Drivers and Barriers for Energy Saving Technological Change

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ABSTRACT

Change in the average input intensity of energy flows in industry is commonly broken out into three separate components; change due to technological change, structural change and input substitution. Energy saving technological change can either be embodied or disembodied. Embodied technological change only affects new capital vintages, as new, more efficient technologies become embodied through investment into the capital stock. Embodied change thus often requires substantial capital investments. Disembodied change is a change in the energy efficiency of "older" capital as a function of often low-cost operational improvements. This different character of embodied and disembodied energy saving technical change is fundamentally important when promoting investment in energy efficiency, or when designing policy aimed at enhancing energy efficiency (or e.g. in the case of climate change policy). This paper presents (1) an analysis of the different drivers and barriers (such as path dependency, capital inertia, learning and a reduction in uncertainty, changes in input prices) for embodied and disembodied energy saving technological change and (2) captures the relative importance of embodied and disembodied technological change, in energy intensive U.S. industries, focusing on the US pulp and paper industry. Derived from that analysis the paper illustrates how different climate change policy approaches may influence changes in energy efficiency.

Introduction

The price hike of crude oil in late 2008, and the enhanced focus on climate change mitigation as the December Copenhagen climate change negotiations approach, has somewhat redirected the focus of the policy community to improved energy efficiency as a policy objective. Clearly the attention of the climate policy community has gradually sharpened its focus to three main pathways: (1) carbon capture and sequestration, (2) substitution of carbon rich fuels to carbon neutral energy sources, and (3) improvements in energy efficiency. Most analyses of the cost of carbon mitigation illustrate that the most cost effective way to reduce emissions of greenhouse gasses is to improve energy efficiency, which in turn improves greenhouse gas efficiency and *ceteris paribus* greenhouse gas emissions.

Capital stocks constitute the building blocks of industrial systems. It is therefore through changes in capital that mature industrial systems "grow" and/or "evolve" as new capital is added and old capital is retired, influencing output volume and structure, input mix and volume in addition to waste flows. Understanding and properly capturing the dynamics of capital stocks of different age classes or "vintages", is a fundamental prerequisite to anticipating responses of industry to changes in the external environment, such as to new policies and therefore the expected impact of climate change policies on changes in energy efficiency, for example (Davidsdottir & Ruth 2008, Gray & Shadbegian 2001, Nystrom 2001, Ruth &and Amato 2003, Worrell & Biermans 2005).

Unfortunately to date, policy analyses have paid insufficient attention to the influence that the structure and dynamics of the capital stock has on industrial dynamics and therefore on changes in energy efficiency. Conventional top-down analyses that assess the economic impact and effectiveness of climate change policies that in turn are expected to affect energy efficiency do not capture the structure of the pre-existing stock (exceptions are e.g. the AMIGA model), capital dynamics nor do they contain sufficient descriptions of past investment behavior or future technology potential which is a serious drawback when the objective is to capture the potential impact on changes in energy efficiency (IPCC 2007, Davidsdottir & Ruth 2004, Stern 2006). Technology in many cases is represented in these models through production functions that assume substitutable and homogenous inputs – including a homogenous and perfectly malleable capital stock and autonomous technological change (DeCanio 2004, Jacoby & Wing 1999). Neglecting important attributes of the capital stock and the dynamics of technological change leads these models to prefer price-based policy instruments over other forms of policy intervention, as model structures improperly presume the possibility for swift change as a response to changes in price, despite significant capital inertia in the system.

Recognizing the role that capital vintage effects play in constraining industrial change and the effectiveness of climate change policy, early efforts to capture the heterogeneity of the capital stock (Johansen 1959, Kaldor & Mirrlees 1962) have been extended and applied to analyze energy flows in industry (Davidsdottir & Ruth 2004, 2005, 2008, Jacobsen 2000, Ruth, Davidsdottir & Amato 2004, Ruth & Amato 2003,). This paper builds upon the theoretical capital vintage models developed by Meijer (1994), Ruth et al. (2004) and Davidsdottir & Ruth (2004, 2005, 2008) and explores the importance of incorporating capital vintage dynamics that capture the drivers and barriers of energy saving technological change when assessing industrial change in the context of climate change policy. The paper in particular focuses on the impacts that capital vintage and capital vintage dynamics have on policy effectiveness and the relative importance of embodied and disembodied technological change, path dependency and learning-by-doing on changes in energy efficiency.

This article is organized as follows. We first describe the different drivers and barriers such as path dependency, capital inertia, learning, reduction in uncertainty, and changes in input prices for embodied and disembodied energy saving technological change. Second, the paper quantifies the relative importance of different types of energy saving technological change in an energy intensive U.S. industry, and the impact of the various drivers and barriers on the different types of technological change. The model used for that analysis has been described elsewhere (e.g., Davidsdottir & Ruth 2005), and therefore is not described in this paper. Third, derived from that analysis the paper illustrates how different climate change policy approaches influence differently changes in energy efficiency with a particular focus on the relative effectiveness of different investment promoting strategies.

Components of Industrial Change

A change in industry's input intensity of energy and material flows is commonly broken out into three separate components: technological change[1], structural change and input substitution (Farla, Blok & Schipper 1997), all of which are affected by capital vintage dynamics. The focus here is on changes in energy efficiency, but the close link between changes in energy and material flows as a result of the attributes of the embodied capital stock must be kept in mind (Davidsdottir 2004).

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[1] Technological change is defined as a reduction in the use of an input, holding other inputs and output constant. Structural change can of course change the input use, but at the same time will change the output mix.

Capital Vintage Dynamics

Each industry or industrial system consists of different age cohorts of capital, called capital vintage, just as the human population consists of different age cohorts of individuals. Each cohort differs in size as investment is always lumpy (Doms & Dunne, 1998), and each capital vintage is characterized by vintage specific attributes such as input efficiency e.g. energy efficiency, output volume, output structure and other factors, such as capital utilization and depreciation rates (Davidsdottir & Ruth 2004, 2005, 2008).For instance, an older vintage is likely to require a larger amount of input materials to produce the same amount of physical output, when compared to a new vintage (De Beer 1998, Lempert 2002). An industrial system evolves as new capital is added to the existing stock of capital that contains different attributes than pre-existing vintages and when old capital is retired and thus removed from the capital stock. Retirement in most cases is gradual and thus leakage occurs from each vintage, until the vintage is completely retired.

Technological change and capital vintage dynamics. An industrial system evolves when the attributes of its capital stock change, as a result of capital stock expansion or the gradual replacement of old, worn out or retired structures. The expansion of a capital stock and thereby increased production will, by definition, increase the total use of input materials and slightly improve input efficiency (De Beer 1998, Lempert et al. 2002). Replacement investment, which includes retrofits, more extensively increases energy and material efficiency, and keeps constant or reduces total use of material and energy inputs as new replacement investment tends to be incrementally more efficient than older capital. Thus, the investment process incrementally changes the flows of energy into and out of the system. In this context, a distinction is made between embodied technological change, which influences new capital vintages, and disembodied change, which influences the efficiency of already installed capital (Berndt 1993, Davidsdottir & Ruth 2005, Meijer 1994, Solow 1957, Sue Wing & Eckaus 2004). As a result, the associated capital vintage defines in many cases the type of energy saving technological change in question.

Embodied change. Energy saving embodied technological change occurs as technology becomes embedded within the capital stock, due to either expansion or replacement investment, and is therefore driven by investment behavior. Therefore, in the spirit of Schumpeter, it can be argued that embodied technological change implicitly captures the three phases of technological change: invention, innovation, and diffusion (Schumpeter, 1938). It is, however, through diffusion that the innovated invention becomes part of the capital stock via either replacement or expansion investment. As a result, embodied energy saving technological change requires significant direct and indirect capital investments. Indirect capital investments occur at earlier two stages of technological change (invention and innovation) through research and development expenditures (R&D). Direct investment is undertaken by the industry using the capital, through which the capital becomes embodied into the capital stock. R&D expenditures have much impact on the character (e.g. efficiency) of available new capital, and usually occur outside of the industrial system in question (Scherer 1982). In this paper, however, the focus is on direct investments. The extent to which embodied technological change occurs depends on input prices and learning, and is highly path dependent (Arthur 1994, Unruh 2000, Kuper & Soest 2003). Path dependency is the result of mature industries continuing to invest in similar technologies through time (Arthur 1994, Unruh 2000) fostering incremental rather than radical changes. Choices made early on in the development of an industry gradually rigidify (technology lock-in), defining the future technology trajectory as a function of the structure of the existing capital stock. Capital inertia further reduces the rate of technological change and efficiency improvements. If an industry is mature, capital intensive and dominated by early-vintage capital stock, capital vintage structure can act as a significant deterrent to change in energy efficiency in response to altered external economic or environmental conditions.

Learning, which here is defined as a change in input intensity per unit of output or the operational or capital costs per unit of output as a function of cumulative experience, also influences the speed of diffusion and thus embodied technological change. As learning or experience is gained, capital, operational cost and input intensity tend to decline (Woerlen 2003).

Evidence of substantial embodiment has been confirmed, for example, by Sakellaris and Wilson (2004), which find that each vintage is about 12 percent more productive on average than older equipment and that embodied technological change accounts for 2/3 of all output growth in the United States. Greenwood (1997) demonstrates that 58 percent output growth in the U.S. between 1954 and 1990 was due to embodied technological change.

Disembodied change. Disembodied energy saving technological change occurs not as a result of retrofits or replacement investment, but as a function of regular minor maintenance (Lempert 2002) and of low- or no-cost operational changes (Ross 1991) or learning, that lead to improvements in energy efficiency (Davidsdottir & Ruth 2005). Such changes can be in the form of improved housekeeping practices, and typically do not require a substantial investment in fixed capital structures. Examples are improved insulation and the use of more energy efficient light bulbs. Learning-by-doing plays a central role in disembodied change as employees gain experience in operating equipment, and thus efficiency improves after capital is installed (Davidsdottir 2002, Davidsdottir & Ruth 2004, Meijer 1994, Ruth, Davidsdottir & Amato 2004). According to Sakellaris & Wilson (2004), disembodied technological change accounts for about 1/3 of all productivity increases in the United States between 1972 and 1996. Empirical evidence illustrates that different drivers facilitate embodied and disembodied change, and therefore it is fundamentally important to distinguish the two.

Path dependency, capital inertia and learning. The impact of capital vintage on technological change also clearly manifests itself through path dependency and technology lock-in. Path dependency characterizes technology choice in industrial systems and manifests itself in repetitive investment patterns (Arthur 1994, Unruh 2000, Ahman & Nilson 2008). Due to path dependency, investment choices gradually become “locked-in”. As a result, past investments define the structure of future investments and, in the case of capital with long service life and slow turnover, influence energy and material flows far into the future (Norberg-Bohm & Rossi 1998, Davidsdottir & Ruth 2005). This is exactly the case seen in many energy intensive industrial systems such as the pulp and paper industry, aluminum industry, iron and steel industry and the cement industry.

The combination of path dependency, technology lock-in, and a long-lived capital stock creates capital inertia, which leads to incremental technological change and reduced ability of the industrial systems to react swiftly to any external change such as a climate change policy (Davidsdottir & Ruth 2005, 2008, Norberg-Bohm & Rossi 1998). As a result, path dependency must be considered and understood if the purpose of a policy is to accelerate change in such a system, such as reducing greenhouse gas emissions by improving energy efficiency (Ahman & Nilson 2008).

Learning influences both embodied and disembodied technological change, and is characterized either as learning-by-doing or investment-learning. On the one hand, learning-by-doing has a central role in disembodied technological change (Davidsdottir & Ruth 2005, 2008, Meijer 1994, Ruth, Davidsdottir & Amato 2004), and describes how efficiency of production processes increases when individuals become more adept at doing certain tasks with increased experience. Investment-learning speeds up embodied technological change. Such learning occurs when investment in a certain process increases, and experience is gained which results in declining operational and investment costs and reduced risks involved for future investors. Through a positive feedback loop, learning facilitates increased diffusion and thus embodiment affecting future technology trajectories (Watanabe & Asgari 2002). This feedback loop is fundamentally important when it comes to the diffusion of energy saving technological change and investment in new low-carbon energy sources.

Structural Change and Input Substitution in the Context of Capital Dynamics

Structural change in an industrial system is defined as a change in output mix such as, e.g., a shift in the paper industry from producing newsprint towards printing and writing papers. Because fiber and energy requirements differ substantially for those two products, such a shift influences both energy and material intensity as well as the character of those flows (Ruth & Harrington 1998, Energetics 1990, Davidsdottir 2004).

Since in some cases different specialized machinery is needed to produce different categories of output, prior investments (and thus capital vintage) shape and in some cases lock-in specific output categories. An industrial system also changes due to input substitution. Three main variants of substitution are frequently distinguished. Substitution may be "putty-putty" – it is equally feasible to substitute inputs within both new and old vintages; "putty-clay" – substitution is only feasible for new vintages; or "clay-clay" – substitution is not possible for neither new, nor old vintages as input mix is relatively fixed for each technology. In disaggregated industrial systems analysis it is appropriate to use clay-clay specifications, as relationships among broad input groups, such as materials, energy labor and capital, are relatively fixed for a given technology. However, substitution within input groups such as between different energy types may be possible as is e.g. the case in the pulp and paper industry.

Summary. The change in energy efficiency in industrial systems is shaped by capital vintage dynamics such as the character of existing capital vintage and the extent of path dependency, and without explicit descriptions of its structure and attributes, models are unlikely to adequately capture the limits to and the potential for change. The next section describes an empirical assessment of the U.S. pulp and paper industry where capital vintage dynamics are explored with a focus of the extent of the barriers and drivers to energy saving technological change, and then the implications of the impact of those barriers and drivers are assessed in the context of an implementation of a price based climate change policy.

Drivers and Barriers to Energy Saving Technological Change: Empirical Assessment

Capital Vintage Modeling

The approach used in this study is a capital vintage model. Capital vintage models were first developed in the 1950's and 1960's (e.g. Johansen 1959, Kaldor & Mirrlees 1962). Such models have recently been used to analyze energy flows in industrial systems (Davidsdottir & Ruth 2004, 2008, Ruth, Davidsdottir & Amato 2004, Ruth and Amato 2003). Capital vintage models capture the age structure of the capital stock and its associate age-specific attributes such as size, rate of replacement, input efficiency and input substitution possibilities. For example, an older vintage is likely to require a larger amount of input materials and energy to produce the same amount of physical output compared to a new vintage. In these models the industrial system "evolves" as the capital stock changes via investment, through either expansion of the capital stock (expansion investment) or through the gradual replacement of old, obsolete, or worn out structures (replacement investment). The extent of each type is empirically estimated.

The capital vintage approach used in this study expands the vintage models developed by Meijer (1994), Ruth, Davidsdottir & Amato (2004) and Davidsdottir & Ruth (2004). This approach differs from others in four important ways. First, as regions are heterogenous in the attributes of their capital stocks, the model is regionally disaggregated. Second, the model simultaneously captures material, energy and waste flows. Earlier models only analyzed either energy or materials, and in most cases did not capture waste-flows. This is of course particularly important in the context of climate change policy, and the enhanced focus on the assessment of a product from a cradle to grave. Third, the model incorporates both embodied and disembodied technological change, and quantifies the impact on each type from a change in the cost of carbon. Fourth, replacement investment and thus depreciation is endogenous, and differences in vintage specific capital depreciation and replacement rates are accounted for. The structure, size and capital utilization of new and existing vintages, determine – together with the vintage specific input efficiency of each individual process and its vintage specific rate of disembodied change – the total flow of a specific input (e.g. energy) through the system. The input efficiency changes as a function of substitution, structural change and technological change, which is modeled as endogenous and embodied as well as disembodied change and is influenced e.g. by capital inertia, learning and path dependency.

Efficiency by vintage and output levels by type and vintage determine total input requirements. Total requirements are disaggregated into different energy and material types based on econometrically estimated input substitution equations. The total size of energy and material flows by type, combined with engineering parameters, provide estimates of total waste flows from the system. The overall methodological approach is thus based on a combination of material flow/energy flow analysis, which is linked by capital vintage accounting and system dynamics modeling to simulate total material and energy flows using non-linear differential equations (see e.g. Beukering & Janssen 2000). The industrial system chosen for this study is the U.S. pulp and paper industry (NAICS code 322). More detailed descriptions of this industry can be found in e.g. Ruth & Harrington (1998), Smith (1998)) Davidsdottir (2004) and Davidsdottir & Ruth (2005).

Implications from Empirical Assessment: Parameter Estimation

Production module and choice of fibers. The level of production is rarely affected by the cost of capital or labor except in the Northeast, and the price of virgin fibers never has significant price elasticity. The price elasticity of waste fibers ranges from -0.09 to -0.15. An extensive ownership by the pulp and paper industry in forest resources may explain this result, but the pulp and paper industry holds over 40% of all privately held timberland in the United States.

In contrast, regional energy price elasticity was in almost all cases significant, and ranges from zero to -0.728. In regions where virgin fibers are the prevalent fiber type, which means that the % share of wastepaper (WUR) is low – the energy price elasticity was low or insignificant, with energy price elasticities of recycled paperboard significantly higher than in regions with high WUR. In regions that have high WUR, energy price elasticity of total paper and paperboard and recycled products was high but not significantly different. This indicates that in the case of an increase in energy prices in those regions, such as due to an increase in the cost of carbon the industry will not shift from virgin to waste-fibers, but rather reduce overall production levels potentially indicating regional winners and losers of a price drive climate policy. In regions with low WUR's results indicate a potential shift away from the use of recycled fibers in the case of an increase in energy prices.

Physical Vintage and Investment: Capital Turnover and Investment Behavior

1. An increase in energy prices <u>reduces</u> the <u>rate of increase</u> in expansion investment.
2. Capital depreciation, and thus <u>replacement investment</u>, is significantly influenced by the age of capital and energy prices. As energy prices increase, the depreciation curve shifts, effectively <u>reducing</u> depreciation rates for "young" capital but <u>increasing</u> the depreciation rates for "older" capital. An increase in energy prices such as due to an increase in the cost of carbon will reduce the scale of expansion investment and will increase or decrease replacement investment, depending on the structure of the capital stock.
3. Capital turnover and expansion of the capital stock is significantly affected by increasing capital utilization rates, which indicates that slower growth in the industry may negatively affect investment in energy saving equipment. This finding is particularly important in the light of recent economic events all over the world.
4. Due to immense capital inertia, the system will respond only slowly to changes in input prices.

Energy Efficiency

1. The impact of an increase in energy prices on energy saving embodied technological change is ambiguous. An increase in energy prices negatively affects expansion investment, positively affects the rate of replacement of older capital but reduces the rate of replacement of younger capital. As a result the actual impact on embodied technological change depends on the structure of the capital stock.
2. Energy saving disembodied technological change is positively affected by an increase in energy prices, but learning-by-doing, which influences energy saving disembodied change, is negatively affected since output levels are negatively affected.

Implications from Empirical Assessment: Simulation

Base case. Total energy intensity (or total carbon intensity) overall is declining in all regions, with the intensity of purchased fuels (or net carbon intensity) declining faster than the intensity of self-generated fuels due to the continued shift towards self-generated energy. This implies reduced reliance on purchased energy at the national level.

Change in energy intensity is significantly influenced by embodied technological change or by 70%, but disembodied technological change is responsible for 30%. Learning by doing is a significant driver of disembodied change, which indicates that increased production levels affect both disembodied change through learning, and embodied change through higher capacity utilization rates. Therefore, regions that experience increasing growth levels will exhibit faster reduction in both energy and carbon intensity, due to both embodied and disembodied technological change.

Increasing energy prices as a result of an increase in the cost of carbon by 100$: climate change policy scenario. A comparison to the base scenario and an increase in the cost of carbon reveals:

1. <u>Expansion investment in all regions declines</u> when compared to the base scenario. The investment that occurs shifts toward processes that are more energy intensive in total, but rely less on purchased energy and waste-fiber pulping.
2. <u>Replacement investment increases in all regions</u>, because replacement rates increase for older capital with higher energy prices, and older capital dominates the vintage capital structure of the industry. Thus the increase in energy prices outweighs the reduction in learning, which occurs due to reduced production rates.
3. <u>Energy intensity increases in all regions</u>. The rate of decline in energy intensity due to technological change is a function of the relative movements in expansion and replacement investment (embodied change) and disembodied change. The rate of embodied technological change significantly diminishes, and thus *embodied energy intensity* in 2020 in all regions is *higher* than in the base scenario. This indicates that the increase in replacement investment is unable to outweigh the decline in expansion investment compared to the base scenario.

Policy impact. An increase in the cost of carbon through changes in energy prices reduces the rate of embodied energy saving technological change and the increase in disembodied changes is unable to outweigh the decline in embodied change. Thus, a 100$ increase in the cost of carbon is unable to overcome the significant capital inertia in the industry and facilitate sufficient change. Also, because disembodied changes are often reversible due to very small capital costs, a decline in intensity due to disembodied changes are less permanent than if they occurred due to embodiment. This indicates that a climate policy that relies on a relative increase in energy prices as a function of carbon content is not likely to facilitate sufficient permanent change in this industry.

An increase in the cost of carbon reduces the use of recycled paper and waste-fiber utilization rates. This increases virgin fiber intensity in the industry, because virgin fibers provide lower yield than waste-fibers.

Gross carbon intensity (sum of greenhouse gas emissions measured in CO_2 eq.), increases beyond what it was in the base scenario as a result of significantly reduced recycling rates, and thus increased waste-paper accumulation in landfills in addition to the continued shift to self-generated energy. This assumes no methane capture from landfills.

Regional winners and losers emerge, as production levels in regions that have high WUR's are negatively affected, resulting in shifts of production levels towards regions that use virgin fibers.

Discussion

The research presented in this paper highlights several important findings. First, an increase in the cost of carbon is likely to reduce production rates in areas that use wastefiber as their primary fiber source and thus reduce wastefiber utilization rates. Second, such increase may reduce expansion investment, but increase energy saving replacement investment and disembodied technological change due to the sensitivity of low cost changes to changes in energy prices. Both replacement and expansion investment contribute to embodied technological change. As a result, the age structure of the capital stock determines the actual impact of an increase in the cost of carbon on embodiment. The simulation results indicate that the increase in replacement investment and disembodied change is unable to outweigh the decline in expansion investment in the US pulp and paper industry.

Regardless of the region, resource endowments or production structure, an increase in the rate of capital turnover is the most important factor in permanently changing energy use in the pulp and paper industry (see similar conclusion in e.g. Nystrom and Cornland 2003). This is due to the long-lifetime of capital in the sector, low rates of capital turnover and high capital intensity. The immense capital intensity and capital inertia ensure the capital stock will change slowly and thereby only gradually improve energy and carbon efficiency. In addition, the long lifetime of capital and path dependency ensure that each managerial decision will have significant impact on the industry and the environment, for decades to come. This study illustrates that an increase in energy prices such as by increasing the cost of carbon is **not** sufficient to overcome such capital vintage effects since the system adapts **very** slowly to change – but such an increase is likely to rather facilitate fuel switching and disembodied changes in efficiency rather than accelerate sufficiently embodied changes. Consequently, to enhance the long-term move to low carbon futures in this particular industrial system, policies need to provide investment incentives to facilitate faster turnover of older capital and facilitate investment in climate friendly technologies, which would result in permanent changes in energy and carbon intensity. Such policies could include investment tax rebates, demonstration projects to reduce uncertainty and incentive driven voluntary sector agreements.

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