# 4.1.1 Energy demand

Detlef van Vuuren, Bas van Ruijven, Bastien Girod, Vassilis Daioglou, Oreane Edelenbosch, Sebastiaan Deetman

## Key policy issues

- How will energy demand evolve particularly in emerging and medium- and low-income economies?
- What is the mix of end-use energy carriers to meet future energy demand?
- How can energy efficiency contribute to reducing the growth rate of energy demand and mitigate pressures on the global environment?

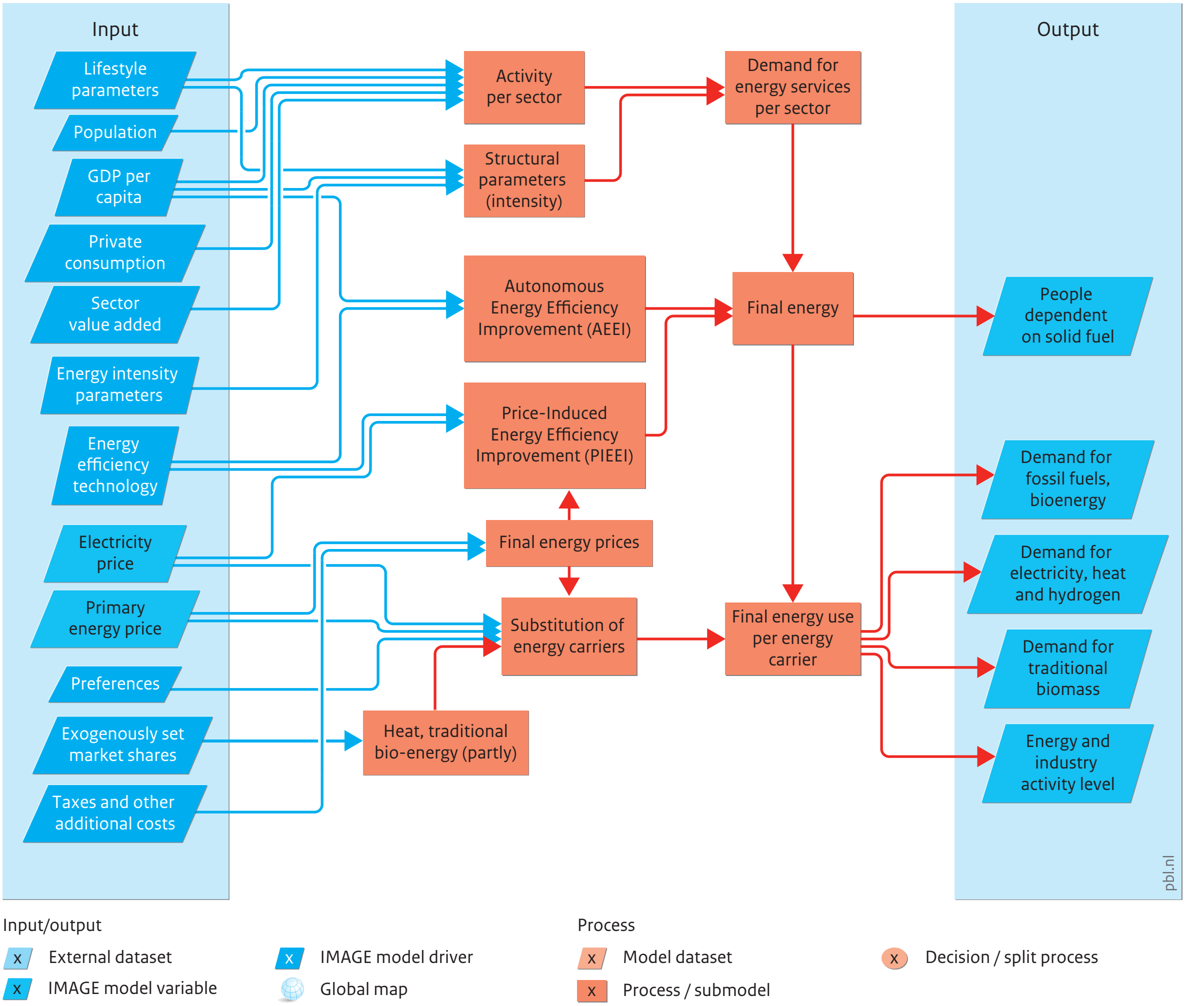
## 1. Introduction

Global energy use has increased rapidly since the industrial revolution. For a historical perspective, most increases have occurred in high-income regions but more recently, the largest increase is in emerging economies. With the aspirations for income growth in medium- and low-income countries, energy demand is to be expected to grow in the coming decades, with major implications for sustainability.

In the TIMER energy demand module, final energy demand is simulated as a function of changes in population, economic activity and energy intensity (Figure 4.1.1.1). Five economic sectors are considered: industry; transport; residential; public and private services; and other sectors mainly agriculture. In each sector, final energy use is driven by the demand for energy services, such as motor drive, mass displacement, chemical conversions, lighting, heating and cooling. Energy demand is considered as a function of three groups of parameters and processes:
- activity data, for example on population and income, and more explicit activity indicators, such as steel production;
- long-term trends that determine the intensity of use, for example, economic structural change (SC), autonomous energy efficiency improvement (AEEI) and price-induced energy efficiency improvement (PIEEI);
- price-based fuel substitution (the choice of energy carrier on the basis of its relative costs).

These factors are implemented in different ways in the various sectors. In some sectors, a detailed end-use service-oriented modelling approach is used while in other sectors, the description is more generic and aggregate. Energy prices link the demand module with other parts of the energy model, as they respond dynamically to changes in demand, supply and conversion.

Figure 4.1.1.1
**TIMER model, energy demand module**




Source: PBL 2014

*Some sectors are represented in a generic way as shown here, the sectors transport, residential and heavy industry are modelled in specific modules. More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.1.1.1).*

## 2. Model description

The energy demand module has aggregated formulations for some sectors and more detailed formulations for other sectors. In the description that follows, the generic model is presented which is used for the service sector, part of the industry sector (light) and in the category other sectors. Next, the more technology detailed sectors of residential energy use, heavy industry and transport are discussed in relation to the elements of the generic model.

In the generic module, demand for final energy is calculated for each region (R), sector (S) and energy form (F, heat or electricity) according to:

$$FE_{R,S,F} = \frac{POP_R * (ACT_{R,S} / POP_R) * SC_{R,S,F} * AEEI_{R,S,F} * PIEEI_{R,S,F}}{\sum_F \eta_{R,S,F} * MS_{R,S,F}} \qquad (4.1.1.1)$$

in which FE represents final energy, POP represents population, ACT/POP the sectoral activity per capita, SC a factor capturing intra-sectoral structural change, AEEI the autonomous energy efficiency improvement and PIEEI the price-induced energy efficiency improvement. In the denominator, η is the end-use efficiency of energy carriers used, for example in boilers and stoves, and MS represents the share of each energy carrier. Population and economic activity levels are exogenous inputs into the module. Each of the other dynamic factors in equation 1 are briefly discussed below.

**Structural change (SC)**
In each sector, the mix of activities changes as a function of development and time. These changes, referred to as structural change, may influence the energy intensity of a sector. For instance, using more private cars for transport instead of buses tends to increase energy intensity. Historically, in several sectors, as a consequence of the structural changes in the type of activities an increase in energy intensity can be observed followed by a decrease. Evidence of this trend is more convincing in industry with shifts from very basic to heavy industry and finally to industries with high value-added products than in other sectors, such as transport where historically, energy intensity has mainly been increasing (De Vries et al., 2001).

Based on the above, in *generic model formulations*, energy intensity is driven by income, assuming a peak in energy intensity, followed by saturation of energy demand at a constant per capita energy service level. In the calibration process, the choice of parameters may lead, for instance, to a peak in energy intensity higher than current income levels. In the *technology-detailed* energy demand (see below), structural change is captured by other equations that describe the underlying processes explicitly (e.g., modal shift in transport).

**Autonomous Energy Efficiency Increase (AEEI)**
This is a multiplier used in the *generic energy demand module* to account for efficiency improvement as a result of technology improvement, independent of prices. In general, current appliances are more efficient than those available in the past.

The autonomous energy efficiency increase for new capital is a fraction (f) of the economic growth rate based on the formulation of Richels et al. (2004). The fraction varies between 0.45 and 0.30 (based on literature data) and is assumed to decline with time because the scope for further improvement is assumed to decline. Efficiency improvement is assumed for new capital. Autonomous increase in energy efficiency for the average capital stock is calculated as the weighted average value of the AEEI values of the total in capital stock, using the vintage formulation. In the *technology-detailed submodules*, the autonomous energy efficiency increase is represented by improvement in individual technologies over time.

**Price-Induced Energy Efficiency Improvement (PIEEI)**
This multiplier is used to describe the effect of rising energy costs in the form of induced investments in energy efficiency by consumers. It is included in the *generic formulation* using an energy conservation cost curve. In the *technology-detailed submodules*, this multiplier is represented by competing technologies with different efficiencies and costs.

**Substitution**
Demand for secondary energy carriers is determined on the basis of demand for energy services and the relative prices of the energy carriers. For each energy carrier, a final efficiency value (η) is assumed to account for differences between energy carriers in converting final energy into energy services. The indicated market share (IMS) of each fuel is determined using a multinomial logit model that assigns market shares to the different carriers (i) on the basis of their relative prices in a set of competing carriers (j).

$$MS_i = \exp(\lambda x_i) / \sum_j \exp(\lambda c_j) \qquad (4.1.1.2)$$

MS is the market share of different energy carriers or technologies and c is their costs. In this equation, λ is the so-called logit parameter, determining the sensitivity of markets to price differences.

The equation takes account of direct production costs and also energy and carbon taxes and premium values. The last two reflect non-price factors determining market shares, such as preferences, environmental policies, infrastructure (or the lack of infrastructure) and strategic considerations. The premium values are determined in the model calibration process in order to correctly simulate historical market shares on the basis of simulated price information. The same parameters are used in scenarios to simulate the assumption on societal preferences for clean and/or convenient fuels. However, the market shares of traditional biomass and secondary heat are determined by exogenous scenario parameters (except for the residential sector discussed below). Non-energy use of energy carriers is modelled on the basis of exogenously assumed intensity of representative non-energy uses (chemicals) and on a price-driven competition between the various energy carriers (Daioglou et al., submitted).

### Heavy industry

The heavy industry submodule was included for the steel and cement sectors (Van Ruijven et al., 2013). These two sectors represented about 8% of global energy use and 13% of global anthropogenic greenhouse gas emissions in 2005. The generic structure of the energy demand module was adapted as follows:

- Activity is described in terms of production of tonnes cement and steel. The regional demand for these commodities is determined by a relationship similar to the formulation of the structural change discussed above. Both cement and steel can be traded but this is less important for cement. Historically, trade patterns have been prescribed but future production is assumed to shift slowly to producers with the lowest costs.
- The demand after trade can be met from production that uses a mix of technologies. Each technology is characterised by costs and energy use per unit of production, both of which decline slowly over time. The actual mix of technologies used to produce steel and cement in the model is derived from a multinominal logit equation, and results in a larger market share for the technologies with the lowest costs. The autonomous improvement of these technologies leads to an autonomous increase in energy efficiency. The selection of technologies represents the price-induced improvement in energy efficiency. Fuel substitution is partly determined on the basis of price, but also depends on the type of technology because some technologies can only use specific energy carriers (e.g., electricity for electric arc furnaces).

### Transport

The transport submodule consists of two parts - passenger and freight transport. A detailed description of the passenger transport (TRAVEL) is provided by Girod et al. (2012). There are seven modes - foot, bicycle, bus, train, passenger vehicle, high-speed train, and aircraft. The structural change (SC) processes in the transport module are described by an explicit consideration of the modal split. Two main factors govern model behaviour, namely the near-constancy of the travel time budget (TTB), and the travel money budget (TMB) over a large range of incomes. These are used as constraints to describe transition processes among the seven main travel modes, on the basis of their relative costs and speed characteristics and the consumer preferences for comfort levels and specific transport modes.

The freight transport submodule is a simpler structure. Service demand is projected with constant elasticity of the industry value added for each transport mode. In addition, demand sensitivity to transport prices is considered for each mode, depending on its share of energy costs in the total service costs.

The efficiency changes in both passenger and freight transport represent the autonomous increase in energy efficiency, and the price-induced improvements in energy efficiency improvement parameters. These changes are described by substitution processes in explicit technologies, such as vehicles with different energy efficiencies, costs and fuel type characteristics compete on the basis of preferences and total passenger-kilometre costs, using a multinomial logit equation. The efficiency of the transport fleet is determined by a weighted average of the full fleet (a vintage model, giving an explicit description of the efficiency in all single years). As each type of vehicle is assumed to use only one fuel type, this process also describes the fuel selection.

**Residential energy use**

The residential submodule describes the energy demand from household energy functions of cooking appliances, space heating and cooling, water heating and lighting. These functions are described in detail elsewhere (Van Ruijven et al., 2011; Daioglou et al., 2012).

Structural change in energy demand is presented by modelling end-use household functions:

- Energy service demand for space heating is modelled using correlations with floor area, heating degree days and energy intensity, the last including building efficiency improvements.
- Hot water demand is modelled as a function of household income and heating degree days.
- Energy service demand for cooking is determined on the basis of an average constant consumption of 3 $MJ_{UE}$/capita/day.
- Energy use related to appliances is based on ownership, household income, efficiency reference values, and autonomous and price-induced improvements. Space cooling follows a similar approach, but also includes cooling degree days (Isaac and Van Vuuren, 2009).
- Electricity use for lighting is determined on the basis of floor area, wattage and lighting hours based on geographic location.

Efficiency improvements are included in different ways. Exogenously driven energy efficiency improvement over time is used for appliances, light bulbs, air conditioning, building insulation and heating equipment, Price-induced energy efficiency improvements (PIEEI) occur by explicitly describing the investments in appliances with a similar performance level but with different energy and investment costs. For example, competition between incandescent light bulbs and more energy-efficient lighting is determined by changes in energy prices.

The model distinguishes five income quintiles for both the urban and rural population. After determining the energy demand per function for each population quintile, the choice of fuel type is determined on the basis of relative costs. This is based on a multinomial logit formulation for energy functions that can involve multiple fuels, such as cooking and space heating. In the calculations, consumer discount rates are assumed to decrease along with household income levels, and there will be increasing appreciation of clean and convenient fuels (Van Ruijven et al., 2011). For developing countries, this endogenously results in the substitution processes described by the energy ladder. This refers to the progressive use of modern energy types as incomes grow, from traditional bioenergy to coal and kerosene, to energy carriers such as natural gas, heating oil and electricity.

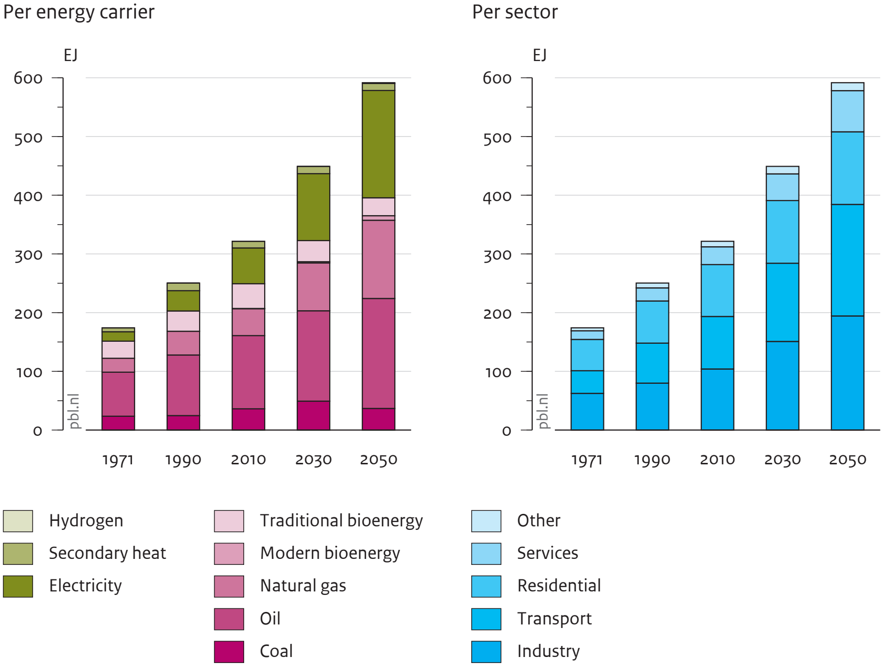
The residential submodule also includes access to electricity and the associated investments (Van Ruijven et al., 2012). Projections for access to electricity are based on an econometric analysis that found a relation between level of access, and GDP per capita and population density. The investment model is based on population density on a 0.5x0.5 degree grid, from which a stylised power grid is derived and analysed to determine investments in low-, medium- and high-voltage lines and transformers.

## 3. Policy issues

**Baseline developments**

The model shows that under a typical baseline scenario such as the one of the Rio+20 study, energy demand is projected to grow significantly during the 21st century (Figure 4.1.1.2). Most growth will be driven by an increase in energy use in low-income countries. Per capita use in high-income countries is projected to remain more or less constant, consistent with recent historical trends. The increase in energy demand in the first half of the century will be mostly met by fossil fuels and electricity. In this model simulation, hydrogen becomes competitive in the transport sector in the second half of the century, as a result of increasing oil prices and the assumed progress in hydrogen technologies. An alternative assumption could result in a similar role for electricity.

Figure 4.1.1.2
**Global final energy demand under a baseline scenario**




Source: PBL 2014

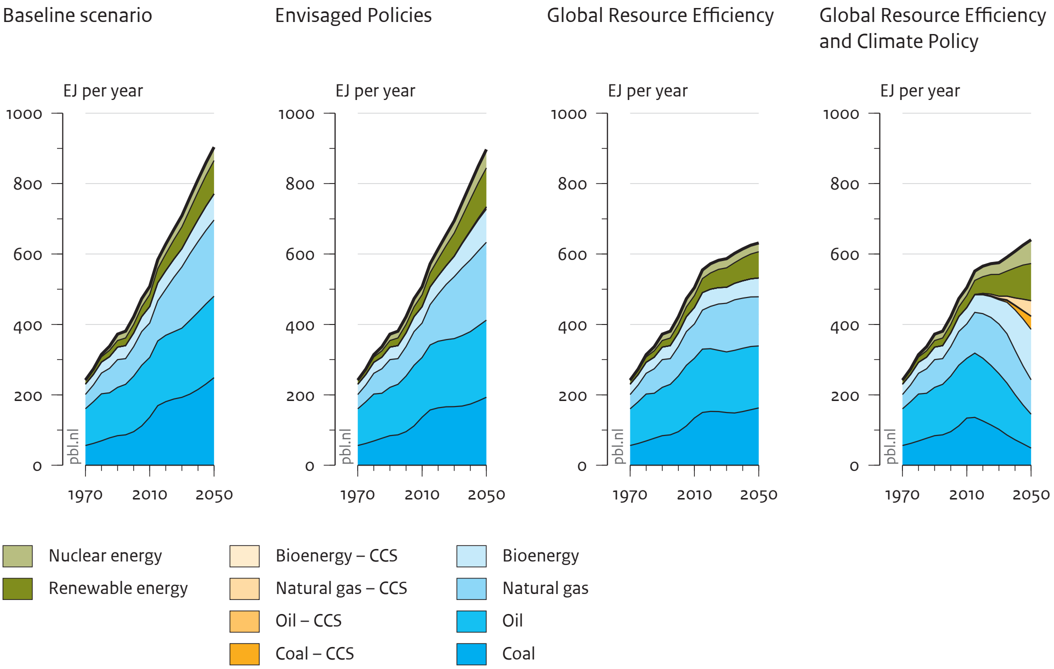
*Between 2010 and 2050 energy demand for transport and industry, and for natural gas and electricity contribute most to the overall increase.*

## Policy interventions

Various policy interventions can be implemented in the energy demand submodules in different ways:

- Energy tax and carbon tax. This changes the prices for the energy carriers, and influences the choice of technology.
- Discount rate/payback time. In the residential submodule , the perceived costs of capital (discount rate) influence the extent of energy efficiency improvement (PIEEI) and the choice of fuel and/or technology in the residential submodule.
- Preferences. Fuel choice can be influenced by correction factors, representing aspects that influence fuel choice but are not incorporated in the price, such as fuel characteristics (e.g., cleanliness, availability), comfort and speed considerations, and infrastructure.
- Efficiency standards. Such improvements can be introduced for the submodules that focus on specific technologies, for example, in transport, heavy industry and households.

Figure 4.1.1.3
**Global primary energy use under baseline and policy scenarios**




Source: Van den Berg et al. 2011

*The 'envisaged policies' scenario includes currently planned policies, the 'global resource efficiency' scenario assumes ambitious energy efficiency policies, and the 'global resource efficiency and climate policy' scenario additionally assumes policies to meet the 2 °C target. Total primary energy use could be significantly reduced by policies on energy efficiency, whereas additional climate policy would mostly affect the type of resources used. (Van den Berg et al., 2011)*

– Enforced market shares of fuel types. Such an analysis could, for instance, provide insight into the implications in the model of increasing the use of biofuels, electricity or hydrogen (Van Ruijven et al., 2007).

The PBL study Resource Efficiency (Van den Berg et al., 2011) provides an example of how TIMER can be used to explore the impact of radically improving energy efficiency (Figure 4.1.1.3). The study included an accelerated trend to best available technologies in iron and steel production and other industries, most efficient passenger vehicles and aircraft, a moderate shift from aircraft to high-speed trains, and building highly efficient housing (mostly insulation measures). The study also assumed that newly installed power plants will be based on the best available technologies. The measures in this global energy efficiency scenario will considerably reduce energy use than under the baseline scenario. Primary energy consumption will be reduced by about 30% by 2050.

## 4. Data, uncertainties and limitations

**Data**
The energy demand module has been calibrated for the 1971–2007 period in order to reproduce historical trends in fuel and electricity use (see papers on individual model components, such as Van Ruijven et al., 2010a). Using the historical input data on population and value added and the calculated energy prices as given, other drivers and model parameters were varied systematically within the range of values derived from the literature, in order to improve the fit (Van Ruijven et al., 2010a; Van Ruijven et al., 2010b).

The primary data source on energy use was the International Energy Agency (IEA). These data were complemented with data from other sources, such as steel and cement demand and production, and transport data from as described in the references of the different model components. The residential submodule uses data from national statistical agencies and household surveys (Van Ruijven et al., 2010a).

**Uncertainties**
The main uncertainties in modelling energy demand relate to the interpretation of historical trends, for instance, on the role of structural change, autonomous energy efficiency increases and price-induced efficiency improvements and their projection for the future (Van Vuuren et al., 2008).

Two uncertainties are the existence of saturation levels and the potential for efficiency increases. The representation in TIMER is based on the assumption that demand for energy services tends to become saturated at some point. This is based on physical considerations and historical trends in sectors, such as residential energy use. However, economic models assume that income and energy use remain coupled, often even at constant growth elasticities. Evidence for a constant growth can also be found in some sectors, notably transport and services.

In deciding between these different dynamics, the extent to which historical trends would be the best guide for the future is also unclear. A similar issue concerns the role of energy efficiency. Many techno-economic analyses of efficiency potential suggest large possibilities at rather low payback times. However, from a historical perspective, investments in efficiency have been significantly lower than optimal for cost minimisation. Other factors must be assumed to play a role in the form of perceived transaction costs. A critical issue is whether this efficiency potential could be exploited in the future.

In the model calibration, there is a large degree of freedom in parameter setting so that results fit historical observations. A method has been developed to identify the implications of different outcomes of model calibrations and has been applied to the transport and residential submodules (Van Ruijven et al., 2010a; Van Ruijven et al., 2010b).

The starting point is that insufficient data are available to fully understand historic trends and calibrate global energy models. TIMER has room for different sets of parameter values that simulate historical energy use equally well, but reflect different historical interpretations and result in different future projections. The recent trend to replace some energy models by a description of end-use functions and applying physical considerations will reduce some uncertainties as this enables better estimation of reasonable saturation levels. However, this method suffers from the fact that new energy functions may be developed in the future that could increase energy demand.

**Limitations**

The main limitations of the TIMER energy demand model are listed in the introduction to the model. A critical factor in modelling energy demand is the level of detail, given the large number of relevant technologies. TIMER uses an intermediate approach, in which some key technologies are modelled explicitly, and others are included implicitly. For more detailed estimates of the potential of energy efficiency, it would be more appropriate to use a different model.

## 5. Key publications

Daioglou V, Van Ruijven BJ and Van Vuuren DP. (2012). Model projections for household energy use in developing countries. *Energy* 37(1), pp. 601–615, DOI: 10.1016/j.energy.2011.10.044.

Girod B, Van Vuuren DP and Deetman S. (2012). Global travel within the 2 degree climate target. *Energy Policy* 45, pp. 152–166, DOI: 10.1016/j.enpol.2012.02.008.

Van Ruijven BJ, Schers J and Van Vuuren DP. (2012). Model-based scenarios for rural electrification in developing countries. *Energy* 38(1), pp. 386–397, DOI: 10.1016/j.energy.2011.11.037.

# 6. Input/Output Table

Table 4.1.1.1
**Input in and output from the energy demand module of TIMER**

| Input | Description | Source (section/ other) |
|---|---|---|
| *IMAGE model drivers and variables* | | |
| Population | Number of people per region. | 3 |
| GDP per capita | Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity. | 3 |
| Sector value added | Value Added for economic sectors: Industry (IVA), Services (SVA) and Agriculture (AVA). These variables are used in IMAGE to indicate economic activity. | 3 |
| Private consumption | Private consumption reflects expenditure on private household consumption. It is used in IMAGE as a driver of energy. | 3 |
| Energy efficiency technology | Model assumptions determining future development of energy efficiency. | 3 |
| Taxes and other additional costs | Taxes on energy use, and other additional costs | 3 |
| Energy intensity parameters | Set of parameters determining the energy use per unit of economic activity (in absence of technical energy efficiency improvements). | 3 |
| Lifestyle parameters | Lifestyle parameters influence the relationship between economic activities and demand for energy. | 3 |
| Preferences | Non-price factors determining market shares, such as preferences, environmental policies, infrastructure and strategic considerations, used for model calibration. | 3 |
| Primary energy price | The price of primary energy carriers based on production costs. | 4.1.3 |
| Electricity price | The price of electricity. | 4.1.2 |
| *External datasets* | | |
| Exogenously set market shares | Market shares of traditional biomass and secondary heat, for all demand sectors except the residential sector, exogenous scenario parameter. | IEA |

| Output | Description | Use (section) |
|---|---|---|
| People dependent on solid fuel | Proportion of population using traditional biomass and coal for cooking and heating. | 7.7 |
| Energy and industry activity level | Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil. | 5.2 |
| Demand for electricity, heat and hydrogen | The demand for production of electricity, heat and hydrogen. | 4.1.2 |
| Demand traditional biomass | Regional demand for traditional bioenergy. | 4.2.2 |
| Demand for fossil fuels and bioenergy | The demand for the production of fossil fuels and bioenergy. | Final output |