morgan *et al.*, 2010). In a context of increasing energy service prices, energy poverty may occur driven by the fact that people may not be able to afford to purchase expensive efficient technology. As technology often comes in clusters, lack of capital may imply that some parts of society may be completely deprived of certain technologies required for saving energy.

A further impact of decarbonization on the wider economy is the result of a change in tax revenues: Assuming that the taxation system remains as it currently is, revenues from fuel taxation will fall. In the context of decarbonization there will be a shift away from highly taxed fuels such as oil toward fuels/energy carriers with lower taxation such as electricity or renewables. Although VAT from the additional capital investments in households will increase, it will imply significantly lower revenues for the state than the revenue that will be lost due to the changes in fuel consumption. The revenues from the auctioning of emission allowances will not compensate for the lost revenue, as through decreasing emissions the auction revenues will decrease throughout the time period to 2050. As the state will require the taxation revenue to remain unchanged from a base case, an additional cost which is not included in energy system modeling is that taxes will probably be raised elsewhere (in non-energy activities) leading to a further increase of total costs with uncertain distributional impacts.

3.6. *An illustrative example of energy system modeling results on mitigation costs*

Models focusing on energy systems do not track the rest of the economic sectors, therefore, GDP, consumption, and welfare are usually treated as given. Then, the models take into consideration energy system costs related to different policies. A definition of energy system costs varies between different models. Depending on model specification, it includes the costs for: (1) purchasing energy commodities at prices which include recovery of auctioned allowances; (2) purchasing energy equipment; (3) investing in energy efficiency improvement and savings; and (4) paying taxes and levies. As energy prices affect all sectors of the economy, this measure provides only a partial coverage of the cost of a policy.

For illustrative purposes, cost estimations using the PRIMES model for European Commission's Energy Roadmap scenarios (European Commission, 2011b) are presented in Tables 1 and 2 (Capros *et al.*, 2012a,b). The cost figures presented in Table 2 which refer to the entire energy system are the summation of cost figures only for final consumers (i.e., households, services, agriculture, industry, and transport) which are presented in Table 1. The electricity and fuel supply costs (shown in Table 1) are obviously included in the payments by final consumers for purchasing electricity and fuels.

Useful insights which illustrate the concepts mentioned above can be drawn by considering the last column of Tables 1 and 2 which shows the cost differences between decarbonization and the reference scenario in cumulative terms over the period 2005–2050. It can be seen that for all final consumers decarbonization implies higher capital costs and lower variable and fuel costs. Fuel costs are decreased in decarbonization relative to the reference not only because of lower fuel demand but also

Table 1. Example of energy cost decomposition by sector according to PRIMES model results.

Billion EUROs of 2008	2010	Decarbonization scenario for EU27			Decarbonization	Reference	Diff. from reference
Figures for EU27 member-states		2020	2030	2050	Cumul. 2005–2050	Cumul. 2005–2050	
					Households		
Costs excl. disutility	457	670	744	1,135	33,000	33,125	−125
annual capital costs	148	288	364	809	16,984	13,779	3,205
variable and fuel costs	309	382	379	326	16,016	19,347	−3,331
Households disutility costs		26	87	183	3,434	1,919	1,515
Household transport costs	342	587	868	1,007	33,268	31,642	1,626
Households total costs	799	1,283	1,699	2,325	69,701	66,686	3,015
as % of households income	11.60	15.00	17.10	17.30	15.80	15.10	0.70
					Services and agriculture		
Costs excl. disutility	211	279	277	350	12,421	13,656	−1235
annual capital costs	40	67	82	201	4,156	3,093	1,063
variable and fuel costs	171	212	195	149	8,265	10,563	−2,298
Services disutility costs		10	40	78	1,495	581	914
Services transport costs	176	312	479	562	18,003	17,618	385
Services total costs	387	601	797	990	31,919	31,855	64
as % of services value added	4.80	5.90	6.50	5.90	6.00	6.00	0.00
					Industry		
Costs excl. disutility	241	309	342	394	14,524	16,365	−1840
annual capital costs	53	71	87	117	3,708	3,597	111
variable and fuel costs	188	237	251	269	10,664	12,645	−1,981
CO_2 auction payments		1	4	8	152	123	30
Industry total costs	241	309	342	394	14,524	16,365	−1,840
as % of industry value added	14.20	15.00	14.20	12.50	13.70	15.50	−1.70

Table 1. (*Continued*)

Billion EUROs of 2008	2010	Decarbonization scenario for EU27			Decarbonization	Reference	Diff. from reference
Figures for EU27 member-states		2020	2030	2050	Cumul. 2005–2050	Cumul. 2005–2050	
					Transport		
Costs excl. disutility	518	881	1297	1,455	49,251	48,077	1174
Add. annual capital costs	38	328	751	1059	26,820	20,139	6,681
variable and fuel costs	481	551	542	394	22,332	27,823	−5,491
CO_2 auction payments		2	4	2	99	114	−16
Transport disutility costs	0	18	50	114	2,020	1,183	837
Transport total costs	518	899	1347	1,569	51,271	49,260	2,011
as % of GDP	4.30	6.00	7.60	6.60	6.60	6.30	0.30
					Electricity and distr. heat supply		
Revenues of electricity & heat	368	504	563	594	23,572	25,001	−1429
for annual capital costs	157	218	255	300	10,638	10,403	235
for variable and fuel costs	150	187	194	197	8,456	9,910	−1,454
for taxes	60	74	81	92	3,560	3,621	−61
for CO_2 auction payments		25	33	6	918	1067	−149
					Fuel supply		
Revenues of fuel supply	920	1054	988	710	41,459	54,467	−13007
for annual capital costs	147	181	177	141	7,377	9,705	−2,328
for variable and fuel costs	523	641	628	501	26,155	34,409	−8,254
for taxes	250	232	183	68	7928	10353	−2,425

Table 2. Example of energy system cost decomposition according to PRIMES model results.

Billion EUROs of 2008	2010	Decarbonization scenario for EU27			Decarbonization	Reference	Diff. from reference
Figures for EU27 member-states		2020	2030	2050	Cumul. 2005–2050	Cumul. 2005–2050	
Entire energy system							
Annual capital costs	583	1153	1716	2,627	69,683	60,716	8967
Variable and fuel costs	534	652	640	567	27,182	35,234	−8,052
Disutility costs	0	55	178	375	6,948	3,683	3,266
Taxes	310	306	264	160	11,488	13,974	−2,487
Auction payments	—	28	41	16	1,169	1,304	−135
Payments in consumer premises	278	754	1284	2186	51,668	40,608	11,060
Payments to energy suppliers	1149	1382	1368	1138	57,278	70,378	−13,100
Total energy system costs incl. auctioning	1427	2193	2839	3744	116,470	114,911	1,559
as % of GDP	11.90	14.70	16.00	15.70	15.00	14.80	0.20
Total energy system costs excl. auctioning	1427	2165	2798	3729	115,301	113,606	1,694
as % of GDP	11.90	14.50	15.70	15.60	14.80	14.60	0.20

because of reduction of fossil fuel prices due to lower global demand for fossil fuels, as the decarbonization scenario assumes global climate action.

The cost figures clearly show that the additional costs of decarbonization incurred by final consumers mainly concern consumers' equipment, buildings, and vehicles, whereas electricity and fuel purchasing bills tend to decrease. The energy system net additional costs of decarbonization as a percentage of GDP is small, only 0.20% in cumulative (non-discounted) terms until 2050. However, the cost figures show that the additional cost incurred by households as percentage of households' income is much larger: 0.70% in cumulative terms until 2050. The figures also show decreasing state revenues in decarbonization (relative to reference) from energy and carbon taxation.

It is worth noting that disutility costs are an important element to consider when comparing costs between decarbonization and the reference scenario. Omitting disutility costs would lead to misleading conclusions about cost impacts of decarbonization in particular for households. CO_2 auction payments are rather small and decrease in decarbonization relative to the reference scenario despite higher carbon prices in the former scenario. The reference scenario assumes that the EU Emission Trading Scheme applies until 2050 but projects emissions to stay at higher levels than in the decarbonization projection.

4. Macroeconomic Costs

The increase of energy service costs in the context of decarbonization strategy act by crowding out effects to the rest of the economy and reducing demand for non-energy goods and services. On the other hand, the implementation of clean energy technologies and energy efficiency investment act toward increasing demand for non-energy goods and services. In addition, the reduction of fossil fuel consumption reduces the cost of imports when fossil fuels are imported and reduces export revenues in case fossil fuels are exported. The net effect on the economy is uncertain, therefore, justifying the use of macroeconomic mathematical models. The cost concepts that are often used in the modeling studies are: change in GDP, change in consumption, change in welfare, energy system cost (already mentioned), and area under MAC curve. Below we briefly discuss them.

4.1. *GDP change*

GDP is a country-level measure of an economic activity that is the most familiar to a general audience. Therefore, a change in GDP as a measure of cost is often used because the public can easily relate to it. To estimate a GDP change, one first needs to get a projection of a level of GDP in a certain year under the assumption that no emission-reduction related policy is introduced. Such projection is usually referred to as a reference, or BAU scenario. Then, an introduction of a GHG emissions reduction policy leads to a different level of GDP projection in that year. A comparison of two projections in absolute or percentage terms provides an estimate of the GDP cost of a policy.

GDP is defined as the sum of consumption, investment, government spending, and net exports (exports minus imports). It is a measure of economic activity in a country counting total final output. A change in GDP is not a fully-satisfactory indicator of cost, because economists and policy-makers prefer to assess a policy based on its impact on consumers rather than on the total output in a country. In addition to consumption, GDP measure includes investment activity that does not add to consumption in a given year, but may add to availability of goods over time. Government spending may be productive or not and can impact consumption in a different way. Net exports may include substantial changes in terms-of-trade, when prices of exports and imports change. With a change in terms-of-trade, for the same amount of domestic currency, consumers may be able to purchase more or less foreign goods, and this change in consumption of goods is not directly reflected in the net of export payments over import payments.

As climate policy affects energy prices, countries with large energy exports or imports can experience large terms-of-trade effects. For example, based on the Kyoto Protocol analysis Viguier *et al.* (2003) show that emissions targets improve terms-of-trade for most of the EU countries as they are affected by declining import prices for energy, while the UK and the Netherlands, which are energy exporters, face deteriorating terms-of-trade. They show that percent changes in GDP can be twice as big as percent changes in consumption for some European countries. In extreme cases, changes in GDP and consumption may be in opposite directions as shown by Babiker *et al.* (2000), where for some countries substantial changes in terms-of-trade lead to gains in GDP from a climate policy, while aggregate consumption (a component of GDP) decreases relative to a no-policy scenario.

4.2. *Consumption change*

A change in macroeconomic consumption is determined in a similar fashion as a change in GDP. It is a comparison of two projections: One is a projection of a total consumption level in an economy with an assumption of no carbon reduction policy, and the other is a projection of consumption with carbon policy introduced. It is arguably a better measure of cost than GDP as it looks at the impact on a country's population, netting out terms-of-trade effects, investment, and government expenditures that somewhat distort the implications of a policy on the consumers.

A direction of the difference between consumption and GDP changes is ambiguous. For example, some models that report both GDP and consumption in the EMF28 have changes in one measure larger or smaller (in percentage terms) than the other measure depending on time period and scenario. For some models in this exercise, percentage change in consumption is consistently smaller than percentage change in GDP.

A downside of measuring cost as a change in macroeconomic consumption is that it usually represents only market activities. On the other side, a valuation of non-market activities (such as leisure time, consumption of public goods, non-formal economic activities, etc.) is subject to uncertainty and some controversy, while macroeconomic consumption is better measured. Therefore, consumption change is a popular measure of cost that is understandable by policy-makers and the general public.

4.3. *Welfare change*

For many economists the preferred measure of cost is a change in welfare. It can be measured as "equivalent variation" or "compensating variation" and can be loosely interpreted as the amount of extra income consumers would need to compensate them for the losses caused by the policy change. Welfare measure is close to a change in consumption but it also usually includes changes in leisure time (i.e., the monetary value of the change in non-working time) that occur in response to the policy. Most of the models that can track both consumption and welfare use "equivalent variation" as a measure of welfare change. If the model does not include non-market activities (like leisure, etc.), then the changes in consumption and in welfare are the same. With explicit representation of leisure, welfare changes are usually smaller than consumption changes because an increase in the prices of consumption goods (due to an increase in energy prices) leads to re-allocation of available time to non-market activities increasing leisure. The magnitude of the shift depends on the labor supply elasticity.

4.4. *Economic activities that affect mitigation costs*

Mitigation policies may affect economic activities in different ways. Emission intensity reductions are achieved by replacing fossil energy technologies with low carbon alternatives such as renewable or nuclear energy, or by introducing carbon capture and sequestration. Such low carbon technologies are generally more expensive, thus their widespread introduction will increase market prices for energy. Similarly, more efficient end-use technologies reduce energy intensity, but may have higher installation costs. Zero costs or beneficial efficiency improvements are also possible, but usually they are limited to a particular economic sector or owners of particular technologies.

The changes in the price of energy and energy services will affect consumption. Households facing more expensive energy might be forced to cut back on other activities. Energy intensive goods and services will be scaled back and replaced, to some extent, by less energy-intensive goods and services. New market opportunities for carbon and energy-saving products will emerge, which need to be weighed against market losses for other products. Investments streams on the supply slide will adjust to a change in relative prices, with increased investments in alternative energy technologies and energy-efficient goods and services. Because this requires overall higher investments, investments in other sectors, such as medicine and construction, may be crowded out. Investments in labor and energy-augmenting innovation processes will also be altered, affecting both the scale and the direction of technological progress.

International trade flows and the terms of trade of countries will be affected, with a particularly strong impact on energy markets. Owners of fossil resources will see a depreciation of their resource rents. To the extent that mitigation policies affect land use (e.g., *via* forest conservation or deployment of bioenergy) land rents and the price of agricultural commodities will be impacted. Fragmented climate policy action may give rise to GHG leakage when dirty and energy intensive industries migrate to countries with less stringent climate policy regimes. Climate policy can also produce new revenue streams, e.g., *via* carbon taxes or the trade of emissions allowances. Those revenues accrue to the government or to the allowance holder and may be recycled in the wider economy or used for the provision of public goods.

Macroeconomic models represent the economic activities described above to estimate the costs. Numerous studies (Paltsev *et al.*, 2008; Clarke *et al.*, 2009; Edenhofer *et al.*, 2010; Fawcett *et al.*, 2013; Kriegler *et al.*, 2013) show that mitigation costs depend critically on assumptions about: (1) innovation and the availability of low-carbon alternatives to conventional fossil fuels, (2) flexibility of substitution within the energy-economic system, (3) the credibility of future policies that trigger long term investments, (4) additional government standards and regulations, and (5) the immediate action of all countries or of major emitters. Costs also depend on economic development and assumptions about the efficiency of markets in a no-climate-policy (reference) scenario.

5. Issues with Estimating Mitigation Costs

Cost estimates of policies require assumptions about "baselines" (also called "Reference" or "BAU"). It is true even for estimates of costs for policies in the past when the realized outcomes are known, because for cost assessments one needs a comparison between the realized outcome and a hypothetical situation of what would have been otherwise. The estimates of such outcome of "what would have been otherwise" sometimes differ dramatically. For example, for the U.S. Clean Air Act, a program that reduced air pollution in the USA, the EPA (1999) has estimated benefits of $27.6 trillion, while Matus *et al.* (2008) has estimated the benefits at $5.4–7.9 trillion.

Assessments of the future programs have even more uncertainties as both "baseline" and policy scenarios are the results of the modeling rather than known from realization. Emissions reduction takes place in a counterfactual scenario and impacts are evaluated as changes from a Reference scenario, therefore, a definition of the reference matter. For example, EMF28 exercise defines the no-policy baseline (denoted as EU 11) with no constraints on emissions as if no current policies were introduced, and the reference scenario (EU 1) which includes current policies but excludes possible additional policies. As shown in Knopf *et al.* (2013), the current policies have already incurred some costs and an assessment of additional policies can be done relative to either "no-policy" world or to "the current policies" world. In the example of the EMF28, if one wants to estimate the full costs of mitigation, the proper comparison is to the no-policy scenario. On the other hand, one might argue that the costs of the current policies have been already realized or will happen in the future anyway, so the proper comparison is with the "current policies reference". As the no-policy and current policy scenarios deviate over time, a difference in estimating the costs of mitigation might be substantial.

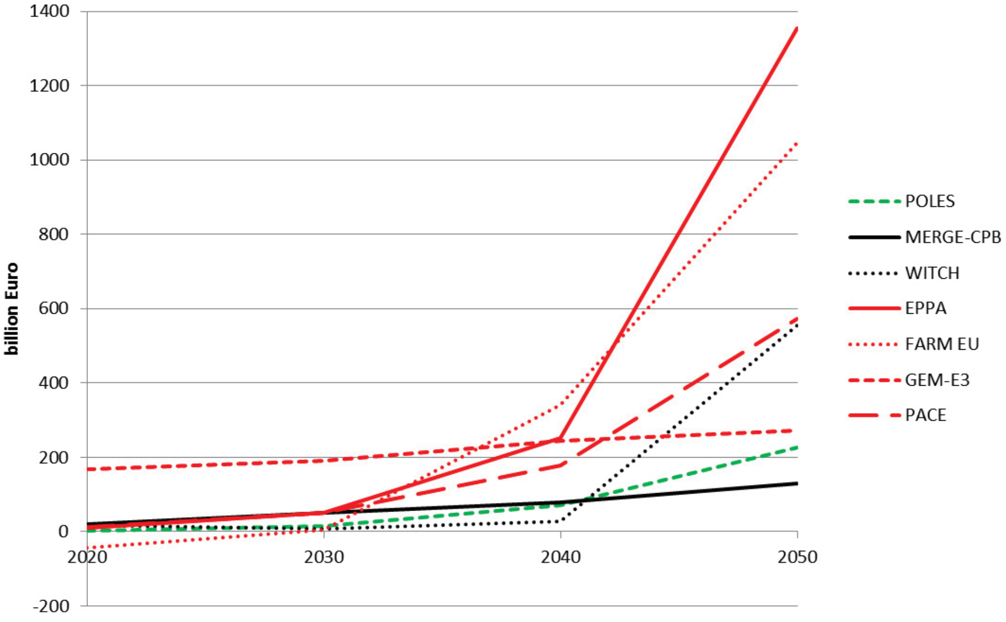
Another issue related to the current policy scenario is that it assumes that the policy is fully implemented as legislated. A history of many programs (for example, the requirement of a certain amount of second-generation biofuels in the U.S. Energy Independence and Security Act of 2007) shows that requirements can be adjusted or abandoned, therefore, the "current policy reference" also might be altered over time.

As mentioned before, cost impact assessment depends on modeling methodology. Models that focus on energy systems do not consider the whole economy and therefore, usually do not provide GDP, consumption, or welfare changes. On the other hand, economy-wide models tend to simplify details of the energy sector that are represented in comprehensive energy models and, as a result, may underestimate the complexities and rigidities on the energy system. It has been shown that interaction of different policies (for example, emissions constraints, renewable electricity requirements, and fuel efficiency standards for automobiles) may lead to increased or decreased costs that are sometimes not visible to consumers (Fawcett *et al.*, 2013). The assumptions about technological learning, and generally the modeling of induced technology progress enabled by decarbonization strategies, have significant implications on the estimation of mitigation costs in a macroeconomic context (as illustrated in Capros *et al.*, 2012; Bosetti *et al.*, 2011; De Cian and Tavoni, 2012; Löschel and Schymura, 2013).

One also may be interested in a summary measure of the cost borne over the life of the policy. To compare costs over time, conventional economic practices apply a discount rate to future costs on the basis that money today would earn a return over time. Annualizing capital costs from an end-user perspective involves a discount rate (annuity), and a calculation of the weighted average cost of capital (WACC) involves subjective discount rates and reflecting the long-term structure of capital rather than the current capital structure. For macroeconomic growth models, balanced growth equivalents can be used to capture a change of inter-temporal welfare in terms of annual average consumption changes. A more broadly applicable measure is the average annual discounted GDP, welfare, or consumption change either as a percentage, an aggregate total or per household. A related measure is a net present value (NPV) of welfare (consumption, GDP) or welfare change, where all variables are summed over a certain period and discounted to the present values. A key variable in this calculation is a discount rate, i.e., how much less we value the future payments in comparison to the present payments of the same size, and there are different views on what the appropriate rate is for climate policy (see, for example, Nordhaus (2007) for a discussion about a discount rate).

The models in the EMF28 exercise can be broadly divided into three categories: recursive-dynamic GE models that cover all economic sectors (EPPA, FARM EU, GEM-E3, PACE), OG models (MERGE-CPB, WITCH), and PE models of the energy sector (POLES, TIAM-UCL, TIMES-VTT, PRIMES, TIMES Pan EU, PET, EMELIE-ESY). GE and OG models report GDP, consumption and welfare costs, PE models report either area under MAC or energy system costs. Figure 2 presents the results (in billion EUROs of 2010) for consumption changes and area under MAC for the emission mitigation scenario EU6 (this scenario assumes 80% GHG reduction by 2050) relative to the reference scenario EU1 (we provide the figure for illustrative purposes to compare the cost measures, for scenario definition see, Knopf *et al.* (2013)).

Figure 2 is indicative of the results for other scenarios in the EMF28. GE models tend to show higher costs as they capture economy-wide interactions and distortions. OG models assume perfect foresight and perfect information and they optimize over time periods, which results in lower costs than in GE models. PE models tend to show lower costs as they represent only direct costs and usually neglect the costs imposed on other sectors of the economy and other distortions. As definitions of energy system costs differ among the models we do not report them here as they are not directly comparable. Also, for GE and OG models here we show the consumption changes only. As most of the models do not consider leisure, welfare, and consumption measures coincide. Changes in GDP and changes in consumption generally show a



Source: EMF28 database.

Figure 2. Consumption change (for GE and OG models) and area under MAC (for PE models) in the mitigation scenario EU6 relative to the reference scenario EU1. GE models consist of EPPA, FARM EU, GEM-E3 and PACE. OG models comprise MERGE-CPB and WITCH. The only PE model here is POLES.

similar pattern, so for illustrative purposes we focus on consumption changes for GE and OG models and area under MAC for PE models.

6. Conclusion

Substantial emission mitigation requires actions that would not have been taken without climate policy intervention, otherwise, no dedicated climate policies would be needed. Actions that change economic behavior and force alternative technologies or different consumption patterns usually come at a certain cost to producers and consumers. In different models and studies the costs of emission mitigation are reported in different metrics, most of which are not directly comparable. A wide range of factors influence the costs of meeting particular goals, including the policy structures, the technologies available for mitigation, and reference scenario assumptions such as economic and population growth. A vast majority of models are set to report aggregate costs for the economy or energy system costs, but distributional effects that show impacts on different income categories of population are important. Modeling of the distributional impacts is still in its infancy due to lack of reliable data on income sources and expenditures and the more complicated modeling structures that are required to capture distributional issues.

The paper reviews the different cost concepts that can be used to evaluate the economic costs of mitigation policies. We focus on gross costs, meaning that we do not consider any offsetting climate benefits from mitigation or potential ancillary non-climate benefits (e.g., from reduced air pollution). A full policy appraisal will need to take into account mitigation costs and benefits. It is also necessary to note that the models provide an optimal solution given certain constraints and most of the models do not take into consideration many aspects of the costs such as, for example, lack of public acceptance for CCS, or logistical and infrastructure bottlenecks.

In summary, mitigation costs are reported in different metrics, most of which are not directly comparable. In economic theory, an appropriate cost measure is a change in welfare due to changes in the amount and composition of private consumption. Welfare measures can account for additional factors such as the provision of public or environmental goods, but estimates of welfare changes due to emissions mitigation have mostly focused on consumption. Because impacts of a policy are evaluated as changes from a reference scenario, a definition of the reference scenario matters. MAC cost measures tend to exclude existing distortions in the economy, while existing energy taxes and subsidies are substantial in many countries. Carbon prices are inadequate measures of the policy costs as they do not reflect the full cost of the policy. We conclude that: (1) there is no one ideal metric of costs, (2) for measuring macroeconomic policy costs — changes in macroeconomic consumption or welfare are the most appropriate, (3) depending on objectives — other indicators can be appropriate, (4) studies on mitigation and climate change policy cost should always be explicit about the cost metric used.

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