Modelling energy efficiency and carbon dioxide emissions in energy-intensive industry under stringent CO_2 policies: comparison of top-down and bottom-up approaches and evaluation of usefulness to policy makers

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Keywords

top-down, bottom-up, hybrid, energy-economy model, energy-intensive industrial energy use, energy efficiency, climate policy, European pulp and paper industry

Abstract

The question of how different climate policies will influence carbon dioxide (CO_2) emissions in the energy-intensive industry is complex. It is not obvious that increased costs for emitting CO_2 will lead to investments in new, low-emission technologies, since the energy-intensive industry is very capital intensive, and reduced CO_2 emissions beyond a certain point require large investments and possibly also radical process changes.

Traditionally, either top-down or bottom-up models have been used to analyze the influence of specific policies on energy efficiency and CO_2 emissions in industry. Bottom-up models describe technologies in detail, but are not realistic in their characterization of corporate decision-making, e.g., how businesses select technologies and make investments, and fail to depict macro-economic equilibrium feedbacks. Top-down models, in contrast, address these deficiencies by representing macro-economic feedbacks and by estimating parameters of technological change from observations of aggregate market responsiveness to cost changes. However, since top-down models lack technological detail, they are weak in assessing the use of new, low-emission technology. Because of these methodological differences, top-down and bottom-up models often make divergent cost predictions, and consequently suggest different policies, for meeting climate targets. This methodological divide has stimulated exploration of hybrid approaches that integrate the technological explicitness of bottom-up models with the micro-economic realism and macro-economic feedbacks of top-down models. To better understand the dynamics and policy responses of industry, such methods and models need to be further developed and applied.

In this paper we analyse and compare top-down, bottom-up, and integrated (hybrid) approaches that have been used for evaluating potentials for CO_2 emissions reductions and CO_2 policy analysis in energy-intensive industry. We also evaluate the usefulness of these approaches and models to policy and decision makers.

Introduction

Energy-intensive industry can play a key role in the transition toward a sustainable European energy system. The energy-intensive industry is a large contributor to carbon dioxide (CO_2) emissions in Europe, and the technical potentials for CO_2 emission reductions are substantial, especially if emerging technologies are considered. In 2005, energy-intensive industry in EU 27 accounted for 60% of total energy use in industry, which is about 18% of the total energy use in EU 27 and corresponds to about 15% of all CO_2 emitted in EU 27 (EC 2008). Approximately 20% of all electricity produced in EU 27 is used in the energy-intensive industry. Furthermore, energy-intensive industry is comprised of a relatively limited number of very large plants, and changes in each single plant will have significant effects on the energy use in each subsector of European industry. For example, there are about 100 refineries, 400 large pulp and paper mills, and 40 large integrated steel works with blast furnaces in the EU 27.

The question of how different climate policies will influence CO_2 emissions in the energy-intensive industry is complex, and it is not obvious that increased costs for emitting CO_2 will lead to investments in new technology and thus increased CO_2 emissions reductions. Several parameters, technical as well as economic, influence if and when the technologies and system solutions that reduce CO_2 emissions will be implemented. Some of these parameters are site-specific, like the configuration and age of the process equipment, others depend on the surrounding energy and transport infrastructure and future energy market prices and costs for emitting CO_2. Also, energy-intensive industry is capital intensive and reduced CO_2 emissions beyond a certain point require radical process changes and large investments.

Traditionally, either top-down or bottom-up models have been used to analyze the influence of specific policies on energy efficiency and CO_2 emissions in industry. These contrasting approaches generally reach very different conclusions regarding the cost of carbon dioxide emission reductions and thus the effects of different policy measures, since they do not take into account all parameters that influence real-world decisions on investments in industry. To better understand the dynamics and policy responses of industry, methods and models that merge the traditional bottom-up and top-down models need to be developed and applied.

Several studies that integrate or link bottom-up and top-down approaches have been carried out in the field of energy-economic modelling at the economy-wide level (e.g. Böhringer 1998, Jacobsen 1998, Koopmans and te Velde 2001). These studies range from completely integrated models with hard-linking to models with soft-linking where parameter values in one model are estimated using the complementary model. However, integration attempts are rare when it comes to analyses that focus on individual sectors of the economy, such as industry, and even more so as regards separate industry sectors.

In this paper, we analyse and compare top-down, bottom-up, and integrated (hybrid) approaches that have been used for evaluating potentials for CO_2 emissions reductions and CO_2 policy analysis in energy-intensive industry. We also evaluate the usefulness of these approaches and models to policy and decision makers. The paper focuses mainly on the pulp and paper industry. One reason for focusing on this industry is that it differs from the rest of the energy-intensive industry on one important point: if the pulp and paper industry reduces its energy demand beyond a certain point, eventually it will be able to export bio energy, either as bark, lignin, transportation fuel, or electricity. Thus, reducing energy demand in the pulp and paper industry will not only reduce CO_2 emissions on site, but also contribute to reduced emissions in, for example, the power or transportation sector. Thus, when studying CO_2 emission reductions in the pulp and paper industry, the surrounding energy system has to be included in the analysis.

Comparison of bottom-up, top-down, and hybrid approaches

GENERAL DESCRIPTION OF APPROACHES

Conventional bottom-up analyses use disaggregated models containing a detailed representation of current and emerging technologies that can be used to meet demands for energy services. Technologies that provide the same energy service are generally assumed to be perfect substitutes, except for differences in estimated capital and operating costs, energy use, and emissions profile. When their financial costs in different time periods are converted into present value using a discount rate, many emerging technologies available for abating greenhouse gases and other emissions appear to be profitable relative to existing stocks of equipment and buildings. Bottom-up models typically suggest, therefore, that substantial environmental improvement related to energy use can be profitable or available at low cost if these low-emission technologies were to achieve market dominance. Conventional bottom-up models can be considered partial equilibrium models since they focus on optimization of costs within the energy sector or subsector (i.e. an industry branch) but omit linkages between these sectors and the rest of the economy.

A major limitation of the conventional bottom-up approach is its assumption that a simple capital and operating cost estimate indicates the full social cost of technological change. New technologies present greater financial risks, as do the longer paybacks associated with irreversible investments – such as most energy efficiency investments. In addition, some low-cost, low-emission technologies are not perfect substitutes for their competitors. Therefore, conventional bottom-up models may suggest the wrong technological options and the wrong policies (or policy intensities) to policy makers. Another limitation with the conventional bottom-up approach is that its partial-equilibrium approach restricts its ability to assess macro-economic effects of policies, notably the trade and structural implications from changes in energy prices and costs throughout the economy. Bottom-models may therefore prescribe inappropriate policies and technologies.

Conventional top-down analysis typically estimate aggregate relationships between relative costs and market shares of energy and other inputs to the economy, and link these to sectoral and total output in a broader equilibrium framework. The principal exogenous parameters are elasticities of substitution, which indicate the substitutability between any pair of aggregate inputs (capital, labour, energy, materials) and between energy forms (coal, oil, gas, etc). Often, top-down models also have a parameter called autonomous energy efficiency improvement, which indicates the rate at which price-independent technological evolution improves energy productivity. To the extent that these parameters are estimated from real market behaviour, top-down models reflect the actual preferences of consumers and businesses, as well as the market heterogeneity of real-world financial cost conditions. Since top-down models lack technological detail, they are restricted to simulations of financial policy instruments. The magnitude of the financial signal necessary to achieve a given emission reduction target indicates its implicit cost, including the intangible costs related to the risks of new technologies, the risks of long payback technologies, and preferences for the attributes of one technology over its competitor. Therefore, estimates of the cost of achieving an environmental goal obtained using a top-down model are usually higher than bottom-up estimates.

The conventional top-down approach also has severe methodological limitations. The elasticity and autonomous efficiency improvement parameters in top-down models are estimated from empirical data. Even if the confidence intervals of these estimated parameters are narrow, these values derived from past experience may not remain valid in the future. Parameter values could change dramatically in the future as financial costs of technologies change due to economies of scale in production or accumulated experience, and as consumers become more accepting of emerging technologies as these are established in the market. Hence, their values may not show the full adaptation of firms and households to policies that significantly affect economic conditions. This can in turn lead to high cost estimates for policies to abate energy-related emissions. Another limitation of the top-down approach is that the constraints of policy formation often push policy makers toward technology-specific rather than economy-wide policies in the form of tax credits, subsidies, regulations, and information programmes. Yet with their aggregated depiction of technologies, top-down models are limited in simulating the effects of technology-specific policies.

Hence, conventional bottom-up models describe technologies in detail, but do not realistically portray microeconomic decision-making by businesses and consumers when selecting technologies, and fail to depict potential macro-economic equilibrium feedbacks. Conventional top-down models, in contrast, address these deficiencies by representing macroeconomic feedbacks in an equilibrium framework and by estimating parameters of technological change from observations of aggregate market responsiveness to cost changes. However, since they lack technological detail, top-down models cannot be used to assess how future market responses and autonomous trends might differ from the past as technology-specific regulations, research and development, and new expectations interact with market incentives over long time periods. Because of these methodological differences, top-down and bottom-up models often predict divergent costs, and consequently suggest different policies, for meeting climate targets.

This methodological divide has stimulated exploration of hybrid approaches that integrate the technological explicitness of bottom-up models with the micro-economic realism and macro-economic feedbacks of top-down models. Efforts toward integrated modelling usually involve either incorporation of technological detail into a top-down framework or incorporation of behavioural realism and/or macro-feedbacks into a bottom-up framework.

STUDIES AND MODELS COMPARED

To further illustrate methodological differences as well as options for methodological integration, five specific studies covering the pulp and paper industry are described in more detail. Major methodological characteristics of these studies are summarized in Table 1. Within the family of bottom-up analyses we here distinguish between two categories of studies, "Techno-economic evaluation" and "Techno-economic optimization". The five studies are:

- *Heat integration opportunities in an average Scandinavian fine paper mill: model study and comparison with a market pulp mill*, Axelsson and Berntsson (2007); techno-economic optimization, bottom-up.
- *Excess heat from kraft pulp mills: Trade-offs between internal and external use in the case of Sweden—Part 2: Results for future energy market scenarios*, Jönsson et al. (2008); techno-economic evaluation, bottom-up.
- *The impact of increased efficiency in the industrial use of energy: A computable general equilibrium analysis for the United Kingdom*, Allan et al. (2007); conventional top-down.

Two examples of hybrid approaches were selected for deeper analysis, one of which uses a top-down framework and the other a bottom-up framework.

- *Capital vintage and climate change policies: the case of US pulp and paper, Davidsdottir and Ruth (2004); hybrid*, top-down framework.
- *Hybrid modeling of industrial energy consumption and greenhouse gas emissions with an application to Canada*, Murphy et al. (2007); hybrid, bottom-up framework.

BOTTOM-UP APPROACH – TECHNO-ECONOMIC EVALUATION

General description of techno-economic evaluation methodology

Techno-economic evaluation is a commonly used approach for assessing energy saving and CO_2 emissions reductions potentials in industry. The methodology can be used for evaluating both modifications of new or existing processes and/or implementation of new technology. Normally a specific technique or process change is studied, and the effect on energy balance and corresponding economics is assessed by calculations and/or simulations. For the pulp and paper industry, either model mills are used or case studies of real mills are performed. When estimating the potentials for energy savings in a whole mill some kind of process integration method should be applied. Process integration is a holistic approach to process design that considers the interactions between different unit operation from the outset, rather than optimising them separately. Process integration methods include for example pinch technology which can be used to find the best way to heat integrate different parts of a process.

When doing a techno-economic evaluation, normally a series of calculations of primarily energy and mass balances and costs are made with some tool, e.g. Excel or Matlab, and/or simulations using simulation software e.g. Aspen or Matlab/Simulink. For process integration studies there are special tools such as ProPi. Often new models are developed for each specific study. The calculations of costs are schematic and for example expressed as payback period or annual savings compared to a base case. Input data is typically technical and economic data for the studied process or technique such as e.g. investment cost as function of size and efficiency as function of different designs. Sometimes a surrounding system in the form of energy market prices and emissions are partly or fully integrated with the studied system, and then data regarding energy prices and real or marginal emissions of CO_2 are needed.

Techno-economic evaluation studies typically result in curves and diagrams displaying how the energy balance of the studied process and the corresponding economics are affected by process integration measures and implementation of new technology. Occasionally, the emissions of CO_2 are also calculated based on the changed energy balance. Considering the characteristics of the results, questions such as the following can be addressed; "How does the implementation of a certain technology affect the resulting energy balance and economics of a mill?" or "Which is the preferred design of the equipment to reach a certain goal of energy reduction and/or economics?" The method is mainly of value to decision makers in industry.

"Heat integration opportunities in an average Scandinavian fine paper mill: model study and comparison with a market pulp mill" by Axelsson and Berntsson (2007)

In this study, the potentials for energy savings and CO_2 emission reductions in an integrated fine pulp and paper mills are calculated and compared to potentials for a market pulp mill. The results are based on a techno-economic evaluation of computer model mills representing the Scandinavian average. The model mills are simulated using Win Gems, a commercial simulation software, and energy and mass balance calculations using the Microsoft Excel based programs e.g. Optivap (Olsson and Berntsson 2007) as well as specially designed Microsoft Excel spread sheet models of relevant parts of the pulping and papermaking process developed by the authors. Assumptions about the technologies used in the mills are verified with case studies as well as performance indicators from equipment suppliers. When evaluating energy saving measures and technologies that have not yet been performed in industry, Axelsson and Berntsson (2007) make assumptions about the technologies and system designs based on either pilot runs or research results found in literature, as well as personal communication with experienced mill personnel, equipment suppliers, and consultants.

In the model mills, steam savings are achieved by process integration measures and installation of new technology, e.g. a more efficient evaporation plant, and then the steam savings are used for electricity production or to achieve fuel savings. In order to compare the economic performance of the suggested energy efficiency improvements, investments costs, reduced costs for purchased fuels, and increased income for sold bark and electricity are calculated. Investment costs are transformed to annual costs using capital recovery factors of 0.1 and 0.2.

The main finding in the paper by Axelsson and Berntsson (2007) is that there are fewer opportunities for heat integration and thus fewer opportunities for energy-savings in an average Scandinavian integrated pulp and paper mill than in the corresponding market pulp mill, but that possible steam savings still are more than 16% of the mill's total steam demand. Steam savings enable increased electricity production which could be profitable with high electricity prices (including policy instruments promoting green electricity). Compared with the market pulp mill, the profitability is slightly less. As an alternative to electricity production, fuel savings in the form of bark can be achieved, which provides good profitability with high bio-fuel price, low electricity price, or both. Compared to the market pulp mill, the profitability of fuel savings is better, because fuel savings in the market pulp mill requires that lignin is extracted from the black liquor, which leads to additional investments.

BOTTOM-UP APPROACH – TECHNO-ECONOMIC OPTIMIZATION USING THE MIND METHOD

General description of the MIND method

The MIND method is an optimization tool that has been developed to study industrial energy systems. Using the method, a new model, depicting the studied industry, is constructed for each case and adapted to the studied industry's specific characteristics. The MIND method can be used for analysis of, e.g., trade-offs between different investment options or production planning in a mill.

The models of the mills are constructed using the energy systems modelling tool reMIND (Method for analysis of INDustrial energy systems). With the reMIND tool the objective function, Z, of the modelled system is minimized by using mixed-integer linear programming (Nilsson and Söderström 1992). Each model includes both the studied energy system (the different mills) and a surrounding system (energy market and emissions).

Input data to the model are technical and economic data for both the existing system and the possible investments in energy efficiency technologies and system solutions. This data can preferably be selected from earlier techno-economic studies of process integration measures and implementation of new technology. For the surrounding system, input data are energy prices and emissions associated with production/consumption of electricity and biomass.

The result using the MIND method is a file showing the structure of the optimal solution with corresponding system cost and set of investments. In the results file all physical flows in the system are presented. The system's emissions of CO_2 are also calculated. Considering the characteristics of the results e.g. the following questions can be addressed; "How do the energy market prices affect the total system cost?", "How do the energy market prices affect which investment/investments are economically preferable and consequently the global emissions of CO_2?" or "Are there any investments that are more robust than others with respect to varying energy market prices?" Consequently, the method and the results are beneficial both for decision makers in industry and public policy makers.

"Trade-offs between internal and external use in the case of Sweden—Part 2: Results for future energy market scenarios" by Jönsson et al. (2008)

The study presented in the paper by Jönsson et al. (2008) is based on optimization calculations using the MIND method. The overall objective of the paper is to examine the trade-off, in terms of economics and CO_2 emission reductions, between internal process use and external use for district heating of excess heat from an average Scandinavian kraft pulp mill in Sweden, under different future energy market scenarios. The trade-off is analyzed by economic optimization of an energy system model consisting of a pulp mill and an energy company (ECO). In the model, investments can be made, which increase the system's energy efficiency by utilization of the mill's excess heat, as well as investments that increase electricity production. The kraft pulp mill and the ECO are evaluated within the same system boundary, this way the *potential* for profitable excess heat cooperation can be assessed. The widened system boundary broadens the scope of the study from being mill specific to more regional co-operational. Results from Axelsson and Berntsson (2007) and similar studies are used as input data.

In the model a capital recovery factor of 0.1 is used for the investments both at the mill and at the ECO, representing a strategic view on investments in increased energy efficiency. The age of existing plants has not been considered, assuming that the existing plants can be used in the foreseeable future. In order to simulate and evaluate decisions and trade-offs for future investments, energy market price scenarios developed by Axelsson and Berntsson (2007) are used. The energy market price scenarios reflect four different future energy markets

Table 1. Summary of main methodological features and usefulness to decision makers

	Bottom-up approach – techno-economic evaluation (Axelsson and Berntsson 2007)	**Bottom-up approach – techno-economic optimization (Jönsson et al. 2008)**	**Top-down approach – computable general equilibrium (Allan et al. 2007)**	**Hybrid approach – top-down framework (Davidsdottir and Ruth 2004)**	**Hybrid approach – bottom-up framework (Murphy et al. 2007)**
Approach and method	Bottom-up Process simulations based on mass and energy balances	Bottom-up Optimization based on mixed-integer linear programming (MIND)	Top-down Computable general equilibrium model (UKENVI)	Hybrid w. top-down framework Macro-econometric model with capital vintaging	Hybrid w. bottom-up framework Hybrid model (CIMS) with explicit representation of technology, real-market behaviour and equilibrium feedbacks
Scope and resolution	Model mills representing typical Scandinavian mills	Model mills representing typical Scandinavian mills and district heating systems located near the mills	UK economy	US pulp and paper industry, disaggregated into 8 regions	Canadian economy with focus on the industry sector
Type of research questions – examples	How does the implementation of a certain technology affect the resulting energy balance and economics of a pulp/paper mill?	How do energy market prices affect which investments are economically preferable and consequently CO_2 emissions?	How large are the rebound effects for improvements in energy efficiency in a developed economy?	What would be the response of pulp and paper industry in terms of its energy use and CO_2 emissions to different policy measures aiming at abating greenhouse gas emissions?	What would be the response of industry in terms of its energy use and CO_2 emissions to an economy-wide greenhouse gas reduction policy (e.g. tax or cap-and-trade scheme)?
Type of results – examples	Data displaying how the energy balance of the studied process and the corresponding economics are affected for changes in specific process parameters and/or energy prices.	Identifies the set of investments that yields the lowest system cost. Emissions and new energy balance are presented.	Economy-wide descriptions of energy use and CO_2 emissions in response to price-based policy measures or exogenous technology assumptions	Scenarios of mid to long-term industrial energy use and CO_2 emissions in response to different policy measures (economy-wide, e.g. carbon taxes, and technology-specific, e.g. investment subsidies)	Scenarios of mid to long-term industrial energy use and CO_2 emissions in response to different policy measures (economy-wide price-based instruments)
Decision maker target group	Decision makers in industry	Decision makers in industry Policy makers	Policy makers	Policy makers	Policy makers
Technological explicitness	Very high	Very high	Very low	Medium	High
Behavioural realism	Low	Low	Medium	Medium	High
Ability to capture economy-wide equilibrium feedbacks	None	None	High	None	Medium

with different combinations of level (high/low) of oil price and CO_2 charge and consequently the different scenarios have different fuel prices and marginal production techniques. Use of energy market scenarios acknowledges the uncertainty of the development of the energy market and also acts as a kind of sensitivity analysis.

The results show how the trade-off depends on energy market prices, the district heating demand, and the type of existing heat production. The results also show how the trade-off influences the global emissions of CO_2. From an economic point of view, external use of the excess heat is preferred for all investigated energy market scenarios systems with small district heating loads. For the cases with medium or large district heating loads, the optimal use of excess heat varies with the energy market price scenarios. However, from a CO_2 emissions perspective, external use is preferred, giving the largest reduction of global emissions in most cases.

TOP-DOWN APPROACH – COMPUTABLE GENERAL EQUILIBRIUM MODELS

General description of computable general equilibrium models

Computable general equilibrium (CGE) models are a class of economic model that use empirical economic data to estimate how an economy might react to changes in policy, technology or other external factors. A CGE model consists of equations describing model variables and a database consistent with the model equations. The equations are normally neo-classical in character, often assuming cost-minimizing behaviour by producers, average-cost pricing, and household demands based on optimizing behaviour. However, most CGE models do not adhere strictly to the theoretical general equilibrium paradigm. For example, they often allow for imperfect competition (e.g. monopoly pricing), a range of taxes, and externalities such as pollution. A CGE model database consists of tables of transaction values, often as a social accounting matrix, and several types of elasticities, such as demand and supply elasticities. CGE models are useful for estimating the effect of changes in one part of the economy upon the rest, for example, the effect of imposing taxes. They are now extensively used in studies of the economy–energy–environment nexus at both national (e.g. Beauséjour et al., 1995) and regional levels (e.g. Li and Rose, 1995). The popularity of CGEs in this context reflects their multi-sectoral nature combined with their fully specified supply-side, facilitating the analysis of economic, energy and environmental policies.

"The impact of increased efficiency in the industrial use of energy: a computable general equilibrium analysis for the United Kingdom" by Allan et al. (2007)

This study used a (CGE) model for the UK economy to measure the so called "rebound" effect of increased energy efficiency. Rebound effects occur because an improvement in energy efficiency produces a fall in the effective price of energy services. The response of the economic system to this price fall at least partially offsets the expected beneficial impact of the energy efficiency gain. In this study, the rebound effect of a 5% across the board improvement in the efficiency of energy use in production sectors was assessed.

The CGE model used in this study was parameterised to be in long-run equilibrium in the base-year period. This implies that the capital stock in each industrial sector was initially fully adjusted to its desired level. There are no vintage effects in the model and the only exogenous technical change introduced in the simulations concerns the one-off 5% improvement in energy efficiency.

The results indicate that a general, across the board, improvement in efficiency in energy use in UK production sectors has a rebound effect on the order of 55% in the short run and 30% in the long run, but no backfire (no increase in energy use). The energy efficiency improvement primarily increases the competitiveness of energy-intensive sectors through a reduction in their relative price. In the long run, two mechanisms drive this change in competitiveness. First, the increase in energy efficiency raises the production efficiency of energy-intensive sectors by the greatest amount. Second, the production techniques used in energy sectors themselves are typically energy-intensive, so that the price of energy tends to fall. For both these reasons, energy-intensive sectors experience relatively large reductions in unit costs, which are passed through to lower prices. The increased efficiency of energy inputs expanded the output of all non-energy sectors, with the increase almost always being greater in the long than in the short run. Outputs increase most in those non-energy sectors that have greater energy intensities, notably iron & steel and pulp & paper where output increases in the long run by 0.67% and 0.46% respectively.

HYBRID APPROACH – CAPITAL VINTAGE MODELLING IN A TOP-DOWN FRAMEWORK

General description of capital vintage modelling

Capital vintage models were first developed in the 1950s and 1960s (e.g., Johansen 1959; Kaldor and Mirrlees 1962). Such models have recently been used to analyze energy flows in industrial systems (Davidsdottir and Ruth 2004, Ruth et al. 2004). Capital vintage models capture the age structure of the capital stock and its associated 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 as a new vintage. An industrial system evolves as the capital stock changes via investment, either through expansion of the capital stock (expansion investment) or through the gradual replacement of old, obsolete, or worn-out structures (replacement investment). The expansion of capital stock will increase the use of input materials and slightly improve material and energy efficiency – given that the industry invests in more efficient capital. Assuming the industry invests in more efficient capital, replacement investment will more extensively increase energy and material efficiency and help keep constant (or reduce) the total use of material and energy inputs. Thus, the evolution of a mature industrial system changes the efficiency of material and energy use, which, combined with output levels and structure of the output, determines the size of total material and energy flows.

"Capital vintage and climate change policies: the case of US pulp and paper" by Davidsdottir and Ruth (2004)

This study used a capital vintage model to assess changes in energy use and carbon emissions profiles of the US pulp and paper industry. The study distinguished between changes in demand for and production of paper and paperboard, changes in the capital vintage structure of the industry and accompanying changes in demand for seven different fuels. Econometric time series analyses were used to specify these changes through time and a dynamic capital vintage model was developed for sensitivity analysis of the resulting system of equations and for analysis of likely impacts of alternative climate change policies on energy use and carbon emissions profiles.

The results of the study indicate that a combination of different policies, such as an increase in the cost of carbon and an incentive for the industry to invest in more efficient new capital could be quite successful in stimulating a reduction in carbon emissions by leveraging tendencies of the industry to change its fuel mix and improve efficiencies. In contrast, use of only carbon or energy taxes is unlikely to permanently increase the industry's aggregate energy efficiency since energy cost is not seen to have significant impact on gross investment and thus on the turnover rate of capital. The authors put forward three reasons for this. First, energy expenditures are a small proportion of the total production cost, which is dominated by fibre inputs. Second, the total cost of installing, e.g. new, more efficient recovery boilers using black liquor gasification is much greater than those recouped through energy-savings. Third, industry often requires a three-year payback maximum period on energy-saving equipment. For these reasons, investments in energy saving equipment are often a side-bonus to other investments in energy-intensive industry, e.g. to capacity expansion. Hence, purely price-based policies such as energy taxes or an increase in the cost of carbon may fall short in affecting the evolution of the capital stock towards increased efficiency.

HYBRID APPROACH – MODELLING IN A BOTTOM-UP FRAMEWORK

General description of the CIMS hybrid model

Originally, CIMS was a bottom-up model, but it has evolved into a economy-wide hybrid model by inclusion of macroeconomic feedbacks and parameters for simulating technological evolution. The CIMS model has the technological richness of a bottom-up model, but simulates technology choices by firms and households using empirically estimated behavioural parameters instead of portraying these agents as financial cost optimizers. In addition, it integrates energy supply and demand, and includes links between energy and the entire economy.

CIMS represents technologies explicitly in both its energy supply and energy demand components. Within the industry sector, the model includes explicit representations of chemical products, industrial minerals, iron and steel, metal smelting, metals and mineral mining, other manufacturing, pulp and paper, and petroleum refining. Each industrial sub-model in CIMS has its own driving variable, usually expressing the total amount of final product produced or the amount of raw input processed (e.g. tonnes of pulp). Similar to the Davidsdottir and Ruth (2004) model, CIMS uses a capital stock vintaging framework, where technologies are retired according to an age-dependent function, and new technologies fill the gap between service demand and existing capital stock in each five-year period of the simulation.

CIMS simulates the competition of technologies at each energy service node based on a comparison of their life cycle costs (LCCs) and some technology-specific controls, such as a maximum market share limit in the cases where a technology's market share is constrained by physical, technical, or regulatory factors. CIMS applies a definition of LCC that includes intangible costs representing consumer and business preferences and the implicit discount rates revealed by real-world technology acquisition behaviour.

CIMS estimates the effect of a policy by comparing a reference case market equilibrium with one generated by a policy. The model operates by iteration of two sequential phases in each five-year period, with as many iterations as necessary to arrive at a new policy equilibrium in each period.

"Hybrid modeling of industrial energy consumption and greenhouse gas emissions with an application to Canada" by Murphy et al. (2007)

This study used the CIMS model to explore the implications for Canada's industrial sector of an economy-wide, compulsory greenhouse gas reduction policy, such as a tax or emissions cap and tradable permits system. GHG charges of $50 and $150/tonne CO_2 were chosen to represent a medium and a high level, respectively, of financial constraint on GHG emissions.

The results showed that the observed potential for changes in energy consumption and GHG emissions increased over time, reflecting additional opportunities for technological transformation afforded by capital stock turnover. This phenomenon suggests that policy makers should consider implementing GHG policies that impose a constraint or financial penalty that is modest at first but that increases gradually in stringency over time according to a schedule announced up-front. This formulation would avoid the high costs associated with prematurely forcing the retirement of existing capital stocks, while at the same time providing a strong signal for the adoption of low-GHG technologies when capital stock is retired and new technology acquired.

Evaluation of usefulness of models to policy and decision makers

Obviously, it is impossible for any policy-oriented energy-economy model of industry to be completely accurate in its representation of current conditions and in its assessment of future dynamics under different technology and policy paths. Instead, it must be accepted that in the design of models, significant compromises between accuracy and practical feasibility are unavoidable, and that the deliberately chosen model limitations will vary considerably depending on which questions the model is intended to answer. To enhance model usefulness, the process of model formation should be related to and guided by criteria that judge the ability of a model to be more useful to policy makers seeking to induce technological change. Policy makers, as well as decision makers in industry, need models that can realistically evaluate the combined effect of policies that range from economy-wide to technology-specific, including command-and-control instruments (e.g. performance standards, stipulated technology) and price-based instruments (e.g. taxes, subsidies). Murphy et al. (2007) suggested three key criteria for the evaluation of the usefulness of a model for policy makers:

- Explicitly represent the technologies that compete to provide services in the analyzed industry sector as well as throughout the entire economy
- Simulate the way in which consumers, firms and producers choose between these technologies in a way that closely reflects the real world
- Capture equilibrium feedbacks between energy-technology decisions and the overall structure and performance of the economy

Each of these criteria is described in more detail below, and the compliance with the criteria of the five studies presented in the previous section is briefly analyzed.

TECHNOLOGICAL EXPLICITNESS

To the extent a model is technologically explicit, it can incorporate model technologies that are currently only at the development stage, but that may come to be commercialized, especially under a sustained and compulsory policy aimed at reducing GHG emissions. Explicitly tracking alternative technologies is particularly important in the energy-intensive industrial sector, where the potential exists for large, discrete jumps in types of technologies. For example, Mathiesen and Maestad (2004) showed how failure to explicitly account for alternative steel refining technologies can lead to incorrect conclusions about international competitiveness when GHG policies are implemented.

There are a number of details models need to include in order to explicitly describe the current status of industry as well as the existing and emerging technologies that industry can choose between:

- *Mill-specific characteristics e.g. type of process, size of plant, technical age of installations.* A mill that wants to reduce its CO_2 emissions has several different technical measures to choose from. What technology a mill will choose to a large extent depends on mill-specific characteristics and some technologies are not even possible to implement in some mills, e.g. it is not likely that a mill with high water consumption will be able to generate as much excess heat as a mill with low water consumption.
- *Technical infrastructure surrounding the mills e.g. distance to harbours, district heating systems, gas and CO_2 storage facilities* The geographical position of a mill will also influence the mill's possibility to reduce its CO_2 emissions. The cost for CCS will for example be high for mills situated far away from storage places, and mills located near a town or city with a large district heating system are more likely to export excess heat than a mill located far away from a town or city.
- *Technologies available on the market and the description of these technologies* To achieve really large reductions of CO_2 emissions new technologies need to be developed and put on the market. Depending on what assumptions about future technologies are made in a model, different results will be obtained. Examples of future technologies which, if they are developed and put on the market, will have a large effect on the possibilities for the pulp and paper industry to achieve large reductions of CO_2 emissions are carbon capture and storage (CCS) and black liquor gasification.

Among the bottom-up studies analyzed in this paper, both Axelsson and Berntsson (2007) and Jönsson et al. (2008) used mill-level models constructed in Win Gems to represent the pulp and paper industry (FRAM 2005).These computer models were created to represent typical mills in Scandinavia today regarding equipment and level of resource utilization and the mills are therefore highly energy-efficient compared with international standards (Francis et al. 2006). To capture technological differences there are different versions of the mills, for example regarding high or low water usage compared in the paper by Axelsson and Berntsson (2007). Since the Scandinavian pulp and paper industry is rather homogenous the model mills represent the technological composition of the industry rather well, both regarding type of equipment and energy consumption, even though there of course are variations. However, the model mills poorly represent the technical infrastructure surrounding the mills, and Axelsson and Berntsson (2007) do not consider these kinds of factors at all in their study. Jönsson et al. (2008) however take these factors into account to some extent by evaluating mills with differently sized nearby district heating systems.

Axelsson and Berntsson (2007) and Jönsson et al. (2008) include detailed descriptions of future energy-saving and CO_2-reducing technologies in their papers. In the paper by Axelsson and Berntsson (2007) two future alternatives are evaluated: increased electricity production and decreased fuel consumption, and in the publication by Jönsson et al. (2008) increased electricity production is compared to increased export of heat to a nearby district heating system. None of the papers represents all future technologies that a mill can choose; the results thus must be combined with other similar studies to be able to cover all technology options. In order to be able to combine results from different papers it is however important that the different studies make similar assumptions for example about the mills overall design and energy market conditions. If using the approach suggested by Jönsson et al. (2008) several future technologies can be included in one study; in work in progress, technologies such as CCS, lignin separation, and black liquor gasification are included. The number of future technologies to be included in a study is mainly limited by the fact that it is difficult to find concise, up to date, and detailed studies about energy saving potentials and costs for future technologies. The work performed by Jönsson et al. (2008) is based on findings from a large Swedish research program called KAM/FRAM (FRAM 2005). Within this program, the model mills used by Axelsson and Berntsson (2007) and Jönsson et al. (2008) have been developed and numerous techno-economic evaluation studies of various future energy-saving technologies have been performed. Data and results from this research program can after minor revisions and updating be used for the optimization studies using reMIND.

Since the study by Allan et al. (2007) used a computable general equilibrium model, the analysis is not based on any explicit description of technologies. However, in this particular type of study, the quantification of rebound effects of energy efficiency, this is unlikely to be a major methodological limitation.

The hybrid capital vintage model used in the study by Davidsdottir and Ruth (2004) contains explicit technology descriptions, although at a relatively aggregated level since the model framework essentially is top-down. The pulp and paper industry output is disaggregated into four paper products (newsprint, tissue, printing & writing, and packaging paper) and four paperboard products (kraft paperboard, bleached kraft paperboard, semi-chemical paperboard and recycled paperboard). Material input is disaggregated into wood pulp and waste paper, and three pulp categories (mechanical and semi-chemical, chemical, and recycled fibre). Energy input is disaggregated into self-generated energy and six different purchased fuels. Self-generated energy is modelled as an aggregate of spent liquor, hogged fuels, bark, and waste paper. Combined heat and power is not modelled, but is implicitly included in the parameter values of efficiency for chemical pulping as self-generated energy. Each vintage of the pulp and paper industry capital stock is explicitly described in terms of efficiency and mix of input (e.g. energy) as well as learning curves of input efficiency. The structure, size, and capital utilization of new and existing vintages along with the vintage-specific input efficiencies and learning curves determine the total flow of a specific input through the system.

The CIMS hybrid model used by Murphy et al. (2007) has a bottom-up framework and consequently contains explicit descriptions of technology with a substantial degree of detail, although not to the extent of the models used by Axelsson and Berntsson (2007) and Jönsson et al. (2008). The structure of the pulp and paper industry sub-model of CIMS is disaggregated into six processes and products. For these six product groups in total, the sub-model contains descriptions of 26 different energy services, i.e. different types of energy use. Each energy service can be satisfied by a number of different competing technologies, including new technologies that may not yet have achieved market penetration. For the pulp and paper sub-model, in total about 140 different competing technologies are included. In addition, explicit descriptions are included of industry-generic auxiliary energy services, such as steam generation systems; lighting; heating, ventilating, and air conditioning (HVAC) systems; and electric motor systems (motors and the pumps, fans, compressors, and conveyers driven by them).

BEHAVIOUR REALISM

To accurately depict real-world behaviour of consumers and producers in their technology choices, a model's technology choice algorithm has to include implicit discount rates revealed by real-world technology acquisition behaviour, intangible costs that reflect consumer and producer preferences, as well as heterogeneity in the marketplace. To the extent these factors are included in the model's market share equation along with the financial costs of technologies the model is likely to accurately estimate the microeconomic response to policy given the realities of firm and household decision making.

Real-world implicit discount rates may be much higher, on the order of 30-50%, than those normally used in bottom-up models. Non-market failure explanations reflect why this behaviour is optimal, explaining why it is rational to use a high discount rate or to wait and see. For instance, irreversible investments in energy efficiency whose benefits depend on uncertain, future energy prices require the use of high discount rates by risk-averse investors. Uncertainty may also explain why a wait-and-see policy can be optimal. Intangible costs include those related to the increased risk of new technology, transaction costs, and the risks of long pay back technologies as well as non-financial preferences for one technology over its competitor. Heterogeneity in the marketplace refers to the fact that different consumers and producers normally experience different life cycle costs. A technique may be profitable for an average firm in the sector, but, in reality, not for all firms since they face heterogeneous cost functions.

The bottom-up studies by Axelsson and Berntsson (2007) and Jönsson et al. (2008) analyzed in this paper only take into account investment costs and costs for increased or decreased fuel, heat and electricity consumption. They do not take into account the intangible costs mentioned above or non-financial preferences. Thus they mainly can be used for comparing technologies with similar costs or for identifying at what ratio between different energy market prices a certain technology is more profitable than other technologies. Axelsson and Berntsson (2007) for example compare lignin extraction to increased electricity production – co-generation of electricity is a well established technology in the pulp and paper industry whereas lignin removal has not yet been built large-scale. Even though the technologies differ in maturity, the authors only compare investment costs and changes in running costs for the technologies and leave to the reader to add intangible costs for implementing the new technology.

Computable general equilibrium (CGE) models, the model type used in the top-down study by Allan et al. (2007), typically take as axiomatic that producers behave as cost-minimizers, and that household demands are based on optimizing behaviour. Although these conventional neo-classic behaviour functions to a significant extent are substantiated by empirical data, they still imply a major simplification in the CGE models' representation of real-world behaviour. For example, imperfect information and transactions costs are aspects that are neglected in the optimisation processes that underlie neo-classic behaviour functions. Although adjustment costs can be incorporated into CGE models, such models might still privilege market forces against behavioural ones.

The hybrid capital vintage model used in Davidsdottir and Ruth (2004) has a macro-economic top-down framework in which sets of demand elasticities are used to determine the use of energy and other inputs. Values on these elasticities were estimated using comprehensive time series data and other empirical data. This means that the model is likely to fairly well reflect actual preferences and behaviour in the pulp and paper industry. However, although parameter values are estimated from real market behaviour, the parameterization is aggregated and does not explicitly represent different aspects of importance, such as intangible costs and market heterogeneity.

The CIMS hybrid model used in Murphy et al. (2007) contains a technology choice algorithm that explicitly represents implicit discount rates, intangible costs and preferences, and heterogeneity in the marketplace. Values on these parameters were estimated from empirical data. Since these factors are included in the market share equation along with the financial costs of technologies, the CIMS model parameterization allows for an accurate representation of real-world behaviour in industry. However, the authors point out that the non-financial preferences of consumers and producers are difficult to estimate, and the behavioural parameter values are therefore associated with a high degree of uncertainty.

EQUILIBRIUM FEEDBACKS

The establishment of an economy-wide GHG tax or emissions cap and tradable permits system imposes a significant regulatory constraint or financial penalty on emissions, and it can be expected that the interaction of energy supply and demand as well as the overall structure and performance of the economy will be affected as high cost actions are taken. Particularly when examining policies that impose medium to high costs on GHG emissions, it is essential for the modelling methodology to take into account the interaction of energy supply-demand and the macroeconomic performance of the economy, including trade effects.

Obviously, the studies by Axelsson and Berntsson (2007) and Jönsson et al. (2008) do not capture any wider effects on economy since they are based on conventional bottom-up models without any linkages of the pulp and paper industry to the rest of the economy.

Equally obvious, the study by Allan et al. (2007) does fully capture equilibrium feedbacks between energy-technology decisions and the overall economy since the study was based on a computable general equilibrium model.

The study by Davidsdottir and Ruth (2004) used a macroeconomic model framework, but did not explicitly include any equilibrium feedbacks. Hence, the study does not explore impacts of climate change policies on the rest of the economy, and how these may feed back to affect investment and material and energy use by the US pulp and paper industry.

The CIMS hybrid model used in Murphy et al. (2007) includes explicit equilibrium feedbacks between the energy supply-demand module and the macroeconomic performance of the economy, including trade effects. However, unlike most computable general equilibrium models, the CIMS model does not equilibrate government budgets and the markets for employment and investment. Also, its representation of the economy's inputs and outputs is skewed toward energy supply, energy-intensive industries, and key energy end-uses in the residential, commercial & institutional, and transportation sectors. Therefore, the study does not capture some of the important feedbacks that could influence the response of Canada's industrial sector to GHG policies that cause significant shifts in the cost of production for certain sectors.

Conclusions

In this paper we compare top-down, bottom-up, and integrated (hybrid) approaches used for evaluating CO_2 reduction potentials and policy in industry, and evaluate the usefulness of these approaches and models to policy and decision makers. We conclude that conventional bottom-up and top-down approaches are inherently limited in providing sufficient and adequate information to decision makers regarding effective policy instruments for CO_2 abatement in industry. Therefore, methods and models that merge the conventional bottom-up and top-down approaches need to be developed and applied. Our review suggests that hybrid approaches that combine characteristics of conventional bottom-up and top-down approaches open up a fruitful path that should be explored further. Soft-linking of conventional contrasting models is another path that is likely to generate useful information for policy makers.

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Acknowledgements

This study was co-funded by the AGS project "Pathways to Sustainable European Energy Systems" and the EU ENCAP project (SES6-CT-2004-502666, within the EU 6th Frame Work Programme). The work done by Jönsson is also partly carried out under the auspices of the Energy Systems Programme, which is primarily financed by the Swedish Energy Agency.