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Energy infrastructure and their impacts on societies' capital assets: A hybrid simulation approach to inclusive wealth

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ABSTRACT

Measuring how energy policy affects intergenerational well-being is a problematic task policymakers face. There is a compelling need for a comprehensive evaluation criterion that is versatile enough to allow for exploring different possibilities and options. The inclusive wealth framework is a suitable tool for such a task, as it accounts for the changes in the three major capital assets –produced, human, and natural- that compose a nation's wealth. Here, we apply the inclusive wealth framework within a hybrid simulation model to evaluate energy infrastructure projects in terms of their impacts on different capital assets. We chose hybrid simulation as a technique that allows for a better realization of technologies, as well the economy as a whole. The developed model is generalized and can be applied to different economies as well as all types of energy projects. In addition to accounting for the capital assets, we also account for CO_2 damages and health capital. We provide the simulation for different proposed projects representing different fuel cycles in Belgium and Egypt. The results show how the model can be used to demonstrate the changes brought to wealth by the different projects and how policymakers can change policies to make wealth take more favorable tracks.

1. Introduction

Successful infrastructure projects are a major component of a nation's development. Energy projects, in particular, are necessary for development in both developed and developing countries. Energy is, as described by E. F. Schumacher, 'not just another commodity, but the precondition of all commodities' (Brown and Sovacool, 2007, P. 338). However, important questions arise when policymakers plan and evaluate the infrastructure projects. What is the real cost of these projects? Can we really estimate this cost? To answer these questions, such projects need to be evaluated against a comprehensive metric that accounts for all the impacts imposed by infrastructure projects. In this study, we apply the Inclusive Wealth index as a measure of intergenerational well-being, along with a hybrid simulation technique for energy policy evaluation and planning. Our work in this paper is a contribution to weak version of sustainable development where the value is based on economic value (see Dasgupta et al., 2015, Kurniawan and Managi, 2018a, and Kurniawan and Managi, 2018b).

Inclusive wealth is one of the contemporary wealth accounting methods, and it can be defined as the sum value of any society's capital assets, namely human, natural, and produced capital, valued at social prices (or shadow prices)(UNU-IHDP, and UNEP, 2014, P.180). The inclusive wealth framework overcomes the "mis-measurement" of development that occurs through using conventional measures such as the Gross Domestic Product (GDP) (Stiglitz et al., 2010). If $k_i(t)$ is the stock of asset i at time t and $P_i(t)$ is the shadow price of asset i at time t, then wealth at time t is the linear summation of each asset stock at that time t, multiplied by its associated shadow price at the same time as shown in Eq. (1) (UNU-IHDP, and UNEP, 2012).

$$Wealth(t) = \sum_i k_i(t)\bullet \quad P_i(t) \tag{1}$$

A broad examination to the purpose of this research would indicate that we are trying to model a system of systems, i.e. a system that contains ecological, social, and economic subsystems. One of the earliest approaches for using simulation and modelling in studying how development policies affect social and ecological systems, was Meadows et al. (1972) "Limits to growth". "Limits to growth" showed the potential of System Dynamics (SD) to model complex social-ecological systems (Elsawah et al., 2017). Since then, several efforts have been made to use different modelling and simulation techniques for understanding and representing problems containing social, environmental, and economic aspects. For example, Guo et al. (2001) used system dynamics to support regional environmental planning, while

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Croke et al. (2006) used it for integrated modelling and management of water resources in Australia. As the focus of this research is evaluating energy infrastructure projects, we will review the research attempts made using single or combined simulation techniques to study systems with environmental, social, and economic components. Some researchers tried to evaluate the social and ecological changes associated with adopting new infrastructure policies. For example, Verhoog et al. (2016) work using agent-based modelling (ABM) to study the evolution of social and ecological systems with the development of biogas infrastructure, and Joyce et al. (2017) work using multi-scale modelling to assess the resilience of drainage infrastructure in a coastal watershed. Rai and Robinson (2015) used ABM to study the environmental, social, and economic factors that affect energy technology adoption, while other researchers, like Janssen (2002), used ABM in order to understand this complex relationship between humans and nature. Additionally, Triantafyllidis et al. (2018) presented a platform that uses ABM to evaluate new infrastructure in terms of design efficiency and how it contributes to human well-being.

Other works that tried to perform quantitative wealth-based analysis for infrastructure policies include the work of Arndt et al. (2012) in studying road infrastructure in Mozambique, Sartori et al. (2017) work in evaluating the sustainability of Brazilian electricity industry. Additionally, Bieber et al. (2018) work that combines ABM with network optimization to support the planning of urban energy systems at city region level. Unlike those studies, our study focuses on IW considering both physical and natural capital accumulation instead of showing different units such as monetary and energy units.

We can notice that all these approaches are limited to a certain country and they are policy oriented rather than being project oriented. Furthermore, none of them considered the collective impacts on three main capital assets comprising a nation's wealth.

On the other hand, few attempts have been made to either predict the trajectory of wealth or evaluate policies in a forward-looking manner, based on the inclusive wealth. Tokimatsu et al., (2011, 2014) investigated the future dynamics of wealth under different scenarios like population or technological changes. Collins et al. (2014) and Pearson et al. (2013) introduced demonstrative models for policy evaluation, but probably the most related effort to this research is the work published by Collins et al. (2017). The authors applied the inclusive wealth to prospective policy evaluation, and their work focused on the impacts of shifting to a non-fossil electricity policy on produced, human capital and Oil reserves in oil-exporting countries.

In this paper, we provide a model for evaluating the impact of energy infrastructure projects on the trajectory of wealth. The model applies hybrid simulation and data analysis to quantitatively measure how a prospective energy generation project, or a mix of projects, will affect the different capital assets that comprise the wealth base of the society under study. This enables us to exploit the edges of different simulation techniques, particularly (SD) and (ABM), to perform a more in-depth analysis with the flexibility to study several cases and combinations and even variations within the same fuel cycle. The model we present herein considers a more comprehensive scope of wealth, as we included impacts on cropland along with extractable fuel depletion in natural capital calculations and impacts on health capital and employment in human capital calculations. Moreover, it addresses air pollution and CO_2 damages resulting from different fuel cycles. One more important characteristic of our approach is that it is built in a generalized manner that makes it suitable for analysing projects in developed and developing economies. The developed model enables policy evaluators -whether they are government officials, development agencies, or decision-makers- to choose the energy option that does not compromise the ability of future generations to meet their needs. Monitoring the future changes in the capital assets after introducing a project to the economy not only allows for policymakers to study the effects of projects from different categorical fuel cycles, such as renewable and non-renewable, but also allows for them to quantify the impacts of projects from the same category (e.g. wind and Photovoltaic).

The remainder of this paper is organized as follows. In Section 2, we present the methodology that we followed to simulate and evaluate projects. In Section 3, we describe the model formulation, what its constituting parts are and how are they connected together. Section 4 presents the model application and case studies. The final two Sections, 5 and 6, include policy implications and the conclusion.

2. Methodology

Evaluating projects based on wealth is equivalent to carrying out a social cost-benefit analysis for that project, using the same set of shadow prices used in sustainability analysis (Partha Dasgupta, 2009). The project under study represents a perturbation in the wealth course (Arrow et al., 2003, P. 655), which is initiated at time t_p. If we think about W_o as the original course wealth shall follow, had the project not been introduced, and W_n as the new wealth course after project introduction, then we can say that:

$$W_n = W_u + \Delta W_p \tag{2}$$

The first component of Eq. (2), W_u, is the part of wealth that is unexplained by this project; this part changes according to the dynamics of the economy that are not related to the project. On the other hand, ΔW_p is the change in wealth due to the impact of the project on the different capital assets (Fig. 1).

We calculate the change in wealth that resulted from the project introduction, in the same way we would calculate wealth using Eq. (3):

$$\Delta W_p(t) = \sum P_i(t)\, \Delta K_i(t) \tag{3}$$

where ΔK_i, is the change in each capital asset caused by the project. The capital assets we are considering in this research are human capital (HC), natural capital (NC), and produced capital (PC), thus the vector of capital assets will be as is shown in Eq. (4):

$$\Delta K = \{\Delta HC, \quad \Delta NC, \quad \Delta PC\} \tag{4}$$

As previously explained, P_i should be the shadow price corresponding to the capital asset K_i. The shadow price of a capital asset is defined in the 2012 inclusive wealth report (IWR2012) as “the contribution a marginal unit of it is forecast to make to human well-being”(UNU-IHDP & UNEP, 2012, P. 18). Although this definition shows how shadow prices can be effective for valuing capital assets, it makes estimating them problematic. According to the definition, an asset's shadow price should reflect its market and non-market benefits. Additionally, future scarcities of assets need to be accounted for in present shadow prices of goods and services (Arrow et al., 2013). Thus, instead, in the context of this research we use market prices as an approximation. Although not using shadow prices represents a limitation in applying the inclusive wealth theory, such an approximation has been used in different studies. IWR2012 relied on rental prices whenever there was a lack in shadow prices, while Collins (2013) used the market prices of natural resources.

Quantifying the impact of a single project or even a mix of projects

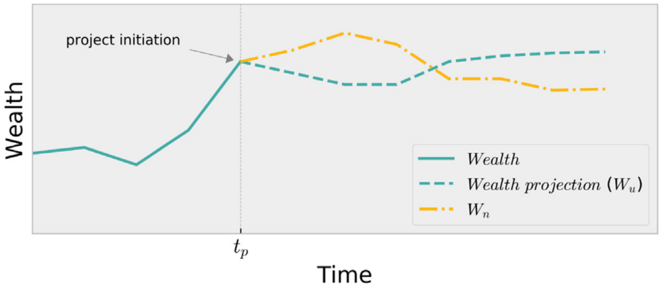

Fig. 1. The wealth trajectory after introducing new project to the economy.