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Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework☆

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ABSTRACT

Model-based support of climate policy is scientifically challenging because climate change involves linked physical and social systems that operate on multiple levels: local, national, and international. As a result, models must employ some strongly simplifying assumptions. The most frequently used models typically assume hyper-rational and homogenous human behavior. These ensure tractability but, as a trade-off, abstract away the effects of less-than-rational decision-making and actor heterogeneity on domestic policy effectiveness and the influence of domestic constituents on international policy agreement. In this paper, we introduce a multi-level model framework, called ENGAGE, that relaxes some common modeling assumptions by adopting an agent-based approach. ENGAGE is styled after the Putnam two-level game, in which negotiators at the international level are constrained by the heterogeneous policy preferences and power of constituents at the domestic level. We proceed to provide a detailed description and demonstration of the prototype domestic-level module. Domestic actors include firms and households who function as agents within an evolutionary representation of economic growth, energy technology, and climate change. This allows an evaluation of policies that accounts for agent decision-making and social and technological change. Ultimately, we plan to use the ENGAGE model to simulate the two-way dynamic feedback between international agreements and domestic policy outcomes.

1. Introduction

The development of climate policy represents a global, collective decision-making problem unprecedented in scale and complexity. To inform stakeholders in the policy process, scientists have spent more than thirty years developing integrated assessment models (IAMs) that combine the salient features of natural and social scientific theory into linked representations of economic, societal, and environmental systems (Harris, 2002; Parker et al., 2002; van Delden et al., 2011). While there is no doubt that IAMs have provided key insights into mitigation options and climate change dynamics and impacts, for the purposes of supporting real-world policy, there are clearly opportunities for further improvement (Ackerman et al., 2009; DeCanio et al., 2000; Morgan et al., 1999; Schneider and Lane, 2005; Weyant, 2009).

Formulating effective climate policy is a System-of-Systems (SoS) problem, which occurs when a complex system consists of heterogeneous, distributed, and partially independent systems embedded in a dynamic, hierarchical network (Agusdinata and DeLaurentis, 2008; DeLaurentis and Ayyalasomayajula, 2009). An SoS is difficult to model and manage because macro-level properties cannot be directly understood from the behavior of lower level systems and system constituents. In addition, scientific knowledge of lower level components, such as human decision-making, is often deeply uncertain.

A variety of methodologies exist for mapping the complexity of an SoS into a manageable model. One approach is to make assumptions about lower level system behavior that lead to tractable aggregate model structures. For example, many climate policy IAMs assume that the economy is composed of homogenous households and firms that have perfect information, have infinite

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cognitive ability, and are perfectly rational. By invoking these assumptions, the economy can be modeled as if it is managed by an omniscient central planner who makes investment and policy choices to maximize expected global or regional welfare and minimize energy system costs. The result is a model that can be investigated using well-known techniques of mathematical optimization.

With tractability, however, comes trade-offs in model flexibility and fidelity. This has implications for the type of questions that can be answered using an aggregate IAM. For example, state-of-the-art multi-level aggregate models, such as WITCH (Bosetti et al., 2011), address international climate policy by assuming that countries can identify and build least-cost energy systems, as well as enter into international agreements that conform with either cooperative or non-cooperative equilibria. Such a result is useful because it identifies normatively desirable or undesirable outcomes for those specific assumptions. However, only identifying these outcomes leaves many other plausible policies and futures unexplored. There are many retarding factors on emissions mitigation, such as the constraints that heterogeneous domestic actors place on possible agreements and outcomes, that are of scientific and policy interest. Unfortunately, addressing these factors in an aggregate model such as WITCH would require changes in assumptions likely to make it intractable.

Another modeling approach that is able to incorporate some key lower-level factors constraining climate policy is agent-based modeling (ABM). ABMs do not attempt to achieve tractable aggregate model structures. Rather, they represent the world as a collection of heterogeneous, boundedly rational agents who act largely in their own interests and interact with other agents according to characteristic protocols of communication and decision making (Miller and Page, 2007). In the environmental and social change literature, ABMs have seen significant use in land use and water planning models (e.g., Barthel et al., 2008; Brown et al., 2004; Monticino et al., 2007), because allowing for agent heterogeneity couples well with the spatially explicit models in those fields. The specification and interpretation of ABMs can be a challenge, and as a result their application to energy and climate change has been relatively limited (Lempert, 2002; Moss et al., 2001). The extant ABM energy and climate change literature can be classified into four groups, distinguished by techno-economic and geopolitical level. The lowest *Level 4* ABMs focus on either the diffusion of one or more technologies in a single market with little or no feedback to the broader economy (De Haan et al., 2009; Eppstein et al., 2011; Faber et al., 2010; Mueller and de Haan, 2009; Schwoon, 2006; Sopha et al., 2011; van Vliet et al., 2010) or on local adaptation to climate change (Acosta-Michlik and Espaldon, 2008; Berman et al., 2004). *Level 3* ABMs have a broader focus on the electricity market or overall energy use with little or no macroeconomic feedback (Batten and Grovez, 2006; Conzelmann et al., 2005; Wittmann, 2008; Xu et al., 2008). At *Level 2*, system boundaries include the entire macro-economy of a country, region, or the world, but typically sacrifice technological detail and resolution of household decisions (Beckenbach and Briegel, 2010; Janssen and de Vries, 1998; Nannen and van den Bergh, 2010; Robalino and Lempert, 2000). Analysis at *Level 1* entails interactions among countries or regions, with little or no feedback between underlying domestic actors and international policy (Voudouris et al., 2011).

To our knowledge, there are no examples in the literature integrating ABMs between Level 1 and lower levels. In this paper, we provide a qualitative overview of a new multi-level ABM, called ENGAGE, which is designed to fill this gap and help explore the effect of domestic actors on international and domestic climate policies. In addition, we present a detailed description and preliminary results of the prototype domestic module of ENGAGE and describe plans for future model development.

2. An evolutionary economic model of climate policy and negotiation (ENGAGE)

ENGAGE is a flexible multi-module modeling framework designed to simulate the interaction among international climate treaty negotiation, national policy formation, and the dynamics of domestic economic and technological systems. Conceptually, it is a probabilistic, multi-agent, evolutionary economic model (c.f. Safarzyska and van den Bergh, 2010) in which the feedback between international negotiation and domestic dynamics is structured after the Putnam two-level game (Putnam, 1988). In ENGAGE, a diverse set of agents (negotiators, firms, and consumers) engages in purposeful behavior by observing and interacting with their surrounding environment and other agents. Their choices exhibit bounded rationality in the sense that the agents have limited cognitive abilities and incomplete information (Simon, 1955). They rely on decision heuristics that are based on theoretical and empirical findings from the literature (e.g., Thaler (1985), Heath and Soll (1996), Bettman et al. (1998), Gigerenzer and Brighton (2009) for consumers, Dosi et al. (2010) for firms, and Lai and Sycara (2009) for negotiators). Domestic economy-energy dynamics are based on the evolutionary macro-economic model of Dosi et al. (2010).

ENGAGE is designed to support robust decision-making in two capacities. The first is as a *scenario discovery* tool, as outlined by Robalino and Lempert (2000), Lempert et al. (2006), Groves and Lempert (2007), and Bryant and Lempert (2010). This mode allows one to engage in a participatory, computer-based approach that achieves fully integrated scenario creation for exogenously supplied policies. A question such as, "What are the conditions under which a policy performs well or poorly?" can be investigated with scenario discovery. A particularly useful aspect of the scenario discovery mode is that policy solutions from other modeling frameworks can be used as an input into ENGAGE, allowing for testing of policy robustness to imperfect information, technological change, and bounded agent rationality. We demonstrate application of the domestic module for scenario discovery in a companion paper (Gerst et al., 2012).

The second role for ENGAGE is as a *policy discovery* tool. In this mode, policy formation is endogenous to the model and allows for the investigation of scenarios in which policy formation and system structure co-evolve (Faber and Frenken, 2009) This allows one to ask questions such as, "What are the likely enhancing or retarding factors of international climate treaty formation and subsequent successful domestic implementation?" In this capacity, the model may also uncover plausible but non-intuitive scenarios of discontinuous social and technological change. Using the model in this mode is especially conducive to testing robustness to structural uncertainties, such as the specification of agent decision rules and representation of the innovation process.

2.1. Putnam two-level game

In ENGAGE, the conceptual link between the international Level 1 and lower levels is based on the Putnam two-level game (Fig. 1). The theory of two-level games has had a profound influence on thinking about the way states behave in international negotiations. According to the metaphorical frame put forth by Putnam (1988), international negotiations take place at two levels. At the international level (Level 1), negotiators bargain for a tentative agreement. Each negotiator is assumed to have "no independent policy preferences, but seeks simply to achieve an agreement that will be