Barriers to Implementing Low Carbon Technologies

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1. Introduction

With the threat of anthropogenic global warming becoming all the more apparent, policymakers around the world have looked to a variety of low carbon technologies to help reduce reliance on fossil fuels and decrease greenhouse gas emissions. Wind, solar, and geothermal are three primary renewable energy sources often promoted as the solution to the problem. Many such technologies have been deployed, although in small quantities. Yet some writers have argued that if it were not for politics we could power 100% of the planet with such renewables (Jacobson and Delucchi 2009). Other authors and policymakers look to carbon capture and storage technology to allow the world to continue burning fossil fuels while sequestering carbon dioxide underground. Similarly, many also see great promise in a variety of technologies and approaches to improve energy efficiency and reduce the demand for energy, including some as low-tech as improved weatherization and as high-tech as devices that provide continual feedback about a household's electricity use.

Yet, the market penetration of these low carbon technologies remains limited. According to the US Energy Information Administration, only about one percent of the primary energy used in the United States in 2009 was from wind, solar, and geothermal (EIA 2010). All but a handful of other countries in the world have a similarly small contribution from these renewable energy sources to total energy production. Carbon capture and storage technologies have for the most part not yet made it past the demonstration stage, with the exception of pumping carbon dioxide into oil and gas wells for enhanced recovery. Energy efficiency technologies and approaches are now part of the portfolio of many electric utilities in the United States, but prominent reports, such as the McKinsey (2009) study, suggest that we have only begun to tap the potential for improving energy efficiency in the economy.

This paper first asks the question: *what are the barriers to the adoption of these technologies to reduce carbon dioxide emissions*? The logical follow-on to this question is the question: *what should be done about these barriers*? To address the two questions, we first must define exactly what we mean by "barriers." In particular, we must differentiate between "barriers to adoption" and "market failures" or other failures.

We define "barriers" as *anything* that that substantially reduces the probability of adoption of low carbon technologies. Many macroeconomic and technology-specific factors may act as barriers to the implementation of low carbon technologies. These barriers substantially reduce implementation of low carbon technologies and, if they remain, may keep the market penetration of these low carbon technologies to low percentages.

Some, but not all, market barriers provide a rationale for policy intervention to improve economic efficiency.[1] Economists tend to take economic efficiency as a primary criterion for policy design. Policies that increase economic efficiency have the potential for making all, or most, people better off than they would be absent the policy intervention. Conversely, policies that decrease economic efficiency by definition make some people worse off than they would be absent the policy interventions.

Economists and the policy community also consider distributional issues as an important criterion. Such issues may be most important for the implementation of energy efficiency options, since it is plausible that the failures relating to energy efficiency may be most significant at the lower income levels. However, for other distributed energy technologies such distributional issues are likely to be less important, at least in the next decade or so. Therefore, in what follows, we will focus most sharply on the economic efficiency issues.

[1] An "economically efficient" allocation is defined as an allocation of goods in the economy where there are no potential Pareto improvements, where "Pareto improvement" is a change in allocation that leads to at least one person being better off and no one worse off. So an economic efficiency improvement provides the possibility to improve welfare for at least some people, while at the same time making no one worse off.

It may be that consumer and producer decision-making in unfettered markets face barriers that lead to less market penetration of low-carbon technologies than would be most economically efficient. We refer to such situations as "market failures." Market failures stemming from barriers that reduce market penetration of low-carbon technologies reduce economic efficiency. With such market failures, interventions designed to increase market penetration could increase economic efficiency.

Conversely, it may be that consumer and producer decision-making in unfettered markets leads to the economically efficient market penetration of low-carbon technologies or even to *more* market penetration of low-carbon technologies than would be most economically efficient. In such situations, interventions designed to increase market penetration could *decrease* economic efficiency.

Therefore, we differentiate between barriers that result in lower than efficient market penetrations of low carbon technologies and those that do not have this overall impact. We aim to identify cases where consumer and producer decision-making in unfettered markets leave possibilities for economic efficiency improvements through increases in the market penetration of low-carbon technologies.

Classic "market failures" include externalities and asymmetric information. There may also be failures of individual consumer or firm decision-making, or institutional or regulatory failures. These could create barriers that keep the market penetration of low-carbon technologies substantially below the economically efficient levels. Such barriers leave the possibility of gains to economic efficiency by changing policies relating to low carbon technologies.

This paper examines the major barriers to the implementation of low carbon technologies, and differentiates between those that may provide a motivation for policies to improve economic efficiency and those that do not. We proceed by discussing each of the four broad technology categories: central generation renewable energy technologies, carbon capture and storage technology, distributed generation renewable energy technologies, and technologies to reduce the demand for energy. For each category, we discuss the latest evidence on the possible barriers to implantation of the technologies, and further assess whether and how policy might improve economic efficiency by addressing these barriers. In order to cover the breadth of low carbon technologies, we focus on the key messages for each category. Finally, we conclude with the most important take-home messages about the implications for policy of barriers to implementing low carbon technologies.

2. Central Generation Renewable Energy Technologies

Central generation renewable energy technologies generate electricity at centralized plants and bring the generated electricity to consumers through transmission and distribution systems. These technologies include wind turbines, large-scale solar thermal technology, geothermal technology, biomass electricity generation technologies, and hydropower. Each of these technologies has a different set of barriers and issues to implementation as low carbon technologies.

Without question, the most important barrier to a larger-scale implementation of all of these technologies comes down to one factor: the cost of the technology, and in particular, the private cost borne by the organization implementing the technology. The higher the private cost, the less likely an organization is to implement the technology, absent factors that force implementation.[2]

While the cost of some renewable energy technologies has been dropping, relative to many fossil technologies, the cost remains very high. Table 1 summarizes the large-scale generation technology cost of each of these technologies based on estimates from recent literature reviews from around the world. The levelized cost of energy is reported for it is the most common metric used to compare the costs across electricity generation technologies. The levelized cost is the constant cost per kilowatt hour economically equivalent to the actual time-varying costs of installing and operating the technology.[3] This methodology may be the most common way to compare technology costs, but it is by no means perfect and it is subject to a variety of assumptions. Foremost among those is the assumption of the discount rate to choose

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[2] The importance of the distinction between private cost and social cost will be discussed more fully at a later point.

[3] The levelized cost is calculated as the discounted costs of installing and operating the technology over the lifetime of the installed capacity divided by the discounted generation of electricity over the lifetime of the installed capacity.

when calculating the net present value. Assumptions about the capacity factor, input fuel prices, and whether to include subsidies are also critical.

Table 1. Recent cost ranges for different electricity generation technologies (nominal $)		
Electricity Generating Technologies	**Levelized cost of energy ($/MWh)**	**Source**
Central Generation Renewables		
Wind	35-140	IEA (2010)
Central Station Solar Thermal	109-335	EPA (2010)
Geothermal	59-94	EPA (2010)
Central Fired Biomass	50-144	Borenstein (2011)
Central Generation Fossil		
Coal	25-60	IEA (2010)
Natural Gas	37-63	IEA (2010)
Nuclear	30-50	IEA (2010)

There are a few important messages to take from Table 1. First, for each technology, there is a wide range of estimates of the levelized cost of energy. The estimates vary in part because of the different assumptions going into the estimates, but also due to the heterogeneity in costs associated with differences both across sites and in the exact technology implemented. Second, the table indicates that at present, central general fossil technologies remain by-and-large less expensive than renewable energy technologies on a simple cost of technology basis. This underscores the primary barrier to the implementation of low carbon technologies–these technologies have not advanced far enough to be cost-competitive with the fossil-fuel technologies.

Moreover, the levelized cost numbers in Table 1 do not consider any implicit costs from the intermittency of generation, which may be a major concern if we are considering widespread adoption of renewables (Forbes, Stampini, and Zamepelli 2011; Joskow 2010). The concern is simply that must-run, intermittent generation requires keeping a backup generation source (usually natural gas) online and ready to turn on should the wind die down or sun stop shining. For example, Gowrisankaran, Reynolds, and Samano (2011) find that the upfront cost of solar in Tucson, Arizona is a much more important factor in the total system cost of implementing more solar on the grid than the intermittency–but that intermittency does increase the total system cost.

The estimates in Table 1 compare levelized costs for the entire life of the plant, including new construction costs. However, if we focus only on the levelized costs of continuing to run already existing plants, the levelized costs would be substantially smaller than estimates in Table 1 because the initial capital costs would not be included. Initial capital costs are particularly large for central station coal and nuclear power plants, as well as for many renewables. Importantly, such plants have lives measured in decades. Even if life-cycle levelized costs of low-carbon technologies were the same as those of central station plants, the existing central station plants–in particular the existing fossil-fueled central station plants–could be expected to continue operating until the end of their normal lifetimes, often several decades in the future. While new low carbon technologies could compete effectively for new construction, the large number of existing power plants provides a barrier limiting the speed at which such plants can replace central station plants. Note, in addition, that the more slowly the overall consumption of electricity grows, the fewer the number of new plants that would be needed. Thus, the slower the growth of electricity consumption, the more important this barrier will be to market penetration of low carbon renewable energy technologies.

How the relative cost of central generation electricity technologies will evolve in the future depends on many factors, including primary fuel prices and the pace of innovation. As discussed above, the higher the private cost, the less likely an organization is to implement the technology, absent factors that force implementation. However, regulatory rules, such as renewable portfolio standards, can encourage implementation of very costly technologies. For example, central station solar thermal electric generation may be constructed in order to help meet the standard even when it costs substantially more than conventional generation plants. So, private cost may not be an insurmountable barrier to implementation. Moreover, tax or other financial subsidies could create large deviations between the private cost and social cost. Since large-enough financial subsidies could encourage broad-scale implementation of costly technologies, high social cost may not be an insurmountable barrier to implementation, at least at relatively small scale. However, at large scales, the budgetary implications of large subsidies applied to a large fraction of electricity generation may well be fiscally prohibitive.

Whenever the private cost borne by the implementing organization matches the social cost, high social cost will be a barrier to implementation. But, as referenced above, this is a market barrier that does NOT provide a rationale for policy to increase market penetration. When private cost matches social cost for a technology and for its substitutes, interventions designed to increase market penetration could be expected to *decrease* economic efficiency.

In short, high social and private costs can be expected to be an important barrier to market implementation of low-carbon technologies. But such high costs do not provide a rationale for encouraging or forcing increased implementation of these technologies.[4] However, private costs and social costs are not equal for many energy technologies. Such deviations can be expected to lead to market failures and addressing such market failures may increase economic efficiency. In addition, high costs could motivate R&D efforts designed to reduce cost, say by improving the technology. This issue will be discussed more fully at a later point.

2.1 Possible Market Failures in Central Generation Renewables

Prices for fossil fuels currently do not fully reflect several negative externalities, including external damages relating to greenhouse gas emissions and some local air pollutant emissions. To the extent that these negative externalities remain unpriced, there is an economic-efficiency based policy rationale to encourage substitution away from those fuels having large negative externalities and towards those for whom there are little or no externalities. Important instruments for motivating such substitution are taxes or regulations on the fuel with externalities or subsidies (or direct interventions) for those without such externalities.

An ideal change from the perspective of economic efficiency would be to provide taxes or equivalent financial incentives directly on the fuel with negative externalities. The marginal tax ideally would be just equal to the marginal externality. This change in market incentives would decrease supply and decrease consumption of such a fuel.

[4] When there is a sufficient amount of learning by doing in new technology implementation, such increases can increase economic efficiency, as will be discussed at a later section.

However, if for distributional or political reasons such direct interventions are not chosen, then there are second best interventions. Subsidies or other interventions encouraging substitute energy sources can be efficiency-enhancing if these interventions reduce use of the fossil generation associated with the externalities. Similarly, there may be national security externalities to the extent that imported fuels are used in the production of electricity, which may be the case in some countries.[5] An efficiency-decreasing consequence of such subsidies, however, is that they effectively lower the price consumers face for energy and thereby reduce investment in energy efficiency.

If the externalities from greenhouse gases and local air pollutants are already internalized through other policies, then this policy motivation no longer applies. For example, in the United States, there is a tradable permits system for sulfur dioxide emission under the Clean Air Act, which already at least partly internalizes the externality from sulfur dioxide emissions.

However, even if externalities from the burning of fossil fuels are internalized, there may still be market failures relating to the pace of innovation in bringing down the cost of central generation renewable technologies that have yet to be internalized. These market failures may be at the early stage of technology development or closer to the actual implementation of the technology. The concept underlying these market failures is a difficulty in appropriating all of the gains from the effort put into innovation. For example, in the early stages of technology development, firms may only imperfectly be able to capture all of the gains from research and development (R&D), for there may be spillovers to other firms. Nordhaus (2010) suggests that R&D spillovers may be much more important very early stage research and development, rather than technologies at the pilot or implementation stage.

For technologies in the process of moving from the pilot project stage to full implementation, the cost of the technology may be declining with the cumulative production of the technology, corresponding to a learning-by-doing (LBD) process. The intuition for this is that as a firm produces more of the technology, it may "learn" how to produce more efficiently, and some of the learning may spill over to other firms through the transfer of employees,

[5] Very little electricity in the United States is produced from fuels that are sourced outside of the US or Canada, so the national security externalities are not likely to be a major issue in the US for central generation renewables.

observing the output of the process, or other means. Just as in the R&D market failure, the lack of full appropriability of the gains forms the basis for the LBD market failure.

These appropriability market failures in R&D and LBD lead a firm to underinvest in R&D or under-produce at the beginning, relative to the economically efficient level. One obvious policy response to these market failures, which can be thought of as positive externalities, is to subsidize production and implementation of technologies that have the characteristics of high learning-by-doing, in addition to subsidizing or otherwise encouraging in early-stage R&D (Gillingham and Sweeney 2010).

This straightforward policy prescription is complicated by two factors. First, R&D and LBD appropriability market failures are not unique to central generation renewable energy technologies. Any emerging technology, whether in biotechnology, information technology, or new energy technology may exhibit imperfect appropriability of R&D expenditures and perhaps even imperfect appropriability of the gains from LBD. Thus, in theory, the policy prescription appears to apply to a wide variety of industries and it would be inconsistent to focus only on renewable energy technologies. Second, the evidence on the extent of the R&D and LBD appropriability market failures remains very limited. Quantifying the degree of appropriability in R&D and in learning-by-doing is very difficult. Similarly, quantifying learning-by-doing separately from economies of scale and exogenous technological change is a difficult empirical challenge for which there is only very limited evidence (e.g., Nemet 2006; Gillingham and Bollinger 2012).

Can economies of scale be considered a barrier or market failure to the implementation of central generation renewable energy technologies? The short answer is no, unless there are capital constraints or a simultaneous coordination problem. Economies of scale represent a non-convexity in the production function, which implies multiple equilibria – with one equilibrium at zero quantity produced and the other at a much larger quantity. If there are economies of scale in the production of a good and the firm recognizes these economies of scale, then the firm would have an incentive to scale up to achieve the lower costs.

The firm might not scale up if it does not have access to the requisite capital.[6] But for countries such as the United States, there are active angel investors, venture capitalists, and private equity institutions. Given these sources of capital, capital market constraints are likely to be an issue only for very large investments and at a time of major turmoil in the financial markets – and thus should probably be viewed as a transient concern. Moreover, just like innovation market failures, capital market constraints are not unique to renewable energy, but affect all markets.

Simultaneous coordination problems occur when many actors must simultaneously invest or ramp up production in order for a new technology to be commercialized. These "chicken-and-egg" problems are unlikely to be a concern for central generation renewable energy directly, but may be a concern for some technologies that allow centralized renewable energy generation to be used. For example, such problems are likely in developing a new infrastructure for electric or hydrogen vehicles (Gillingham and Sweeney 2010).

A policy response to capital market constraints is much broader than a renewable energy policy and likely would require policy intervention in financial markets. A simultaneous coordination problem has some similarities to a public goods problem, and may provide motivation for either government coordination of the different agents or possibly government provision of the good or service.

3. Carbon Capture and Storage Technologies

Carbon capture and storage (CCS) technologies present the promise of using fossil fuels in a low carbon fashion. With CCS technologies, central generation coal and natural gas could conceivably be very low carbon electricity generation sources. However, there are numerous barriers to implementation of CCS technologies.

The most fundamental barrier to implementation of CCS technologies is simply the high cost of capture and storage of the carbon. Creating a further barrier is the absence of a sufficiently high carbon price anywhere in the world. Even in Europe, where carbon dioxide emissions fall

[6] Alternatively, the firm may not have access to this capital because there is a large risk that the investment will not succeed. But such a failure is a social cost as well as a private cost. Thus such failure to expand is not a market failure but rather an outcome that is desirable from both the private and the social perspectives.

under the European Union Emissions Trading System (ETS), there are no active CCS plants beyond the demonstration phase, except for carbon dioxide injection used to extract oil.

The high cost of CCS stems from several factors. First, the capture technology is still a relatively early-stage technology. Second, the process of carbon capture is a highly energy intensive process. Thus, the efficiency of fossil fuel electricity generation is significantly reduced by capturing and storing the carbon, with the extra generation requirements ranging from 10 percent to up to 40 percent depending on the technology (IPCC 2005). Storage uses additional energy which thus is not available for end uses.

But there are additional barriers to implementation of CCS technologies. One important barrier is the concern that the stored carbon will not be permanently sequestered, and may leak out over time. This is a scientific question and the answer depends on the particular geology and CCS technology. Carbon dioxide has been sequestered to facilitate extraction in nearly depleted oil and gas wells for many years, and there has been little evidence of leakage from these wells. Some scientific estimates suggest that for properly chosen and managed CCS sites, the probability of leakage is extremely small (IPCC 2005). Yet, the possibility of leakage would have to be carefully addressed for any large scale plan to implement CCS technologies.

Finally are the public acceptance issues with CCS. If there is a risk of abrupt release of underground carbon dioxide, that carbon dioxide could temporarily form low-lying high concentrations of carbon dioxide, which could lead to deaths of people and animals in the high-concentration pools. Will population clusters be at significant risk? Who would be liable? Until these issues are fully settled, there may be continuing public acceptance barriers.

3.1 Possible Market Failures in CCS Technologies

Do market failures also apply to CCS technologies? Just as for central generation renewable energy technologies, the use of CCS technologies would lead to lower fossil fuel emissions and thus would reduce the external costs of burning fossil fuels. Of course, a policy to promote only CCS technology would be second-best to a policy directly internalizing the environmental externality from fossil fuel emissions, for the direct policy would provide greater flexibility in finding ways to reduce emissions.

It is possible that the same appropriability market failures that may occur with central generation renewable energy technologies may also occur for CCS technologies. However, much of the research and development of CCS technologies is currently being done by the public sector already, and in this case, the appropriability market failures would not apply.

4. Distributed Generation Renewables

Distributed generation renewable energy technologies include rooftop solar photovoltaic panels, rooftop solar hot water heaters, microturbines for harnessing wind, and residential ground source heat pumps. These technologies face many of the same barriers as central generation renewable energy technology. One major difference is that in the case of distributed generation renewable energy technologies, consumers (and sometimes firms) are the purchasers of the technology, rather than electric utilities.

As with central generation renewable energy technologies, the primary barrier is the private cost, although this cost is rapidly decreasing. Each of the distributed generation renewable energy technologies remains costly for consumers relative to other options. The intermittency of distributed generation renewable energy technologies may also be a challenge, just as for central generation renewable energy technologies. However, neither high cost nor intermittency are market failures that provide the opportunity for economic efficiency enhancing increases in those renewables.

Moreover, distributed generation renewable energy technologies already are subsidized. There are occasional federal or state subsidies. In addition, retail electricity prices typically have much of the fixed cost of transmission and distribution included in the variable electricity prices. Thus, retail prices of electricity substantially exceed the marginal cost of electricity generation, transmission, and distribution. Accordingly, electricity bill savings from implementing distributed generation technologies can be substantially larger than the electricity system cost reductions from their implementation.[7] Taken alone, this suggests that efforts to subsidize additional implementation of renewable generation technologies may reduce economic efficiency.

[7] This issue will be relevant for energy efficiency investments as well.

4.1 Possible Market Failures in Distributed Renewables

The market failures associated with central generation renewable energy technologies also apply to distributed generation renewable energy technologies. Avoided damages from fossil fuel emissions equally apply. National security externalities may in some cases apply. Appropriability market failures in research and development and LBD may also be relevant. For distributed generation solar photovoltaic technologies, LBD appears to be relevant for the balance of system costs (i.e., all costs besides the panel and inverter cost), including the installation cost (van Benthem, Gillingham, and Sweeney 2008). And LBD may also be relevant for the solar panel manufacturers, although Nemet (2006) finds limited evidence for LBD at this level. Given the limited empirical work focused on ascertaining the importance of these market failures in distributed generation renewables, we consider this a promising area for future research.

However, there may be other barriers as well that are specific to consumer purchases of renewable energy technology that may lead to market failures. For example, there may be information market failures relating to poor information about prices and energy use. There may also be principal-agent problems relating to consumers not paying for their energy use. Furthermore, there may be "network externalities," which are sometimes called "network effects" or "peer effects," in the adoption of distributed generation renewables, whereby the decision of others to adopt influences the utility an individual receives from adopting (and thus the probability of adoption). Thus, a critical mass of consumers must adopt in order for the technology to become widespread. Bollinger and Gillingham (2011) find strong empirical evidence for such effects in the adoption of solar photovoltaic panels in California. Of course, network effects may not always constitute a market failure, for in many cases there may be compensation for the spillover (e.g., neighbors may help each other out in a variety of ways, perhaps already internalizing the externality).

With the exception of environmental externalities, empirical evidence on the importance of these potential market failures in distributed generation renewables remains limited and is an open topic for future research.

5. Energy Efficient Technologies

Technologies to improve energy efficiency are considered here as low carbon technologies because they reduce the demand for energy, and thus displace fossil fuels that would be emitting carbon dioxide. These technologies include everything from weatherization to more efficient appliances to more efficient vehicles. There may be numerous barriers to both consumer and firm adoption of these energy efficient technologies, and the importance of these barriers depends in part on the type of technology. Importantly, whether some of these barriers are failures that provide motivation for policy intervention is not as clear-cut as in the previous sections of this paper, and is very much an open research topic. Thus, for this section, we will not separate the discussion of market failures and market barriers.

For some investments in energy efficiency, the primary barrier is again the high cost of the technology. For example, the cost of retrofitting residential buildings by installing wall or sub-floor insulation, low-heat loss windows, or ultra-efficient furnaces, or heat pumps may exceed the value of energy savings, particularly in mild climate regions. Cost savings from plug-in hybrid vehicles typically are too small to justify the high costs of the batteries needed for such vehicles.

Yet other low-market-penetration energy efficient technologies appear to be less costly, on a levelized basis, than other technologies with higher market penetration. In this situation, interventions designed to increase market penetration of low-levelized cost energy efficient technologies can enhance economic efficiency. In order to identify policy interventions that could be economic efficiency enhancing, it is important to understand why low-cost energy efficient technologies are not adopted as much as would seem to be optimal.

We classify possible barriers to the implementation of energy efficient technologies into three categories: <u>institutional barriers</u>, <u>market failures</u>, and <u>behavioral issues</u>. Institutional barriers are based on the institutional structure of our society. Market failures are based on incentives embedded in the existing structure of market interactions. These include the same issues as discussed for renewable energy technologies. Behavioral issues are based on consumer or firm decision processes. These issues are more likely to be relevant for energy efficient technologies than for renewable energy technologies or CCS.

Many of these possible barriers relate closely to each other, and the same phenomenon may be placed in more than one category. These three categories provide one, but not the only one, way to describe the possible barriers. However, we believe the three categories do provide a useful way to highlight areas that have received less discussion in the previous literature, with the goal of pointing to areas of greater research need. We do not discuss each barrier in great detail, but we will endeavor to cover the most important topics and areas for future research.

5.1 Institutional barriers

Institutional barriers are not often discussed by economists, but may have particular relevance to the implementation of energy efficient technologies. Most of these issues do not yet have adequate empirical support because there has been relatively little research into these barriers.

In new construction settings, workers with different types of training (e.g., plumbers, roofers, electricians) each put in their respective parts of the building, but may not coordinate at all to improve the energy efficiency of the building (Sheffer 2011). Similarly, there currently are limited building tools for architects and designers to use to examine the energy efficiency characteristics of a new building as it is being planned. The building energy performance models that are available are often considered to be relatively inaccurate. In addition, alternations during construction can change energy use characteristics of new buildings. These factors imply that the actual energy performance of a building can vary sharply from that projected using the current generation of planning tools. This was illustrated in a study by Turner and Frankel (2008) that

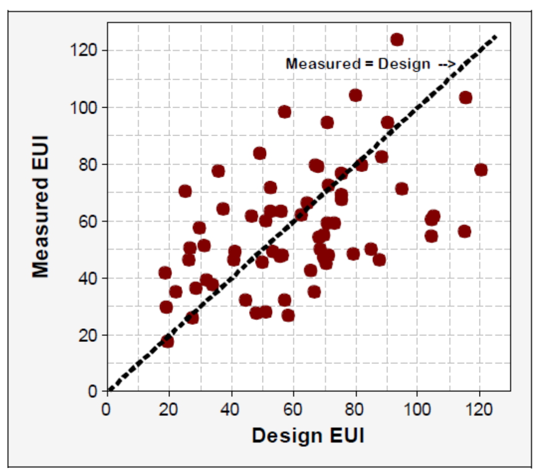

Figure 1. LEED Building Measured EUIs vs Design EUIs (measured in kBTU/sf). Source: Turner and Frankel (2008)

examined Energy Use Indicators (EUI), measured as annual KBtu/square foot, for LEED certified buildings. The study compared the actual EUIs against the design EUIs, as estimated by the project developer. The comparison for the set of buildings examined by Turner and Frankel is provided in Figure 1 that shows measured and the design EUIs for various LEED certified buildings. This figure illustrates the very large variation between the design performance and the actual measured performance. Thus, even if both the building planners and future occupants may desire energy efficiency improvements, actual improvements cannot be assured. The extent to which these issues are important is very much an open question, with some evidence suggesting that they could be important, but little academic work has yet attempted to tackle these questions.

Regulatory and fiscal policies also can get in the way of energy efficiency improvements. Building codes set minimum standards for construction, including in some states for energy performance.[8] But minimum standards can also become the norm, with contractors simply striving to meet the existing building codes. When building permits are issued, the builder typically must provide evidence that the building codes will be met, but are not asked by regulatory bodies to exceed the codes. Although the intended owner of the building could contractually require the contractor to exceed codes and build an energy efficient home, such agreements require reasonably sophisticated knowledge.

Many corporations have a decentralized managerial structure in which financial reporting is used to evaluate and to reward performance of various organizational units. However, traditionally the costs of providing building services, including electricity, heating, and cooling have been included as overhead, rather than directly measured as a cost. When energy is a relatively small part of the cost structure and measuring energy use for the various organizational units is difficult, such a structure is completely rational. However, typically there is little incentive in organizational units to actively manage overhead items. When energy is treated as overhead, this institutional structure discourages organizational units to put in sufficient efforts to reduce energy use.

[8] California's Title 24 Energy Efficiency Standards for Residential and Nonresidential Buildings (http://www.energy.ca.gov/title24/) are an exception. They specify aggressive building energy performance standards and are revised every few years.

Local and regional governments can have significant impacts on transportation energy by their land use regulations, including zoning codes and approvals for new residential or commercial development. Typically residential buildings cost more in public services than they pay in local taxes (dominantly property taxes), while the reverse is true for commercial and industrial buildings, some of which may generate sales tax revenues in addition to property tax revenues. Thus, commercial and industrial buildings generally subsidize the cost of public services for residential buildings. This differential provides an incentive for city governments to compete for new commercial and industrial activities relative to the amount of new residential construction. Early urban economics literature has shown this system to have led to "urban sprawl" and a separation of residences from work places. It is a reasonable speculation that this fiscal system has led to systematic increase in commuting and an over-use of transportation energy. However, to our knowledge, this issue has not been systematically researched in the context of energy use.

5.2 Market Failures

Market failures are the most well-known and well-understood of the potential market barriers relating to energy efficiency. Importantly, market failures have the potential to provide a motivation for policy, should they be empirically important.[9]

Split-incentive issues[10] come about when one person or firm is responsible for capital costs of an investment, another is responsible for operating costs, and operating costs could be decreased by increasing capital expenditures. If the two entities separately make their optimal decisions, then the overall outcome will not be collectively optimal. Additional capital expenditures could reduce operating costs enough to reduce the overall cost.

For buildings, split incentives occur when the tenant is responsible for paying the utility bills for the home or office and the owner is responsible for capital investments that change the energy performance of the building. Unless the potential tenants have good information about

[9] Externalities associated with energy usage do not provide motivation for energy efficiency policy if these externalities are already priced correctly. Similarly, if the electricity system is decarbonized through widespread implementation of renewable energy (or nuclear power), the greenhouse-gas externalities would disappear.

[10] Principal-agent issues can be viewed as a class of split-incentive issues.

the building energy performance, and have that information at the time they negotiate the lease, the owner would not capture the benefits of energy efficiency investments. Likewise the tenant would not have an incentive to make permanent investments in a building they do not own. Thus neither the owner nor the tenant is likely to invest in as much energy efficient investment as would be collectively optimal.

Split incentive problems would also occur even if the owner is responsible for paying both the utility bills and the capital investments that change the energy performance of the building. Capital investments could be expected to be optimal for the usage patterns. However, the tenant would have no incentive to take into account the energy implications of thermostat settings, appliance usage, or appliance purchases. Therefore energy would still be overused.

There is evidence that split-incentive issues may be empirically relevant in energy efficiency decisions in residential buildings. Davis (2011) finds that Energy Star appliances are less likely to be purchased in rented dwellings. Gillingham, Harding, and Rapson (2012) show that owner-occupied dwellings in California are more likely to be well-insulated. Sudarshan (2011) shows that after controlling for a variety of other factors owner-occupied homes use approximately 30 percent less heating fuels than rented dwellings. Using data from the US Department of Energy Residential Energy Consumption Survey (RECS), Sudarshan (2011) shows that owner occupied homes are substantially more likely than rental homes to include such energy efficient technologies as double-paned or triple paned windows, good insulation, or programmable thermostats. However, this RECS comparison does not control for other causal variables.

A study by the National Resources Defense Council (2011) shows that set-top boxes provided by cable television companies operate at near full power even if the consumer is neither watching nor recording television. The energy cost could be reduced substantially with very little capital cost, but most consumers are unaware of the energy-inefficient design of these boxes and there apparently has been little consumer pressure for the cable operators to provide energy efficient set-top boxes.

Such split-incentive problems are most likely to be important when there are information limitations. If tenants had complete knowledge of the energy performance of buildings, they presumably would be willing to pay more to lease buildings that use less energy. The possible increase in rental payments would provide incentives for the building owner to invest in energy efficiency upgrades. Similarly, if consumers had good information about the energy use of set-top boxes, then the energy costs would influence their maximum willingness to pay for the cable service, and may motivate complaints to the cable service provider. These in turn would provide incentives for the cable television companies to supply more energy efficient set-top boxes.

Externalities associated with energy use also lead to market failures. Use of electricity requires electricity to be generated. Much of the generation, in turn, releases greenhouse gases and leads to other environmental problems. Unless these externalities are internalized, there is an incentive to use too much energy.

One possible market failure, however, cuts in the opposite direction. Like distributed generation technologies, energy efficiency investments already are implicitly subsidized. Besides the occasional federal or state subsidies, retail prices of electricity substantially exceed the marginal cost of electricity generation, transmission, and distribution. Thus electricity bill savings from energy efficiency investments technologies can be substantially larger than the electricity system cost reductions from their implementation. This factor along would lead to too little use of electricity.

The empirical evidence on the importance of these market failures is more limited for energy efficient appliances than it is for buildings. Therefore additional empirical research would be valuable for these other failures.

5.3 Behavioral Issues

Only in the past several years have economists begun taking behavioral issues more seriously with the rise of behavioral economics. We view these behavioral issues as features of human decision-making that often interact with information failures to lead to systematic biases in the decision made. The systematic biases do not necessarily mean that there will be under-investment in energy efficient technologies.

However, there is an empirical regularity found in many papers on energy efficiency going back several decades: consumers appear to “undervalue” the future fuel savings from improved energy efficiency relative to other decisions. This empirical regularity is often known as the "energy efficiency gap" or "energy efficiency paradox," for there appears to be a gap between the amount of investment we would expect consumers (and firms) to make in energy efficiency and what we actually observe in the world (Jaffe and Stavins 1994, 1994). This "energy efficiency gap" has long been explained in empirical studies as being consistent with a significantly higher *implicit* discount rate for investments in energy efficiency than the interest rate on even a high interest rate credit card (Hausman 1979, Train 1985). Yet there are other reasons that appear more plausible than an explanation based on the idea that consumers simply increase their discount rates only for those investments that would reduce energy use. And there are numerous papers written with different explanations for this energy efficiency gap, including many explanations consistent with neoclassical economic theory: transaction costs, information gathering costs, heterogeneity among consumers, the option value of waiting, and consumer uncertainty.

More recently, with the greater acceptance of behavioral economics, economists have begun to consider behavioral issues as at least part of the reason for this energy efficiency gap. Suppose consumers systematically have cognitive difficulties in weighing future fuel savings into decisions today. There are several theories from behavioral economics that could help explain why consumers might have this bias, including prospect theory (i.e., loss aversion), bounded rationality, and heuristic decision-making (Gillingham, Newell, and Palmer 2009). These features of human decision-making may interact with information failures, such as poor information on the price and usage of electricity, leading to the result of an undervaluation of future fuel savings relative to what we might otherwise expect.

Energy efficiency can be expected to have low salience among consumers as they make residential energy use decisions. The 2009 US average expenditure on all energy in the residential sector (not including transportation) was 2.2% of disposable personal income.[11] Two thirds of this expenditure is on electricity. This expenditure is the result of literally dozens daily actions, such as turning on and off electronics, lighting, or appliances. Each of these choices is made with little or no direct feedback about the financial costs of the individual choices, with the only feedback for most people is the monthly utility bill, a bill that does not

[11] Data from the US Energy Information Administration and the US Bureau of Economic Analysis.

(and perhaps cannot) distinguish among the various pieces of energy using equipment. The problem extends to the purchase of much energy using equipment, where it is typically difficult for consumers to get information about the financial consequences of their purchases. Refrigerators and automobiles are well-labeled and clearly show the probable annual energy cost of the particular models. But very few other appliances have such easy-to-interpret labeling. Thus the combination of the small financial consequence for each decision coupled with little information about the financial consequences of any decision may well imply that such choices have low salience for each consumer.

Yet the empirical evidence is not yet conclusive enough to indicate that the behavioral issues dominate other plausible explanations, such as heterogeneity of consumers and real cognitive constraints (Bento, Li, and Roth 2012; Smith and Moore 2010). This state of the literature is in part due to the great difficulty of empirically disentangling the different explanations.

5.4 Policy Relevance

The taxonomy of possible barriers lays out a fairly extensive list of these barriers, but do all of barriers provide motivation for policy? Realistically, it may be difficult to address some of these issues with regulation. While externalities are straightforward to address, split-incentive problems may be require a great deal of information and individual tailoring of the policy to the circumstance.[12]

The role for policy to address behavioral issues remains an area of active research and thought. Several important issues arise. Neoclassical welfare economics is built on a foundation that consumers are optimizing appropriately to maximize their well-being. Yet, in the behavioral economics literature, consumers are shown to be easily swayed in their decisions by objectively irrelevant conditions and may be using simple heuristics to make decisions. Most examples in the behavioral economics literature are of small decisions, so it is possible that when consumers are considering larger decisions, they are more careful.

[12] Some analysts have argued that the most sensible policy to address split-incentive problems is a performance standard. This may be a sensible approach if there is not a great deal of heterogeneity in consumer preferences (Hausman and Joskow 1982).

There are other ways to envision interventions. Thaler and Sunstein (2003, 2008) take a perspective they call *libertarian paternalism*. Thaler and Sunstein argue that since much work in behavioral economics has suggested that how choices are framed influences the outcome, one approach to policy would be to allow as much freedom as possible in individual decision-making, but involve the government in establishing the conditions that lead to ex-post good decisions. They refer to such policy actions as "nudges." The difficulty is in determining what makes a good or bad decision, although in many cases there are objectively better choices: e.g., whether to start smoking or whether school lunches should be primarily nutritious foods or primarily desserts. Work by Bernheim and Rangel (2009) and Bernheim (2009) begins to develop a theory of "behavioral welfare economics" that defines welfare directly in terms of choices (i.e., revealed preference) rather than some notion of well-being or underlying objectives. This work aims to build a theoretical framework for a general normative framework that can handle non-standard models of choice. Putting such a framework to use is nontrival.

Allcott, Mullainathan, and Taubinsky (2011) use a simpler theoretical model of consumer inattention and argue that when consumers are inattentive to energy costs, there is a rationale based on economic efficiency for alternative policies. For example, they suggest that they may be a role for subsidies that reduce the relative price of energy efficient durable goods. Yet they also suggest that "behavioral targeting," whereby the misoptimizers are targeted with policies would be preferred. The difficulty may lie in determining who is misoptimizing and how are they misoptimizing.

6. Conclusions and Areas for Future Research

This paper points to a variety of different barriers to the implementation of low carbon technologies. Only some of these barriers provide a motivation for policy intervention on economic efficiency grounds. One of the most important barriers – the high cost of renewable energy and CCS technologies – does not present a rationale for economic efficiency-improving policies.

Yet the innovation and learning processes that bring down the cost may have appropriability market failures that can provide motivation for policy. On these grounds, we should perhaps be hesitant about using policy to push the implementation of renewable energy technologies, unless there is clear evidence suggesting sizable LBD spillover effects. Similarly, it follows that on the supply side we should be most interested in innovation policies focused on cases where there are R&D spillovers. Indeed, the patent system and public funding for research already at least partly addresses a market failure from R&D spillovers. The difficulty with policy prescriptions relating to appropriability market failures is the relative lack of empirical evidence quantifying these market failures. This is a critical area for further research.

For energy efficient technologies, the issue may not simply be the cost, but institutional failures and behavioral issues that influence how consumers make decisions that weigh the upfront cost of the technology against future fuel savings. The institutional failures are a largely unaddressed area in the economics literature and we have little idea about how important they may be – yet they have potential to be important in certain circumstances. The behavioral issues relating to energy efficient technologies have the potential to justify a variety of paternalistic policies that require consumers to purchase more efficient technologies than they would otherwise. However, fully exploring where and when they are most important remains largely underdeveloped. For example, one of the underlying factors that may be creating behavioral issues in energy efficiency is the low salience of energy prices. Energy use in the residential sector (not including transportation) involves hundreds of energy actions or decisions, yet collectively includes only about 2.2% of average household disposable income. However, not all energy prices are less salient; the price of gasoline is likely to be highly salient to consumers who observe the gasoline price every time they purchase gasoline, while for electricity use the price may be much less salient, particularly because the relationship between use of various appliances and the resulting energy bill is difficult to determine.

Why are behavioral issues not a concern for distributed generation renewables? After all, in both cases, individual consumers are the decisionmakers. The difference is that for some distributed generation renewables, such as solar photovoltaic systems, businesses have stepped in to offer to pay the upfront cost and maintain the systems in exchange for a promise by the consumer to purchase the power (i.e., power purchase agreements). Thus the decision of whether to install distributed generation renewables is most likely based more on the information about the technology and consumer preferences for having the technology installed.

While the behavioral issues themselves may not be an issue for distributed generation renewables, there are still underdeveloped research areas relating to how to think about welfare economics in situations where our preference ordering is influenced by both what we do and what our neighbors do – such as in the case of network effects of peer effects in distributed generation renewables. Understanding whether these effects are empirically relevant externalities that provide motivation for policy is an area with possibly great importance for understanding policies relating to distributed generation renewable energy technologies.

In outlining what we know about the barriers to the implementation of renewable energy technologies, this paper points to a variety of important areas for future research. Many of these research areas relate to quantifying the importance of different market failures, but some are more fundamental questions about the theory of welfare economics in the face of behavioral anomalies. We remain optimistic that future work in these areas can provide useful guidance for policymakers considering ways to further implementation of renewable energy technologies.

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