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Long-term Energy Scenarios for the Industry Sector: Use of Physical Indicators

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Contents

Abstract

In this paper, we describe an industrial energy demand projection model, which we developed as a tool to generate scenarios of global as well as regional industrial energy demand until 2100. The prime element in the model is projection of industrial energy intensity development. In defining industrial energy intensity, we used physical production data, instead of monetary output data, to represent the level of industrial activities. The use of physical output data enabled us to incorporate some important features into long-term energy demand scenario development. The model relates a given level of GDP per capita with industrial production, and then with industrial energy demand.

The model was applied to dynamics-as-usual scenarios for Western Europe and Centrally Planned Asia & China. 13 separate industry sub-sectors were analysed. The analysis shows that past and future structural changes in the Western European industries are characterised by an increase of the lighter industries and a decrease of the heavier industries (except for the chemicals industries). The analysis shows that past and future structural changes in Centrally Planned Asia & China are characterised by relatively slow growth in the steel industry, and relatively high growth in several other industry sectors.

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Long-term Industry Energy Scenarios for the Scenario Generator II: Use of Physical Indicators for Scenario Analysis

Niels J. Schenk

1. Introduction

The United Nations Conference on Environment and Development in 1992 in Rio de Janeiro (UNCED 1992) made the curbing of greenhouse gasses (GHG) an important issue on the international political agenda. Scientific information on the size and nature of the threat of climate change is needed by politicians in order to weigh their decisions. Anthropogenic climate change is an environmental threat with complex dynamics: cause-effect relations span a very long time (e.g. sea-level rise), the effects are very uncertain, and decreasing GHG emissions is a slow process because societies tend to have strong inertia particularly with respect to technologies and lifestyles, which are required to change to meet GHG mitigation goals. Therefore it is, both for scientists and politicians, important to know the range of plausible future GHG emissions (Nakicenovic et al. 2000).

Because of the complexity of all factors associated with climate change, computerised models are extremely useful tools to quantify the long-term effects of current policies. In order to improve the quality of scientific information on plausible ranges of future GHG emissions, continuous improvements of scenarios as well as advancement with modelling are needed. This paper describes a new modelling approach that allows formulation of industrial energy demand projections consistent with the assumptions for scenario drivers such as GDP and population. In the model, a level of industrial production is used as a key variable, and we define it in physical units, rather than in monetary units. Throughout the paper we discuss the advantage of using physical production indicators over monetary output indicators for the purpose of developing industrial energy demand scenarios.

The aim of this research is to increase insights that come with long-term energy demand scenarios by incorporating physical characteristics of industrial commodity production. Monetary production indicators are often preferred in energy intensity analysis because the production data of different commodities can be readily aggregated. However, energy demand projections based on monetary production indicators fail to take physical limits associated with industrial commodity consumption into account. We aim to examine ways to incorporate such an aspect into scenario building. This research is explorative in two ways, to contribute to scenario building, and to demonstrate the potential and limitations of modelling based upon energy intensities using physical production indicators.

This research focuses on the industry sector. The industry sector is of special interest regarding the use of physical production indicators because its energy consumption can often be directly related with materials processing. Moreover, physical indicators for the industry sector have been widely used as a monitoring tool for energy intensities (see e.g.: Farla & Blok 2000), and therefore extending the approach from monitoring to projecting is logical step (Groenenberg et al. 2005).

This paper researches the feasibility of using non-monetary indicators as explanatory variables in long-term energy models. Therefore this paper will discuss the pros and cons of physical indicators for energy projections comprehensively. The model discussed in this paper is driven by GDP *per capita*, as rather common in energy models.

Because of the explorative character of this research the aggregation level of the data was as low as possible (depending on data availability). Because the method of 'flexible extrapolation' (as described in section 3.2.2) is labour intensive and full application to all 11 MESSAGE[1] world-regions and all 13 industry sub-sectors requires 11 * 13 = 143 separate analyses, the model is implemented on only two regions: Western Europe (WEU) and Centrally Planned Asia & China (CPA). From these two regions conclusions are drawn regarding future use of physical indicators for energy scenario analysis.

The main research question is to find numerical scenario results for two selected world-regions and thus gaining insights in the size and nature of industrial energy demand under a business-as-usual setting. Emphasis will be on the differences of industrial metabolisms[2] between the two regions.

2. Motivation for developing physical explanatory variables

Energy analysis and indicators – like 'energy intensity' – are based on monetary or physical approaches[3] (IPCC 2004, p372; Worrell et al. 1997). Monetary indicators are characterised by the measurement of a factory's "useful output"[4] based upon economic indicators like value added or production value, while physical indicators are characterised by the measurement of a factory's "useful output" based upon physical indicators like total weight of products (Farla & Blok 2000; Patterson 1996).

Monetary approaches are primarily chosen because data can be aggregated. Moreover, regarding the climate-change issue and GHG emissions from fuel combustion, policymakers' main interests are the effects of climate change policies on the economy. Therefore the initial focus on monetary indicators is completely rational and justifiable. Nevertheless, some of the society's energy consumption is associated

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[1] For more information on MESSAGE, see: (Messner & Strubegger 1995).

[2] "The 'industrial metabolism' concept refers to the flows of natural resources entering the production side of the economy and the flows of goods and services—to be consumed and/or exported—and of wastes and emissions to the environment leaving the production sectors" (Moll et al. 2005). For application of the 'industrial metabolism' concept on energy see: (Haberl 2001a; Haberl 2001b).

[3] The term approach refers to the measure of societal behaviour that is assumed to be related with energy consumption. Indicators are tools associated with approaches.

[4] "The 'useful output' of the process need not necessarily be an energy output. It could be a tonne of product or some other physically defined output, or it could be the output enumerated in terms of market prices." (Patterson 1996).

with physical flows rather then economic output. This is where physical indicators come into scope.

Physical approaches are based upon the ‘touchable’ exponents of the society, like the number of tonnes produced of a specific product (Farla 2000), or total material requirement of a nation (Matthews et al. 2000). Also passenger-kilometres – often used to calculate passenger transportation efficiencies – fits in this category. Despite the many benefits of monetary indicators they tend to be (unnecessarily) narrow in view. The use of physical indicators for industry energy scenario analysis offers three distinguished advantages:

- Several researchers have identified cases in which physical (energy intensity) indicators were argued to be more meaningful than monetary indicators regarding industry output when related to energy consumption, especially with respect to developing countries (Ayres 1998; Schipper et al. 2001; Worrell et al. 1997).[5,6]
- Physical indicators provide a possibility for a reality check by incorporating saturation effects of commodity consumption that cannot be revealed by monetary indicators. E.g. the amount of money a person can spend on his dinner is virtually unlimited, while the quantity in physical terms is very much limited.
- Intra-sectoral structural changes are less disturbing for physical indicators than monetary ones. The negative correlation between product value per unit (i.e., value per unit of weight) and product volume (see Figure 1) has been observed for commodity production (Fischer-Kowalski & Amann 2001). Therefore, when monetary indicators are used, intra-sectoral structural change may result in data inconsistencies. For instance, structural change towards more specified products is associated with higher value added per volume added, but also with decreasing physical output and decreasing energy consumption both per (monetary) unit of value added. In contrast, when physical indicators are used in this case, intra-sectoral structural change has a more limited effect on the data consistency because no negative correlation exists.

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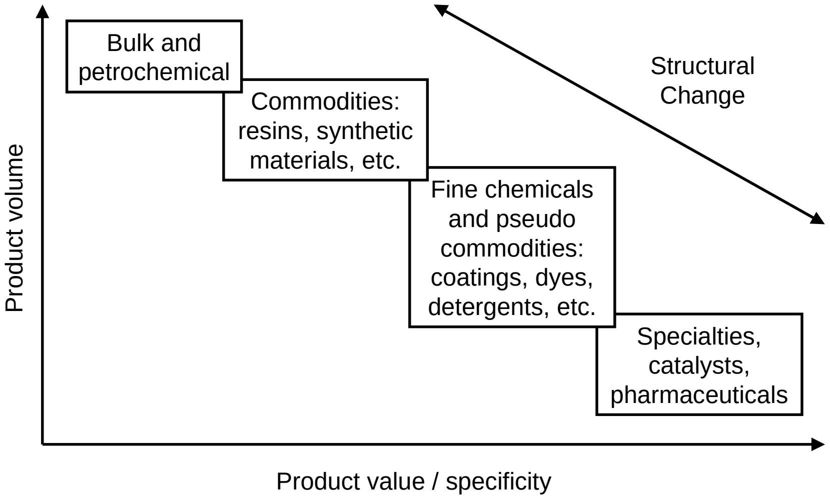
[5] For a comparative study on monetary and physical indicators for the iron & steel sector see: (Worrell et al. 1997).

[6] Similar reasoning can also be found in models for passenger transport (Rühle 2006) and freight transport (Fischer-Kowalski 2004).

Figure 1: Segmentation within the chemical industry



Source: (Venselaar & Weterings 2004)
Note: The inverse relation between product specificity and product volume is general for all industry sectors (Fischer-Kowalski & Amann 2001).

Despite the advantages summarised above, physical and monetary indicators should be seen as complementary, rather than substitutes of each other. Insights derived from monetary approaches should be used in physical approaches and *vice versa*.

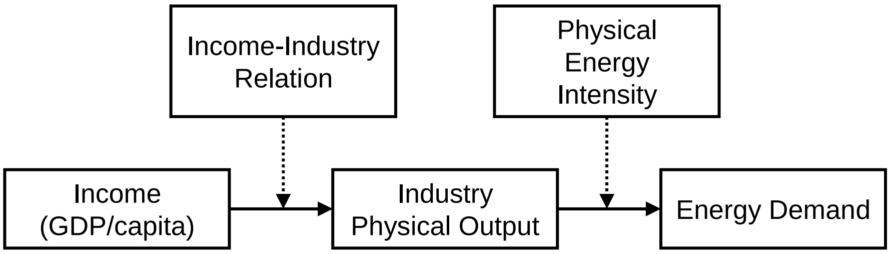
3. Description of a model based on physical explanatory variables

The model using physical explanatory variables is described in the sections below. In section 3.1 the model framework is described and in sections 3.2 and 3.3 the two main elements in the model framework are described.

3.1. Model framework

The model framework visualises the information flow starting from scenario driving forces to industry energy consumption. Figure 2 shows the model framework, running from GDP and population to industry physical output to industry energy demand. GDP per capita is used as an ultimate driving force in our energy demand projection model. We established a relationship between industrial energy demand and GDP per capita using a 2 step approach to project energy demand: first by relating GDP per capita and industrial production pattern, and second by relating industrial production and industrial energy consumption. We elaborate on the successive steps in sections 3.2 and 3.3.

Figure 2: Model framework using physical energy intensity indicators



3.2. Relation between Income and Industrial Physical Output

This section starts with background information on the relation between income and industrial (physical) output, and then elaborates on the use of historic relationships for scenario analysis using the "flexible extrapolation" method.

3.2.1. Theoretical background

The use of GDP *per capita* as an one of the major driving forces for energy scenarios represents the consensus of the energy research field (Burniaux et al. 1992; de Vries et al. 2001; Gritsevskyi 1998; IEA 2004; Kaya 1990; Nakicenovic et al. 2000; Newman et al. 2001; OECD 2001). In our model *per capita* income determines *per capita* "Industry Physical Output". The rationale for this relation stems from Equation 1. *Per capita* income determines household savings (and thus business investments), taxes (and thus government spending), and household consumption (Froyen 1996, p85). Household consumption patterns determine industry output and consequently industry energy demand (Moll & Groot-Marcus 2002; Vringer & Blok 2000; Wilting 1996).[7]

$$Y = E \equiv C + I + G$$

Equation 1

With:
Y = output (GDP)
E = aggregated demand
C = household consumption
I = investments
G = government spending
Source: (Froyen 1996)

Although household consumption patterns do depend on income, their relation is ambivalent. The consumption of low income households is bounded by their incomes, while the consumption of higher income households is bounded due to saturation effects, and determined by taste and choice (Biesiot & Moll 1995; Geyer-Allely & Cheong 2001; Moll et al. 2005). Therefore increasing *per capita* income can result in both materialisation (increasing quantity) or dematerialisation (increasing quality) (de Bruyn 2002; Godet 2002).

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[7] "Households use energy directly for many kinds of application, such as heating, lighting and driving. In addition, households use energy in an indirect way. This indirect use of energy concerns, for example, the energy used to manufacture consumption goods, to gather the raw materials for these goods, to transport these goods, or to provide services. " (Benders et al. 2001).

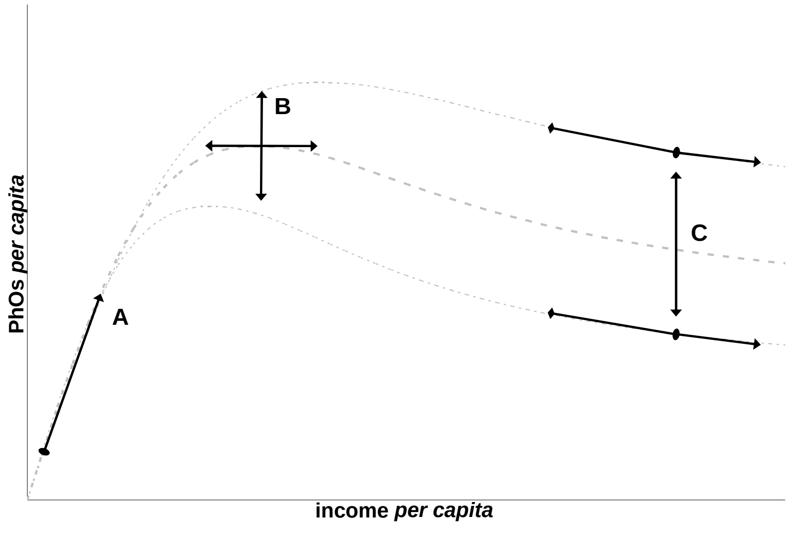
3.2.2. 'Flexible extrapolation' approach

The relation between *per capita* income and industry physical output (PhO_s) is the core of this industry energy consumption model. The conceptual model needed to describe this relation between *per capita* income and industry physical output is accomplished by a set of properties that define the 'flexible extrapolation' approach:

- An extrapolation model is needed because the aim of this research is to provide numerical output rather than insights in systems dynamics (Kleijnen 1993).
- The model needs to be backed-up by observations, research and common sense.
- The extrapolations need to be flexible to a certain extent in order to represent different scenarios.

De Bruyn et al. (1998) identifies four elemental types of relations between income and environmental pressure.[8] The most complex one – the N-shaped curve – is rare and therefore not considered in this research. Therefore the minimal complexity of this relation is bounded by the ability to result in an inverted-U-shaped relation between per capita PhOs and income. It should be noted that the inverted-U-shape relations are typically characterised by a Maxwell-Boltzmann distribution shape (Atkins 1990, p726) rather than a symmetrical inverted U shape. An illustration of the model is given in Figure 3.

Figure 3: Model of the relation between *per capita* income and *per capita* sectoral physical industry output



Based on: (Riahi 2004)

The curves in Figure 3 are characterised by three distinguishable stages of development. In stage-A increasing income is associated with increasing industry physical output. However, as income increases the relation between income and industry physical output becomes weaker until it flattens and reaches stage-B. After the

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[8] In the context of this paper materialisation, and thus physical industry output, is accounted for as an environmental pressure (de Bruyn 2002; de Bruyn & Opschoor 1997).

peak the industry physical output slowly decreases and may end-up as a constant value or a gentle decreasing slope in stage-C. The OECD regions reached stage-C for some industry sub-sectors, but are in stage A. for other sub-sectors. Non-OECD regions are still in stage-A for all industry sub-sectors.

The relation between *per capita* income and *per capita* industry physical output is determined by several effects appearing at different stages of increasing income. Saturation effects, efficiency improvements, dematerialisation, infrastructure development stage, policies, and fashion are among the factors that may lead to inverted-U-shaped relations.[9] OECD regions have shown peak and decline behaviour for some of the physical properties of industry production, e.g. in the iron and steel sector. The conceptual model shown in Figure 3 is supported by research ranging from world level to national level: a systems dynamic model study on world metal use shows an inverted-U-shape relation for metals intensities in monetary terms (van Vuuren et al. 1999) and a consumption-based statistical study on national level also shows this behaviour for some consumption categories (Rothman 1998).

The conceptual model needs to be flexible to a certain extent in order to be able to represent different scenarios. Let stage-A be the trajectory of a developing country in the past decades. In the next 100 years this country develops and may end up in stage-C with a resource intensive economy (upper graph) or a resource extensive economy (lower graph), depending on the type of storyline. Note that both end-states can be reached from a single state for stage-A. Therefore the model must be developed in such a way that it is rigid in stage-A and flexible in stages-B and -C.

The idea that indicator-levels of developing countries with certain qualification move into the direction of indicator-levels of developed countries is hereafter referred to as the “conditional convergence assumption”, see e.g. (Miketa & Mulder 2005). This assumption is very important regarding industrial energy consumption because, rather than following the linear path derived from stage-A, the indicator-levels can simulate trend-breaking events when certain critical levels of material wealth are achieved.

3.3. *Physical energy intensities*

Energy intensities are defined as energy consumption per unit of industrial output. In the model they change over time similar to the autonomous energy efficiency improvements (AEEI) as common practice in long term energy models (Braathen 2001; de Vries et al. 2001; Gritsevskyi 1998; Nakicenovic et al. 2000). A significant difference with monetary-based AEEI’s is the limitation of efficiency improvements. The use of physical indicators restricts energy efficiency improvements because of the thermodynamic limitations associated with e.g. the production of a tonne crude steel.

4. Model formalisations

The model described in section 3 is implemented and formalised in this section. This section solely deals with formalisation issues; implementation of the equations is dealt with in Section 5. First, Section 4.1 formalises the model framework described in

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[9] For an comprehensive overview see de Bruyn (2000).

Section 3.1. Next, Section 4.2 formalises the relation between income and industrial physical output described in Section 3.2. Finally, Section 4.3 formalises the physical energy intensities described in Section 3.3.

4.1. Formalisation of the model framework

The primary scenario drivers for this model are GDP, population, and the composite, income. Decomposition with physical industrial output, analogous to IPAT/Kaya-identity decomposition (Ehrlich & Holdren 1971; Kaya 1990),[10] gives Equation 2.

$$PEC_s = P * \frac{PhO_s}{P} * \frac{PEC_s}{PhO_s}$$ **Equation 2**

With:
P = population, PEC_s = sectoral primary energy consumption, PhO_s = sectoral physical output

Equation 2 is however not suitable for energy scenarios because it lacks the key scenario driver GDP. In our model *per capita* income determines *per capita* "Industry Physical Output" (see Section 3.2). Equation 3 is a formal representation of this relation.

Equation 4 defines the sectoral physical energy intensity ($PhEI_s$) as the quotient of sectoral primary energy consumption and sectoral physical output.

$$\frac{PhO_s}{P} = f_s\left(\frac{GDP}{P}\right)$$ **Equation 3**

$$PhEI_s = \frac{PEC_s}{PhO_s}$$ **Equation 4**

With:
$PhEI_s$ = sectoral physical energy intensity

Next substitution of Equation 3 and Equation 4 into Equation 2 gives Equation 5. Equation 5 represents the formalisation of the model chain as shown in Figure 2 in Section 3.1.

$$PEC_s = P * f_s\left(\frac{GDP}{P}\right) * PhEI_s$$ **Equation 5**

The next logical step is to develop a conceptual model for the function *f*, and thus for the relation between *per capita* impact indicators and income.

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[10] $I = P * A * T = P * \frac{GDP}{P} * \frac{I}{GDP}$
with: I = Impact, P = population, A = Affluence, T = technology, GDP = Gross Domestic Product

4.2. Formalisation of the relation between income and industrial physical output

The conceptual model shows two important features: a peak and an asymptote (hereafter called tail). Not only is it desired that a formalization of the model can reproduce the conceptual model, but it is also desired that variables in the formalization represent features of the conceptual model, e.g. the co-ordinates of the peak and properties of the tail. A possible general formula for growth and decline is shown in Equation 6 (Riahi 2004).

$$y = \frac{2 * P_y * P_x * x}{P_x^2 + x^2} \qquad \textbf{Equation 6}$$

The benefit of Equation 6 is that the peak co-ordinates are explicit. However, when this formulation is compared to historic data the fit is not very accurate because with this formulation the origin has to be crossed and historic series often do not show that behaviour. In order to allow the trend line to move away from the origin, Equation 6 was extended with an x-axis interception variable (I_x), resulting in Equation 7. For practical reasons it was chosen to use separate formulations for the left-hand side and right-hand side of the conceptual model. Equation 7 was used to represent the left-hand side of the conceptual model. The right-hand side of the model, the tail actually, needs to be altered in order to be able to determine the height of the tail and the speed of approach. This was done by adding two variables to Equation 7, one to set the y-value of the asymptote (T_y), and one to alter x in order to set the speed of approach (T_x), resulting in Equation 8.

$$y = \frac{2 * P_y * (P_x - I_x) * (x - I_x)}{(P_x - I_x)^2 + (x - I_x)^2} \qquad \textbf{Equation 7}$$

$$y = \frac{2 * P_y * P_x * \left(P_x + (x - P_x)^{T_x}\right)}{P_x^2 + \left(P_x + (x - P_x)^{T_x}\right)^2} * \frac{P_y - T_y}{P_y} + T_y \qquad \textbf{Equation 8}$$

With:
I_x = x-intercept
P_x = X co-ordinate of the peak, P_y = Y co-ordinate of the peak
T_x = Factor to adjust broadness of the tail, T_y = Hight of the tail

Note: It should be noted that Equation 8 is in a sense a simplification of Equation 7 because now I_x has been left out. Therefore I_x equals zero for regions were only Equation 8 is considered.

Section 6.1 describes the implementation of Equation 7 and Equation 8 by means of the “Flexible Extrapolation” method described in Section 3.2.2.

4.3. Formalisation of physical energy intensities

Energy intensities are usually modelled based on the assumption of (autonomous and/or induced) annual efficiency improvements (AEI) (see e.g. de Vries et al. 2001), which is formalised in Equation 9. When monetary indicators are used there is no *a-priori* reason to restrict the energy intensity to go below a certain value. On the other hand, when physical indicators are concerned boundaries need to be considered because of the thermo-chemical limitations of industrial processes. Therefore Equation 9 was extended with a minimum value of the physical energy intensity, which results in Equation 10.

$$EI_t = EI_{t=0} * \left(1 - AEI\right)^t$$ **Equation 9**

$$PhEI_t = PhEI_{Min} + (PhEI_{t=0} - PhEI_{Min}) * (1 - AEI)^t$$ **Equation 10**

With:
$PhEI_t$ = Physical energy intensity in year t
$PhEI_{Min}$ = Minimum value of PhEI
$PhEI_{t=0}$ = Base-year value of PhEI
AEI = Annual efficiency improvement

Section 6.2 describes the implementation of Equation 10.

5. Data sources and analysis

5.1. *Scenario driving forces*

In this model scenario driving forces are kept very basic. Population, GDP, and *per capita* income drive the industry energy consumption analogous to IPAT/Kaya (see Section 4.1).

Changes in energy use by society can be caused by several factors (e.g. current energy consumption for private transportation is related to the fashion to drive SUVs), however in order to research the use of physical indicators under *ceteris paribus* conditions this research treats population and income scenarios as driving forces.

5.2. *General data and dimensions*

The model was developed as a world model with a regional focus consistent with world models from IIASA and WEC (Nakicenovic et al. 1998), which consist of 11 world regions. The timeframe was set from 2000 to 2100 because most data is available until 2000 and the period until 2100 has been determined as the most relevant for climate change issues (Nakicenovic et al. 2000).

The sectoral focus was chosen to be as detailed as possible, because higher disaggregated data is closer to the industrial process itself (Ramirez et al. 2005). Moreover, because of the explorative character of this research, a high level of disaggregating potentially reveals more information about the feasibility of the use of physical indicators. Because the energy analysis was based on IEA datasets, the sectoral focus of this research is the same with 13 industry sectors (IEA 2002a; IEA 2002b).

For this analysis the ‘dynamics-as-usual’ B2 scenario was chosen (Riahi & Roehrl 2000) in order to be able to compare the results with other models. Historical data analysis is limited by data availability and therefore most of the analyses describes the period 1970-2000.

Past population developments were taken from IEA datasets (IEA 2002a; IEA 2002b). Population scenarios were taken from the medium UN scenario (UN 1999) which are also used for the B2 SRES scenarios. Incomes and GDP are expressed in terms of constant 2000 US$ at market exchange rates (MER). Historical GDP data was taken from (Miketa 2004). GDP scenarios are based on B2 scenarios and obtained from IIASA (Riahi 2004).

Energy consumption was expressed in terms of primary energy because 1) the character of the research – a long-term energy model – requires macroscopic data, and 2) data availability for world regions is limited to macroscopic data. Energy data was taken from IEA datasets (IEA 2002a; IEA 2002b).

5.3. Choice of the physical indicators

The choice for the indicators to represent the entire sector depends on several interrelated factors. A first, essential one is data availability. Second, the indicator must be expected to be robust given the possibilities of intra-sectoral change in order to be representative. Third, the commodities must allow aggregation. The commodities used as indicators to represent the sectors came from the UN industrial statistics database (UNIDO 2002); analogous to (Rothman 1998). The indicators selected to represent the 13 industry sub-sectors are listed in Table 1. Due to the diversity of the industry sub-sectors the indicators are subsequently diverse.

Basic industry sub-sectors produce relatively homogenous bulk products. Therefore these indicators can be chosen in line with bottom-up energy indicator studies and represent a measure of industry output volume. Examples are: “Iron and Steel”, and “Paper, Pulp and Printing”.

Some of the sub-sectors listed in Table 1 produce heterogeneous products. However, several of those sub-sectors are nonetheless characterized by relatively homogenous inputs[11], which therefore have been chosen as indicators. Examples are: “Chemical and Petrochemical”, “Wood and Wood Products”, “Construction,” and “Non-specified industry”.[12]

Specified industry sub-sectors with heterogeneous inputs are the most difficult to categorise. Regarding these sub-sectors single commodities or several commodities that can be aggregated are chosen to represent the entire sub-sector. Examples are: “Transport Equipment”, “Food and tobacco”, and “Machinery”. These sub-sectors should be observed with extreme caution because intra-sectoral structural changes affect the outcomes.

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[11] Take ‘wood and wood products’ for example: the outputs are very heterogeneous and measured in ‘pieces’ (numbers of chairs, etc) rather than mass. The industry’s input, however, is timber wood, which is rather homogeneous, convertible to mass and thus more suitable when a single indicator is needed for the entire sub-sector.

[12] When only “Manufacture of rubber and plastics products” is considered.

Table 1: commodities selected to represent industry sub-sectors

Sub-sector	Commodities (ISIC Rev. 2 – based code).
Iron and Steel[13]	Crude steel for casting (3710-16), Crude steel, ingots (3710-19).
Chemical and Petrochemical[14]	Ethylene (3511-10), Naphthalene (3511-11), Propylene (3511-13), Toluene (3511-14), Xylene (3511-15).
Non-Ferrous Metals	Copper, primary, refined (3720-041), Copper, secondary, refined (3720-042), Aluminium, unwrought, primary (3720-221), Aluminium, unwrought, secondary (3720-222).
Non-Metallic Minerals	Drawn glass and blown glass (3620-01A), Float glass and surface ground or polished glass (3620-04A).
Transport Equipment	Passenger cars, produced (3843-10).
Machinery	Refrigerators, household (3829-58).
Mining	Iron ores and concentrates (2301-01), Copper ores and concentrates (2302-01), Nickel ores and concentrates (2302-04), Aluminium ores and concentrates (2302-07), Lead ores and concentrates (2302-10), Zinc ores and concentrates (2302-13), Tin ores and concentrates (2302-16), Manganese ores and concentrates (2302-19), Chromium ores and concentrates (2302-22), Tungsten ores and concentrates (2302-25).
Food and tobacco	Meat of bovine animals (3111-01), Meat of sheep or goats (3111-04), Meat of swine (3111-07), Meat and edible offal of poultry (3111-10), Other meat (3111-13).
Paper, Pulp and Printing[15]	Newsprint, in rolls or sheets (3411-19), Other printing and writing paper (3411-22), Household and sanitary paper (3411-24), Wrapping and packing paper and paperboard (3411-25), Cigarette paper in rolls exceeding 15 cm or in rectangular sheets (3411-28), Other paper and paperboard (3411-31).
Wood and Wood Products	Sawnwood, coniferous (3311-04), Sawnwood, broadleaved (3311-07).
Construction	Quicklime (3692-01), Portland, aluminous and other hydraulic cements (3692-04), Asbestos-cement articles (3699-01A), Abrasives, agglomerated or not (3699-04).
Textile and Leather	Wool yarn, mixed (3211-04), Cotton yarn, mixed (3211-10), Flax, ramie and true hemp yarn (3211-16), Yarn (other than sewing thread) of man-made staple fibres, whether or not put up for retail sale (3211-19), Jute yarn (3211-22), Yarn of other vegetable textile fibres (3211-25).
Non-specified industry[16]	Polyvinyl chloride (3513-28).

Selected from: (UNIDO 2002).

It should be noted that specific knowledge of the sectors is required in order to select the appropriate commodities. These chosen commodities should be seen as educated-try variables.

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[13] in line with (Farla & Blok 2001; Worrell et al. 1997)

[14] based on (Farla & Blok 2000)

[15] in line with (Farla et al. 1997; Schenk et al. 2004)

[16] ISIC Divisions 25 (Manufacture of rubber and plastics products), 33 (Manufacture of medical, precision and optical instruments, watches and clocks), 36 (Manufacture of furniture; manufacturing n.e.c.), and 37 (Recycling). (IEA 2002a; IEA 2002b)

6. Historical data analysis & extrapolation for model parameters

As mentioned in Section 3.2.2 intra-regional convergence is an important assumption in this analysis. In this section the Equations from Section 4 are fitted against historical data using the “Flexible Extrapolation” method to incorporate the convergence assumption.

6.1. Income vs. commodity production

In our approach *per capita* sectoral industrial physical output is assumed to be a function of income. In our analysis time-series of regional aggregates are considered. Figure 4 shows an example of this relation in the iron and steel sector. Other sectors show similar patterns although differences between industries can be huge.

In order to determine the parameters for Equation 7 and Equation 8 the ‘flexible extrapolation’ approach described in sector 3.2.2 is implemented. The regions North America (NAM), Western Europe (WEU), and Pacific OECD (PAO) were first fitted[17] against Equation 7 to determine the x and y coordinates of the peak (P_x and P_y) .[18] Next, the values for T_y (y-value of the asymptote) in Equation 8 were chosen based on their current dynamics (ability to fit to the data-points) and the scenario storyline of B2 (Nakicenovic et al. 2000).

Figure 4 illustrates the “flexible extrapolation” method by applying it to the “iron and steel” industry. The extrapolations for NAM, WEU, and PAO all show a decreasing steel intensity, although at very different levels. The scenario is rather conservative, and therefore the dematerialisation trend stagnates relatively soon.

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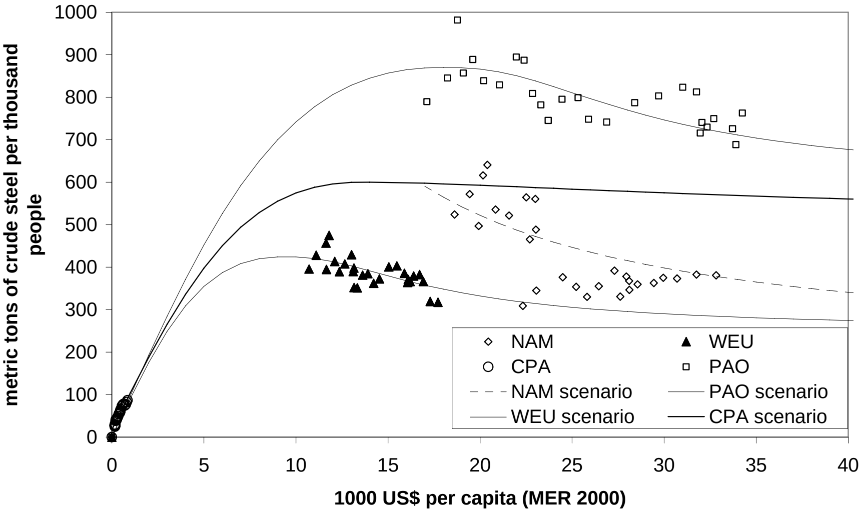
[17] all fitting is done using least-square values method

[18] I_x was set to zero because it has no meaning for commodities that are ‘over the top’

Figure 4: relation between *per capita* income and *per capita* physical industry output for the iron and steel industry



With: NAM = North-Americas, CPA = Centrally Planned Asia & China, WEU = Western Europe, and PAO = Pacific OECD (Australia, New-Zealand, Japan, and South-Korea).
Source: (IEA 2002a; IEA 2002b; Miketa 2004; UNIDO 2002)
Notes: Because of the steep decline in the NAM region the fit of Equation 8 resulted in extreme values for the top co-ordinates ant therefore this part of the graph is omitted.
The markers for WEU and CPA correspond with "steel" in Figure 5 and Figure 6

The region Centrally Planned Asia & China (CPA) was first fitted against Equation 7 to determine an x-axis interception (I_x) and initial values of the P_x and P_y co-ordinates. Next, the values of the P_x and P_y co-ordinates were adjusted in such a way that crude steel intensities approach (but not exceed) the values of the most steel intensive region in the world (PAO). After the peak however, there is virtually no dematerialisation.

The same 'flexible extrapolation' procedure was used for the other industry sub-sectors in a similar way to determine the relation between *per capita* income and sectoral physical output. The results for the historic series are described in the sections below.

6.1.1. Western Europe

Figure 6 shows average annual changes in *per capita* GDP growth and *per capita* physical industrial output for WEU. The figure shows that structural changes took place in the industry sector. Textile declined the most, while in particular the chemicals industry and "Non-specified industry"[19] increased in terms of *per capita* physical output. The figure also shows that *per capita* industry output more or less stabilised regarding several industries.

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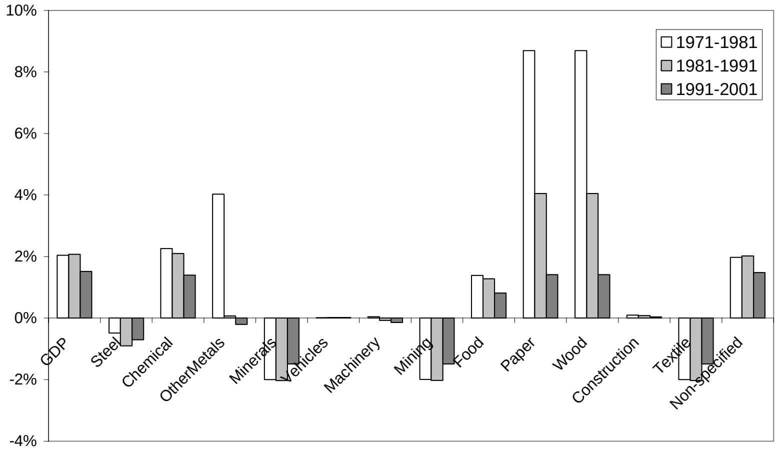
[19] Non-specified industry: Any manufacturing industry not included above [ISIC Divisions 25, 33, 36 and 37]. Note: Most countries have difficulties supplying an industrial breakdown for all fuels. In these cases, the non-specified industry row has been used. Regional aggregates of industrial consumption should therefore be used with caution. Please see Country Notes. (IEA 2002a; IEA 2002b)

Figure 5: WEU average annual changes in per capita economic output and per capita physical industrial output

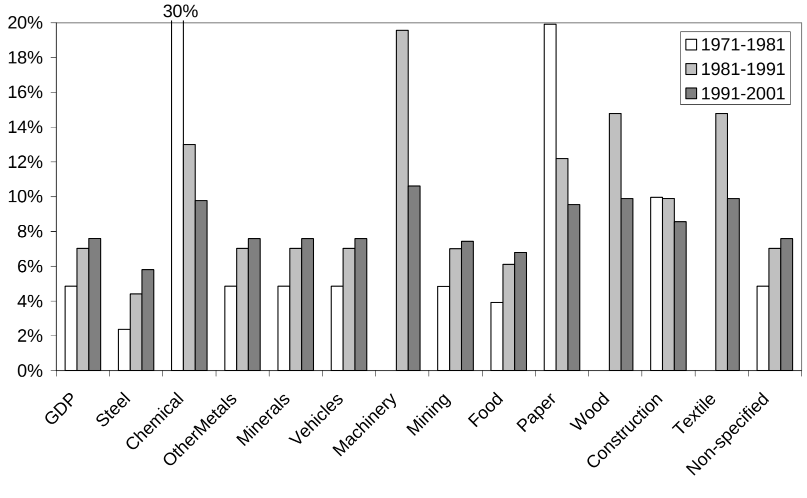


Source: (IEA 2002a; IEA 2002b; Miketa 2004; UNIDO 2002)

6.1.2. Centrally Planned Asia & China

Figure 6 shows average annual changes in *per capita* GDP growth and *per capita* physical industrial output for CPA. The figure shows that structural changes took place in the industry sector. The figure shows that industries grow at different speeds. Steel is a relatively slow growing sector, several sectors show growth rates similar to GDP, and several other industries grow much faster than GDP.

Figure 6: CPA average annual changes in *per capita* economic output and *per capita* physical industrial output



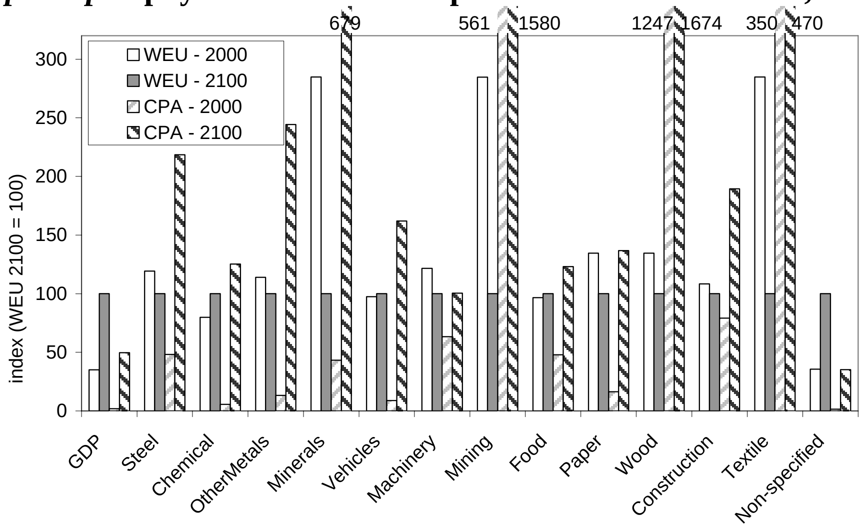
Source: (IEA 2002a; IEA 2002b; Miketa 2004; UNIDO 2002)
Note: 1971-1981 series are incomplete for some sub-sectors.

6.1.3. Extrapolation of per capita physical industrial output in a B2 scenario

Figure 7 shows the 2000 and 2100 levels of *per capita* GDP and of *per capita* physical industrial output relative to WEU 2100 levels. The CPA 2100 levels of *per capita* physical industrial output are higher than the WEU 2100 levels for all sectors except “Non-specified industry”.

Figure 4 is illustrative for most industries in a sense that levels of *per capita* physical industrial output are higher in other OECD regions. Therefore CPA projections for 2100 exceed WEU levels for most industries.

Figure 7: *per capita* physical industrial output levels in a B2 scenario, 2000-2100



Notes: The *per capita* PhO_s’s are indexed to WEU-2100 values in order to compare convergence in all sub-sectors.
WEU is relatively dematerialised compared to other OECD regions. See e.g. Figure 4.

6.2. Physical energy intensities

Physical energy intensities were determined by fitting Equation 10 to historical data of sectoral energy consumption in terms of primary energy with physical output of that particular sector.

The convergence assumption and constant annual efficiency improvement (AEI) assumption restricted the values of the parameters in Equation 10. Moreover the base-year values needed to be calibrated. In an iterative process the values of the parameters in Equation 10 were restricted until both assumptions were met.

Figure 8 shows the base-year values ($PhEI_{t=0}$ in Equation 10) and the minimum values ($PhEI_{Min}$ in Equation 10) of the physical energy intensities for both regions. Convergence is expressed by equal minimum values of PhEI. The convergence assumption is abandoned, however, when data points strongly in other directions and significant differences in industry structure are plausible (e.g. ‘food’, ‘wood’, and ‘Non-specified industry’).

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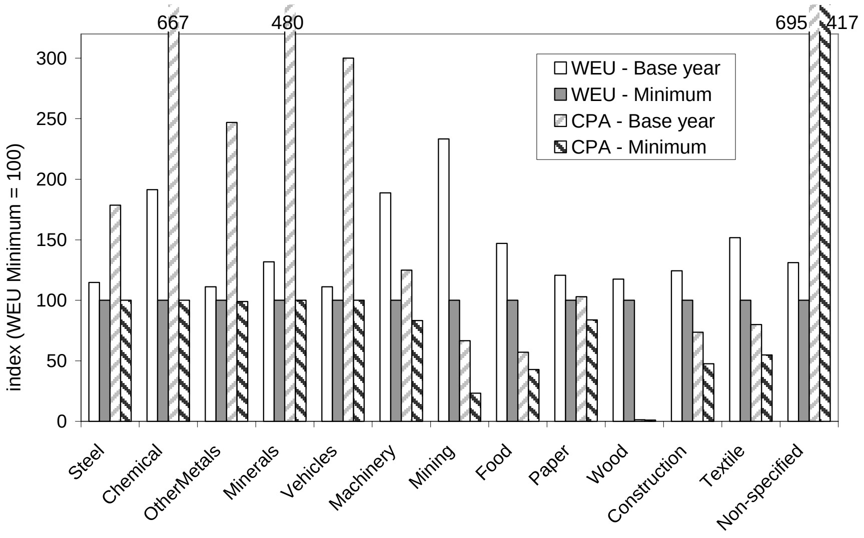
Figure 8: base-year values and minimum values of physical energy intensities in WEU and CPA



Note: the PhEI's are indexed to WEU-Minimum values in order to compare convergence in all sub-sectors.

In Western Europe all sectors are expected to increase their energy efficiency, although the improvements are low compared to Centrally Planned Asia & China. In WEU the largest efficiency improvements are expected in the 'chemical', 'machinery', 'mining', and 'textile' industries. In CPA the largest efficiency improvements are expected in the 'chemical' and 'minerals' industries, although improvements are significant in all industry sub-sectors.

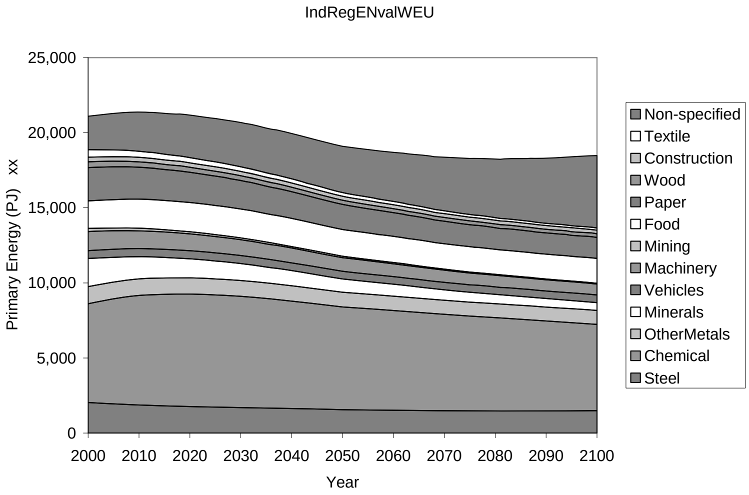
7. Energy scenarios

In this section the previously discussed information is implemented into industry energy demand scenarios. The scenarios for WEU and CPA are shown and compared to the MESSAGE B2 scenario.

7.1. Western Europe

Figure 9 shows the energy scenarios of the individual industries in Western Europe. Notable are the chemicals industry and "Non-specified industry", not only because their current level of energy consumption is quite high, but also because of their development patterns. This analysis shows that the non-energy intensive industries (relevant for "Non-specified industry") deserves special attention in OECD countries, which is consistent with a study for the Netherlands (Ramirez et al. 2005).

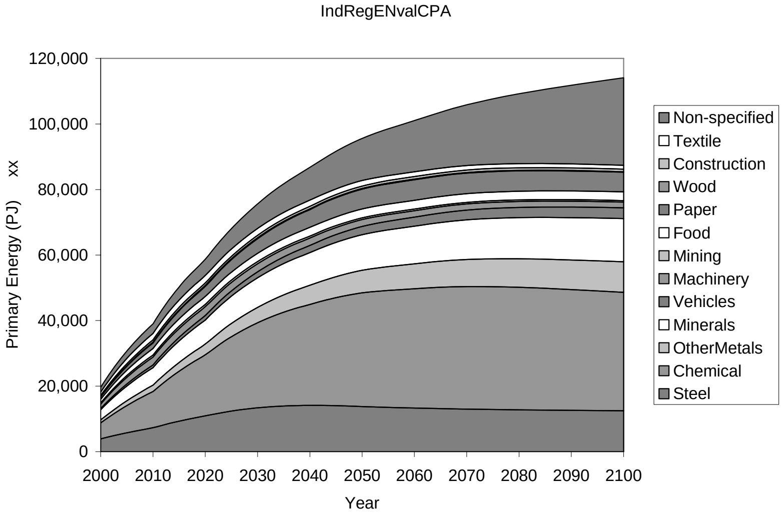
Figure 9: WEU industry energy scenarios



7.2. Centrally Planned Asia & China

Figure 10 shows the energy scenarios of the individual industries in Centrally Planned Asia & China. The picture differs from Western Europe in several points. Steel is expected to play an important role in this scenario, while the less energy intensive industries ("Non-specified industry") become dominant in the second half of the century. Chemicals industry is the strongest rising in energy consumption, but in this scenario its share in energy consumption is low compared to the current situation in Western Europe.

Figure 10: CPA industry energy scenarios



7.3. Comparing the results with other scenarios

In this section the model described in this paper is compared to the industries sector from the B2 MESSAGE scenario. We do so to analyze fundamental aspects of the difference between monetary-based approaches and physical-base approaches.

Figure 11 shows an indexed comparison between the results of this research with the B2 MESSAGE scenario for Western Europe. As can be seen the differences in WEU are remarkable: in the first decades this model appears to be optimistic by indicating relatively small increases compared to B2 MESSAGE. In the second half of the model period however, the B2 MESSAGE indicates strong decreases in energy consumption, while this model is more pessimistic. These effects are hard to explain because in first decades one would expect dynamics as usual models to have similar outcomes. The differences at the end may be explained by trend-breaking new technologies in B2 MESSAGE that cannot appear with our simplistic top-down approach.

Figure 11: comparison of this model with MESSAGE B2: Western Europe

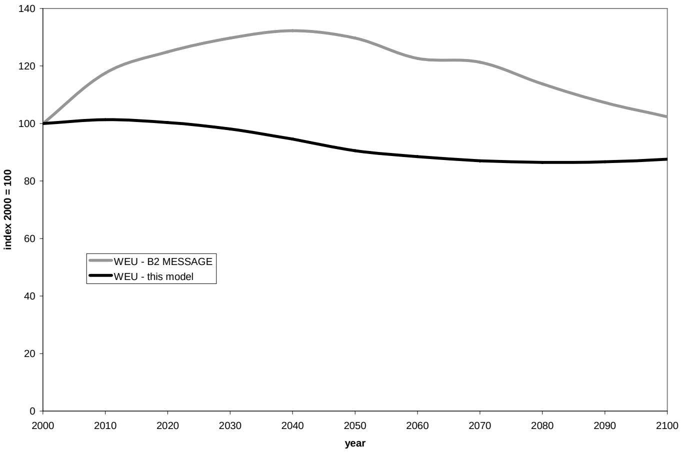
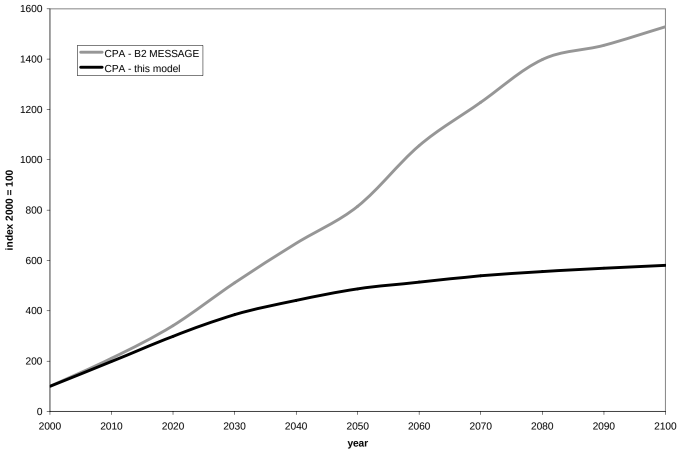


Figure 12 shows an indexed comparison between the results of this research with the B2 MESSAGE scenario for Centrally Planned Asia & China. The differences in CPA are of another nature than in WEU. In the CPA region both model scenarios seem to follow the same path. However, after ca. 2-3 decades this model indicates stagnation in industry energy consumption while B2 MESSAGE indicates undistorted increases. This result indicates that saturation effects may be underestimated in the B2 MESSAGE scenario. Moreover, it indicates that in the B2 MESSAGE scenario physical industry output in CPA region must be about three times as high as expected based on 'dynamics-as-usual' trends of industry physical output growth.

Figure 12: comparison of this model with MESSAGE B2: Centrally Planned Asia & China



However, it is hard to say if the differences between B2 MESSAGE and this model are fundamental differences between the indicators, or differences in modellers' interpretations of business-as-usual developments.

8. Discussions

The main achievement of this research is the use of physical indicators for energy scenarios. Because of the explorative character this model comes with a wide range of discussion points.

8.1. Measurement of income

Economic output is measured at constant 2000 US$'s in market exchange rates (MER) rather than purchasing power parities (PPP). Constant prices are needed for inter-temporal measurement of real output (Maddison 2004). The use of MER needs a bit more explanation, especially because PPP is developed for inter-country comparison (Maddison 2004; The Economist 2004). When GDP is used as a measure of (material) welfare MER is incorrect because commodity prices usually differ from country to country. To convert MER to PPP a commodity basket is used to compare price levels between countries and convert them to a common currency. The appropriate measurement of welfare and the effect on energy scenarios has been discussed and the advantages and disadvantages of both measurements should be kept in mind (Castles & Henderson 2003a; Castles & Henderson 2003b; Grübler et al. 2004; Nakicenovic et al. 2003; Nakicenovic et al. 2000). In this research welfare is expressed in terms of MER.

The use of MER is not without caveats and attention should be paid to differences in dynamics between goods due to market distortions (trade barriers, exchange rate interference (China!), transportation distances, and *etceteras*). Moreover, although China is a relatively poor country it showed that it can adopt high technology standards by launching its own space flight program. Therefore the argument that China will have to buy energy technologies like combined-cycle gas turbines at MER prices (Grübler et al. 2004) is probably not true. As energy imports may become strategically undesired fast adoption of energy efficient technologies should be considered in energy scenarios.

8.2. Trade liberalisation

Trade is not explicitly included in this model (see Section 3.2.1). However trade, and the liberalisation of international trade, has major implications for the development of the industries. Characteristics of trade liberalisation are: the steady expansion of the multilateral trading system, the creation of regional trading blocks, the evolution of truly global corporations, the rapid growth in income (particularly in the most dynamic developing countries), the explosive expansion of means of communication, the collapse of Soviet-style communism, and the general acceptance of a liberalising, deregulatory model of economic policy (Brack 2000). The environmental (and energy) impacts can both be negative and positive, depending on the aggregate outcome of a number of effects: scale effects, structural effects, technology effects, product effects, distribution effects, and regulatory effects (Brack 2000).

OECD exports remained dominant particularly in the hi-tech and medium-tech sectors: non-electrical machinery, chemicals and pharmaceuticals, motor vehicles, iron and steel and electrical machinery and aerospace. Non-OECD exports are dominant in low-tech goods and telecommunication and computer equipment (Brack 2000).

In Section 3.2 the link between *per capita* income and *per capita* “Industry Physical Output” was explained based upon Equation 1. In real life, economies are open. However, in this research trade is not taken into account.

$$Y = E \equiv C + I + G + X - Z$$

Equation 11

With:
Y = output (GDP)
E = aggregated demand
C = household consumption
I = investments
G = government spending
X = exports
Z = imports
Source: (Froyen 1996)

An argumentation for this simplification is the high aggregation level of production and consumption. The higher the aggregation level, the more production patterns reflect consumption patterns. Moreover, on the long term imports are roughly in balance with exports.

8.3. Monetary vs. physical approaches

The physical approach appears to have several benefits compared to the monetary approach. Physical indicators can be used for energy scenarios, although the use is not without caveats. The benefits of the use of physical indicators are not hard to identify:

the connection with the real world is much clearer than with monetary units. A clear disadvantage is data: physical indicators are heterogeneous and often not well documented.

Notable is the similarity between the MESSAGE B2 scenario for CPA (Figure 11) and the energy scenarios that were developed in the 1950's for Western Europe and Northern America (see e.g. (Smil 2000)). The CPA scenario from this model shows more similarity with the actual developments in Western Europe and Northern America. These results indicate that monetary indicators may be accurate for developed regions, but for regions in development physical indicators seem to produce more realistic scenarios.

The differences between monetary and physical approaches are stunning when it comes to the 'limits of growth'. In monetary terms the output of the industry sector is virtually unrestricted. In physical terms however, the output of the industry sector is restricted. Even in a world where a Hummer is considered a small car, the infrastructure will have a restricting effect on the amount of materials used to construct a car.

Energy intensity in the monetary approach actually was criticised as having little or no physical meaning (Fischer-Kowalski & Amann 2001) In the approach presented in this paper the physical meaning of energy intensities is ambivalent. Regarding sub-sectors where both the industry inputs and the products are heterogeneous (see Section 5.3) the physical meaning is as low as with monetary approaches. Regarding other sub-sectors the physical meaning is high and can be comparable with 'Specific Energy Consumption' indicators (Farla 2000).

Physical indicators cannot be simply added to yield an aggregate indicator (Farla & Blok 2000). This problem remains persistent and can only be dealt with by approaching each sub-sector individually and aggregating e.g. the energy demand.[20] Further research in this direction should focus on bulk industry inputs and use them as an indicator for industry activity level. Bulk industry inputs can be aggregated (with some caution).

8.4. Directions for further research

In the opinion of the author, this research suggests that analysing 13 separate industry sectors would probably be overdoing it. Further research in this direction should therefore rather aim to distinguish between primary manufacturing and final manufacturing. This means that the chemicals and steel industries need to be split-up according to the product specificity, while other sectors should be aggregated.

The obvious direction for further research is to combine insights from energy modelling based on monetary indicators with insights from the Life Cycle Assessment research community and the Industrial Ecology research community.[21] An integrated energy and materials modelling approach potentially increases accuracy and reliability of energy scenario analysis.

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[20] Although energy is actually also heterogeneous and even a single form like 'electricity' cannot be aggregated because the GHG emissions from peak-production and off-peak-production may differ (Schenk et al. 2005).

[21] Especially 'Materials Flow Analysis' (MFA) should be considered.

9. Conclusions

This research clearly shows that physical indicators can be used for scenario analysis. The use of physical indicators instead of monetary indicators seems to affect the energy scenarios significantly. As Figure 11 shows, however, the differences with monetary indicators are larger in developing regions than in OECD regions. In the CPA region the industrial energy consumption calculated based on physical indicators is only $^1/_3$ of the calculations based on monetary indicators. Although only in-depth research can reveal the differences between the scenarios, this research points in the direction of measurement.

We conclude that an integrated energy and materials approach reveals developments that are hardly visible using a monetary approach. Moreover, this research shows the potential and benefits of the use of physical indicators for scenario development.

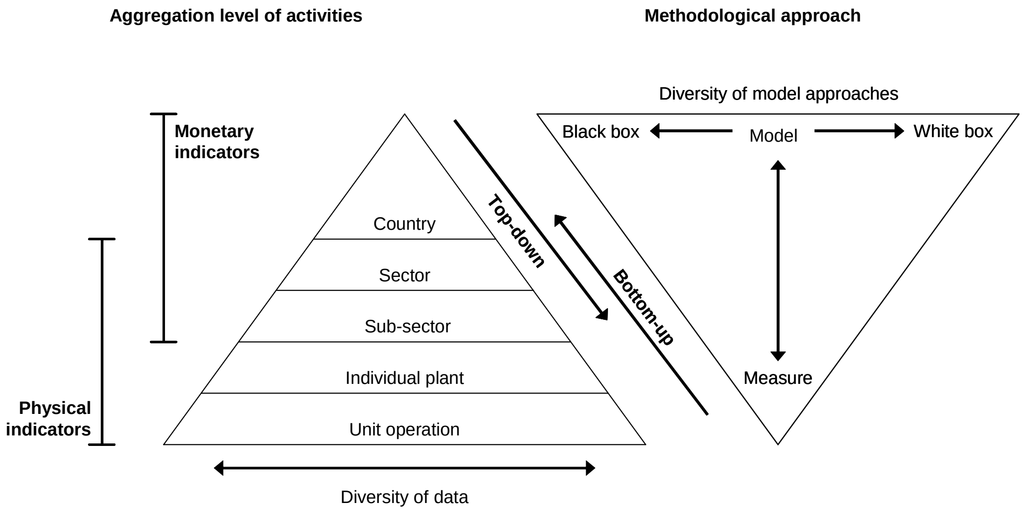
The ‘reality check’ provided by this approach indicates that, for the CPA region, in order to consume the amount of energy as indicated in the B2 MESSAGE model, the materials consumption must be three times higher then one would expect based on BaU developments of materials flows. Such huge materials flows can be considered unrealistic. This factor three difference indicates the urge to apply integrated energy and materials modelling into energy scenario analysis.

10. Appendix A: methodology review

10.1. Overview of methodological approaches and choices

Energy analysis is very broad in terms of methodological approaches. Energy analysis varies from engineering-level research to global energy balances. Important distinctions between the several approaches are the aggregation level of the used data, the starting point of data analysis (TD or BU), the type of model, and of course the indicator used to measure societal activities. Figure 13 gives a schematic overview of the diversity in energy analysis approaches.

Figure 13: data aggregation and associated modelling approaches



Based on ideas of: (Farla 2000; Kleijnen 1993; van Beeck 1999; Worrell 1994).

The left-hand pyramid shows data aggregation for industry energy analysis. At the base of the pyramid the data is diverse and huge amounts of data are needed. Physical indicators are the normal measurement at this level. At the top of the pyramid the data is aggregated at the highest level. Monetary indicators common at this level although aggregated values for energy (IEA 2002a; IEA 2002b) and materials (Matthews et al. 2000) are also common. Aggregation of energy or materials is, however, more problematic than aggregation of monetary indicators. On the (sub-) sectoral level both monetary and physical indicators have been used in energy analysis.

The right-hand reverse-pyramid shows the variety in model approaches in industry energy analysis. The methodological approach may be top-down or bottom-up. Top-down approaches are – in general – associated with higher data aggregation levels, while bottom-up approaches are – in general – associated with lower data aggregation levels. At the highest data aggregation level the methodological emphasis is on modelling, while on the disaggregated level the methodological emphasis is on measuring. Modelling approaches vary in terms of data intensities and causalities. On the left are the data-depend black-box models and on the right are the causality-driven white box models.

In this section we will give a brief review of the different aspects related to the different dimensions of the scheme in Figure 13. This brief review is needed in order to explain the issues associated with the use of physical indicators.

10.2. Top-down vs. bottom-up

Energy efficiency analysis on the (sub-)sectoral level can be performed with both top-down and bottom-up approaches. Bottom-up and top-down approaches serve different research aims. As can be seen in Figure 13 top-down (TD) approaches are macroscopic-oriented and use highly aggregated data – often national statistics – as a starting-point. Bottom-up (BU) approaches on the other hand use data obtained from individual units or plants (end-use technology) as a starting point. TD and BU approaches tend to produce opposite outcomes for the same problem (van Beeck 1999). It is therefore that hybrid approaches are quite common.

In BU approaches data from single case-studies are generalised. BU approaches can be brilliant for comparing technologies in Life Cycle Assessment (LCA), but up-scaling – e.g. from individual plants to the sub-sector – tends to produce optimistic answers (van Beeck 1999). BU approaches usually express energy consumption for industries in terms of useful energy, i.e. electricity and heat. Although BU approaches alone are poor for energy analyses on higher aggregated levels, they can be superb when combined with TD approaches.

In TD approaches national statistics are often the starting point for research. TD approaches perform well in monitoring and predicting over-all trends and developments, but may fail when trends are broken (Craig et al. 2002). Moreover, natural occurring limitations (e.g. fishing yields or agricultural yields) and saturation effects may remain unnoticed by TD approaches. TD approaches usually express energy consumption for industries in terms of obtained energy, i.e. fuels and traded electricity and heat. Primary energy consumption is the common yardstick for energy analysis on aggregated levels (IFIAS 1974).

The purpose of this research is to develop energy scenarios on a meta-national level therefore a TD approach should be applied. In this research we aim to overcome some of the shortcomings of TD approaches by using physical indicators rather than monetary indicators.

10.3. Black box vs. white box

The top-down approaches are very rich in terms of model typology, ranging from black box (noncausal) models in the social sciences through grey box models in ecology to white box (causal) models in physics (Kleijnen 1993). Figure 13 shows the black box models close to the data – to illustrate their data dependency – and the white box models far away from the data – to illustrate their focus on insights in the dynamics of systems.

In environmental sciences white box models are based on common sense and on direct observation of the real system. Emphasis is on the (qualitative) understanding of systems. The nature of feedback loops and differences in time-lags in the systems are modelled in a stock-and-flow environment and calibration is often impossible and considered less relevant. See e.g. (Ford 1999).

In environmental sciences black box models are based on data analysis. Emphasis is on (quantitative) relations between variables and on statistical relevance. Econometric models describing relationships between economic growth and emissions are typical examples. See e.g. (de Bruyn et al. 1998).

The purpose of this research is to provide numerical output and therefore a black box model should be applied (Kleijnen 1993). The discussion section of this paper is used to give qualitative feedback on aspects that are not covered by the data and thus our model.

11. Appendix B: Structural change

Changes in production patterns can be distinguished into inter-sectoral and intra-sectoral changes (Worrell et al. 1997). Inter-sectoral changes (e.g. a relative decrease of the value added from the steel industry) are quantitatively represented in the datasets and are analysed in this paper.

Intra-sectoral changes are not quantitatively represented in the dataset and are generally treated here. Intra-sectoral changes can occur because of changes in the process mix (e.g. primary steel vs. secondary steel) and the product mix (e.g. bulk chemicals vs. fine chemicals). Figure 1 shows the segmentation within the chemicals industry, from high-volume to high-specific chemicals. Value added based energy intensities cannot distinguish between energy efficiency improvements and intra-sectoral changes in the direction of more specialised products.

On the aggregated level intra-sectoral changes appear as changes in energy intensity, both monetary and physical. A clear benefit of the physical approach is that analysis of commodity productions gives insight in intra-sectoral changes.

Differences between countries and regions – both monetary energy intensities (MEI) and physical energy intensities (PhEI) are influenced by several factors. MEI’s differ from region to region and also evolve in time. Differences in MEI’s are often explained by differences in technologies used in individual countries (Miketa 2001). Smil (2000) identifies country size, climate, the composition of the primary energy supply, the degree of energy self-sufficiency, differences in industrial structure, and discretionary personal consumption of energy as key factors for difference in national energy intensities. Regarding PhEI process mix and product mix (intra-sectoral changes) influence the energy efficiency (Worrell et al. 1997).

It should be noted that local prices do influence MEI, but not PhEI. This is a possible explanation why PhEI is considered a more meaningful indicator especially regarding developing countries (Worrell et al. 1997).

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