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Long-run carbon emission implications of energy-intensive infrastructure investments with a retrofit option

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ABSTRACT

Investments in long-lived, fossil-fuel intensive infrastructure can have large effects on carbon emissions over a long future period. We simulate a 2-period model of infrastructure investment with subsequent retrofit to purge its carbon emissions, under uncertainty about climate and retrofit costs. The energy intensity chosen upon investment depends on current and expected future energy and environmental costs, and on future retrofit cost. Simulations of a simplified but realistic model indicate that energy consumption and carbon emissions can be highly excessive when future energy and climate costs are not considered at the time infrastructure investments are made, and charged at globally suboptimal rates when operated; often by more than 50% when energy costs are undervalued at this rate both ex ante and ex post. Good anticipated retrofit options reduce ex post energy costs, but lead to ex ante choice of more energy-intensive infrastructure, which could more than fully offset the energy-reducing effect of the retrofit. These results are of particular importance for emerging economies with large current and anticipated energy-related investments, where long-term climate policy goals may be seriously jeopardized by policy makers facing too low energy prices, now and in the future.

1. Introduction

Long-lasting energy-intensive infrastructure gives rise to much of the energy consumed and greenhouse gases (GHGs) emitted by modern societies. It can also tie up fossil energy consumption at high levels for long future periods, and thus potentially jeopardize important climate policy goals. Coal-fired power plants, in particular, usually have lifetimes of 40–50 years or more, locking in high carbon emissions. These can in principle be eliminated later, but only through very expensive "carbon capture and storage" (CCS) retrofits. Choosing low-carbon power technologies (solar, wind, geothermal or hydro) will by contrast lock in much less future emissions. Related energy demand effects are found in urban planning.[1] "Sprawling" cities remain car-oriented with high GHG emissions per capita. Urban structure, once established, is difficult to alter. Shorter-lasting but still important energy-consuming infrastructure locking in future emissions includes motor vehicles, household appliances, and home heating and cooling systems.[2] Such energy demand is particularly crucial for rapidly growing emerging economies with expanding cities and massive infrastructure investments. All exemplify path dependence: current choices have direct effects on the costs of implementing future policies.

This paper addresses such issues through analyzing and simulating a stylized model of energy-intensive infrastructure investments. We will study whether related carbon emissions can be eliminated by costly infrastructure "retrofits." Almost trivially, when policy makers do not fully account for energy and climate costs, energy consumption and emissions will then be excessive in both the short and the long run. Our focus is more on the degree to which emissions are excessive, through simulations on a stylized model with two periods: the "present" ("period 1"); and the "future" ("period 2"). Energy costs, and "retrofit" costs (discussed below), are unknown in period 1, but have known (or knowable) period 2 distributions in period 1. We assume that the infrastructure lasts for both periods, but may be abandoned in period 2. Fossil-fuel consumption can be modified in period 2, in two ways: (1) by a (costly)

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[1] See further discussion in Shalizi and Lecocq (2009); Glaeser and Kahn (2010); and Larson et al. (2012).

[2] A slightly different categorization, based on the longevity of the capital stock, is found in Jaccard (1997), and Jaccard and Rivers (2007).

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"retrofit" in period 2, removing all carbon emissions from the infrastructure either by using non-fossil sources or removing carbon through CCS or similar processes; (2) by then abandoning the infrastructure. The latter can be viable only when energy and retrofit costs of continued operation both turn out very high, the lower being higher than the utility value of continued operation.[3]

Our simulations illustrate excessive energy consumption from two types of inefficiency. First, investment decisions are based on too low future energy prices, but energy prices are still charged correctly at the operation stage. Secondly, energy prices are too low at both the investment and operating stages. We will sort out how much of an "overall" inefficiency is due to the investment decision alone; and how much to failing policies later.

In Section 3 we derive analytical solutions for the initial infrastructure investment decision including its (fossil) energy intensity in period 1, jointly with strategies for retrofitting and operating the infrastructure in period 2, under uncertainty — as only the future distributions of the energy and retrofit costs are known in period 1. We focus on the case where emissions are phased out completely by the retrofit; but also, more briefly (in Subsection 3.2), consider the case of incomplete phase-out. In Section 4 these solutions are simulated on a parameterized model. We identify factors behind too energy intensive infrastructure. We also study whether, and to what extent, an initially high energy intensity level can be modified later through retrofit or closedown, when energy and environmental costs are high.

A key issue on which we focus is that infrastructure decisions involving long-run climate impacts are typically non-optimal from a global perspective. Carbon emissions require a global view for their optimal control, incorporating globally correct carbon costs. This is unlikely in practical policy, except when international agreements require, and enforce, globally efficient prices (for emissions and energy, currently and in the future). The practical decision maker is usually a local or national government, who will incorporate prices, costs, discount rates etc. at the respective (local or national) decision level. We here aim to study how such a decision maker deviates from a globally optimal decision.[4]

In studying effects of uncertainty about climate or retrofit costs on infrastructure-related GHG emissions, two countervailing factors are at work. First, emissions are avoided in future periods with better retrofit and closedown options, and in states where emission costs are very high and retrofit costs low. Such states are, overall, more frequent with greater uncertainty. Higher uncertainty makes both low-cost and high-cost outcomes more likely; emissions tend to result only when emission costs are relatively low. Expected emission costs, and expected emissions, are then reduced with greater uncertainty, for a given initial infrastructure.

However, greater uncertainty and better retrofit options raise the chosen energy intensity of infrastructure. Expected future operating costs are then reduced when uncertainty is greater, since there will be more (desirable) low-cost states, and also many high-cost states but where these costs will be avoided through closedown or retrofit. This makes higher initial energy intensity attractive when uncertainty is great.[5] From our simulations, expected lifetime energy consumption may either increase or decrease when uncertainty increases. The tendency for energy consumption to be reduced due to more retrofits and closedowns often dominates; but the net effect is often small.

Infrastructure investments could be made without sufficient concern for future climate costs, but these costs are still actually incurred when the future arrives. Our simulations indicate strong "path dependence": One could end up with an initial infrastructure investment whose energy intensity is highly excessive, and is very difficult to reduce later.

When the energy cost is too low both ex ante and ex post, additional inefficiencies result as infrastructure investment and operation are both too energy intensive. The impacts on investment and operation are here compounded, and the overall effect in terms of excessive energy use and emissions can be far greater, as also illustrated in our simulations referred to in Sections 3–4. This issue is particularly important for many emerging economies today.

2. Background literature

Among earlier literature, Arthur (1983), David (1992), and Leibowitz and Margulis (1995) discuss the related issue of "path dependency". The more specific context of infrastructure choice and its implications for mitigation policy is studied only more recently. Ha-Duong et al. (1997), Wigley et al. (1996), Ha-Duong (1998), and Lecocq et al (1998) focus on infrastructure whose energy commitments can form obstacles to effective mitigation policy. A seminal contribution is Kolstad's (1996) analysis of sequentially optimal climate-related policy under uncertainty with potential irreversibilities. Shalizi and Lecocq (2009) discuss infrastructure costs and constraints which is more applied and intuitive than that provided here. Persistent effects of infrastructure choice on energy consumption and carbon emissions are discussed also by Brueckner (2000), Gusdorf and Hallegatte (2007a,b), Glaeser and Kahn (2010), Larson et al (2012), and Vogt-Schilb et. al. (2012). Gusdorf and Hallegatte (2007a) study the energy intensity of urban infrastructure for given population density, focusing on inertia resulting from established urban structure, in response to low but uncertain energy prices. Permanent energy price shocks can then lead to a long (20 years or more) and painful transition period (with high energy costs and carbon emissions), but with energy consumption eventually falling substantially. Glaeser and Kahn (2010) quantify relationships between energy consumption and spatial patterns in the U.S. One finding is much lower per-capita energy consumption and carbon emissions in central cities than in suburbs, indicating that "compact" infrastructure is less energy demanding than "less compact". Viguié and Hallegatte (2012), applying multi-criteria optimization of transport plans for Paris up to 2030, study long-run fuel consumption due to alternative transport infrastructure investments, which can be substantial. Framstad and Strand (2013) study optimal infrastructure investment in continuous time, generalizing Pindyck's (2000, 2002) analysis of optimal climate-related retrofits, where future energy prices follow a continuous stochastic process. An option value then raises the threshold for the ex post retrofit to be implemented, and thus further increases the average energy intensity of such initial infrastructure. Jaccard (1997) and Jaccard and Rivers (2007) discuss retrofit possibilities and costs more practically, with specific infrastructure categories including urban structure, buildings, and equipment. A finding is needed for strong initial considerations for future emissions even when emission prices start low but increase strongly over time.[6] Lecocq and Shalizi (2014) discuss infrastructure-related energy demand and supply more broadly, arguing that energy-intensive infrastructure involving supply is often more rigid than that involving demand; but sometimes (but not always) more prone to complete retrofit.

Our paper also relates to literature on a "low-carbon society" with high concern for infrastructure investment design (Strachan et al (2008a,b), Hourcade and Crassous (2008)).[7] Two World Development Reports from the World Bank, in 2003 ("Sustainable Development in a Dynamic World"; World Bank (2003)), and 2010 ("Development and Climate Change"; World Bank (2009)), also have "inertia in physical capital" as main theme.

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[3] A more general interpretation of this case is that energy consumption and emissions in the "closedown" alternative serve as a reference point against which the "business-as-usual" and retrofit alternatives are valued.

[4] See Strand (2011) for further elaboration.

[5] This result holds when decision makers are risk neutral, which is assumed here. Under risk aversion, the utility effect of greater uncertainty could here go either way.

[6] For a complementary discussion but in the context of an overall climate policy see Wigley et al. (1996).

[7] An early champion of this line of thinking and discussion was Lovins (1977).