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1 Introduction

The objective of this proposal is to test the hypothesis that interacting agents are unable to collectively manage a transition from non-renewable to renewable resources to avoid negative impacts of resource depletion. Since Hardin's seminal paper, "The tragedy of the commons", it has been understood that individuals acting purely out of self-interest are likely to degrade commonly-owned resources citeHardin1968. This finding is in direct tension with the notion of "the invisible hand" of the market, promoted within economics [1]. The depletion of stock-based resources (especially fossil-based energy resources and their associated climate change impacts), necessitates a transition to flow-based, renewable resources and the closing of material pathways within our economies. Policy planning is currently guided by integrated assessment models (IAM). Such models typically represent resource utilization and infrastructure investment decisions, purely in terms of financial transactions controlled by a centralized authority. Unfortunately, such a representation fails to account either for (i) the physical resources (energy and materials) to build out the required infrastructure, and (ii) the multiplicity of individual decision-makers that comprise global resource supply and investment networks. The Energy-Economy-Environment (E^3) Systems Analysis group at Clemson has expertise both in material and energy requirements for critical infrastructure and in modeling multiple-actor interactions. In developing an agent-based approach to test our hypothesis, we will be able to generate better models and recommendations for policy and decision support.

2 Background and motivation

The modern energy-economy-environment (E3) system is incredibly complex. Dynamics within the natural system impact and are themselves impacted by increasingly complex dynamics within the human-built system. Over the course of the 21^{st} Century, increasing social stressors, including global population, raising living standards improving access to modern energy infrastructure, will place strong pressure on the capacity of the biosphere to support such demands, especially in light of biophysical stressors, such as climate change, resource depletion, and ecosystem degradation [2]. A transition is required within industrial society, to modes of operation that (i) use renewable resources (such as forest products) at rates lower than their rate of regeneration; (ii) emit wastes (such as carbon dioxide) at rates lower than their assimilation by environmental systems; and (iii) reduce the use of non-renewable resources (such as crude oil) to rates at which renewable substitutes can be deployed [3, 4].

Models and tools for policy planning and decision support overwhelmingly cast interactions within the economy purely in terms of flows of financial dataIntegrated assessment models (IAM) represent the economy using a number of separate modules, including the energy sector (such as MESSAGE [5] or MarkAL [6]), and the macro-economy, modeled via computable general equilibrium model (such as GEMINI-E3 [7] or E3MG [8]). Demand for energy depends on various factors including population, gross domestic product (GDP, disaggregated by sectors), and sectoral energy intensity.

The core of the energy sector module is typically some reference energy system where demand for energy services (transport, space heat, light, etc.) is met from a variety of energy resources (coal, gas, etc.) by linking appropriate energy conversion technologies, each with an associated financial cost, determined by the user. The module seeks to meet an objective function wherein energy demand is met at the minimum overall system cost. The only input required by the energy sector are sufficient monetary flows, not the necessary energy and materials required for infrastructure investment or operation.

Whilst financial flows represent an important aspect of modern society, it is crucial that we also gain a better understanding of the physical structure of our economies, for it is in the exchange of energy and materials, that human societies interface with the natural systems within which they are embedded and upon which they are entirely dependent [9, 10]. The field of net energy analysis (NEA) seeks to understand and characterize the energy and materials that society must invest in order to transform primary energy resources into economic services, at a variety of scales ranging from individual solar photovoltaic (PV) panels to whole industries or even whole economies. A number of models have been developed which trace physical flows of energy (and materials) through the economy to explore the economic implications of resource constraints. Undoubtedly the most famous of this type of physical resource model is the World3 model from the 'Limits to Growth' report by the Club of Rome [11]. Other models include the System, Time, Energy & Resources (STER) model [12]; the Dynamic Energy model to explore the New Zealand and global economies [13, 14]; and the Energy and Capital Creation Options (ECCO) model [15].

To build on this work, the PI created the Global Energy Model using a Biophysical Approach (GEMBA) to integrate pertinent data from the field of NEA to enable a model that optimized for energetic costs involved in manufacturing and operating the infrastructure of the energy sector, in an analogous manner to the financial cost optimization in the traditional economic modeling approach. The model includes feedback between the energy sector and the rest of the economy. Subsequent work by the PI has utilized data from LCA and focused in greater detail on specific energy technologies including solar photovoltaic (PV) , wind and storage .

Correspondingly, policy planning models also cast ('top-down') investment decisions within the economy as undertaken via a central agency, with perfect knowledge and perfect foresight, or with some randomly generated, exogenously defined level of 'uncertainty' [16]. The structure of such models is implicitly founded upon the existence both an equilibrium state for the economy and an optimal pathway to reach that state [].

In rejection to this perspective, researchers in non-equilibrium and complexity economics seek to understand the economy as a thermodynamically open system in a state of dynamic balance with both the social and natural systems within which it is embedded []. From such a perspective the notion of 'optimality' is lost, instead economic interactions must instead be understood 'bottom-up' via the transaction and investment decisions undertaken by multitudinous actors seeking to satisfice among multiple competing needs and wants [].

Within this new framework, agent-based modeling has become an important tool. [MCD - John, add some pertinent references here.]

[MCD - discuss Becky's model here.]

[MCD - would be good to have literature of ABM as a learning tool. Becky, do you have any?]

Creating a more resilient future relies on decision making informed by economic, social, and physical factors [9]. The new era of resource depletion requires new models of our economies that bridge the financial and physical and that account for their inherent complexity. Such models can guide advantageous (as opposed to optimal) asset investment and resource consumption strategies that are responsive to the constantly evolving social and environmental landscape.

The proposed project will build on an agent-based model developed by the project co-PI to answer the following questions:

1. are multiple, interacting agents able to collectively manage a transition from non-renewable to renewable resources to avoid negative impacts of resource depletion?
2. if yes, do there exist resource consumption and investment decisions that are more advantageous in managing this transition?
3. [MCD - others?]

In order to answer these questions, this research will explore the behavior of agents in a resource harvesting and investment simulation where resource managers must forage for energy and natural resources while investing some of those resources towards the activities of foraging while also maintaining and building out critical infrastructure. In autonomous mode (agents act according to built-in algorithms), advantageous strategies for resource management can be 'evolved' through the process of 'natural selection'. In learning mode (researchers or learners take control of the agent behavior), successive rounds of the simulation will more closely resemble real-world locations. Researchers can better understand the context for resource and infrastructure management strategies with the aim of developing more informed policies.

2.1 Tasks

The proposed objective will be met over the 3-year time period of the project by carrying out the following tasks:

Task 1 *Concept mapping, scenario development and data collection*:

Task 2 *Model development, simulation and interpretation*:

Task 3 *Dissemination and outreach*:

3 Project Plan

The following sections outline the methodology to meet the proposed objectives, with associated deliverables and milestones.

3.1 *Task 1* Concept mapping, scenario development and data collection

3.1.1 Concept mapping

Much of the groundwork for this sub-task has been accomplished in previous work by the co-PI, in development of the [MCD - insert name of Becky's model here] model. In order to adapt the model to the objective of this proposal, the first task will be concept mapping. The main points of departure from previous modeling efforts is the explicit distinction between renewable and non-renewable resources and the distinction between energy and other primary resources. Much effort will also have to be spent in making the model structure suitable for creating an interactive experience for users during 'learning' mode; the development of successive simulation rounds that more closely mimic the user's chosen region in terms of resource distribution and topology. In order to build a solid foundation for the work, the concept-mapping task will develop a data management plan and a conceptual map for the model development tasks.

3.1.2 Scenario development

The second task involves development of a range of scenarios that will be run within the calibrated model. These scenarios will draw on different scenarios developed by the major global energy policy/planning agencies, including: the International Energy Agency (IEA) World Energy Outlook (WEO) [17]; the US Energy Information Administration (EIA) International Energy Outlook (IEO) [18], Shell's Future Energy Scenarios [19], BP Energy Outlook [20], ExxonMobil Outlook for Energy [21], International Institute for Applied Systems Analysis (IIASA) Global Energy Assessment (GEA) [22], and the Intergovernmental panel on climate change (IPCC) Special Report on Emissions Scenarios (SRES) [23]. During this stage we will also identify output variables of interest.

3.1.3 Data collection

Dr. Carbajales-Dale has done previous work in data collection for the energetic and material investment requirements for a variety of energy conversion technologies, but more work is needed for the other technological processes and systems. Additional data is needed for material extraction and processing and parameters affecting resource depletion, as well as data necessary for simulation.

3.1.4 Deliverables

1. Data management plan (milestone: month 3)
2. Fully specified concept map (milestone: month 9)
3. Qualitative description (narrative) for each scenario (milestone: month 3)
4. Spreadsheet and plots of parameter values (range and distribution or single value) for each of the scenarios (milestone: month 6)
5. Database of xxxx (milestone: month 6)
6. Statistical analysis of data reported as key statistical parameter (milestone: month 9)
7. Analysis of trends in parameter values from historic data (milestone: month 12)

3.2 *Task 2* Model and simulation development, simulation and interpretation

3.2.1 Model development

The first stage involves development of the agent-based model for autonomous mode. There are a number of steps that must be followed during this stage: analysis of historical data to determine distribution, statistical characteristics and trend behavior of parameters (e.g. reduction of energy intensity of a process); verification - specification of the mathematical structure of the model; and validation of model behavior under a range of parameter values.

3.2.2 Simulator development

This stage will include preparation of the model for use in 'learning mode'. The simulator will effectively function as a UI through which users will take control of the decisions of one or more agents. The user will play one round of the simulation based on a randomly-generated landscape. The subsequent round of the simulation will have features that more closely resemble the real world. The third round will, as closely as possible, simulate the user's chosen location in terms of topography, resource distribution, and characteristics of other agents. This version of the model will be hosted on-line on the project website to be used by researchers and decision-makers focused on specific regions, interested members of the public, and also as a learning tool for students during courses. This stage will be performed iteratively with concept mapping and model development. The first goal of this stage will be story-boarding and concept-mapping the simulation experience of the user. This will be followed by assessing the data requirements for the successive rounds of the game. The web-based tool will include associated documentation to accompany the model.

3.2.3 Simulation

The next stage involves running the model in autonomous mode with parameter settings relevant to each of the scenarios. Other parameters within the model will be varied using a Monte Carlo method according to the statistical parameters identified during the first task. The result will be a distribution of values for each of the output variable of interest.

3.2.4 Interpretation

The final stage in this task involves interpretation of the results from the previous stage.

3.2.5 Deliverables

8. Fully verified model (milestone: month 12)
9. Fully validated model (milestone: month 15)
10. Calibrated model (milestone: month 18)
11. Story board for the simulation and preliminary graphics ideas (milestone: month 12)
12. Creation of project website including web platform for the simulator (milestone: month 15)
13. Web-based, accessible version of the model (milestone: month 18)
14. Model documentation (milestone: month 18)
15. List of output variables (milestone: month 24)
16. Spreadsheet and plots of distribution of output variables (milestone: month 30)
17. Qualitative and quantitative description of model behavior and implications (milestone: month 33)

3.3 *Task 3* Outreach and dissemination

The next stage in this task will be to communicate findings and to engage members of the public and policy makers in use of the simulator.

3.3.1 Outreach

The simulator will be used as a learning tool with a variety of different learners. The project will engage with Clemson Engineers for Developing Countries to test the tool with communities in Haiti; and Clemson Emagine to bring the tool to middle and high school students. [MCD - others?] Reflections from users will be collected using pre- and post-simulation surveys. This information will be fed into future development of the model and simulator.

3.3.2 Dissemination

Once the behavior of the model has been described, the final stage involves broadcasting the findings. Dissemination of results will be via peer-reviewed research articles in top-tier energy journals (e.g. Energy & Environmental Science), educational journals (e.g. xxxx) and policy papers (e.g. AAAS Science Policy Forum), policy recommendations/white papers distributed to suitable agencies, presentations at meetings and conferences, and creation of a website describing the project, hosted on the E^3SA website.

3.3.3 Deliverables

14. Database of beta-testers (milestone: month 15)
15. Beta-testing initiated (milestone: month 15)
16. Database of outreach partners (milestone: month 18)
17. Beta-testing concluded (milestone: month 21)
18. Summary of outreach findings (milestone: month 33)
19. Submission of research article describing methodology, scenarios and results (milestone: month 36)
20. Submission of policy paper (milestone: month 36)
21. Production of slide-deck for presentations (milestone: month 36)

4 Project team structure

4.1 Senior personnel

4.1.1 Dr. Michael Carbajales-Dale, Assistant Professor, Department of Environmental Engineering & Earth Sciences, *Clemson University*

Dr. Carbajales-Dale is engaged in research involving the technological improvement in electricity production systems, for a variety of resource inputs (energy, water) over the full technology life cycle. He is currently active within Clemson's Water-Energy Consortium.

Results from prior NSF support None

4.1.2 Dr. Becky Haney, Assistant Professor, Department of Economics (?), *Calvin College*

Results from prior NSF support

4.2 Junior personnel

4.2.1 John Sherwood, Research Assistant

John Sherwood will conduct the balance of this research under the supervision of Dr. Carbajales-Dale at Clemson University's Department of Environmental Engineering & Earth Sciences.

4.2.2 Undergraduate and graduate researchers

Additionally, some of the research tasks will be integrated as class projects into Dr. Carbajales Dale's course (EES 8200: *Environmental Systems Analysis*) and leverage Clemson's REU program *Creative Inquiry*, to be supervised by John Sherwood and/or by Dr. Carbajales-Dale.

5 Project evaluation

The success of the project shall be evaluated on the basis of meeting goals along the timeline of the project, as shown in the gantt chart below (Figure **??**) and by the publication of results.

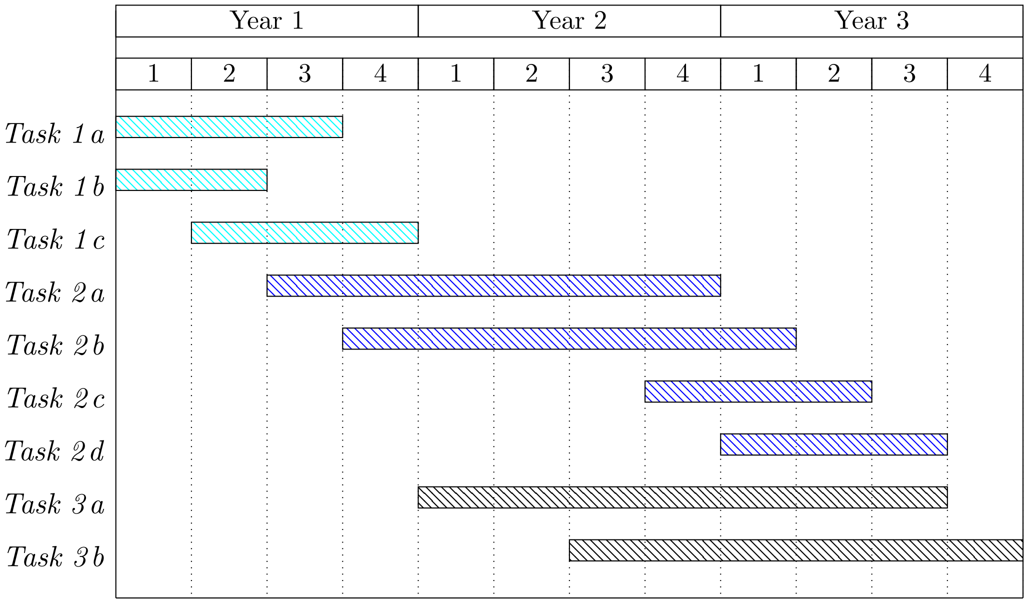

Figure 1: Expected completion of Tasks from Task 1 (cyan): (a) concept mapping, (b) scenario development, and (c) data collection ; Task 2 (blue): (a) model development, (b) scenario development, (c) simulation, and (d) interpretation; and Task 3 (black): (a) outreach, and (b) dissemination over the 3 year duration of the project.

6 Intellectual merit and Broader impacts

6.1 Intellectual merit

The proposed activity will advance the current understanding of resource and infrastructure management and the conditions for successful transition from depleting resources (e.g. fossil fuels) to those that can be used sustainably (e.g. renewable energy). The novel aspect of the research is to employ techniques from social science to better understand resource and infrastructure management strategies.

6.2 Broader impacts

The simulation will identify resource and infrastructure management strategies to better navigate the resource transition faced by our global society. These strategies will be translated into recommendations for resource and infrastructure management and policy decision makers. The knowledge gained will be helpful for (especially rural and isolated) communities to develop strategies for sustainable resource use. The game will be presented as a learning tool within existing courses at Clemson to highlight issues of sustainability and emphasize the role of energy literacy, especially in currently under-served populations through the use of the existing programs at Clemson University.

The long-term educational goal is to improve energy and resource literacy and systems thinking to facilitate better-informed planning for a sustainable future. In pursuit of this goal, the educational objective of this proposal is to provide an interactive, simulated learning environment for learners to understand how individual behavior impacts collective opportunities for sustainable management of resources. Development of the experimental apparatus (game development) will be integrated into term projects, the classroom will be used as a test-bed for subsequent iterations of the game and to gain experimental data by having students play the game.

7 Dissemination

As discussed in Section 3.3, dissemination of results will be via peer-reviewed research articles in top-tier energy journals (e.g. Energy & Environmental Science), educational journals (e.g. xxxx) and policy papers (e.g. AAAS Science Policy Forum), policy recommendations/white papers distributed to suitable agencies, presentations at meetings and conferences, and creation of a website describing the project and with the simulator embedded, to be hosted on the E^3SA website.

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