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ORIGINAL ARTICLE

Modelling the potential for industrial energy efficiency in IEA's World Energy Outlook

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Abstract The industry sector accounts for more than a third of global final energy consumption and nearly the same share of global energy-related CO_2 emissions. Compared with other sectors, however, industrial energy modelling has received less attention due to the variety of sub-sectors, impact of energy-saving measures on product qualities and statistical problems. This paper explains how the industry sector is modelled in the World Energy Outlook and presents energy-saving opportunities from energy efficiency in the sector. Using the World Energy Model, a partial equilibrium model, it is found that exploiting the economic potential of energy efficiency can reduce energy demand growth in industry from 1.5 to 1.1 % per year on average over the period 2010–2035. Savings arise from faster adoption of more efficient technologies, phasing out older facilities, process change and system optimisation, including electric motor-driven systems. Significant barriers to the implementation of energy efficiency are the requirement for short payback periods and concerns that change could interrupt production or affect reliability. In order to realise the potential energy savings, policy makers need to address these issues by improving mechanisms for capacity building, energy management and financing.

Keywords Industrial energy efficiency · Energy-intensive industries · Policy measures · Partial equilibrium modelling

Introduction

Model-based scenario analysis nowadays plays a key part in informing decision makers about future trends in the energy system. It is an essential tool to underpin decision making in the energy field and is the basis for publications at the International Energy Agency (IEA), including the World Energy Outlook (WEO).

Despite the fact that the industry sector consumes more than a third of global final energy (feedstock use included) and is responsible for almost the same share of global energy-related carbon dioxide (CO_2) emissions, it has not received the same attention in energy modelling as supply side modelling of oil and gas extraction and other transformation or demand sectors, such as power generation, transport or building. Nevertheless, industry is expected to maintain a share of energy demand that is roughly constant. Therefore, being able to understand and project changes in industrial energy consumption with reasonable accuracy is an important task. The lack of attention to the sector is linked to several problems that arise when modelling it:

First, in contrast to transport, for example, there is not one sub-sector that dominates. Road transport, for example, accounts for roughly three quarters of total final consumption in the transport sector. The industry sector is characterised by only a few energy-intensive

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industries: iron and steel, chemicals and petrochemicals, cement, pulp and paper and aluminium. Excluding feedstock use and the transformation sector, these capture only half of industrial demand. The rest is consumed in other industrial sectors, which comprise a very diverse set of industries and sub-sectors (including food and tobacco, machinery, mining and quarrying and transport equipment). Such diversity makes it difficult to project future energy demands and calculate specific energy intensities. Using value-added as a common denominator for energy intensity calculations is not without problems since it does not capture structural changes in the industry sector, and price variations for industrial goods can render the metric meaningless.

Second, the same industry sub-sector produces many different qualities of a product. One tonne of steel is not necessarily the same as the others; the same is true for paper, which can come in different forms, such as sanitary paper, packaging paper or newsprint. In many cases, energy-saving technologies cannot be deployed on a large scale without impacting product quality. Increasing the share of recycled fibre from waste paper reduces the specific energy consumption (energy consumption per unit of output) required to produce 1 tonne of paper, but high-grade paper cannot be produced from waste paper. Similarly, lowering the clinker-to-cement ratio by using substitution materials reduces energy consumption in the cement industry, but it alters the strength of the cement, rendering it unsuitable for certain applications.

Third, energy-intensive industries, more so than others, satisfy their own energy needs partly by using waste heat and gas recovery. As this energy is not traded, it is difficult to estimate its true size, which can lead to distorted energy statistics. Similarly, energy statistics generally distinguish between energy transformation and final consumption, while this does not necessarily reflect real-world structures. In an integrated steel plant, for example, a coke oven and blast furnace (considered as energy transformation) and steel production (considered as final consumption) are parts of the same plant. This makes it difficult to estimate energy demand for each part, leading to some cases where energy demand of the transformation sector is estimated based on the output of industrial gases. Moreover, data is not available on occasion to protect competitiveness or because of the lack of strong statistical frameworks.

Because of these challenges, only few dedicated studies have been published that project and analyse global industrial energy use in a comprehensive way. Several studies have been carried out that have looked at industrial energy demand at a regional level, such as for the European Union (Kuder and Blesl 2010), Canada (Murphy et al. 2007) and the USA (Worrell and Price 2001), as well as at a sectoral level, such as for iron and steel (Hasanbeigi et al. 2013; Pardo and Moya 2013), cement (Ke et al. 2012), pulp and paper (Fleiter et al. 2012) and petrochemicals (Saygin et al. 2011). Other researchers have studied the role of energy efficiency in CO_2 emission reduction (Akashi et al. 2011; Saygin et al. 2013). Greening et al. (2007) provide an overview of methods that have been used to model energy use in industry. This includes econometric methods, macroeconometric models, computable general equilibrium models, input/output models and bottom-up optimisation and simulation models. Fleiter et al. (2011) review bottom-up models for industrial energy demand and highlight the insufficient representation of efficiency barriers and policy measures. An example of a bottom-up model is the IEA's Energy Technology Perspectives model (IEA 2012a; Gielen and Taylor 2007). The model is used to analyse how technologies can make a decisive difference in limiting climate change and enhancing energy security.

The subsequent analysis is based on the World Energy Model (WEM), which is used for the IEA's WEO (IEA 2012b). This is a bottom-up simulation model that captures the entire energy system from energy supply to energy demand. It focuses on economic aspects, such as the uptake of energy efficiency options according to payback periods, and projects scenarios based on policies rather than cost optimisation.

The purpose of this paper is not to present solutions to the aforementioned problems but rather to provide some insights on the modelling of industrial energy use in WEM, to present projections for energy demand and CO_2 emissions up to 2035 and to analyse economic efficiency potentials in the industry sector on a global scale, which are derived from the energy efficiency analysis conducted for the World Energy Outlook 2012. The section "Current situation" of the paper gives an overview of current energy consumption and CO_2 emissions in industry. The section "WEO's industry modelling" explains the modelling approach used with a focus on industry modelling. The last two sections present detailed results of the economic energy efficiency potential and offer conclusions.

Current situation

Global primary energy supply in 2011 was 13,113 million tonnes of oil equivalent (Mtoe) (1 Mtoe = 41.868 PJ), while total final energy consumption was 8,918 Mtoe. The global industry sector consumed 2,557 Mtoe, or 29 % of the total (IEA 2013c). This excludes fuel use for feedstock, which is classified as non-energy use in IEA statistics, as well as fuel use in coke ovens and blast furnaces, which is part of energy transformation. If feedstock use (625 Mtoe) and energy use in coke ovens and blast furnaces (253 Mtoe) are added, total energy use in the wider industry sector is 3,435 Mtoe.

While coal makes up almost all the input fuel for coke ovens and blast furnaces, oil dominates petrochemical feedstock consumption. The industry sector itself shows a more balanced fuel mix in final consumption. In 2011, the share of coal was 29 %, electricity 26 %, natural gas 20 %, oil 13 %, biomass and waste 8 % and heat 5 % (Fig. 1).

Including coke ovens and blast furnaces, as well as feedstock use in the industry sector, energy-intensive industries account for around 64 % of total energy consumption in the industry sector. The chemical and petrochemical industry (including feedstock) accounts for 30 % (18 % attributable to feedstock) of total final industrial energy consumption, followed by the iron and steel industry with 22 % (8 % attributable to coke ovens and blast furnaces). The cement and pulp and paper sector accounts for a further 12 % of industrial energy consumption. The remaining 36 % is made up of a variety of mostly non-energy-intensive industry subsectors, such as food and tobacco, machinery, non-ferrous metals, mining and quarrying, textile and leather, construction and transport equipment.

Concerning the distribution of the wider global industrial demand by country and region, China accounts for 30 %, the USA 11 %, the European Union 11 %, India 6 %, Russia 6 %, the Middle East 5 % and Japan 4 % (Table 1). More than half of the Chinese industrial energy demand originates from only two sectors: cement, and iron and steel (including coke ovens and blast furnaces). These two sectors in China consume more energy than Japan as a whole. From 2001 to 2011, Chinese industrial energy consumption increased two and a half times from 316 Mtoe to 785 Mtoe (IEA 2003). While Chinese industry represented about 14 % of global industrial energy consumption in 2001, it overtook the European Union and the USA in terms of energy consumption in the subsequent years and consumes today more than the two regions combined.

CO_2 emissions in 2010 amounted to 5.2 Gt in the industry sector, with an additional 0.2 Gt emitted from coke ovens and blast furnaces. As the total energy-related CO_2 emissions was at 30.5 Gt in 2010 (IEA 2013d), the industry sector accounted for roughly 20 % of all emissions. Almost two thirds of total industrial CO_2 emissions from fuel combustion result from only three industries: iron and steel (including coke ovens and blast furnaces), cement and chemicals and petrochemicals. These numbers do not include indirect emissions resulting from the generation of electricity used in industry, which amounted to 4.6 Gt CO_2 in

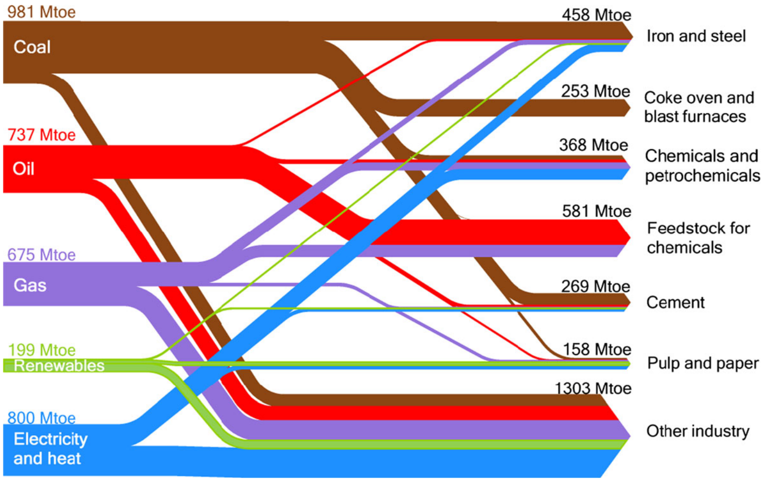

Fig. 1 Energy flows in the industry sector in 2011. Flows below 5 Mtoe are not represented, source IEA (2013b, c)

Table 1 Global industry energy demand by sector and selected regions in 2011 (Mtoe)

	China	USA	European Union	Others	World
Iron and steel	222	21	34	177	458
Chemical and petrochemical	113	73	56	172	368
Non-ferrous metals	47	13	10	45	115
Non-metallic minerals	165	26	37	103	331
Transport equipment	15	11	8	9	43
Machinery	51	21	20	35	127
Mining and quarrying	17	2	3	49	71
Food and tobacco	28	32	28	78	166
Paper, pulp and print	22	54	33	51	158
Wood and wood products	5	13	8	6	32
Construction	15	1	6	21	43
Textile and leather	29	6	5	14	54
Non-specified	57	13	21	448	590
Total	785	287	269	1,208	2,557
Chemical feedstock	58	93	77	356	625
Coke ovens and blast furnaces	138	7	21	100	253

Source IEA (2013b), c

2010. Thus, direct and indirect emissions from the industry sector were 9.8 Gt CO_2 in 2010, or 34 % of total emissions (IEA 2012b).

IEA statistics represent the most authoritative source of information on energy. Due to competitiveness issues in certain sectors and countries, where information is considered sensitive, statistics cannot always be complete. In some countries, the capacity does not always exist to collect data of sufficient quality or in sufficient detail. Such examples of data quality render it difficult to capture all information at the level of detail necessary for energy modelling (see also IEA 2013c). While approaches are continuously being undertaken to improve data quality, good data is essential to improve the modelling of global industrial energy use and CO_2 emissions.

WEO's industry modelling

Since 1993, the IEA has provided from medium- to long-term energy projections relying on the WEM. The model is a large-scale simulation model designed to replicate the functioning of energy markets and is the principal tool used to generate detailed energy and emissions projections for specific sectors and regions for the WEO.

World Energy Model[1]

The WEM is a partial equilibrium model consisting of three main modules: final energy consumption, covering residential, services, agriculture, industry, transport and non-energy use; energy transformation, covering power generation and heat, refinery and other transformation; and energy supply, covering coal, oil, natural gas and biomass (Fig. 2). Much of the data on energy supply, transformation and demand, as well as energy prices, is obtained from the IEA's own databases and economic statistics. The current version of WEM includes energy developments up to year 2035 in 25 regions with 12 countries being individually modelled. More details on the WEM can be found in the documentation of the model (IEA 2013a).

The main exogenous assumptions are economic growth, demographics, CO_2 prices and technological developments. Electricity consumption and electricity prices dynamically link the final energy demand and transformation sectors. International fossil fuel prices are derived through iterative modelling between the demand and supply modules, where energy demand serves as an input for the supply modules. Complete energy balances are compiled on a regional level, and

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[1] This section is largely based on the model documentation of the World Energy Model (IEA 2013a).

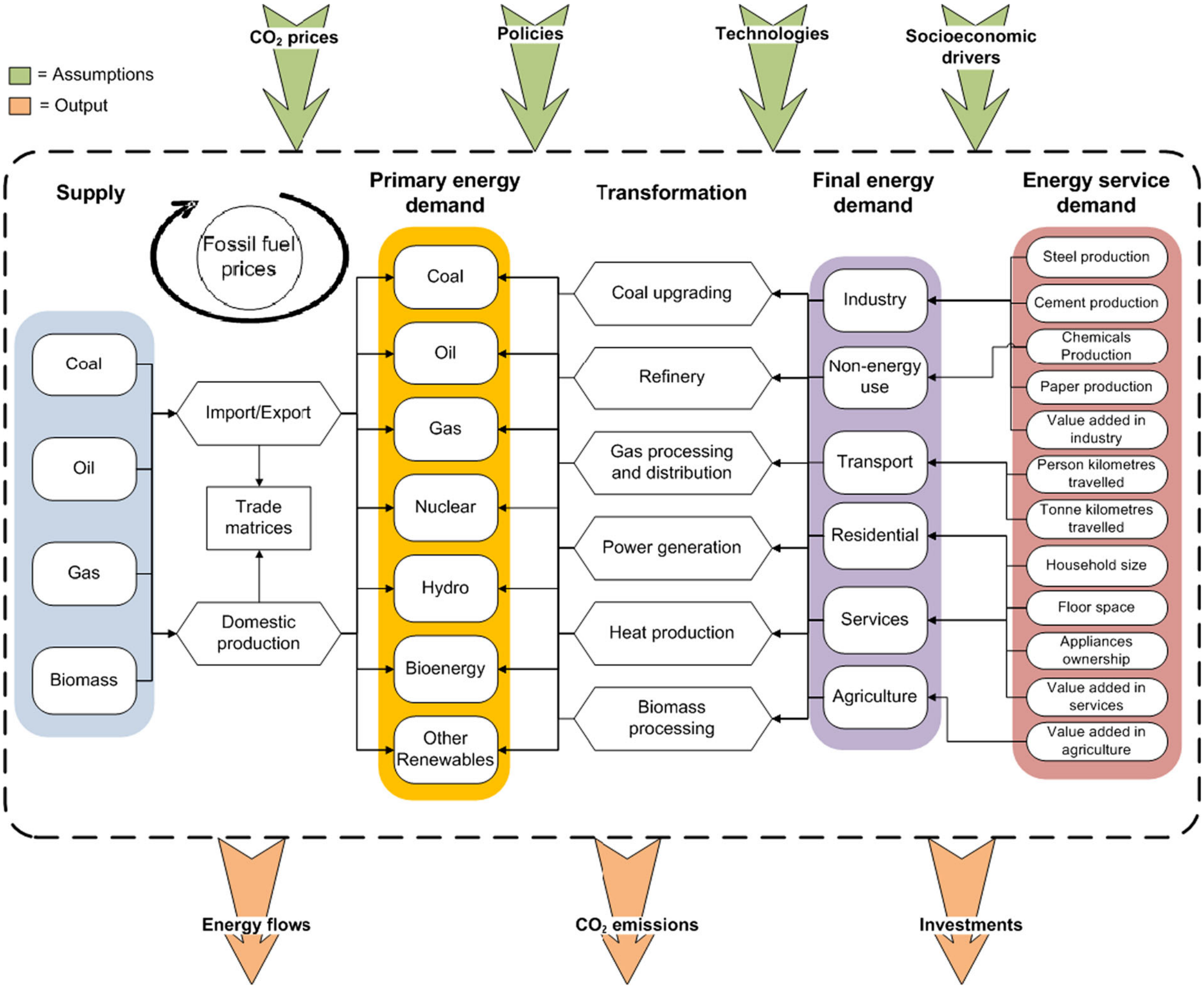

Fig. 2 World Energy Model Overview, source IEA (2013a)

the CO_2 emissions of each region are calculated using derived CO_2 factors. The model is recalibrated every year to the latest available data.

The same macroeconomic and demographic assumptions are used in all scenarios unless otherwise specified. Projections are based on the average retail prices of each fuel used in final uses, power generation and other transformation sectors. These end-use prices are derived from assumptions about the international prices of fossil fuels and subsidy/tax levels.

Rates of population growth for each WEM region are based on the most recent medium fertility variant projections contained in the United Nations Population Division report (UNPD 2011). World population is projected to grow by 0.9 % per year on average, from 6.8 billion in 2010 to 8.6 billion in 2035. Population growth slows over the projection period, in line with trends of the last three decades: from 1.1 % per year over 2010–2020 to 0.8 % over 2020–2035. The population expanded by 1.4 % from 1980 to 2010. Global GDP (expressed in year-2011 dollars at purchasing power parity [PPP] terms) is expected to grow on average by 3.5 % per year over the projection period. That rate is a little higher than in last two decades (3.2 % over 1990–2010) due to the financial crisis and its rebound. Growth is assumed to drop from 4.0 % over 2010–2020 to 3.2 % over 2020–2035.

Demand side drivers, such as steel production in industry or household size in dwellings, are estimated econometrically based on historical data and socioeconomic drivers. All end-use sector modules base their projections on the existing stock of energy infrastructure. This includes the number of vehicles in transport, production capacity in industry and floor space area in buildings. To take into account expected changes in structure, policy or technology, a wide range of technologies are integrated in the model that can satisfy each specific energy service. Taking into account the efficiency level of end-use technologies gives final energy demand for each sector and sub-sector.

The WEM is used to project energy trends for a set of policy developments represented in scenarios. The scenarios differ with respect to what is assumed about the forthcoming government policies related to the energy sector, while socio-economic assumptions (population, GDP growth, industrial production) remain the same. There is a high degree of uncertainty about how governments will intervene in energy markets, and commitments and targets will undoubtedly change in the years to come. Two scenarios from WEO-2012 are analysed in this paper (IEA 2012b):

- The New Policies Scenario—the central scenario—takes into account broad policy commitments and plans that have already been implemented to address energy-related challenges as well as those that have been announced even where specific measures have not yet been introduced.
- The Efficient World Scenario quantifies the implications for the wider energy system where all investments capable of improving energy efficiency are made so long as they are economically viable, and any market barriers obstructing their realisation are removed. For the industry, the average acceptable payback period is 5 years in OECD countries, and 3 years in non-OECD countries in this scenario.

Since the aim of this paper is to explore the economic potential of energy efficiency in the global industry sector, it concentrates mainly on the Efficient World Scenario and compares the results with those of the central scenario, the New Policies Scenario.

Industry model structure

The industrial sector in WEM is split into five sub-sectors: iron and steel, chemicals and petrochemicals, cement, pulp and paper and other industries. The iron and steel industry sub-sector is modelled together with energy transformation in coke ovens and blast furnaces. Similarly, petrochemical feedstocks are modelled together with energy use in the petrochemical and chemical industry. However, in accordance with IEA energy balances, energy demands from coke ovens and blast furnaces, as well as petrochemicals feedstock, are not included in the industry sector in the "Results" section. Due to the variety of products in the chemical and petrochemical sub-sector, it is broken down further according to key intermediate products: ethylene, propylene, aromatics (benzene, toluene, xylenes), methanol and ammonia.

The industry model contains three main features: the activity calculation of industrial goods, the calculation of energy intensity and the projections of fuel shares in the various industrial sub-sectors. The first step in the industry model is to calculate activity variables, such as steel or cement production, based on drivers such as population and GDP. Given information on the age profile of the existing capacity, the production projections are used to derive the amount of newly built infrastructure. In the second step, final energy consumption is determined for each sub-sector taking account of capital stock turnover and specific energy intensities for newly constructed industrial plants. Finally, fuel shares are calculated in a least-cost approach.

Production and capacity projections

Each industrial sub-sector's energy consumption is driven by the production of a specific industrial good, while the chemical and petrochemical sub-sector is divided into key intermediate products (Table 2).

The per capita production of energy-intensive goods is econometrically projected for a specific year based on socio-economic variables and energy prices. In the chemical sector, feedbacks from the supply module and refinery model are integrated to take into account the availability of petroleum-based feedstocks.

As an example, the econometric projection of steel production takes the following form for each model region:

$$\ln\left(\frac{\mathrm{steel}_t}{\mathrm{pop}_t}\right) = \alpha * \ln\left(VA_{\mathrm{ind},t}\right) + \beta * \ln(\mathrm{price}_t) + \gamma * \ln\left(\frac{\mathrm{steel}_{t-1}}{\mathrm{pop}_{t-1}}\right) + \delta_{\mathrm{time}} + \varepsilon \qquad (1)$$

where steel_t is the steel production in year t; pop_t is the population in year t; $\mathrm{VA}_{\mathrm{ind},t}$ is the value-added in industry in year t; price_t is the weighted average energy price in the steel sector in year t; δ_{time} is a time constant and ε is a constant. Thus, the first term represents value-added

Table 2 Activity variables in industrial sub-sectors

Sub-sector	Activity variables
Iron and steel	Crude steel
Chemical and petrochemical	Ethylene
	Propylene
	Aromatics
	Methanol
	Ammonia
Cement	Cement
Pulp and paper	Paper
Other industries	Value-added in industry

in industry, the second represents the energy price, the third represents per capita production in the preceding year, and the fourth is a time constant. The regression coefficients have been estimated from an ordinary least square regression analysis using data for the period 1990–2010. The amount of steel produced in a given region is obtained by applying the exponential function and multiplying by the population in year *t*. The approach is more robust for regions where the overall economic structure is anticipated to remain stable as it is calibrated to the past data. In total, almost two thirds of today's industrial energy demand (including chemical feedstock and coke ovens/blast furnaces) are modelled via physical production.

Building on the production projections for industrial goods in each sub-sector, an estimation of the capacity needed can be derived via a simple assumption of average sector specific capacity utilisation rates. The routinely demolished capacity in each year is calculated based on the age profile of existing infrastructure and using a demolition rate:

$$\text{capacity}_{\text{demolished},t} = \sum_{i=1}^{65} \text{capacity}_{\text{new},t-i} * \text{demolition rate}_i \tag{2}$$

where $\text{capacity}_{\text{demolished},t}$ is the routinely demolished capacity in year *t*, $\text{capacity}_{\text{new},t\text{-}i}$ is the newly built capacity in year *t-i*. The demolition rate is based on a logistic distribution assuming an average lifetime of the industrial infrastructure in each sub-sector.

$$\text{demolition rate}_i = \frac{1}{1+\alpha * \exp(-\beta * \text{i})} \text{ with } \beta = \frac{\ln\alpha}{\text{life time}} \tag{3}$$

where α and β are parameters of the logistic distribution, and *i* describes the time period.

Consequently, new infrastructure can be calculated according to the following equation:

$$c\text{apacity}_{\text{new},t} = \max(\text{capacity}_{\text{required},t} - \text{capacity}_{\text{required},t\text{-}1} + \text{capacity}_{\text{demolished},t}, 0) \tag{4}$$

where $\text{capacity}_{\text{new},t}$ is the newly built capacity in the year *t*, $\text{capacity}_{\text{required},t}$ is the required capacity in year *t* and $\text{capacity}_{\text{demolished},t}$ is the routinely demolished capacity in year *t*.

Energy intensity

Based on the IEA statistics and data for the historical production of industrial goods, it is possible to determine the historical energy intensity in tonnes of oil equivalent per tonne of an industrial good (toe/t). This provides a link between the production of industrial goods and final energy consumption.

For determining the energy intensity of new capacity, the model has two options. The first applies an improvement that is as efficient as the stock average in the base year (this depends on sector and region). The second exploits the economic efficiency potential to some extent (depending on the scenario) and has thus a lower energy intensity. The share between the two capacity types is determined based on energy price developments and a time constant. In order to determine the economic efficiency potential, a range of technologies in each process step, together with their specific investment costs and diffusion potential, were analysed for all sub-sectors (IEA 2012b) (Fig. 3). Based on this information, an efficiency curve was constructed that shows efficiency savings potential as a function of the payback period. Within energy modelling, efficiency cost curves are a widely used tool for the assessment of energy-saving opportunities (Fleiter et al. 2012, Morrow et al. 2012). In WEM, efficiency cost curves are established for each major process steps in the energy-intensive industries and for each cross-cutting technology in non-energy-intensive industries.

Energy policies can have two effects on such cost curves. Either they increase the accepted payback period of an energy efficiency investment, e.g. through the implementation of financial incentives, or they increase the diffusion potential of energy-saving technologies, e.g. through awareness raising or capacity building.

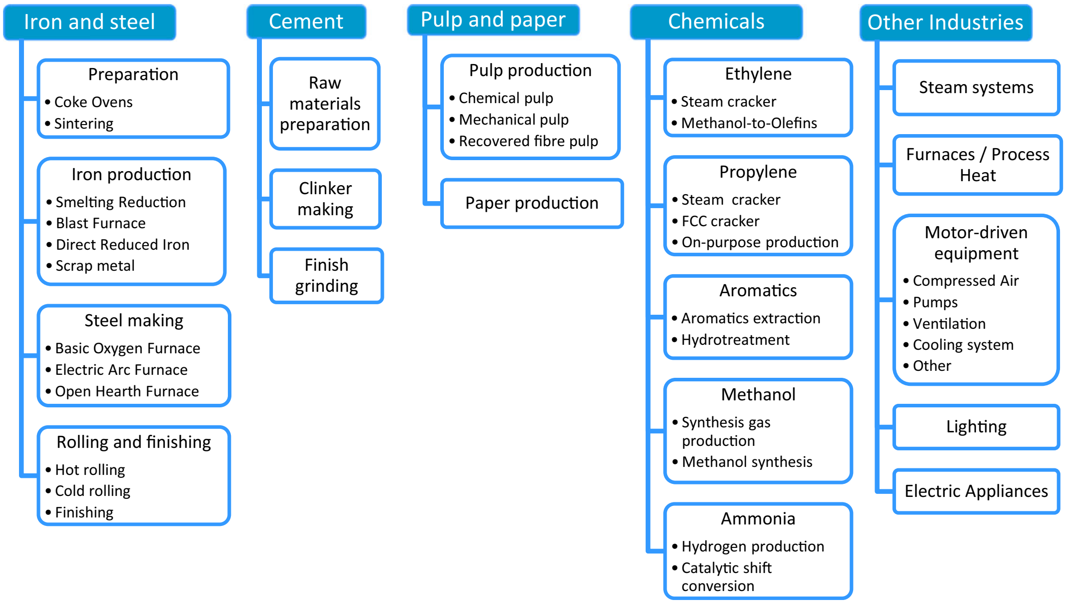

Fig. 3 Major process steps by sub-sector in industry, source IEA (2013a)

Depending on the scenario and the region, the maximum accepted payback period ranges between 2 and 15 years.

In order to increase the diffusion potential of efficiency measures and make higher payback periods acceptable, the Efficient World Scenario assumes an accelerated deployment of existing policy instruments, including enhanced efficiency standards, e.g. the adoption of high-efficiency electric motor systems, benchmarking and the implementation of energy management and energy audits. These are complemented by supportive measures, like capacity building and provision of information. In addition, new policy measures are developed to promote the use of recycled materials, where locally available, to reduce manufacturing energy requirements. Lastly, in order to make investments with long payback periods more attractive, fiscal and financial incentives play an important role.

Historical data on the specific energy intensity of new plants is established as a function of their construction year based on the rough assumption that new infrastructure is a certain fraction more efficient than the stock average at the time. Given information on capital stock turnover and the adoption of energy-saving technologies, the improvement in overall energy intensity can be calculated. As a starting point, the energy intensity in the base year is taken, corrected for the influence of business cycles in the base year through a Hodrick-Prescott filter.[2] Currently, the model does not explicitly allow the option of retrofit but only allows for the adoption of energy-saving technologies at the point of capital turnover. In order to account for the possibility of replacement or retrofit of specific parts in an industrial plant, the lifetime of the industrial equipment was not set to the lifetime of an entire industrial facility, which can easily exceed 50 years, but it was set equivalent to the lifetime of energy-consuming parts with lifetimes between 15 and 30 years.

Technological efficiency is not the only way to improve efficiency in the industry model. Operational efficiency, which is econometrically projected (and influenced mainly by energy price developments), can further lower the specific energy intensity in the short term (Fig. 4).

In general, long-term energy intensity improvements in industry can be classified into three main categories:

1) Adopting better equipment and technology.
2) Managing energy and optimising operations. Systems optimisation means going beyond component replacement towards integrated system design and operation.

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[2] The Hodrick-Prescott filter separates the cyclical component of a time series from the underlying trend.

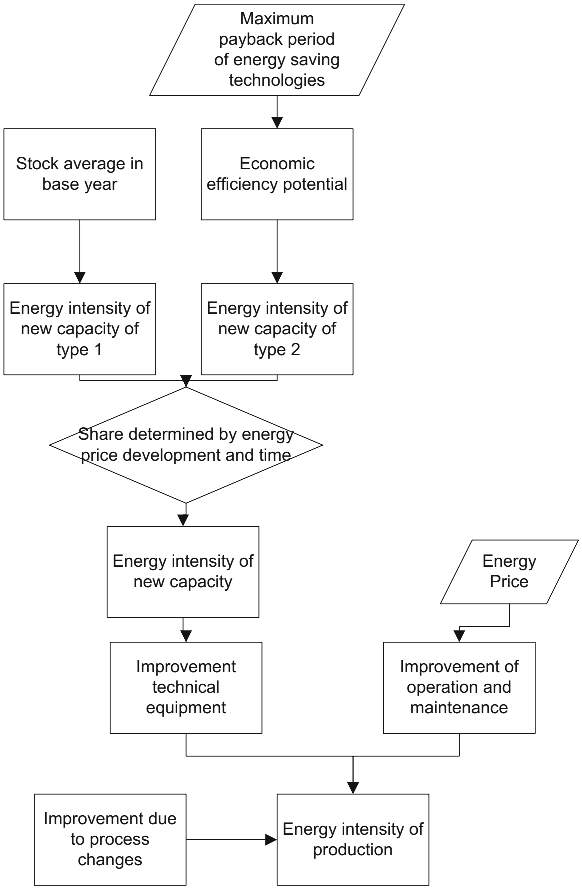

Fig. 4 Overview of energy intensity calculation

3) Holistically transforming production systems. More radical reductions in industrial energy use can be achieved by using an integrated approach to the management or resources and waste, e.g. by using more scrap metal or waste paper.

In the industry model, technical equipment and operational efficiency capture the first two categories, while intensity improvements through process changes are representative of the third. Process changes that affect energy consumption can take various forms in the different sub-sectors: a higher share of direct reduced iron (DRI) in iron production, a higher availability of scrap metal, a higher share of electric arc furnaces (EAF) in steel production, a higher use of waste paper in paper production, or a higher clinker substitution in cement production. Such process changes can offer significant savings potential for energy consumption, but their deployment is limited due to constraints on the availability of resources and impacts on product quality.

The impact of process changes on energy consumption is possible due to the technological detail in the model. For the steel sector, for example, the model distinguishes between three different processes for iron production plus the use of scrap metal and two routes for steel production. Given that these processes have different energy intensities, changes in the production mix directly affect energy consumption. The production shares for each process are exogenous to the model and are based on calculations that take into account scrap metal availability, stock turnover, industry trends and saturation effects with information taken from literature and industry sources.

As an example, the energy intensity calculation in the cement sector for a given region could look as follows: The maximum acceptable payback period for efficiency technologies is set to 5 years which, according to the efficiency cost curve, means that new capacity in year *t* is 19 % more efficient than the average intensity in the base year. The share of the more efficient technology (type 2) is determined to be 38 %, yielding an average efficiency improvement of 7 % for new capacity in year *t*. As newly built capacity represents about 8 % of existing capacity in year *t*, the average energy intensity in year *t* is 1 % less than in *t-1*. As a consequence of a stable price level, the contribution from operational efficiency is negligible, but process change in the form of a lower clinker-to-cement ratio contributes a further 0.3 % in energy savings per tonne of cement. In total, cement production, in this example, uses 1.3 % less energy per tonne in *t* than in *t-1*.

Fuel shares

Since there exist only limited opportunities to substitute electricity for fuels and vice versa in the industry sector, the two are modelled separately. This means that electricity intensity and fuel intensity are calculated for each sub-sector. However, potential electrification of the energy-intensive industry sector is taken into account via wider process changes (for example, by increasing the share of electric arc furnaces in steel production). In addition, the potential for the use of industrial heat pumps to provide low temperature heat, particularly in the food, paper and chemicals industry, is accounted for separately. Fuel switches, for example, from oil-based products to natural gas are modelled separately for each industrial sub-sector via a multiple logit model. First, a utility function is defined for each fuel:

$$V_{i,t} = \alpha_i * \frac{\text{price}_{i,t}}{\text{price}_{\text{fuel average},t}} + \beta_{\text{time}} * t + \gamma_{\text{adj}} \quad (5)$$

with $i =$ coal, oil, natural gas, heat and biomass

where $V_{i,t}$ is the utility function of fuel i at year t; α_i is a regression coefficient for fuel i; $\text{price}_{i,t}$ is the fuel price of fuel i at year t; and $\text{price}_{\text{fuel average},t}$ is the weighted average price of all fuels at time t. β_{time} is a time constant and γ_{adj} is an adjustment factor that represents non-price influences, such as energy policies. The regression coefficients were calculated using a maximum likelihood estimation based on data for the period 1990–2010.

In the next step, the choice probability is determined based on the utility function of each fuel:

$$\pi_{i,t} = \frac{\exp\left(V_{i,t}\right)}{\sum_i \exp\left(V_{i,t}\right)} \quad (6)$$

where $\pi_{i,t}$ is the choice probability of fuel i at time t.

The fuel share is eventually calculated taking into account the fuel share in the previous year and the choice probability:

$$\text{share}_{i,t} = \text{share}_{i,t-1} + \delta * \left(\pi_{i,t} - \pi_{i,t-1}\right) \quad (7)$$

where $\text{share}_{i,t}$ stands for the share of fuel i in year t, and δ is between 0 and 1 and represents the adjustment speed.

Results[3]

In 2010, industry was responsible for 29 % of global final energy use and 34 % of energy-related CO_2 emissions (including indirect emissions). This share is anticipated to stay roughly constant through the projection period to 2035 in the New Policies Scenario. In the WEO projections, most of the increase in industrial production through to 2035 occurs in non-OECD countries. Growth in developing and emerging countries requires the use of energy-intensive goods, such as steel and cement for buildings or petrochemicals for the increasing use of consumer goods. The analysis shows that the need for new industrial capacity will slow significantly after 2020 in the cement sub-sector and also, to a lesser degree, in the iron and steel sub-sector (Fig. 5). In the cement sector, for example, it is projected that between 2021 and 2035, new cumulative capacity installations in non-OECD countries represent only 34 % of currently existing production capacity. This development is mainly driven by slowing demand for cement and steel in China where the rate of urbanisation and the annual increase in floor space area decreases over the next two decades.

The potential for energy efficiency improvements varies across industry sub-sectors. While, in many OECD countries, large energy-intensive industries already use efficient technologies, further improvements can be realised by replacing older facilities, optimising processes or through enhanced energy management practices. Untapped potential particularly remains in the non-energy-intensive industry sector where energy costs usually represent a lower share of production costs. In non-OECD countries, new manufacturing facilities in energy-intensive industries are in most cases equipped with the latest efficient technologies. These new plants are often large in scale and therefore more energy efficient, since production size has a strong influence on specific energy consumption However, older infrastructure in non-OECD regions is in most cases less efficient and accelerating the closure of plants with outdated technology can produce significant energy savings.

In the Efficient World Scenario, demand for final energy in the industry sector increases by 31 % over 2010–2035, compared with a rise of 44 % in the New Policies Scenario. Global energy consumption continues to grow in all sub-sectors, as the annual intensity improvements achieved (ranging from 0.5 to 1.6 %) are unable to counteract the rapid growth in industrial production. Figure 6 highlights the fact that already existing policies and those under discussion, as assumed in the New Policies Scenario, lead to a significant amount of energy efficiency savings, while the Efficient World Scenario goes beyond that by overcoming existing barriers and exploiting the full economic potential.

Most of the cumulative final energy savings in the industry, with respect to the New Policies Scenario, come from reduced use of electricity (40 %), followed by lower use of coal (23 %) and natural gas (18 %). The reduction in electricity is mainly the result of a more efficient energy use in electric motor-driven systems as they represent up to 70 % of the total industrial

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[3] In this section, industry sector energy demand is calculated in accordance with IEA energy balances, i.e. neither demand from coke ovens and blast furnaces nor petrochemical feedstocks are included.

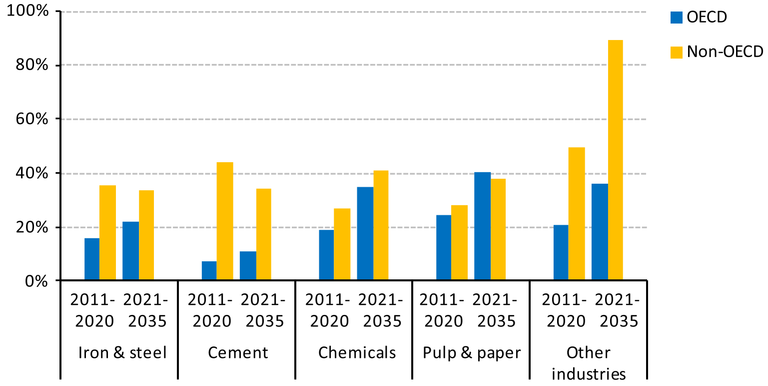

Fig. 5 Cumulative new industry capacity as a share of currently installed global capacity in the Efficient World Scenario. This includes replacements of currently existing capacity, source IEA (2012b)

electricity use. Global demand for oil remains broadly flat in the future, while demand for gas, electricity and biomass increases significantly (Table 3). Oil is mainly used for process heat and in steam systems with a lower share being consumed in off-road vehicles in the construction and mining sector. In most regions, some oil is substituted mainly for natural gas in industrial furnaces and steam systems for cost reasons and also because of lower pollution levels.

On a regional level, China accounts for 39 % of cumulative energy savings and India for 14 %. Only 16 % of savings arise in OECD countries. The extensive deployment of energy-efficient technologies contributes to climate mitigation objectives by slowing growth in energy-related CO_2 emissions from the industry sector. This means that the growth in CO_2 emissions can be limited to 7 % between 2010 and 2035, compared to an increase of 25 % in the New Policies Scenario. Worrell et al. (2009) estimate the CO_2 mitigation potential in the industry by 2030 to be between 5 and 40 % depending on the industrial sub-sector. CO_2 emissions savings in the Efficient World Scenario compared with the New Policies Scenario are rather towards the bottom of that range (12 % in 2030) since significant efficiency savings are already integrated in the New Policies Scenario.

Trends by sub-sector

Within the industry sector, energy consumption in the chemical and petrochemical sub-sector together with non-energy-intensive industries increase the most (Fig. 7). The energy demand growth in the chemical sector is mainly a reflection of the continuing demand for plastics, which require the production of energy-intensive petrochemical intermediate goods. Energy use in non-energy-intensive industries reflects the more general economic growth, which requires higher energy consumption for the production of machines, vehicles and electronic equipment amongst others. Energy consumption in iron and steel, as well as cement, is below 1 % per year as there is very limited growth for these products in OECD countries. More importantly, steel and cement production in China, which accounts for almost half of global steel production and almost 60 % of global cement production, reaches a peak before 2020 as demand from the domestic construction sector slows down.

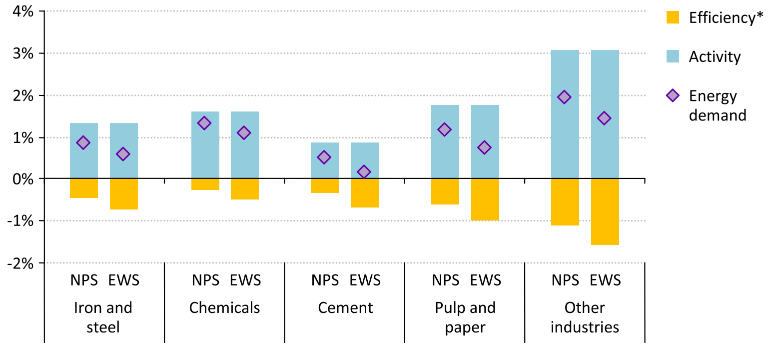

Fig. 6 Average annual change in industrial activity, efficiency and energy demand by industrial sub-sector and scenario, 2010–2035. *Negative values for efficiency represent improvements. *NPS* New Policies Scenario, *EWS* Efficient World Scenario

Table 3 Global industry energy demand by fuel and energy-related CO_2 emissions in the Efficient World Scenario (Mtoe)

	2010	2020	2035	CAAGR[a] 2010–2035 (%)	Change versus New Policies	
					2020 (%)	2035 (%)
Coal	676	769	748	0.4	−4	−9
Oil	321	343	330	0.1	−4	−7
Gas	463	577	688	1.6	−4	−8
Electricity	638	838	999	1.8	−6	−12
Heat	126	133	121	−0.2	−4	−8
Bioenergy[b]	197	242	285	1.5	−4	−8
Total	2,421	2,901	3,171	1.1	−4	−9
CO_2 emissions (Gt)	9.8	10.9	10.5	0.3	−7	−15

CO_2 emissions include indirect emissions from electricity and heat

[a] Compound average annual growth rate

[b] Includes other renewables

Source IEA (2012b)

Iron and steel

Currently, some 70 % of world steel is produced by the blast furnace/basic oxygen furnace route (World Steel Association 2012). With blast furnaces accounting for the largest part of energy consumption (by far), reducing it has been a particular focus. In the Efficient World Scenario, widespread adoption of top pressure recovery turbines and blast furnace gas recovery is implemented. Pulverised coal injection is increased to reduce coke demand, and combined cycle gas turbines are used in place of steam turbines to increase the thermal efficiency of power generation from blast furnace gas.

When electric arc furnaces (EAF) are used for steel making, direct current arc furnaces can significantly reduce energy intensity; but this technology is applicable only to furnaces above a certain production size. In the Efficient World Scenario, we assume a higher proportion of scrap metal is recycled in some economies, resulting in major energy savings. We also assume a higher share of EAFs, which results in higher overall electricity consumption, but of lower fuel consumption. Both process changes—greater use of scrap metal and of EAFs—account for more than a third of all energy savings in the iron and steel sector. Gas-based direct reduced iron (DRI) is another option for less energy-intensive iron and steel making, as emphasised by the DRI facilities recently built in Iran and in Louisiana in the USA. However, the future development of DRI is uncertain, partly due to questions about how gas prices will evolve. In the Efficient World Scenario, the combination of the above changes decreases the fuel intensity of iron and steel production by 11 % in OECD countries and 19 % in non-OECD countries between 2010 and 2035. Energy savings in iron and steel in 2035, compared with the New Policies Scenario, are 35 Mtoe, or 6 %.

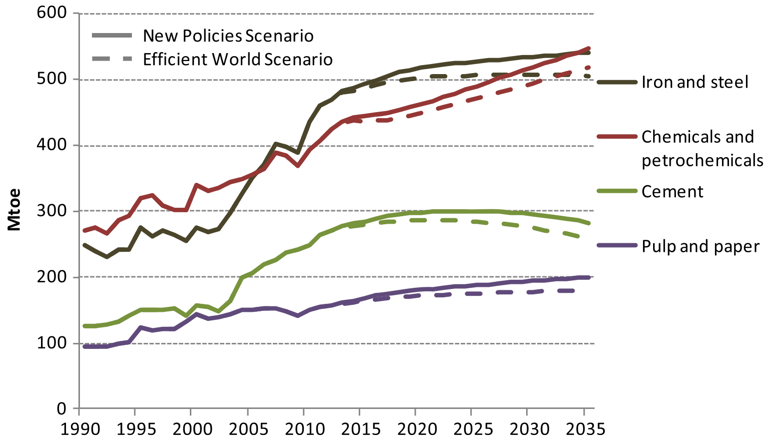

Fig. 7 Global energy consumption by industrial sub-sector and scenario, 1990–2035

Chemicals

The chemicals sector is very diverse, as are the technology options for saving energy. Significant energy savings are possible from the recovery and use of waste heat, co-generation, efficiency gains in steam crackers, increasingly selective catalysts and increasing the size of crackers and furnaces. Additional savings can be realised from the process intensification and the co-ordination of energy use with neighbouring plants. Moreover, the integration of petrochemical and refinery plants can result not only in energy savings but also lower transport costs, lower storage requirements and increased feedstock flexibility. In the Efficient World Scenario, wider deployment of these technologies and organisational measures reduces the sub-sector's energy use in 2035 by 5 %, or 28 Mtoe, compared with the New Policies Scenario.

Cement

The energy intensity of cement production is largely dependent on the type of kiln technology employed for clinker production. Dry kilns with pre-heaters and a pre-calciner are significantly more efficient at clinker production than shaft kilns, which are still found in China and India, or wet/semi-dry/dry kilns which are used in the European Union, Russia and the USA. Important savings can be achieved by implementing heat recovery. In the Efficient World Scenario, it is assumed that there is a complete transition by 2035 to dry kilns with pre-heaters and pre-calciners in North America and the European Union, while shaft kilns are completely phased out in India and China.

Energy savings are realised in raw materials preparation and grinding by the introduction of high-efficiency classifiers and by the use of vertical roller mills (CSI and ECRA 2009). Compared today, additional efforts are made to replace clinker with alternatives, such as fly ash, blast furnace slag, limestone and pozzolana, which yield substantial energy savings. The reduction of the clinker-to-cement ratio accounts for roughly one fifth of energy savings in the cement sector. Globally, the measures adopted reduce energy demand in cement manufacturing in 2035 by 8 %, or 24 Mtoe, compared with the New Policies Scenario.

Pulp and paper

In pulp and paper production, the chemical pulping process is the most energy-intensive step. Black liquor gasification has the potential to save a significant amount of energy in this step, although its use is currently limited. In the mechanical pulp production process, the use of high-efficiency grinding, efficient refiners and pre-treatment of wood chips can reduce energy consumption substantially, compared with conventional processes. However, by far, the greatest potential for savings is from higher use of recycled fibre. Much of this potential has already been realised in some economies, such as in the European Union, but the use of recycled paper in pulp production can be further increased, especially in many non-OECD countries. At the global level, 50 % of waste paper is currently recycled (IEA 2010). The use of recycled paper as an input to paper production is driven not only by energy considerations but also by factors such as availability and product quality specifications. Technologies to reduce energy consumption in paper production include shoe press, heat recovery and new efficient drying techniques. Systems optimisation in the form of improved process control, monitoring and management can help reduce energy consumption beyond what is achievable by single equipment components. The deployment of all of these options is increased in the Efficient World Scenario, reducing energy demand in pulp and paper in 2035 by 10 %, or 19 Mtoe, compared with the New Policies Scenario.

Other industries

The category "other industries" includes the remaining industry sub-sectors, which generally are not energy intensive. This category includes a wide range of diverse sub-sectors. The largest energy consumers are food and tobacco, machinery, non-ferrous metals, mining and quarrying and textiles. In total, this category accounted for 49 % of total industrial energy use in 2010, but in the Efficient World Scenario, it makes up 65 % of the total cumulative energy savings in industry over 2011–2035. This is because energy-intensive sectors have, in the past, made significant energy savings, so that the largest potential for additional energy savings now lies in non-energy-intensive sub-sectors, where the share of energy costs in total production costs rarely exceeds 20 % (UNIDO 2010). Roughly half of all savings in other industries is in the form of electricity, and it is estimated that 70 % of all electricity used in the industry is related to electric motor systems that are used for ventilation, pumps, compressed air and mechanical movement (IEA 2011). The introduction of variable-speed drives and the proper sizing of motors achieve significant savings, since electric motors operate more efficiently at full power. Further areas for energy improvements include boilers, furnaces and specific process technologies. The overall effect is to reduce energy demand in 2035 by 11 %, or 220 Mtoe, compared with the New Policies Scenario.

Conclusions

The Efficient World Scenario developed for the World Energy Outlook 2012 has shown that industrial energy demand growth can be slowed significantly by exploiting the economic potential of energy efficiency. Total energy savings in 2035 amount to 9 %, or 326 Mtoe, in the Efficient World Scenario compared with the central scenario, the New Policies Scenario. The same holds true for CO_2 emissions, which is 1.8 Gt lower in the Efficient World Scenario.[4]

Yet, there are significant barriers to the implementation of energy efficiency measures in industry that are often hard to overcome and currently limit the uptake of energy efficiency (Fleiter et al. 2011; IEA 2012b; Jaffe and Stavins 1994; UNIDO 2011). They include the requirement for short payback periods, lack of awareness and know-how, and concern that time spent on efficiency improvement is a distraction from core business and that change could interrupt production or affect reliability. Government intervention needs to address these barriers in order to realise the savings set out in the Efficient World Scenario by creating incentives for companies and ensuring that enabling and supporting systems are in place.

Since the 1970s, industrial energy efficiency policies have been implemented in many countries around the world. Key measures include the funding of research and technology development, incentives in the form of subsidies or energy taxes, emissions trading schemes, equipment performance requirements and energy management programmes. Additionally, a variety of supporting measures such as capacity building, provision of training, facilitating access to energy efficiency service providers and sources of finance are used to promote the uptake of energy efficient technologies and practices (IIP 2012).

However, there remain gaps that existing policies and policies currently under discussion will not close. To realise the Efficient World Scenario, it is necessary to substantially extend and increase the scale of policy efforts that underlie the New Policies Scenario. This would mean accelerating the development and deployment of existing policy instruments such as energy efficiency targets, benchmarking, energy audits and energy management requirements. Moreover, policy measures, including the promotion of the use of recycled materials and financial incentives that make the uptake of measures with long payback periods more attractive, need to be put in place.

The WEM can play a useful role in the assessment of industrial energy use, energy efficiency and CO_2 emissions. Its strengths include a focus on economic aspects, explicit modelling of policies, explicit modelling of capital turnover, consideration of interactions with other sectors in the energy system and consideration of energy-efficient technologies. The model also has limitations. The model is sensitive to the deployment and cost assumptions for energy-saving technologies, which are uncertain. Finally, the model does not endogenously account for materials trade and materials substitution.

Future research in the area of industrial energy modelling can focus on some of the aforementioned issues, such as incorporating material flows or trying to better model behavioural aspects. In addition, obtaining better data is critical in improving energy modelling of the industry sector. This not only applies to data on energy consumption but also to data on the diffusion of energy-saving technologies, the age profile of existing industrial facilities and the characteristics and potential deployment of new technologies.

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[4] CO_2 emissions savings from energy efficiency alone are not enough in terms of contribution from the industry sector to limit the global temperature increase to 2 °C, but need to be complemented by the use of low-carbon energy and carbon capture and storage (CCS).

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