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Abstract:

The implementation of mitigation policies will be complicated by several real-world imperfections ('second-best conditions') and constraints typically not included in the more idealized economies assumed in Integrated Assessment Models (IAMs), based on which such policies are derived. But which of these numerous imperfections found in real economies are actually relevant in this context? And how could they–in principle–be taken into account by IAMs? Based on a literature review, we propose a typology of three categories of obstacles inhibiting 'first-best' conditions and outcomes: first, obstacles impeding the setting of least-cost abatement incentives; second, obstacles limiting the supply and exploitation of abatement options; and, third, obstacles creating distortions between the price and marginal costs of abatement. By reviewing the implementation of energy policy in China, we put our typology into practice and identify specific empirical evidence for each category. IAMs in principle can (and in practice often do) incorporate several relevant obstacles by means of additional cost or quantity constraints. However, the nature of some obstacles relating to strategic interactions between economic agents appears to be incompatible with the standard representative agent social-planner framework often employed in IAMs, suggesting a need for complementary analysis with decentralized 'Integrated Policy Assessment Models'.

1. Introduction

Scenarios play a central role in the current discussion on the design of climate policies. These scenarios depict possible future developments, e.g., the transformation of the global energy system or changes in land use patterns, under different assumptions, such as future rates of population and economic growth, or availability of fossil fuels and technologies (van Vuuren et al. 2011). As far as the implementation of policies to reduce greenhouse gas (GHG) emissions is concerned, it is frequently assumed that there is only one market failure – namely the environmental externality – that is internalized by an optimal policy. An example is a universal emission price covering all countries and economic sectors, set to its welfare maximizing value at each point in time. Hence, these scenarios usually – at least implicitly – consider the problem of climate change within a so-called 'first-best' economy where frictionless markets produce an outcome identical to the social optimum that would be achieved by a fully informed benevolent social planner.

However, economic theory has shown that in order for an economy to behave in such an ideal way, a number of formal prerequisites must be met (e.g. Arrow and Debreu 1954). They are closely linked to those stated in the fundamental welfare theorems, which describe how and when a socially optimal state of the economy can be reached by means of a competitive equilibrium. These conditions, along with some of their implications, are listed in Table 1.

Assumptions	Implications
Consumers with standard utility functions	*Homo oeconomicus* paradigm: rationality, time-consistency, no social interaction. Consumers can be modeled as one representative agent
Complete markets	Fully defined property rights (i.e. no externalities); prices for all goods including forward-looking prices (i.e. perfect financial markets)
'Free' markets	No distortionary taxes or subsidies: all regulation only to protect property rights and ensure functioning of markets; costless lump-sum transfers of tax revenues; no public cost of finance
Complete information	Information on all prices and all technologies is available to all actors, no actor with informational 'advantage'
No transaction costs	Actors can freely exchange all goods and services, markets perform without costs
Competitive (price-taking) behavior of all firms and consumers	No strategic behavior; producers equate marginal costs to market price
Full mobility and flexibility of production factors	Always full employment of all production factors
Perfect foresight[1]	No uncertainty, e.g. learning curves of all low-carbon technologies known
Convex production technologies	Unique economic equilibrium, ruling out e.g. carbon lock-in

Table 1: Conditions characterizing first-best economies and their implications

These strong conditions are generally judged to be in poor correspondence with reality (Stiglitz 1996). That is, distortions such as external effects (Pigou 1920), imperfect competition (Robinson 1961[1933], Chamberlin 1933), and missing markets and transaction costs (Coase 1960) have long been identified as reasons for why markets may fail to deliver a socially optimal outcome. More recently, issues such as asymmetric information (see Stiglitz 2000 for an overview) or seemingly 'irrational' individual behavior (Simon 1955, Kahneman 2012) have been recognized to further undermine their efficiency. As a consequence, the term 'second-best setting' is used whenever a given economy does not satisfy one or more of the conditions from Table 1, as opposed to the idealized first-best case.[2]

In a second-best setting, markets will lead to suboptimal outcomes and thus cannot be characterized by standard social-planner solutions. More importantly, second-best economies cannot be expected to adjust *optimally* to an exogenously imposed emission or temperature constraint, since this would require, amongst other things, well-functioning innovation markets (for low-carbon technology[3]), and perfect competition in energy markets. In other

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[1] It should be noted that 'perfect foresight' does not constitute a first-best requirement in the strict sense, as agents with rational expectations operating in complete future markets can still reach the efficient social planner outcome. However, in a broader sense the lack of foresight can still be considered a real-world imperfection, as it necessarily increases costs vis-à-vis the idealized deterministic case, e.g., when future learning rates of different mitigation technologies are not known today.

[2] In reference to the seminal work by Lipsey and Lancaster (1956).

[3] Note, e.g., the telling title "A tale of two market failures: technology and environmental policy" chosen by Jaffe et al. (2005).

words, relative to a first-best analysis the actual economic costs for implementing a given climate policy will likely be higher.[4]

For assessing climate policies, therefore, a second-best setting explicitly taking into account additional obstacles that might make climate policy more costly or more difficult to be achieved can be regarded as an appropriate framework, as emphasized by Kriegler et al. (2012, p. 816): "[a]nalyses of climate policy need to take into account existing market failures in the economic system and cannot assume an ideal world in which markets would be complete and perfect".

Following up on this, the present study aims to make a contribution by establishing a typology of obstacles to climate change mitigation found in the literature and discuss its relationship to integrated assessment models (IAMs) used to generate climate policy scenarios. By doing so, we seek to combine two existing strands of research: literature on observed real-world obstacles to least-cost emission reduction and studies on the empirical and conceptual limitations of IAMs.

Research of the first area has mostly focused on barriers to energy efficiency (Hirst and Brown 1990, DeCanio 1993, Jaffe and Stavins 1994, Weber 1997, Sorrell et al. 2000, Sorrell et al. 2011) and diffusion of renewable energy (Reddy and Painuly 2004, Owen 2006, Sovacool 2009). Hirst and Brown (1990) divide barriers into structural barriers, beyond the control of the individual end-user, and behavioral barriers, that influence the decision making of the end-user. DeCanio (1993) highlights bounded rationality, principal-agent problems, and moral hazard as major reasons explaining the divide between theoretical and actual energy use. Jaffe and Stavins (1994) distinguish between market failure explanations, which could justify a government intervention, and non-market failure explanations, which depict the observed behavior as optimal from energy users' point of view. Weber (1997) groups barriers into institutional, economic, organizational, and behavior barriers, while Sorrell et al. (2000) categorize them as market, organizational, and rational behavior barriers. Sorrell et al. (2011) provide a taxonomy of barriers and explain them from orthodox economics and transaction cost/behavioral economics perspectives. Reddy and Painuly (2004) differentiate between lack of awareness and information, economic and financial constraints, technical risks, institutional and regulatory barriers, market failures/barriers, and behavioral barriers. Owen (2006) focuses on market barriers that are either intrinsic features of markets or arise because of market failures. Sovacool (2009) divides obstacles to energy efficiency and renewable power in financial and market impediments, political and regulatory obstacles, cultural and behavior barriers, and aesthetic and environmental challenges. Finally, literature describing how technical innovations come about and are incorporated into society has assessed drivers and barriers of past technology transitions and possible shapes of future decarbonization pathways (see i.e., Anderson et al. 2005, Geels 2012, Ulmanen et al. 2009). As one example, Unruh (2000) widens the scope of previous studies, which are mainly focused on obstacles at the micro level, by exploring larger macro-level forces that can lead to a 'carbon lock-in' of the economy into fossil-fuel based energy systems.

Various studies on the limited ability of IAMs to reflect above-mentioned real-world characteristics in their estimates of mitigation costs have been carried out (Ackerman et al. 2013, Ackerman et al. 2009, Stanton et al. 2009, van der Zwaan and Seebregts 2004). However, they tend to be mostly model-specific or only focus on specific aspects (e.g.

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[4] In theory it is also possible that the implementation costs of climate policy are reduced by the presence of certain imperfections, namely when climate policy implementation allows for (partial) removal of these imperfections. This 'double dividend' effect might occur, e.g. when carbon tax revenues are used to lower distortionary labour market taxes (see, e.g., Goulder 1995).

Ackerman et al. 2013, Ferioli et al. 2009, van der Zwaan and Seebregts 2004). However, relatively few discuss limitations of IAMs from a broader perspective. Among those is Ackerman et al. (2009), who critically explore the use of IAMs in cost-benefit analysis. Stanton et al. (2009) analyze 30 existing IAMs and highlight several key shortcomings found in many of them, mostly regarding their representation of uncertainty about technological change and climate outcomes, as well as equity across time and space.

In this contribution we go beyond the existing literature by describing various types of obstacles and their modeling implications within one consistent framework. We also extend the scope of analysis from ‘pure’ second-best conditions (in the strict economic sense) to include all relevant obstacles and constraints undermining least-cost implementation of climate policy, like, e.g., the potential difficulties of some countries to establish and enforce a unique price on GHG emissions throughout all sectors of their economy. Our study will be of special importance for large emerging economies, such as China and India, where obstacles to least-cost climate policies can be expected to be prevalent. At the same time, due to their large populations and rapid economic growth, these countries play a central role in reducing (or slowing the growth of) global emissions.

The remainder of this paper proceeds as follows: Section 2 discusses potential obstacles to least-cost climate change mitigation and proposes a typology that classifies them as (i) impediments to formally establish least-cost climate policy, (ii) obstacles to the availability and efficient utilization of abatement options, and (iii) imperfections in markets for abatement, technology, and capital. Section 3 illustrates the empirical relevance of these obstacles for the case of China, currently the world’s top emitter of CO_2. Section 4 discusses the relationship of these obstacles to IAMs and whether (and how) they could be incorporated in future modeling work. Section 5 concludes.

2. Real-World Obstacles to Mitigation Policy: Theoretical View and Typology

Based on a literature review, this section proposes a typology of real-world obstacles to climate policy. We define an obstacle (or barrier) to climate policy as any circumstance that makes a given economy-wide emission target more costly to achieve than would be expected in a full information and frictionless first-best economy. The latter serves as a benchmark setting that is characterized by policy designs reflecting all relevant costs, policies being perfectly implemented and enforced, and all actors responding to these policies in a way that collectively leads to the socially optimal outcome. In what follows, we discuss ‘real-world’ barriers within a typology that categorizes obstacles as being related to the demand- or supply-side of abatement, or to market distortions. Its design was guided by the objective to accommodate all obstacles in a plausible manner, and to provide a useful structure in the context of economic modeling.

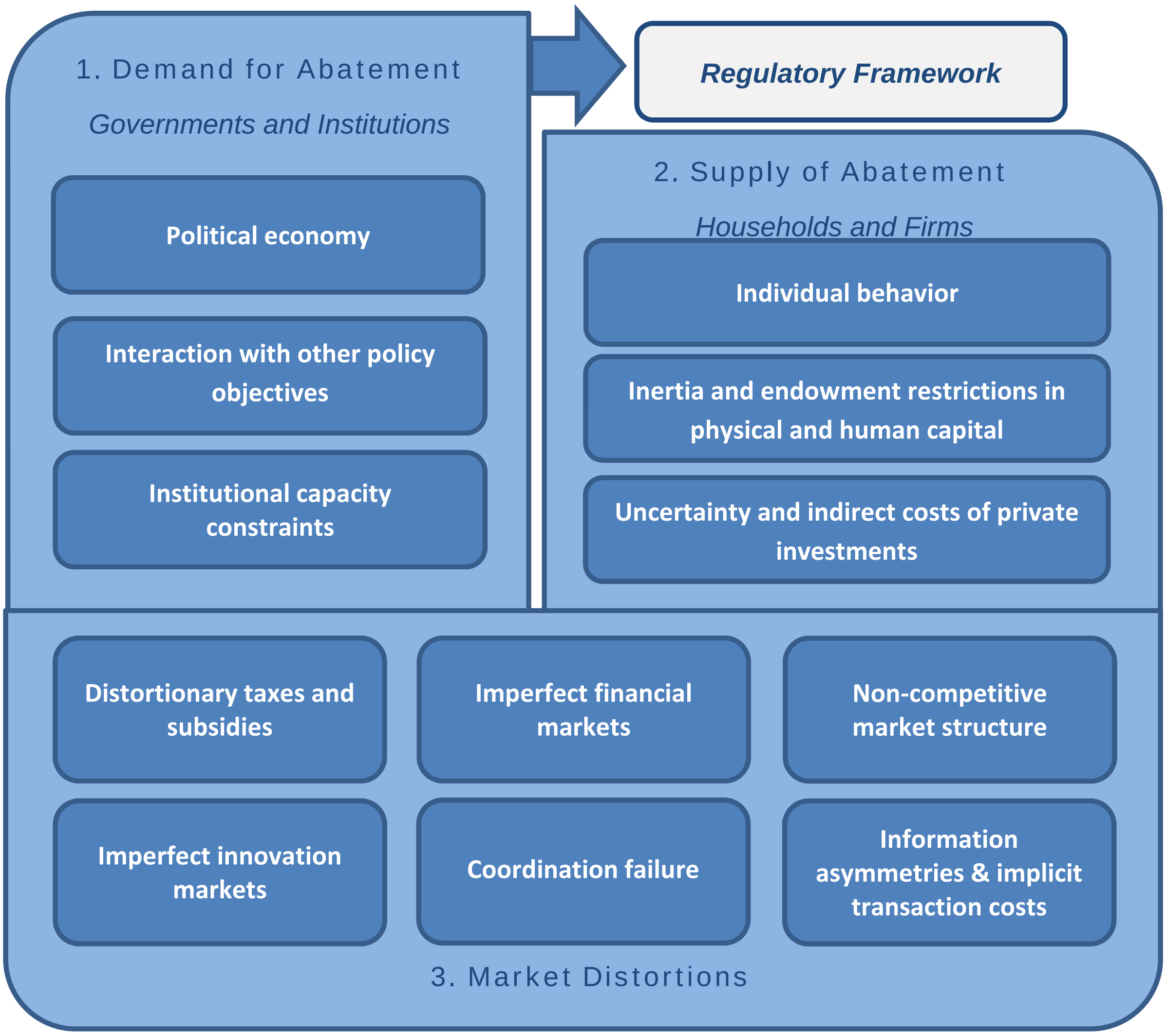

Figure 1: Overview of typology of obstacles to least-cost climate policy

This categorization necessarily exhibits ambiguities, as different obstacles may be interrelated and hence mutually affect each other. Moreover, for the sake of comprehensiveness we discuss a large number of heterogeneous obstacles at a highly aggregated level (in line with the high level of aggregation typically found in IAMs), and consequently must neglect details such as technology or actor-specific manifestations of different barriers, or idiosyncratic social processes such as collective-learning. Though it is impossible to claim completeness, we believe that our typology is capable to accommodate a broad range of different obstacles found in the literature (or potentially identified in the future), thanks to its quite general demand-supply-market framework. Figure 1 illustrates the three main categories of our typology and the specific obstacles discussed below.

2.1 Obstacles on the demand side for abatement: Impediments to implementing least-cost climate policy (Category 1)

Idealized economies in which markets produce socially optimal outcomes typically consist only of exchanges between consumers and producers, assuming that all externalities are internalized by appropriate policies. In reality, however, the implementation of emission targets requires a national government and institutions that must first design, pass, and enforce appropriate climate policy measures, like emission pricing or mandatory standards, in order to signal demand for abatement to households and firms. Furthermore, theory mostly assumes welfare maximizing governments that represent social demand for abatement adequately in their policies.

In view of this, our first category covers obstacles rooted in institutional or political circumstances that explain why policy makers might fail to establish an efficient GHG pricing (or shadow pricing by means of other forms of policy) over all sectors of the economy and over time.

Political economy

Contrary to what is implicitly assumed in a first-best world, governments or other regulating entities may not pursue social welfare as their primary objective (Grossman and Helpman 2001). Indeed, policy-makers and officials can be expected to work towards their own personal objectives, such as re-election, or increasing personal income. This may well have an impact on the design of emission policies, causing them to be more costly than would be expected under first-best conditions.

First of all, politicians facing re-election might be unwilling to implement policies that would be optimal from a social point of view, but are unpopular within important voter groups (Cremer et al. 2008). In the case of climate change, pricing emissions means that overall costs for producers and consumers rise, thereby reducing their perceived income. As a consequence, policy makers confronted with voters' potential resistance against higher energy and fuel prices may be hesitant to implement policies in an efficient way, and will perhaps rather resort to policies with higher costs, like renewable subsidies or energy efficiency standards. Furthermore, there might be a tendency to shift unpopular policy measures into the future, e.g. by taking on laxer reduction targets now but promising stronger ones for the next legislative period, which means that future prices will have to be higher than their inter-temporally efficient level.

Moreover, lobbying from minority coalitions, that bear a large share of the costs of a policy, can influence the policy outcome at the disadvantage of the general public interest (Olson 1982). Lobbying from coalitions of key industries has often been found to block necessary regulations or influence them in inefficient ways: e.g. the German car producers lobbied successfully against efficiency standards by depicting them as threats to German jobs (Greenpeace 2011); similarly, it is generally assumed that the first phase of the European Union (EU) Emissions Trading Scheme (ETS) suffered from an inefficient sharing of the overall reduction burden between ETS and non-ETS sectors, arguably due to successful lobbying efforts by industries included in the EU ETS (Ellerman et al. 2010).

Finally, the inability of most political systems to credibly commit to a long term policy that cannot be reversed by successors, e.g. due to electoral cycles or general political instability, leads to a lack of planning security (see also section 2.2) from the private investors' point of view (Brunner at al. 2012).

Interaction with other policy objectives

Analyzing climate change within a first-best context means that the only problem under scrutiny is the emission externality. In reality, the compliance with emission targets will be only one among a range of social objectives of public policy. Poverty reduction, economic growth, and energy security constitute important goals of their own right, which are usually not reflected by market prices in the second-best setting. Hence, they can alter the optimal mitigation policy and increase mitigation costs.

For example, striving for poverty reduction and economic growth often leads governments to keep energy prices artificially low, which raises market entry barriers for low-carbon technologies and slows down their diffusion (Schmidt and Marschinski 2009). In the same vein, several studies have emphasized the potentially adverse effects of increasing energy prices on the poorest segments of the population (Rao 2012). If financial redistribution to compensate this effect is not feasible ('lump-sum recycling'), e.g. in developing countries with weak institutions, policy makers might resort to more costly indirect policies, like energy efficiency standards or intensity targets.[5]

Pointing in the opposite direction, the decentralized, low-scale, and off-grid nature of most renewable energy technologies that eases energy access in remote areas can make their deployment politically more attractive, especially in developing countries. The same argument holds if energy security is a national concern and countries want to reduce their dependence on imported fossil fuels. However, a potentially high share of renewables in the overall mitigation portfolio may actually lead to additional monetary costs vis-à-vis the least-cost mitigation strategy derived from first-best analysis even though it may increase welfare.

Finally, some low-cost abatement options might not be used due to their lack of social acceptance. Examples include controversial high-risk technologies like Carbon Capture and Storage (CCS) and nuclear power, but also biofuels, which have been criticized for their impact on food prices (Mitchell 2008), or large hydropower projects due their perceived negative impacts on ecosystems (Zoellner et al. 2008).

Institutional capacity constraints

Regulation incurs no costs and compliance is taken for granted under first-best conditions, assuming enforcement and its implied institutional prerequisites and costs are not an issue. But the successful implementation of any policy crucially depends on the capacity of institutions. Lack of financial means, insufficient number, or inadequately trained staff can be major obstacles to the successful establishment of climate policy (Willems and Baumert 2003).

For example, securing the financial and human capital for adequate monitoring is a great challenge for institutions in developing countries. Weak economic conditions may also increase the incidence of corruption, which is a significant problem especially in developing countries (see ,e.g., Olken and Pande 2012, or Transparency International 2012). Sometimes institutions are expected to fulfill duties they were not originally designed for, e.g., the monitoring of renewable energy policies (GNESD 2007). Moreover, regulators may also suffer from constraints in time and skills as

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[5] E.g. China has adopted a voluntary intensity target in 2009 (Stern and Jotzo 2010), arguably as a means to pursue an emissions reduction policy without endangering economic growth. The efficiency of intensity targets, however, is contested (Marschinski and Edenhofer 2010).

well as uncertainty, making it unlikely that regulation dealing with a highly complex issue like GHG emissions is always designed efficiently (Goulder and Parry 2008).[6]

Finally, for some sectors or particular GHGs the transaction costs associated with their regulation (e.g. monitoring) may be prohibitively high, justifying the use of simplified and less cost-effective policies (e.g. fuel efficiency standards instead of emission-measurement for cars) or even their complete exemption from regulation (Goulder and Parry 2008). This will generally be ignored in first-best contexts, where administration costs are assumed to be negligible.

2.2 Obstacles on the supply side of abatement: Limited provision and exploitation of mitigation options (Category 2)

In a first-best setting, it is assumed that firms and consumers respond to the price signal of a given climate policy by optimal technology adoption and cost-minimizing changes in consumption patterns. However, several mitigation options have remained unused although they would be cost-effective even in the absence of climate policy (e.g. McKinsey 2009, Jaffe and Stavins 1994, Hirst and Brown 1990, Backlund et al. 2012). These unexploited ‘no regret’ options clearly contradict the cost-minimization objective of a stylized rational agent (see, e.g., Maréchal 2007). In light of this, the present category collects reasons why households and firms might not react to a price signal as anticipated, i.e. why the supply of abatement falls short of what would be expected in a first-best world.

Individual behavior

The model of perfectly rational economic actors outlined in the introduction assumes an optimization process behind every decision. But in reality, actors are limited in their capacity to grasp the complexity of every decision, i.e. they are subject to bounded rationality (see, e.g., Kahneman 2003). Especially day-to-day decisions are highly routinized and rather based on heuristics than on complex optimization assessing all options (Gigerenzer 2008). This frequently results in irrational decision-making, e.g. a ‘status-quo bias’ by which individuals resist change even if it would leave them better off (Kahneman 2012).

In a similar vein, accustomed consumption patterns or a negative societal attitude against specific technologies might counteract seemingly economically rational behavior[7]. A perception of new technologies as inferior to conventional ones for reasons other than efficiency or costs induces indirect costs due to which low-cost abatement potentials might not be exploited. For instance, a high valuation of convenient, low-effort solutions, or the perceived costs for overcoming settled habits influence individuals’ motivation to act. This is, e.g., confirmed by a study concluding that the main challenge for renewable energy technologies consists in “changing attitudes” (GNESD 2007, p. 20).

Finally, decision-making is not simply an individual choice, but also guided by the social environment and cultural influence (see, e.g., Maréchal 2007). In this context, status consumption – i.e. evaluating personal consumption

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[6] Inadequate institutional coordination might also lead to inefficiencies, which is a relevant issue for many developing countries, where policy initiatives are often driven by development aid, but without proper coordination between different donor-backed projects (see, e.g., WGBU 2012).

[7] Utility is typically assumed to be derived only from consumption of goods, while in reality many other factors such as health, political stability, or time spent with family also contribute to household utility and therefore influence consumption patterns.

against the consumption of others – can be expected to be relevant (Howarth 2000). That is, even if lowering consumption in favor of increased leisure or higher environmental quality would be collectively rational, each individual has an incentive to strive for higher levels of consumption in order to improve his or her relative position in society (Hirsch 1977, Frank 2005).

Inertia and endowment restrictions in physical and human capital

Idealized economic models often assume that production factors are perfectly mobile across sectors such that they can easily be redeployed in reaction to a changing policy environment. Some capital stocks, however, exhibit considerable inertia when old capital stock needs to be retired, which leads to delay or additional costs. Empirical evidence suggests that especially companies in developing countries often have low turn-over rates so that a replacement of existing equipment will take very long (UN-Energy 2009).

Significant investments in human capital will likely be needed in many countries in order to provide the skills necessary to develop, adopt, run, and maintain certain abatement technologies. Consequently, a lack of specialized workforce constitutes a serious obstacle, especially in developing countries (UNIDO 2011, Beck and Martinot 2004). The lack of commercial or marketing skills is likely to further obstruct the dissemination of low-carbon technologies (GNESD 2007), which can result in delayed response or additional costs.

Finally, the endowment with natural resources can have a considerable influence on countries' development patterns. While in theory such endowments should not matter (i.e. assuming that they can be traded at market prices), trade frictions and political economy motives often favor their domestic use over export. A salient example is the combination of coal abundance and energy-intensive industries in South Africa, sometimes described as a 'minerals-energy complex' (Fine and Rustomjee 1996). Consequently, a development model centered on energy-intensive industries can give rise to a 'carbon lock-in' (Unruh 2000) that would require a shift in the structure of industrial activity in addition to a transformation of the energy system to achieve GHG mitigation at least costs.

Uncertainty and indirect costs of private investments

Cost-efficient abatement requires substantial long-term investments in low-carbon technologies as well as R&D (see Bowen et al., this issue). Uncertainty about future prices of fossil fuels or electricity as well as future climate regulations represent a risk for the profitability of investments with a long time-horizon, which may be further exacerbated by the immaturity of new technologies (WGBU 2012). Regular changes of political power and programs due to, e.g., electoral cycles or general political instability, imply a need for costly flexibility in order to deal with potential adjustments in emission policies. I.e., firms incur additional costs and will defer some low-carbon investments because policy makers cannot credibly commit to a long-term emission price trajectory (see Section 2.1). In developing countries high exchange rate volatility, fluctuations in inflation rates as well as political instability can additionally boost investment risks significantly (UNIDO 2011). As a consequence, individual investors may require a risk-premium above the one that would be socially optimal, potentially resulting in significant underinvestment, as seen, e.g., in the case of industrial energy efficiency measures (UNIDO 2011).

High up-front investment costs can further discourage cost-effective investment decisions (Beck and Martinot 2004), especially in combination with imperfect financial markets (see Section 2.3), e.g. if credits have to be repaid before initial costs have been fully amortized (WBGU 2012). Moreover, investment can be accompanied by indirect costs that investors will likely price in, such as disruptions in production process or reduction of quality or productivity due to new equipment (Hirst and Brown 1990). In some cases this is even observed to be resulting in investments in inefficient and costly stand-by power systems that favor reliable power supply over reduced production costs (UNIDO 2011, Mathy and Guivarch 2010). Perfectly functioning insurance markets (see Section 2.3) could attenuate these problems, but additional costs for the insurance against the risk would arise.

Finally, investment decision may be negatively affected by the complex web of regulations investors are confronted with, such as restrictions on the siting and construction of renewable energy parks which have been imposed for other motivations, e.g, nature conservation or security (Beck and Martinot 2004). Similarly, local initiatives opposing the construction of, e.g., a wind park or a nuclear power plant in their region (‘NIMBY’) can provide disincentives for investors (van der Horst 2007).

2.3 Market distortions: Wedge between emission price and marginal abatement costs (Category 3)

In a first-best world the marginal costs of abatement are equal across all sectors of the economy (also across all GHGs) and correspond exactly to the permit price that would emerge in a decentralized cap-and-trade scheme. But this is true only if prices correctly reflect costs. Real economies exhibit distortions that drive a wedge between the two, implying that in some sectors costs will be above and in others below the efficient level. Hence, our third category captures market imperfections that put a wedge between marginal abatement costs on the supply side and the price for emissions set by the policy (demand) side.

Distortionary taxes and subsidies

The efficiency of markets may be undermined by distorting policies, like subsidies or price regulation. Estimated global fossil fuel subsidies amounted to USD 409 billion in 2010, of which a large share was granted in emerging and developing countries (IEA 2011). Fossil fuel subsidies put low-carbon technologies at a competitive disadvantage, and encourage inefficient use of resources. As a consequence, the lack of financial incentives given by governments constitutes a major barrier to efficiency improvements, as confirmed, e.g., by surveys in Asia (UNEP 2006). In terms of climate policy, fossil fuel subsidies imply that a higher emission price is needed to reach a given target and that, in addition, the relative abatement shares of fuel-switching, energy efficiency, and non-CO_2 options become distorted.

Although fossil fuel subsidies constitute the best known example, they are not the only relevant pre-existing price distortion. For instance, Goulder et al. (1997) identify ‘tax interaction effects’ of emission pricing that may exacerbate negative welfare effects from pre-existing distortionary taxes on production factors, e.g. labor taxes, and thereby significantly raise the costs of environmental policy compared to the first-best case.

Imperfect innovation markets

Innovation, especially in low-carbon technologies, is a necessary precondition for cost-effective climate policy. However, it is well known that the private sector suffers from the imperfect appropriability of innovation efforts (externality in the form of ‘knowledge spillovers’), leading to a general underinvestment in R&D (Jaffe 1986; Jaffe et al. 2005). To some extent this adverse effect may be ameliorated by temporarily protecting ’intellectual property’, i.e. by costly patent systems. However, for developing countries adjustment of existing technology to country specific conditions may actually be the more relevant aspect, a costly process that typically cannot be protected by patents. Imitators will diminish the return on investment of a successful domestic first-mover. Consequently, the laissez-faire situation will be characterized by under-investment in technology adoption and development (Hausmann and Rodrik 2003).

Imperfect financial markets

A least-cost implementation of climate policy implies that all investments that are profitable under a given emission price will be undertaken. The lack of access to capital hence becomes an important second-best condition (Ekholm et al. 2013). For example, companies often report problems in obtaining credit for energy efficiency measures (UNIDO 2011). But also households and small businesses – especially in developing countries – can face credit constraints and may hence be unable to finance improvements with a positive payoff because of their lack of collaterals and savings (GNESD 2007). Additionally, financial institutions may be reluctant to finance renewable energy projects due to the lack of experience and specific historical data needed to estimate the involved risks (WGBU 2012). As a consequence, it becomes difficult for project developers to obtain funding on the private capital market at reasonable interest rates, implying a suboptimal low level of such investments under a given emission price.

This is further exacerbated if insurance markets[8] are under-developed and lack suitable financing tools that would allow investors to hedge against the market risk associated with relatively immature low-carbon technologies. If this risk has to be fully borne by the individual investor, it will further discourage socially desirable investments.

Coordination failure

The diffusion of certain new technologies may depend on the simultaneous action of several different market participants, i.e. it requires coordination. This is the case, e.g., for the switch to alternative fuel vehicles: as long as the density of stations providing alternative fuels is low, consumers will be hesitant to purchase such cars. But if the demand for alternative fuels stays low, the economic incentives to expand coverage of such fuelling stations is also low (Corts 2010). This obstacle is known in different variations as ‘chicken-and-egg-problem’ (Corts 2011), path dependency, or lock-in phenomenon (Unruh 2000, Acemoglu et al. 2012).

A related inefficiency arises when the agent that bears the costs of an investment does not also reap in the economic benefits of it. E.g. a landlord has low incentives to insulate an apartment building as it is mainly the tenants who profit from lower heating cost (Jaffe and Stavins 1994, WGBU 2012). Finally, also firms may suffer from coordination failures if split responsibilities between departments prevent the implementation of energy efficiency measures (Backlund et al. 2012, UNIDO 2011).

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[8] see, e.g., chapter 5 in Dlugolecki et al. (2009) for an analysis on insurance market failures.

Non-competitive market structure

Competitive behavior of firms and free entry to markets should in theory ensure that prices reflect production costs, a prerequisite for the efficiency of markets. In a first-best setting firms are atomistic, and hence cannot exert any influence on prices or other firms, but under more realistic assumptions the existence of large firms able to act strategically must be acknowledged, and the ensuing loss of efficiency be taken into account.[9]

Due to their particular characteristics (high upfront infrastructure costs, grid-based distribution), markets for final energy, especially electricity and gas, exhibit a natural monopoly structure. For instance, even in Europe where considerable efforts to liberalize markets have been made in the past, all except seven countries out of the EU27 have highly concentrated electricity markets (EC 2010).

As a consequence, market entry barriers for competitors might be significant. For example, grid-owning companies may not grant grid-access to suppliers of renewable energy (Beck and Martinot 2004). Furthermore, there may be a lack of incentives for investing in the modernization of grids needed to accommodate high shares of intermittent renewable sources, or to expand the grid, e.g., to areas of elevated solar radiation (see, e.g., Pegels 2010).

Information asymmetries and implicit transaction costs

The first-best assumption of complete and costless information has repeatedly been criticized in the economic literature (e.g. Grossman and Stiglitz 1980).

The interaction between government and firms constitutes an example where asymmetric information undermines efficiency. As governments or other regulating entities may not have sufficient information about mitigation potentials and costs of firms (e.g. in different sectors), they may fail to implement the optimal least-costs policy (Laffont and Tirole 1993). For example, firms may use their informational advantage by overstating their true abatement costs in order to trigger regulatory adjustments (Harstad and Eskeland 2010).

Low awareness of saving potentials can also be a significant barrier to energy efficiency measures (see, e.g., UNIDO 2011 or Jaffe and Stavins 1994) and the deployment of low-carbon technologies (see, e.g., GNESD 2007). Individuals usually do not have sufficient information to attribute expenditure shares to each single device used (Hirst and Brown 1990). Similarly, firms are often not aware of technical possibilities and saving potentials (WGBU 2012). Therefore, high transaction costs for obtaining and evaluating relevant information may render seemingly cost-effective investments – expected to occur under first-best conditions – unprofitable.

2.4 Applicability of typology

An economic categorization that relates climate mitigation obstacles to the demand- or supply-side, or to market distortions has in our view three advantages: First, it covers a broad range of different obstacles, integrating them in a comprehensive framework and highlighting interrelations between the different impediments. Second, the concept can be applied to country cases – as will be demonstrated in the next section – systematically identifying possible

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[9] See, e.g., Hahn (1984) or Requate (1993).

challenges to national climate policy. Third, the market-inspired perspective reflects the basic structure of most numerical models assessing mitigation potentials and costs. Thus, this typology can directly be related to the design of IAMs as it allows mapping obstacles identified in the literature onto the assumptions made in the computations of an IAM mitigation scenario.

3. Real-World Obstacles to Mitigation Policy: The Case of China

Based on the typology established in the previous section, this section reviews existing literature to identify obstacles relevant for China's implementation of costs-effective mitigation policies. Energy security, environmental impacts, and socio-economic development are important drivers behind recent climate policy measures (Song and Zheng 2012, Wang et al. 2011a, García 2011), such as the *Renewable Energy Law* and the various energy and carbon intensity targets in the 11th (2006-2010) and 12th (2011-2015) *Five Year Plans* (FYP). The aim of this section is to highlight the difficulties encountered in the implementation of these policies for the current world's top CO_2 emitter, and relate them to our typology. China is an interesting case study because of its decisive role in combatting global climate change and therefore been studied intensively.

Perhaps the foremost obstacle on the demand side for abatement (Category 1) in China is the *interaction with other policy objectives*. As China is still a developing country, the Chinese government seems to set its priority on economic growth and social stability, which from a pure climate perspective has impeded, e.g., electricity pricing reforms (Ma 2011). The government guided price structure hampers the transformation of the energy system (Kahrl et al. 2011) as the low energy prices do not fully reflect environmental costs, resource scarcity, and the large supply-demand mismatch (Chai et al. 2009) suggesting that China might be inclined to sacrifice cost-effectiveness in order to avoid conflicts with other policy objectives.

Establishing least-cost climate policy can be further complicated by *political economy* obstacles, i.e. in form of opposition from the general public when hit hard with adverse impacts from regressive policies. Command and control measures, such as closing of inefficient power facilities, to reach some of the intensity targets of the 11th FYP generated negative attitude among the public and jeopardized social stability (Li and Wang 2012). In this context, it seems likely that China's future policies need to include appropriate instruments that dampen potential regressive impacts of measures for low-carbon development in order to be politically feasible (Li and Wang 2012). Concerning local implementation of policies, the strong resistance from provincial and municipal leaders is another structural obstacle, as their performance is mainly measured in terms of reaching targets related to economic growth within their region (Lo 2012). Finally, *institutional capacity constraints* are likely to undermine the effectiveness of China's planned nationwide emission trading scheme[10]. Past experience from previous pilot projects in China indicates that lack of administrative capacity, poor legal framework, and inadequate emission measurement systems will remain as key barriers (Chang and Wang 2010). The high administrative costs to measure and monitor sectors such as agriculture, transport, and other non-point emission sources is a further obstacle to the implementation of an economy wide emission cap (Li and Wang 2012).

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[10] The Government of China plans to establish a nationwide emission trading scheme by the end of the decade (Wang 2013).

Obstacles on the supply side of abatement (Category 2) can undermine the response to the price signal and result in under-provision of abatement compared to a first-best setting. Due to *inertia in the labor market*, the lack of qualified researchers and engineers is already perceived as an important obstacle to China's renewable energy technology development (Zhang et al. 2010). Grid infrastructure has significantly lagged behind the fast wind power development, resulting in a considerable bottleneck for renewable energy integration in the national grid (Li and Wang 2012). *Individual behavior* can further undermine the effects of a carbon price: Based on a study on household electricity saving in Beijing, inconvenience and discomfort has a significant adverse effect on consumer's disposition for electricity saving (Wang et al. 2011b). The willingness to save electricity was also lower among wealthier consumers because of higher perceived opportunity cost due to greater time constrains (Wang et al. 2011b). *Uncertainty* about future technological change and fossil fuel availability is another important obstacle *for private investments*. Most renewable energy technologies in China are still in early development stages and only few have been fully commercialized (Zhang et al. 2010). The high risk and the low economic return associated with those technologies serves as a barrier for private companies who often are hesitant to invest (Zhang et al. 2010).

Second-best characteristics in the form of market distortions (Category 3) impede the alignment of the emission price and marginal abatement costs. The Chinese government has apparently identified fossil fuel subsidies as a barrier, given that it has made considerable efforts towards their reduction (Boselli 2011). Though the estimated absolute amount of $21 billion in 2010 is still high, the corresponding relative level is in fact already comparably low in China (IEA 2011). The *non-competitive market structure* in the power sector, which is dominated by five large state-owned power generators and two state-owned grid enterprises with considerable market power (Wang et al. 2010, Wang and Chen 2012), is one of the main obstacles to renewable energy development in China (Jiang et al. 2010). The state-owned power generators often bid a low winning price for wind and photovoltaic concession projects. As they can afford losses, they drive prices below the profit margin, resulting in a significant investment barrier for both private and foreign investors (Wang and Chen 2012). The *imperfect financial market* allows for these low productive state firms to enjoy privileged access to capital, while more productive firms can find it hard to obtain financing (Li and Wang 2012). As the Chinese economy evidently represents a mixture of planned and market based economy, including large share of state owned enterprises, heavy governmental control, imperfect financial markets, and general lack of trust in business it is uncertain how well market based mechanisms, such as carbon trading, will function (Wang 2013, SEI 2012).

Control and monitoring of these sometimes large firms may not be very tight, leading to *information asymmetries* between firms and regulator (e.g. national government) and other *implicit transaction costs*, which can be expected to severely undermine efficiency. For instance, the weak control and the lack of transparent performance data in the wind power equipment industry have created significant information asymmetries between foreign investors and domestic firms, hampering innovation in the wind power sector (Wang et al. 2012). Likewise, the substantial discrepancy between emission statistics from regional and national level sources demonstrates the need for adequate and consistent information (Marland 2012).

In terms of *innovation market failures*, protectionist policies and legal obstacles constituting entry barriers for foreign investors were identified as hindering technology transfer for wind power (Klagge et al. 2012). Policies to encourage joint ventures between domestic firms and foreign technology leaders have had limited success because of concerns about intellectual property right violations (Klagge et al. 2012). Finally, one of the main barriers to China's wind power development has been attributed to the lack of coordination between wind farm development (local government) and grid development (national government) (Kang et al. 2012). The lack of incentives for energy managers in large commercial buildings to advise occupants, who pay the energy bills, on energy saving strategies is another form of a *coordination failure* which was evident in all commercial buildings studied by Jiang and Tovey (2009).

In sum, those and potentially more real-world obstacles observed in China's current efforts towards energy efficiency improvements and renewable energy expansion will very likely lead to a fragmented policy approach, price distortions, and added costs to the supply side of abatement, and thus ultimately to higher mitigation costs than would be expected from first-best considerations.

4. Mitigation Policy and Abatement in Numerical Assessment Models

The costs of different mitigation strategies are commonly studied by using Integrated Assessment Models (IAMs) that combine long-term macroeconomic modeling with a technologically detailed description of the energy sector and – in some cases – a representation of the climate system. IAMs, such as the ones contributing to this special issue like AIM, GCAM, IMAGE, MESSAGE, ReMIND, TIAM-ECN, WITCH (reference: this issue), therefore constitute a framework to generate self-consistent long-term climate policy scenarios based on explicit assumptions on energy technologies, the climate system, and economic mechanisms. The modeling of the latter, i.e. the economic equilibrium and its response to emission constraints, usually relies on the validity of at least some of the stylized first-best properties outlined in Table 1, e.g. to justify the computation of (regional) market equilibria by means of the social planner approach.

However, in light of the climate-policy-relevant imperfections discussed in the previous sections of this study, real-world economies are more appropriately described as second-best systems exhibiting market failures and other economic inefficiencies and frictions. The need to include such 'implementation limits and obstacles' in IAMs has been recognized in the literature, stating, for instance, that "2nd best analysis of climate policy will give a more robust picture of feasibility and costs" (Kriegler et al. 2012, p. 821). Leaving them unconsidered means that currently employed climate scenarios may turn out to be overly optimistic with regard to abatement potentials and the overall costs of climate change mitigation.

To date, IAMs often include some relevant obstacles in order to capture some second-best elements. These are typically 'hard' technological and macro-economic constraints such as restrictions on the deployment of renewables or CCS, delays in the setup of an international climate policy regime (Luderer et al. 2012, van Sluisveld et al. this issue), or particular market failures such as imperfect financial markets (Ekholm et al. 2013). However, several other obstacles, especially those discussed in the previous sections rooted in institutional and political factors, as well as those related to individual behavior, have so far not been explored systematically. This is illustrated in Table 2, which relates our categories of obstacles to standard modeling assumptions. Therefore, the aim of the remaining part of this section is to discuss how real-world obstacles to efficient climate change mitigation are currently represented in IAMs and how these models could be improved further by a more comprehensive inclusion of obstacles.

As captured by our first category, efficient climate policies might not be in place due to political economy reasons, lack of institutional capacity necessary for their implementation, or interaction with other policy objectives. These obstacles are generally not included in numerical models that assume that the optimal emission price is levied on all economic sectors. As recent experience has shown, such an idealized setting is unlikely to emerge: e.g., the EU ETS only covers about 40% of total EU emissions, mainly from the power sector and industry, while the remainder is addressed by complementary policies, such as fuel taxes, which has been criticized for leading to an inefficient internal burden sharing (Böhringer et al. 2009b). Even though the ETS proposed under the US Waxman-Markey bill envisaged a considerably broader coverage (despite its political infeasibility), it also only included about 85% of national emissions (Larsen and Heilmayr 2009). These issues might be of special importance for developing countries, which – in addition to political economy considerations – can be expected to dispose of relatively low levels of institutional capacity, such that the implementation of climate polices might prove challenging. Furthermore, other policy objectives can be expected to play crucial roles. These include, e.g. policies designed to promote industrial development that include targeted support for energy intensive industries, poverty reduction measures, and energy security considerations (see, e.g., Jewell et al., this issue).

There are several possibilities how these obstacles could be represented in IAM scenarios: First, certain sectors, such as transport, residential, or agriculture, could be excluded from emission pricing or an emission constraint, or different emissions prices in different sectors can be allowed (cf. Edmonds et al. 2006; Wise et al. 2009). Second, the use of certain technologies that may be politically contentious or face significant opposition from interest groups, such as CCS or nuclear power, could be restricted (as already done for computing 'technology option values', see, e.g., Luderer et al. 2012). Third, 'hard' constraints on GHG emissions, which correspond to an emission cap, could be substituted by alternative policies frequently observed in the real world. These include intensity targets[11], renewable energy policies[12], or a portfolio of policies differentiated by sector and technology. Fourth, while the effect of climate policy on other policy objectives (such as ambient air pollution, energy access and energy security) has been examined (e.g. van Vliet et al. 2012 and van Ruijven et al. 2012), in-depth analysis of synergies and trade-offs between climate and energy policies would require the inclusion of multiple policy objectives as emphasized in van Vliet et al. (2012). Additional constraints, e.g. on the price increase of final energy occurring between two points in time (to reflect concerns related to poverty alleviation), or on the share of imports of a certain energy carrier in a region's total energy consumption (to take into account energy security) could be introduced for this purpose.

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[11] E.g. China has adopted a voluntary intensity target (Stern and Jotzo 2010).

[12] Currently more than 100 countries, many of which do not have emission targets, have adopted renewable energy targets (REN21 2012).

	Obstacle	Relationship to IAMs
Obstacles on the demand side for abatement	Political economy	Economy frequently modeled as representative agent that implicitly implements the cost-efficient climate policy without political interactions. Some scenarios take into account the exclusion of certain sectors or regions, or delay in climate policy.
	Interaction with other policy objectives	Additional policy objectives not taken into account as a policy target. Some scenarios estimate co-benefits of e.g. energy access and local air pollution, or restrict certain technology options (e.g. CCS or nuclear power).
	Institutional capacity constraints	Costless implementation of climate measures is assumed. Institutional capacity constraints and costs for administration are not included.
Obstacles on the supply side of abatement	Individual behavior	Most IAMs either explicitly (optimization models) or implicitly (via market clearing) assume utility maximizing individuals (only based on consumption of goods), behavioral economics or non-monetary costs are not taken into account.
	Inertia and endowment restrictions in physical and human capital	Inertia in transformation of energy system included via technologically explicit modeling of vintage capital stock; human capital constraints usually not taken into account.
	Uncertainty and indirect costs of private investments	Uncertainty or other indirect costs usually not modeled. Hence, risk premia etc. that could act as impediment to investment are not included in IAMs.
Market distortions	Distortionary taxes and subsidies	Prices of fossil fuels and mitigation technologies often determined by techno-economic characteristics, without considering taxes and subsidies. Other distortions, e.g., labor tax, not included.
	Imperfect innovation markets	Technology often assumed to be available to all actors, transfer via spill-overs in e.g. a global learning curve.
	Imperfect financial markets	Usually perfect capital markets, with agents able to borrow at risk-free rate of interest. As uncertainty is not part of regular IAM structure, no need for insurance markets.
	Coordination failure	Interactions between consumers, firms, and government not explicitly represented in IAMs.
	Non-competitive market structure	Perfect competition in all markets is assumed in most models. Market power in the electricity sector is accounted for in only some models.
	Information asymmetries and implicit transaction costs	IAMs commonly built around models of perfect information and costless transactions.

Table 2: Major obstacles to climate change mitigation and their relationship to IAMs

As elaborated before, several factors will raise abatement costs compared to what would be expected in a first-best world, e.g. individual behavior, inertia and human capital constraints, or obstacles for private investments. These obstacles of our second category do not feature prominently in IAMs for two reasons: First, there is a need to keep the models' complexity at a manageable level by e.g. analyzing deterministic scenarios without taking into account uncertainty. So far, full-fledged scenarios that include uncertainty only do so by Monte-Carlo-simulations (i.e. stochastic ensembles of deterministic scenarios; e.g. Pycroft et al. 2011), while approaches featuring a more detailed treatment of decision-making under uncertainty abstract from other relevant factors by, e.g., including only a highly simplified description of the energy system (Lorenz et al. 2012, Hassler and Krusell 2012). The second reason is the limited understanding of the involved economic mechanisms. Arguably, the latter point is of special relevance for obstacles rooted in individual behavior, which are only imperfectly understood (e.g. Kahneman 2012) and hard to quantify.

Possible ways to include these obstacles in IAMs could include the following: First, the models could be extended by including additional features, such as human capital or behavioral factors. In this case, the derived projections should acknowledge the implied uncertainties and knowledge gaps, i.e. they must probably be regarded as qualitative descriptions providing 'insights, not numbers' rather than quantitative assessments. Second, cost mark-ups on technology investments whose return depends on uncertain technology parameters or future emission prices could be introduced in order to capture the risk-premiums demanded by private investors when adopting such technologies. Third, additional constraints could be imposed, e.g. on the speed of penetration for certain energy technologies in order to account for inertias that cannot be appropriately modeled through detailed micro-foundations. Of course, this point might be rendered difficult by the fact that it is hard to (a) come up with reasonable numbers for these constraints, and (b) develop scenarios concerning their future development, such that extensive sensitivity analyses would be required.

With regard to category 3, several second-best conditions can create a wedge between the emissions price and abatement costs, including imperfect innovation markets, imperfect capital markets, asymmetric information, distortive taxes or subsidies, coordination failures, and non-competitive market structure. As most IAMs incorporate some sort of representative agent structure equivalent to a social planner on a regional or country level, they implicitly assume that optimal policies to address these category 3 obstacles are in place.[13] Yet, in reality it seems likely that a multitude of distortions that are not appropriately addressed prevail across the economy, especially in developing countries. As the discussion of the Chinese case in Section 3 has highlighted, these are indeed of empirical relevance. In theory, externalities as well as distortionary taxes and subsidies could be mimicked in IAMs by suitably adjusting the social planner problem (Kehoe et al. 1992). However, this would require a significant computational effort and would only be valid for relatively small deviations from the first-best setting.

Hence, more direct (but also less rigorous) approaches to incorporate these obstacles in IAMs include the following: First, one could assume costs for adopting technologies invented in other regions (in models that feature endogenous technological change), or partial instead of full technology spill-overs (in models with learning curves) to account for imperfections in innovation markets. Second, constraints to the expansion rate of novel energy technologies could act as a proxy for delayed market entry by new firms in a non-competitive market structure. Third, region- as well as technology-specific cost mark-ups or constraints on total capital supply (as already explored by Ekholm et al. 2013) could be included to account for imperfect financial markets.

Finally, it seems unlikely that more complex strategic interactions, such as principal-agent problems, or coordination failures, can easily be represented in a typical IAM framework, in which regions are depicted as representative agents. Improved understanding of these issues would rather require a shift towards a model structure with multiple actors that can be targeted individually with appropriate policy instruments. The PRIDE model (Kalkuhl et al. 2012)

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[13] Exceptions include the modeling of knowledge spillovers e.g. in the ReMIND (Leimbach and Baumstark 2010) and WITCH (Bosetti et al. 2008) model.

which explicitly represents utility and profit-maximizing economic agents (i.e. households, production, fossil and renewable energy firms, and fossil resource owners) as well as a government setting policy instruments is a salient example of such an 'integrated policy assessment model' (IPAM). Furthermore, combining more stylized models which capture specific imperfections with IAMs in order to estimate the impact of specific barriers on model results, or using adjustment factors to modify results from IAMs ex-post could be considered.

In summary, whether a certain obstacle can be represented in IAMs crucially depends on its specific characteristics. The most straightforward modification of existing models would very likely consist of (i) excluding certain sectors from carbon pricing or restricting the use of certain abatement technologies, (ii), replacing hard 'emission pricing' policies by 'softer' but generally less efficient indirect policies, (iii) introducing additional constraints, and (iv) imposing cost mark-ups. By contrast, a more ambitious way forward would be to develop a novel model structure allowing for explicit strategic interactions between decentralized agents.

5. Conclusion

The present study combines two strands of previous research by analyzing real-world obstacles and the limitations of IAMs to take them into account. 'Obstacles', as we have defined them, make the achievement of emission targets more costly than in a first-best setting. This allows us to relate the obstacles identified within our typology to first-best assumptions typically made for numerical IAM computations of a mitigation scenario. Including those real-world obstacles in IAMs would very likely not only lead to rise of overall costs, but also have an impact on the composition of the least-cost mitigation portfolio.

Taking into account real-world obstacles is crucial for assessing mitigation costs, as emphasized by Böhringer et al (2009a, p. S295), who "highlight the importance of initial market distortions and imperfections [...] for the appropriate assessment of EU compliance cost". For example, inefficiencies in policy – for the case of the EU's 2020 policy – was found to result in 100%-125% higher costs than the theoretical least-cost estimate (Böhringer et al. 2009b).

From a general point of view, our analysis suggests that, despite inclusion of detailed description of technological developments, IAMs mis- and more likely under-estimate the costs of an economy to adjust to a carbon constraint because of three general types of simplifications, which could be called *aggregation*, *global optimization*, and *determinism*.

First, as any model can only represent some features of reality with some limited degree of accuracy, simplification and aggregation (see, e.g., Schwanitz submitted), particularly of the macro-economy (see Bowen et al., this issue), are inevitable. Yet, ambitious mitigation policy might also have an impact on areas of the economy that are not explicitly modeled. Aggregation is thus very likely to play down the role of economic frictions and costly adjustment processes and heterogeneity of regions and players. In response to this shortcoming, model design has become increasingly comprehensive, in particular in the energy sector, which can easily be seen when comparing, e.g., the structure of the DICE model (Nordhaus 1992) with the IAMs employed in this Special Issue.

Second, numerical models typically employ a global social planner optimization ('global' in the sense of covering the entire economy and all time-steps) that maximizes a given region's intertemporal social welfare resulting in an overall coherent, optimal response to the emission constraint. This assumption abstracts from the decentralized nature of real economies, and hence ignores many potential inefficiencies stemming from human interactions, including several of those listed in category 3 and also category 1. The already high computational burden does not seem to allow for the explicit modeling of different independent agents with their own objective function within existing IAMs; hence, the long-term strategic interactions between different agents has so far only been analyzed in considerably more stylized models (e.g. Kalkuhl et al. 2012).

Third, determinism in form of perfect foresight, such as on future learning rates of renewables or availability and prices of fossil fuel resources, is often assumed by IAMs and abstracts from irreducible real-world uncertainty that would even lead a social planner to choose costly 'hedging' strategies. Hence, assuming perfect foresight avoids the ex-post inefficiency that is inevitable under uncertainty, and will therefore lead to an under-estimation of abatement costs. A recent tendency in model development to take up this aspect can be seen in the use of Dynamic Stochastic Equilibrium Models (DSGEs), e.g. Hassler and Krusell (2012), or Golosov et al. (2011). However, this approach can only account for stochastic uncertainty, and qualitative methods are perhaps better suited to understand the non-deterministic nature of complex socio-technical transitions, as, e.g., exemplified by the literature on system innovations (Geels 2002; Kemp 2011; Schot and Geels 2007).

In light of our arguments, it will be important to conduct more extensive sensitivity analysis[14] as well as model inter-comparison projects on second-best scenarios to provide better estimates for the impacts of different obstacles on mitigation costs and derive suggestions for policy makers on how to address these obstacles. Finally, it seems unlikely that more complex strategic interactions, such as coordination failures, can easily be represented in a typical IAM framework, in which regions are depicted as representative agents. Improved understanding of these issues would rather require a shift towards a model structure with multiple actors that can be targeted with appropriate policy instruments, such as the aforementioned 'Integrated Policy Assessment Model'.

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[14] Such as Kober et al., this issue, who conduct a sensitivity analysis of the carbon allowances trade to analyze the effect of imperfect trade of emission allowances among world regions.

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