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DEVELOPMENT OF PATHWAYS TO ACHIEVE THE SE4ALL ENERGY EFFICIENCY OBJECTIVE:

GLOBAL AND REGIONAL POTENTIAL FOR ENERGY EFFICIENCY IMPROVEMENTS

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Contents

1 Executive Summary

This study examines the three objectives of the UN Sustainable Energy for All (SE4ALL) initiative:

1. Ensure universal access to modern energy services by 2030.
2. Double the global rate of improvement in energy efficiency (from 1.3% to 2.6% annual reduction in energy intensity of GDP) by 2030.
3. Double the share of renewable energy in global final energy from 18% to 36% by 2030.

The integrated assessment model, ETSAP-TIAM, was used in this study to compare, from an economic optimization point of view, different scenarios for the development of the energy system between 2010 and 2030. This analysis is conducted on a global and regional scale. The scenarios were constructed to analyze the effect of achieving the SE4ALL energy efficiency objective, the SE4ALL renewable energy objective, both together, and all three SE4ALL objectives.

Synergies exist between renewable energy and energy efficiency. When the SE4ALL renewable energy objective is achieved, the economically optimal solution produced by ETSAP-TIAM also includes a reduction in energy intensity: globally, the compound annual reduction in energy intensity of GDP is 1.8% when the renewable energy objective is achieved. Likewise, a scenario that achieves the SE4ALL energy efficiency objective results in a solution that is halfway to the SE4ALL renewable energy objective: the 2030 global renewable energy share of total final energy is 26%. On a global scale, the renewable shares in every sector increase when the SE4ALL energy efficiency objective is achieved. The results from ETSAP-TIAM suggest that the SE4ALL energy access objective is not as synergetic with the other two objectives. When traditional biomass is phased out, the results show that it is more cost-effective to replace it with non-renewable energy sources for residential heating, cooking, and hot water.

ETSAP-TIAM includes 15 world regions that were also analyzed: Africa, Australia & New Zealand, Canada, China, Central & South America, Eastern Europe, Former Soviet Union, India, Japan, Middle East, Mexico, Other Developing Asia, South Korea, United States, and Western Europe. From a global optimization perspective, the Former Soviet Union and China have the greatest rates of reduction in energy intensity though these regions still have relatively high levels of energy consumption given their relative GDPs. Meeting the SE4ALL energy efficiency objective will require an ambitious global effort. According to the ETSAP-TIAM results, Eastern Europe, China, Australia & NZ, Other Developing Asia and India have largest potential for improving energy efficiency. Africa, Canada, Central and South America, and Australia & New Zealand have high potential to increase the proportion of renewable energy within final energy consumption.

In terms of primary energy, the SE4ALL objectives result in a global reduction in coal consumption (particularly in China and the USA) and natural gas consumption in the Former Soviet Union. Few regions reduce oil consumption when the SE4ALL objectives are achieved (relative to when they are not), and those that do, only do so slightly. In most cases, replacing oil is one of the least cost effective measures for reducing energy consumption.

Total global final energy does not change much across the scenarios, as the energy service demands remain constant and the changes are mostly upstream. Nevertheless, many of the industrial subsectors in China have large potential for reduction in final energy consumption. This is also true for the residential heating subsector, particularly under scenarios which include the energy access objective, which would require phasing out the use of traditional biomass, and replacing it with more modern fuels. Iron and steel production in India also is the subsector with a highest potential for reduction in final energy consumption through energy efficiency and fuel switching.

While achieving the SE4ALL objectives does not reduce carbon emissions to the level of the RCP2.6 pathway (a pathway that is described as having a high probability of limiting global warming to less than 2°C above pre-industrial times), achieving either the renewable energy or energy efficiency objective results in an emissions pathway that remains below the RCP4.5 pathway (a pathway that has less than 50% probability for remaining under 2°C warming) (Moss, 2010). This implies that meeting the SE4ALL objectives, particularly the energy efficiency objective, places the probability of remaining under 2°C warming between 50% and 66%. When all the SE4ALL objectives are achieved, most of the greenhouse gas reductions are in CO_2 in the power and industrial sectors. Based on the ETSAP-TIAM results, the SE4ALL energy efficiency objective is slightly more effective at reducing emissions than the SE4ALL renewable energy objective. Achieving all three SE4ALL objectives results in increased emissions in comparison to a scenario where the energy efficiency and renewable energy objectives are achieved without the energy access objective. China is the most important region when it comes to reducing emissions (5.6 $GtCO_2$/year by 2030), but large reductions are also seen in the USA (4 $GtCO_2$/year by 2030) when the SE4ALL objectives are achieved. The level of investment is correlated with a reduction in greenhouse gas emissions across the various scenarios.

Globally industry followed by residential transport, are the most cost-effective sectors for investment into energy efficiency. Regionally, other industries (mining and manufacturing) in China and heavy trucks in USA and China have large potentials for relatively inexpensive efficiency improvements. Commercial cooling in Western Europe also has high potential, but it is also relatively more costly than many other regional subsector improvements. The results from ETSAP-TIAM suggest that meeting the SE4ALL objectives is feasible, though ambitious.

2 INTRODUCTION AND BACKGROUND

2.1 AIM

This report analyzes pathways for achieving the objectives under Sustainable Energy for All (SE4ALL), a United Nations (UN) global initiative. The objectives of the SE4ALL are to achieve, by 2030: 1) universal access to modern energy services; 2) a doubling of the global rate of improvement in energy efficiency; and 3) a doubling of the share of renewable energy in the global energy mix (SE4ALL, 2013). The aim of this study is to determine the most cost optimal global and regional energy mixes that achieve the SE4ALL objectives, particularly the energy efficiency objective.

2.2 HISTORIC TRENDS IN ENERGY EFFICIENCY

There has been some success so far in improving energy efficiency: between 1990 and 2010, over 1 billion people gained access to electricity, global renewable energy share has increased from 16% to 18%, and energy intensity has reduced by an average rate of 1.3% per year (SE4ALL, 2015). Nevertheless, faster progress is necessary if the SE4ALL objectives are to be achieved, summarized in Table 1.

Table 1. Progress in achieving the SE4ALL objectives (SE4ALL, 2015).

Year	Universal access to modern energy services		Doubling global rate of improvement of energy efficiency	Doubling share of renewable energy in global mix
	Electrification (%)	Cooking (%)	Energy Efficiency (% reduction per year)	Renewable Energy (%)
1990	76	47	-1.3	16.6
2010	83	59	-1.3	17.8
2012	84.6	58.4	-1.7	18.1
2030 (projected)	89	72	-2.2	24
2030 (target)	100	100	-2.6	36

National level energy intensity (of GDP PPP) and primary energy consumption data were attained from Global Tracking Framework (GTF) (SE4ALL, 2015) for the years 1990-2010. The energy intensity statistics were divided by the primary energy consumption statistics and inverted to produce internally consistent data for GDP PPP. In Figure 1, the historic regional trends are depicted. China and the Former Soviet Union have the highest energy intensity (highest levels of energy consumption per unit of economic output) whereas Europe has among the lowest energy intensity. The average reduction rates for different world regions are given in Table 2. The global energy intensity has decreased rather steadily over the 20-year timespan.

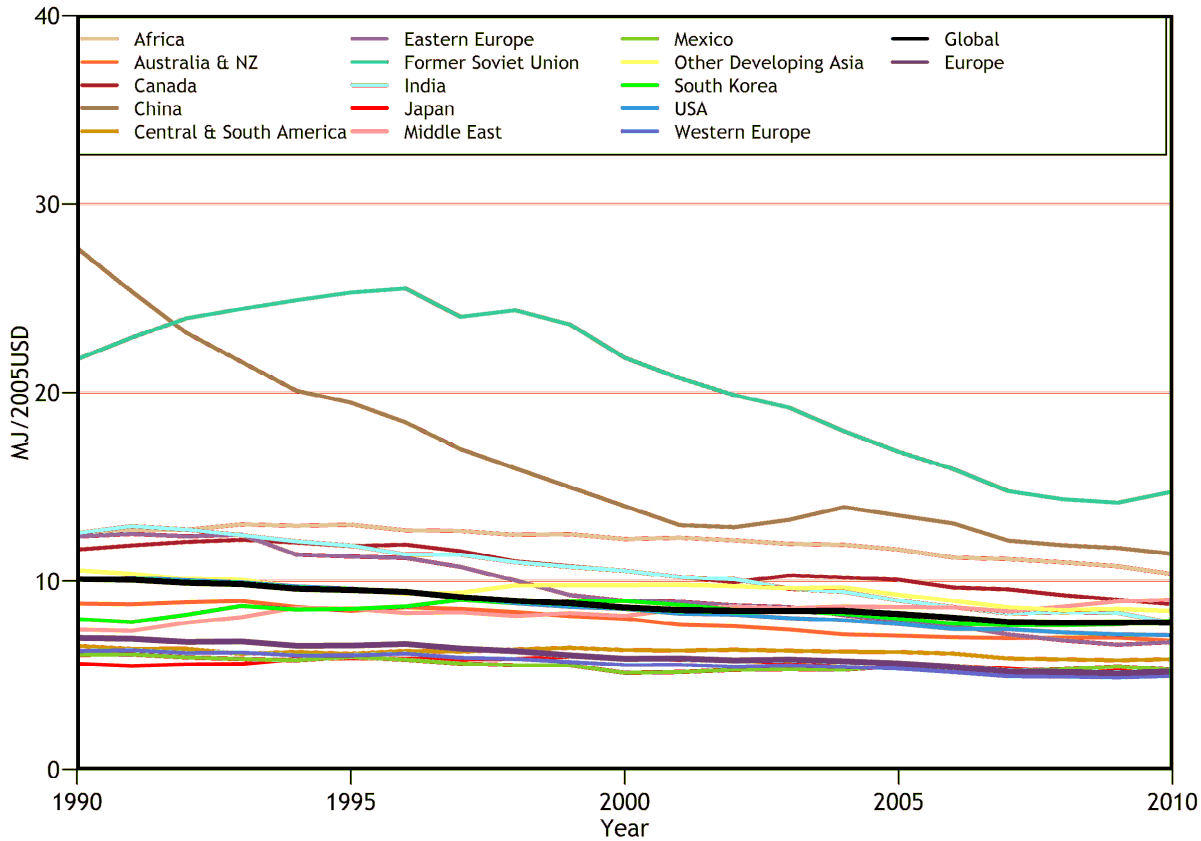

Figure 1. Historical Energy Intensity, by region based on 2005 GDP PPP (SE4ALL, 2015).

Table 2. Average EIIR rates from 1990-2010 for different regions of the world (SE4ALL, 2015).

Region	Average EIIR (1990-2010)
Africa	-0.90%
Australia	-1.20%
Canada	-1.40%
China	-4.30%
Central and South America	-0.60%
Eastern Europe	-2.90%
Former Soviet Union	-1.80%
India	-2.30%
Japan	-0.30%
Middle East	1.00%
Mexico	-0.70%
Other Developing Asia	-1.10%
South Korea	0.00%

United States	-1.70%
Western Europe	-1.20%
Europe	-1.50%
Global	-1.30%

Moreover, the rate of change in energy intensity varies substantially year to year. In Figure 2, different rates of change for global energy intensity are plotted together. The data indicate that the rate of improvement can vary substantially from year to year (which depends on both the economy and the quality of the data). This is the case for both the average rate of change and the compound annual growth rates (CAGR) calculated from the endpoints. Using CAGR, the decadal global change in global energy intensity is between -1.0% and -1.7%. The long term point 20-year CAGR is -1.3%, as seen also in Table 1.

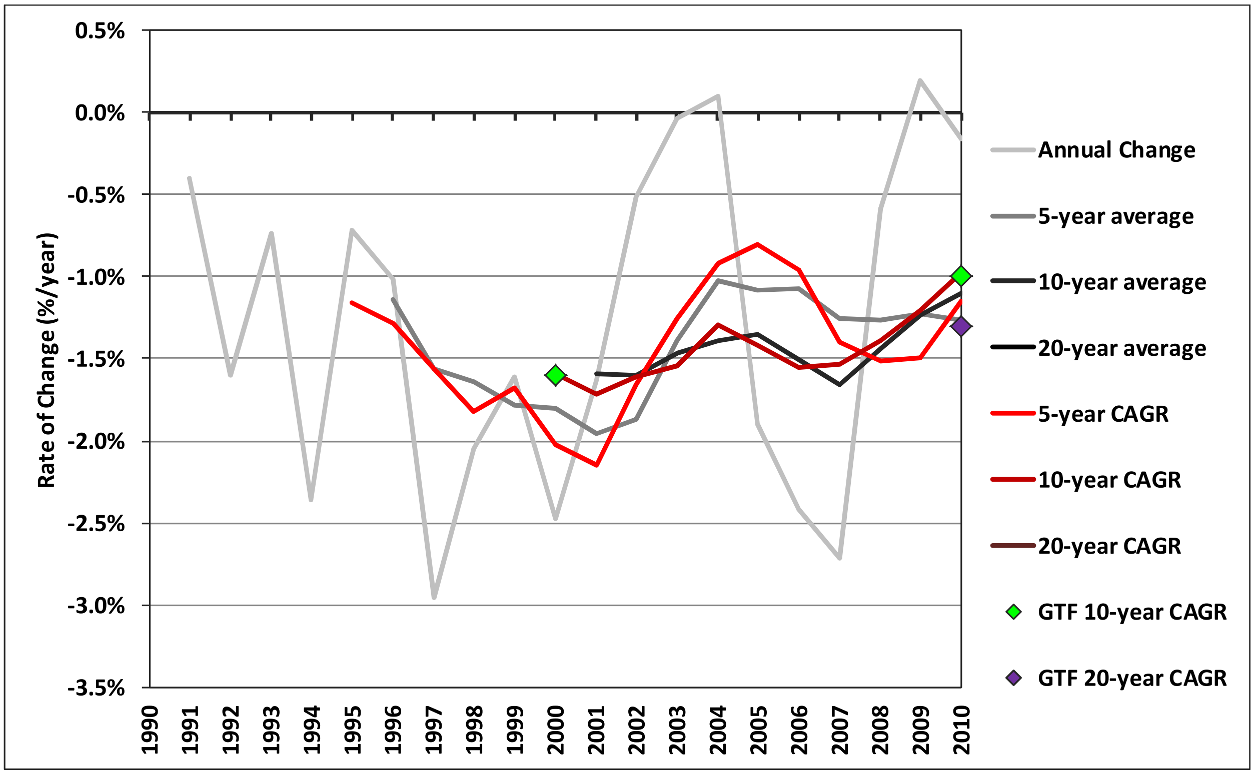

Figure 2. Rate of change in global energy intensity of GDP PPP (using 2005 as a constant price basis): 5-, 10- and 20- year average smoothing has been applied, as well as calculation of the compound annual growth rate (CAGR) for the previous 5, 10, and 20 years. The annual change is calculated by taking the percentage difference in energy intensity from consecutive years. The 5, 10, and 20 year averages are rolling averages of the annual change. The 5, 10 and 20 year CAGR are the annual rates of reduction computed from the energy intensity of the two endpoints (e.g. 1990 to 2010). For reference, the CAGR estimates reported in the Global Tracking Framework (SE4ALL, 2015) are also included here.

2.3 Current Policies for Energy Efficiency

Achieving the SE4ALL energy efficiency objective of 2.6% annual reduction in global energy intensity will require an ambitious effort, given the trends seen in Figure 2. Yet many countries have adopted targets for reducing energy intensity. Table 3 presents a selection of major economies that have adopted targets to reduce energy intensity. Individual national targets within the EU are assumed to be subsumed by the EU Energy Efficiency Directive (2012/27/EU). The goal of this directive is to reduce primary energy consumption in the EU by 2020 by over 15,000 PJ, relative to a reference scenario provided within the policy. This is an ambitious target, requiring nearly doubling the historic rate of energy intensity improvement, and covering countries that represent a large amount of energy consumption.

Japan seeks to reduce energy intensity of GDP by 30% by 2030, relative to 2003 (ABB, 2012a). This is also quite ambitious considering historic rates of reduction in Japan (0.3% between 1990 and 2010, given in Table 2), and because Japan already has a relatively low level of energy intensity of GDP compared to other world regions. South Korea seeks to reduce energy intensity by 46% between the years 2007 and 2030 (ABB, 2013c). Like Japan, this is quite an ambitious target, given the historic trend in energy intensity. Russia and Kazakhstan have the goal to reduce energy intensity by 40% by 2020 relative to 2007 (ABB, 2012b) and 2008 (Kazakhstan Energy Charter Secretariat & Kazenergy, 2014), respectively. Turkey seeks to reduce energy intensity of GDP by 20% between 2008 and 2023 (ABB, 2013d). In Brazil, implementation of the National Policy for Energy Efficiency is expected to result in a gradual energy savings up to 106 TWh/year to be reached in 2030 (ABB, 2013a). The New Zealand Energy Policy promotes energy intensity improvement of 1.3 percent per annum for the years 2010-2030 (New Zealand Ministry of Economic Development, 2011). As part of their 12th 5-year plan, China sought to reduce energy intensity of GDP by 16% by 2015 (ABB, 2013b). This is now a historic target, but the 2015 data are not yet available. The 13th 5-year plan was approved in 2016. Finally, India seeks to reduce energy intensity by 20% by 2020 from 2005 levels, as part of their 12th Five Year Plan (Planning Commission Government of India, 2013). Many other countries have energy efficiency policies targeted at improving specific technologies or sectors, with various metrics for assessment (e.g. the US Corporate Average Fuel Economy (CAFE) standards for vehicle fuel economy (NHTSA 2011)). Those are not included in Table 3, as they are not a policy directly targeting national energy intensity of GDP and fall beyond the scope of this study.

*Table 3. Current Energy Intensity reduction policies of major economies. Historic CAGR is calculated from Global Tracking Framework Data (SE4ALL, 2015). The estimated annual energy savings at the target year is that reported by the specific policy or projected from historic CAGR values versus the target value, calculated with per capita GPD PPP projections from (OECD, 2014) and population projections from the World Bank (2014). *No per capita GDP projections were available for Kazakhstan; therefore, it is assumed that the ratio of per capita GDP to Russia in 2010 is the same in 2020.*

Country/ Region	Historic CAGR (1990-2010)	Target year	Target CAGR (2010-target year)	Estimated Annual Energy Savings at Target Year* (PJ)
EU	-1.3%	2020	-2.4%	15407
Japan	-0.3%	2030	-1.6%	5344
Russia	-1.5%	2020	-2.7%	4383
Turkey	-0.2%	2023	-1.9%	1545
South Korea	0.0%	2030	-3.2%	1172
Brazil	0.2%	2030	0.1%	382
Kazakhstan	-2.0%	2020	-2.6%	212
New Zealand	-0.8%	2030	-1.3%	131
India	-2.4%	2020	-0.8%	-6708
China	-4.7%	2015	-3.9%	-7782

India and China are interesting cases, as the targets for improvement in energy intensity are below the historic rates of reduction. This leads to a negative energy savings, and can be interpreted as targets that are not particularly ambitious. On the other hand, the historic rate of reduction was relatively high from 1990-2000 for China (Figure 1), in particular. There is also a lot of uncertainty concerning both China's GDP and China's energy consumption (Akimoto, Ohara, Kurokawa, & Horii, 2006; Gregg, Andres, & Marland, 2008; Sinton, 2001).

3 METHOD

The framework for the analysis is presented in Figure 3. The method employs a scenario-based modeling approach, where the scenarios are constructed of pre-defined pathways that serve as constraints in the modeling.

First, the data are harmonized to 2010 statistical data. Then, the SE4ALL objectives are translated into targets for 2030. A target is a specific predefined outcome for 2030 for a specific attribute (i.e., energy intensity, renewable energy, or energy access). From there, a pathway is created by linearly interpolating targets for each time step between 2010 and 2030. In the model, a pathway is handled as a minimum constraint for each time step (i.e., that the conditions of the target must be met, and may be exceeded). These are applied at the global level.

From here, scenarios are created by combining pathways. A reference scenario is created based on the historical rates of EIIR, a default energy system (described below), and current carbon taxes. Alternative scenarios are created that represent different pathways (the SE4ALL energy efficiency objective, the SE4ALL renewable energy objective, and universal access as expressed in residential electricity consumption and phase-out of traditional biomass). Each alternative scenario is compared to reference scenario, in order to see how the structural development of the energy system changes when different combinations of the SE4ALL objectives are achieved. Greenhouse gas emissions, levels of investment, and system costs are also considered in the comparison.

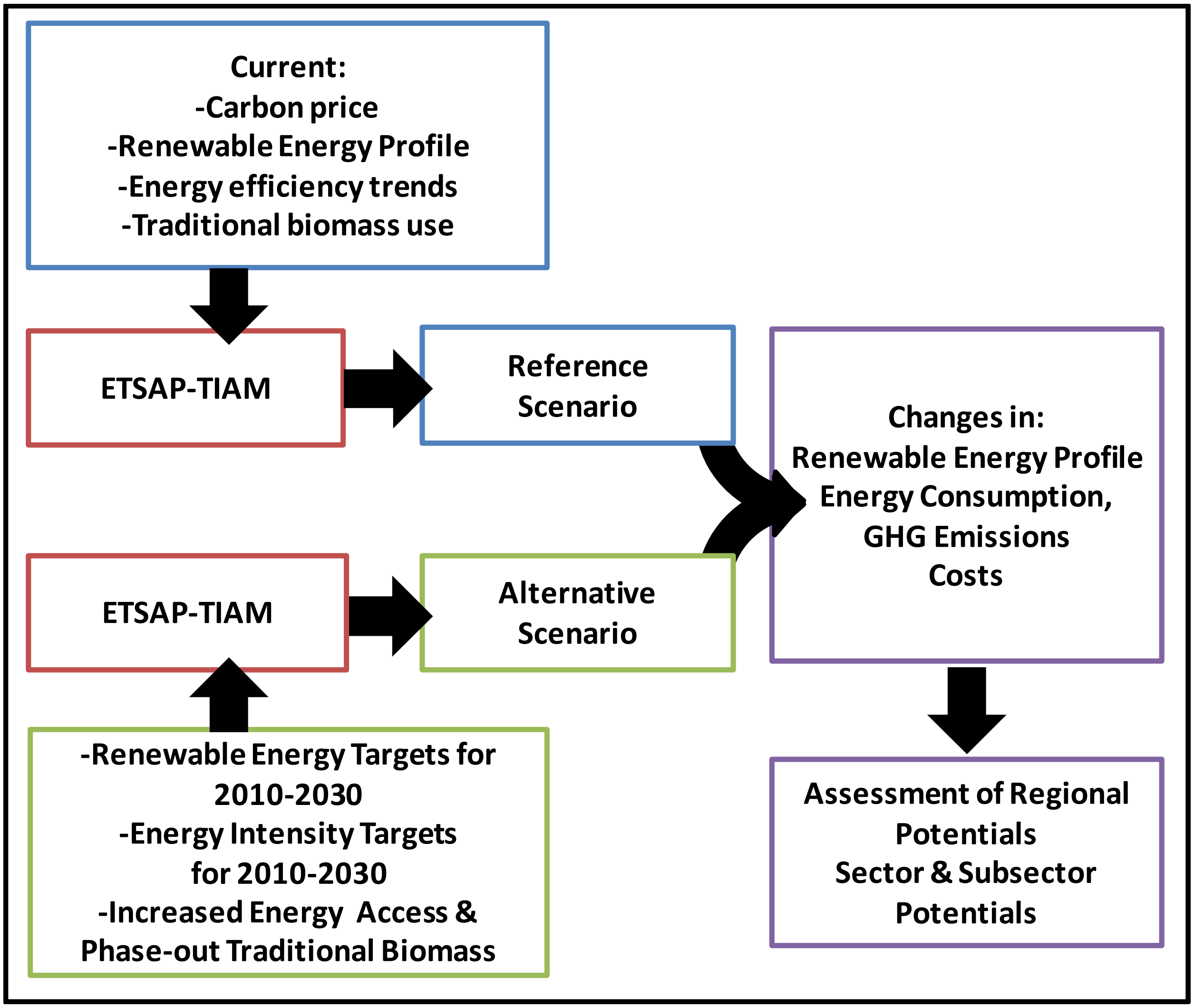

Figure 3. Diagram of framework for analysis and work flow.

3.1.1 Time Frame and Regions

The model is set up to explore the development of the world energy system from the year 2010 to the SE4ALL target year of 2030 using 5-year time steps. We conduct the analysis using 2010 as a base year in energy efficiency improvement calculations. The modeling is done with ETSAP-TIAM (described below) which represents the energy system of the world, divided into 15 regions (Figure 4). ETSAP-TIAM models the procurement, transformation, trade, and consumption of different energy resources.

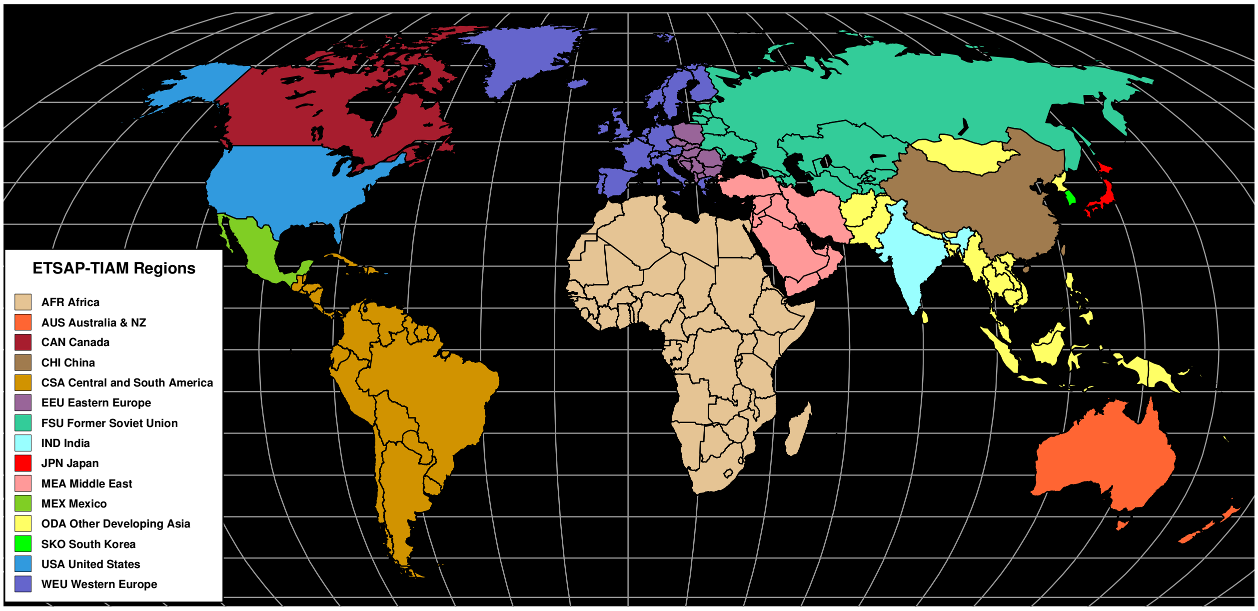

Figure 4. Fifteen regions of the Energy Technology System Analysis Program TIMES Integrated Assessment Model (ETSAP-TIAM).

3.2 Scenarios

The following scenarios are constructed to analyze the energy system and technology profiles.

(i) Reference: The reference scenario reflects the development of the global, regional and sectoral energy demand if current trends are continued. This scenario takes into account current technological mixes, performance and cost data for conventional technologies, and default assumptions for "autonomous energy efficiency improvement" (AEEI)[1]. It also takes into account the current carbon price, holding it constant until 2030. Global energy intensity was projected to 2030 using OECD (2014) GDP PPP projections and the historic average annual reduction rate of energy intensity for the years 1990-2010 (1.3%), calculated from GTF (SE4ALL, 2015). No regional constraints are applied for energy efficiency, allowing ETSAP-TIAM to optimize the regional allocation of energy efficiency improvements, subject to the global constraint. The renewable energy share is set at the IRENA Reference for 2030 (IRENA, 2014).

(ii) EE Scenario: The Energy Efficiency Scenario has a global minimum constraint on energy intensity of at least 2.6% annual rate of reduction. No constraints are placed on renewable energy.

(iii) RE Scenario: The Renewable Energy Scenario and sets a global minimum constraint on renewable energy so that it reaches at least 36% of final energy use by 2030. No constraints are placed on energy intensity.

[1] AEEI is discussed in more depth in the model input data assumptions, section 3.3.3.

(iv) EE+RE Scenario: The Energy Efficiency and Renewable Energy Scenario combines the EE and RE scenarios, so that global energy intensity is reduced by at least 2.6% per year, and the renewable energy reaches at least 36% of final energy use by 2030.

(v) EE+RE+EA Scenario: The Energy Efficiency, Renewable Energy, Energy Access Scenario is similar to the EE+RE scenario, but it also phases out the use of traditional biomass, and meets an assumed minimum electricity demand, thus achieving all three SE4ALL objectives.

The scenarios are summarized in Table 4.

Table 4. Scenario Summary

Scenario	**Global EIIR 1.3%**	**Global EIIR 2.6%**	**Regional RE IRENA Ref**	**Global RE Doubling SE4ALL**	**Energy Access**
i. Ref	fixed		fixed		
ii. EE		min			
iii. RE				min	
iv. EE+RE		min		min	
v. EE+RE+EA		min		min	included

3.2.1 Carbon Price

The current carbon price is included in all scenarios except the base scenario. The World Bank (2015a) released a report that documented the current state of carbon taxes and carbon emission trading schemes (ETS) and their price levels. Some changes and updates to these carbon pricing schemes have occurred: e.g., the carbon tax in Australia was scrapped in July 2014 (Dayton, 2014) and an ETS started in the Republic of Korea, changing the carbon price levels (World Bank, 2015b). Further information on ETS was taken from the International Carbon Action Partnership (ICAP, 2015) and from other nation specific sources (China Carbon, 2015; Cho, 2015; OTC-X, 2015).

For simplicity, carbon markets were modeled as a tax by taking the current carbon price. Some nations have more than one pricing mechanism operating simultaneously, e.g. a national tax and ETS. In such cases, the prices were summed into one price applicable to the specific sector and region. Some regions have several carbon prices applying to different sectors, and this was retained in the ETSAP-TIAM input. Mexico has a carbon tax applying to the approximate ratios in emissions per unit of energy relative to natural gas. In the case where a country has both an upper and lower bound for carbon, then the upper bound was used.

The carbon prices were then aggregated to the ETSAP-TIAM regions. This aggregation was done by computing the nation’s share of energy (and cement production) carbon emissions relative to the total emissions from its corresponding ETSAP-TIAM region. The carbon price was then converted to 2005 US dollars[2] and scaled by this amount. An analogous computation was performed for carbon prices applying only to specific states in the USA, provinces in Canada, and cities in China and Japan. Data on greenhouse gas emissions and the share for different nations, states and cities were taken from the Carbon Dioxide Information Analysis Center (CDIAC) (Boden, Andres, & Marland, 2010), the Global Carbon Atlas (Global Carbon Project, 2014), Environment Canada (2015), United States EPA (Environmental Protection Agency) (2014), Wang, Zhang, Liu, and Bi (2012) and the World Bank (2015c). Carbon taxes are summarized in Table 5 and are applied in ETSAP-TIAM for the periods 2015-2030 in the reference scenario.

Table 5. Current carbon prices in 2005 USD per Tonne CO_2

Region	Industry	Power	Heat	Buildings	Transport (excluding Aviation)	Agriculture	Oil	Coal
AFR								
AUS								
CAN	4.68	6.39			1.00			
CHI	0.88	0.88		0.88				
CSA								
EEU	5.51	5.51	5.51					
FSU	0.72	0.72	0.72		0.63	0.63		
IND								
JPN	1.16	1.16	1.16		1.16	1.16		
MEA								
MEX							0.62	1.00
ODA								
SKO	4.93	4.93	4.93	4.93	4.93	4.93		
USA	0.06	0.14						
WEU	7.02	11.35	7.02		5.43			

3.2.2 Energy Efficiency

The historic average rate of annual change in energy intensity is calculated from the GTF (SE4ALL, 2015) statistics for the historic years 1990-2013 for each ETSAP-TIAM region, and for the world. For the reference scenario, the average reduction rate for the years 1990-2030 was extrapolated to the years 2010-2030. By multiplying these energy intensity projections with the OECD (2014) GDP PPP projections, a total primary energy constraint was created for the world. Similar to the process for establishing the bounds in the reference scenario, the SE4ALL objective of a 2.6% was determined from the exogenous global GDP PPP projections from the OECD (2014) and applying a 2.6% annual reduction in energy intensity for the years between 2010 and 2030. Again, using OECD

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[2] Exchange rates from:

https://www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-usd.en.html
http://www.xe.com/
http://www.bankofcanada.ca/rates/exchange/daily-converter/

(2014) GDP PPP projections for the world, the 2030 global total primary energy targets were calculated and used as constraints for the EE, EE+RE, and EE+RE+EA scenarios.

3.2.3 Renewable Energy

Renewable energy constraints are constructed to set a target proportion of 36% renewable energy sources in global total final energy consumption. Because both the renewable share of electricity generation and electricity consumption are endogenously optimized in ETSAP-TIAM, the set of renewable energy constraints includes system-wide electricity consumption (based on generation, corrected for line losses; i.e. upstream) in addition to direct fuel use in the end-use sectors. This done to avoid non-linearity issues that would occur if the renewable share of electricity was multiplied by electricity consumption only in the end use sectors.

3.2.4 Universal Access

The IEA estimates in their central scenario the number of people in 2030 without access to electricity to below 1 billion and without access to clean cooking facilities to just above 2.5 billion (IEA, 2014). The universal energy access target for 2030 is defined as 100% access to electricity and 100% primary reliance on non-solid fuel (SE4ALL, 2013). The SE4ALL initiative stresses that these binary targets fail to capture many aspects of energy access, such as not considering energy applications outside of the household sector (SE4ALL, 2013). An official target for energy electricity consumption is lacking. The SE4ALL scenario in the Global Energy Assessment assumes a 100% electrification rate and household electricity consumption of 420 kWh/year (SE4ALL, 2013). This corresponds to the use of lighting, air circulation, televisions and light appliances according to World Bank's tiered electricity consumption framework. The level can be traced back to a study in a Tanzanian village where the average household electricity consumption was estimated at the level of 35 kWh/month (Ilskog, Kjellström, Gullberg, Katyega, & Chambala, 2005). Bazilian and Pielke (2013) criticize this level of energy access, pointing out that the per capita electricity consumption in wealthy countries is at least ten times higher. They emphasize the importance of electricity for businesses, industries and hospitals for economic development and want more focus on universal modern energy access that alleviates poverty.

Many studies have looked into the correlation between energy or electricity consumption and economic development (e.g., Asafu-Adjaye, 2000; Lee, 2006; Shiu & Lam, 2004; Wolde-Rufael, 2006). The direction of causality cannot always be shown, but the fact that energy or electricity consumption has a positive connection with economic development (measured in GDP) is clear (Ozturk, 2010). From this follows that one part of a crude target for energy access could be to set a level of electricity consumption that is close to that of wealthy countries. Statistics for per capita electricity consumption in 2011 and the share of the population that had access to electricity in 2010 are shown in Table 6 for certain countries and regions (World Bank, 2015c).

Table 6. Per capita electricity consumption and electricity access for selected countries (World Bank, 2015c)

Country	Per capita electricity consumption (kWh/capita/year)	Electricity access (share of population)
USA	13246	100%
European Union	6115	100%
South Africa	4606	82.7%
China	3298	99.7%
World	3045	83.1%
India	684	75%
Least developed countries: UN classification[3]	174	31.5%
Haiti	32	33.9%

Other ways of measuring energy access have been proposed. For example, Nussbaumer, Bazilian, and Modi (2012) review energy access (or poverty) metrics and suggest a multidimensional energy poverty index that focuses on energy services; cooking, lighting, entertainment and education, communication and services from household appliances.

Chakravarty and Tavoni (2013) calculate the additional energy consumption in 2030 resulting from eradicating energy poverty. They first map the number of people with different levels of energy consumption by using a model that builds on the income distribution data. They then estimate the additional residential electricity consumption in 2030 that comes from raising energy-poor people's electricity consumption to a level that is at least 750 kWh/capita/year. This level is called Productive uses by the UN and corresponds to the level in the IEA's energy access model used to calculate the investments needed to achieve the SE4All objectives (SE4ALL, 2013). The level assumes electricity for lighting, health, education, communication and use in the agricultural sector. It should be noted that the availability of more efficient technologies will reduce the electricity use target over time, whereas electrification of transport and boilers and heaters will act in the other direction. The estimated additional residential consumption of electricity in selected regions based on their data is shown in Table 7; these are used in the modeling to represent the SE4ALL universal access objective.

Table 7 Additional residential electricity consumption in 2030 to eradicate energy poverty (used to represent the SE4ALL Universal Access objective) calculated from Chakravarty and Tavoni (2013)

Region	Electricity (PJ)
Africa	349
India	122
Other Developing Asia	140
China	31
Central and South America	30

[3] The least developed countries consist of 48 countries with a total population of around 900 million people (World Bank, 2015b).

In addition to electricity demand, in order to represent the 100% non-primary reliance on solid fuel SE4ALL goal, traditional biomass is phased out in this scenario component. To do so, traditional biomass consumption is assumed to decrease 7.5% per year, and is completely phased out entirely by 2030 for the alternative scenarios. This is discussed further below. Additionally, the constraints (on the minimum amount of biomass to be used in the residential water heating and space heating) were relaxed for energy sources to hot water and space heating, allowing a greater degree of fuel switching for these end use demands.

3.3 ETSAP-TIAM

ETSAP-TIAM is a global technology-rich model of the entire energy/emission system of the world based on the TIMES model architecture. In all scenarios, ETSAP-TIAM optimizes the energy systems based on resource availability, existing infrastructure stock, and prices, given the exogenous constraints.

3.3.1 TIMES Architecture Background

The TIMES (The Integrated MARKAL-EFOM System) model generator, is an evolved version of MARKAL (MARket Allocation model), developed under the IEA implementing agreement, ETSAP. TIMES is a model generating set of optimization equations[4] that computes an inter-temporal dynamic partial equilibrium on energy and emission markets based on the maximization of total surplus (defined as the sum of supplier and consumer surpluses). In essence, a model generated by TIMES finds the least-cost solution for the entire energy system with flexibility in terms of time resolution and sectorial focus.

3.3.2 Model Structure

As ETSAP-TIAM is based on the TIMES equations, it is a perfect foresight, linear optimization model (ETSAP-TIAM optimizes all time periods simultaneously). The objective function that is maximized is the discounted net present value[5] of the total surplus[6] for the entire world. The surplus maximization can be subject to many exogenously-defined constraints on a regional, sectoral or global basis, such as supply bounds (in the form of detailed supply curves that describe resource availability at different price points) for the primary resources, technical constraints governing the creation, operation, and abandonment of each technology, balance constraints for all energy forms and emissions, timing of investment payments and other cash flows, and the satisfaction of a set of demands for energy services in all sectors of the economy.

As an integrated energy system model, ETSAP-TIAM is built to represent the total energy chain, including energy extraction, conversion and demand (e.g., fossil and renewable resources), potentials of storage of CO_2 (which comes into play with a carbon price and can be adjusted via cost parameters) and region-specific demand developments. The region and sector-specific demands for end-use energy and industrial products are driven by socio-economic parameters which are described below. The model contains explicit detailed descriptions of hundreds of technologies as well as hundreds of energy, emission and demand flows within each region (region-specific parameters can be defined), logically interconnected to form a Base Energy System (Figure 5). Such technological detail allows precise tracking of optimal capital turnover, and provides a precise description of

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[4] A complete description of the TIMES equations appears in http://www.iea-etsap.org/web/Documentation.asp.

[5] A discount rate of 5% is assumed. Net present value is calculated to 2005.

[6] Total surplus is here defined as the sum of supplier and consumer surpluses.

technology and fuel competition. The long-distance trade of energy between the regions of ETSAP-TIAM is endogenously modeled for coal, natural gas (gaseous or liquefied), crude oil, various refined petroleum products, and biofuels. Global and regional (partial agreement) greenhouse gas (GHG) emission trading is also possible. ETSAP-TIAM is driven by a set of demands for energy services in agriculture, residential buildings, commercial buildings, industry, and transportation. Each technology has a hurdle rate that varies from 5% to 20%, depending on the sector. The hurdle rate is used to convert the capital cost in an annual cash flow: discounted multi-year interest rate payments are included when calculating an annual payment for an investment and payback time (a technology with a high hurdle rate means a short payback rate is required, while a technology with a low hurdle rate allows a longer payback time). Learning curves are exogenously assumed for each technology through the price inputs contained in the ETSAP-TIAM database. Thus technologies generally become cheaper in future time periods.

The model's variables include the investments, capacities, and activity levels of all technologies at each period of time, as well as the amounts of energy, material, and emission flows in and out of each technology, and the quantities of traded energy between all pairs or regions. For sectors that use electricity and heat, the flow variables are defined for each of six time-slices: three seasons (summer, winter, and autumn/spring) times two diurnal (day and night) divisions. ETSAP-TIAM is a partial equilibrium model, and although it does not include macroeconomic variables beyond the energy sector, there is evidence that accounting for price elasticity of demands captures the majority of the feedback effects from the economy to the energy system (Bataille, 2005; Labriet, Kanudia, & Loulou, 2012; Scheper & Kram, 1994).

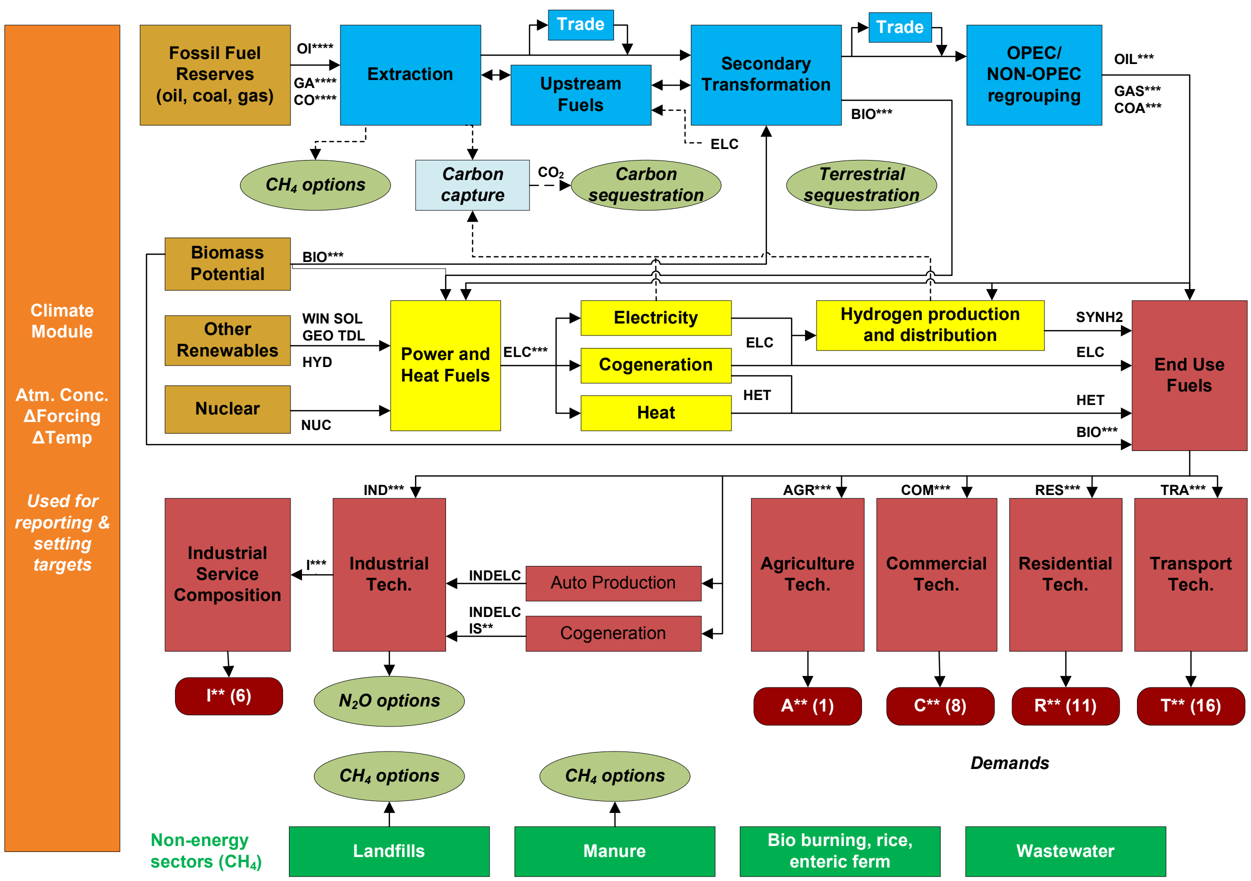

Figure 5. Base energy system within ETSAP-TIAM. Technological efficiencies are included in the industrial, agriculture, commercial, residential, and transport technology boxes. Other efficiency adjustments are possible within the fuel production chains.

ETSAP-TIAM integrates a climate module permitting the computation and modeling of global changes related to GHG concentrations, radiative forcing and global temperature increase. The climate module was originally inspired by the Nordhaus and Boyer (1999) model, but now consists of three sets of equations, dynamically calculating the atmospheric concentrations of the three main GHGs (CO_2, CH_4, and N_2O), the atmospheric radiative forcing of these three gases, and the resultant change in mean global temperature. The climate module has been calibrated and compared to other, more detailed climate modules, during several past multi-model experiments (Loulou, Labriet, & Kanudia, 2009). The CO_2, CH_4, and N_2O emissions related to the energy sector are explicitly represented in the model at the level of the individual technologies. The emissions from non-energy sectors (landfills, manure, rice paddies, enteric fermentation, wastewater, agriculture, land-use) are also included in the model, but in a more rudimentary way. The other GHGs (CFCs, HFCs, SF_6, etc.) are not explicitly modeled, but their radiative forcing is represented in an exogenous manner. Options for GHG emission reductions available in the model include: specific CH_4 and N_2O destruction, mitigation of emissions from agriculture, CO_2 capture (upstream, power plants, biofuel refineries, hydrogen generation) and sequestration (in geological sinks), biological sequestration via reforestation, and finally, numerous fuel and technology switching options in each sector (which would simultaneously improve energy efficiency and correspondingly induce a reduction in energy intensity). Thus, carbon price can be used as a simple lever for policy intervention, and this can be applied globally or differentially across regions.

3.3.3 Technological Change

Technological change is often formalized by an AEEI coefficient. AEEI adjusts energy intensity while holding energy prices constant, reflecting (autonomous) capital turnover without changes in price. Different assumptions about AEEI can result in large differences in future estimates for energy efficiency, and thus the cost of climate change mitigation. The cost of mitigation output is inversely related to the AEEI (as AEEI goes up, mitigation cost goes down, because people choose more efficient products and processes without a price signal). Thus, this parameter is crucial in establishing the underlying set of input drivers within all IAMs.

AEEI is typically based on historical rates of change, though some models now use more optimistic AEEIs for future time steps (Markandya, 2001). This is one of the greatest sources of uncertainty in energy IAMs, specifically, in the rate of adoption and invention of new low-carbon technologies given relative energy prices, as there is a dearth of information in the literature about AEEI (Dean & Hoeller, 1992). Within IAMs, modeling of efficiency is typically done by assuming a specific turnover rate for energy-consuming capital (Markandya et al., 2001), which is one of the main mechanisms in ETSAP-TIAM (e.g., product life varies for different technologies and can be adjusted within a scenario). Within the set of coherent drivers that exogenously define the ETSAP-TIAM input database, AEEI is incorporated within the GEMINI-E3 modeling to project historical trends in efficiency improvements, independent of energy prices or economic growth (Babonneau, Vielle, Haurie, & Loulou, 2010). In GEMINI-3, the AEEI is between 1.0% and 2.2%, depending on the time periods (Babonneau et al., 2010). ETSAP-TIAM does not include a specific AEEI parameter- within ETSAP-TIAM, a given technology will have a set of fixed efficiencies values at different costs, and these are selected based on the maximization of the objective function. Thus, AEEI assumptions were used in producing the underlying exogenous socio-economic drivers. This means that some efficiency improvements are expected in ETSAP-TIAM results, even in a BAU scenario. However, assumptions about the turnover rate, product life, product efficiencies, investment and fixed costs, and availability dates for new technologies can be adjusted for each technology by the user in scenario input files.

Alternative scenarios for renewable energy targets, GHG concentration levels, energy intensity, etc., can also serve as inputs and will affect the consumption of different energy resources as well as the investment, adoption, and penetration rates of different technologies. However, ETSAP-TIAM cannot generate entirely new technologies endogenously and research and development (R&D) costs are not included in the model, except in so far as they are incorporated in the exogenous technology price assumptions.

3.3.4 ETSAP-TIAM Summary

In terms of modeling energy regional and global efficiency potential, ETSAP-TIAM has many advantages over other IAMs. Among IAMs, it is one of the most detailed in terms of its technology database. Furthermore, there are many options for creating constraints, targets, or other policy incentives. A summary of ETSAP-TIAM is given in Table 8.

Table 8. ETSAP-TIAM Summary

Model Type	Integrated assessment model. Linear optimization, perfect foresight based on the TIMES model equations. Technology-rich representation of sectors and includes a climate module based on endogenously calculated emissions. Policies can be modeled by creating alternative scenarios for user defined constraints, taxes, subsidies, etc.
Countries/regions included	The world is divided in 15 regions, modeled separately, yet interlinked through global markets.
Time horizon and time steps	The model period is from 2005 to 2100 in 5- to 10-year steps. Time steps are defined by the user and interpolated based on input data.
GHGs included	CO_2, CH_4 and N_2O are endogenously modeled while CFCs, HFCs, SF_6, etc. are represented with an exogenous radiative forcing.
Data sources	The main data source is IEA statistics. The model is calibrated on 2005 statistics. Population projections are from the UN, and GDP and technology development projections come from case studies, literature, and other general equilibrium models.
Sectors	Extraction of raw materials, refineries, conversion sector, industry, agriculture, commercial, residential and transport
Mitigation options/technologies included: specify scope and level of detail for EE and RE measures sector by sector	Technologies are divided within different sectors and are represented in the model. This covers energy efficiency measures and energy supply technologies.
Main input and assumptions	Main assumptions to the model (exogenous inputs) are demand drivers for each sector, including regional GDP and population. AEEI is assumed in the underlying demand driver inputs and base technology adoption. Pathways for emissions or renewable energy targets and similar constraints can also serve as alternative scenario inputs.
Examples of output/results of the model	Among the results from ETSAP-TIAM are global fuel prices (coal, oil-, gas-, biomass markets are modeled); GHG concentration in the atmosphere, radiative forcing and temperature increases; energy use and production in each region; regional emissions; total system costs; cost of action in specific sectors in specific regions/countries

3.4 INPUT DATA

3.4.1 DEMAND DRIVERS

The algorithm in ETSAP-TIAM is designed to calculate energy production (by resource) that meets the energy service demands for each region. The energy service demands are calculated by a suite of exogenous demand drivers (Table 9).

Table 9. Demand Drivers in ETSAP-TIAM

ETSAP-TIAM Demand Driver	Description
POP	Population
GDP	Gross Domestic Product
GDPP	Per Capita GDP
HOU	Number of Households
GDPPHOU	GDP per Household
PAGR	Driver for Agriculture
PCHEM	Driver for Chemicals and Petrochemical
PISNF	Driver for Iron, Steel and Non-Ferrous Metals
POEI	Driver for Other Energy Intensive Industries
POI	Driver for Other Industry
PSER	Driver for Services

In ETSAP-TIAM, the demand drivers are used to calculate subsector service demands in future time slices using the following relationship:

$$Demand_t = Demand_{t-1} \times k \times Driver_n^{elasticity}$$

Equation 1. Relationship between service demand and demand drivers in ETSAP-TIAM.

In Equation 1, t represents the time step and k is a constant (equal to one unity for most subsectors). The list of subsectors and their associated demand drivers is given in section 3.4.2. The elasticity is a parameter that defines the relationship between the driver and demand (e.g., energy demand elasticity in relation to GDP). We maintained the default constants and the elasticities within the ETSAP-TIAM database.

The current version of ETSAP-TIAM uses 2005 as a model calibration year, so all demand drivers are expressed as indices and are referenced to 2005. Results for 2010 are calculated within ETSAP-TIAM as a modeled year. However, we have used historical data from 2010 (as well as projections to 2030 from various sources) for population, GDP, per capita GDP, number of households, and household GDP in order to update the demand driver indices. This allows ETSAP-TIAM results to match the historic 2010 data for these drivers, as well as gives the latest projections for how these drivers are expected to develop in the future. Though 2010 is a modeled year in ETSAP-TIAM, this year is solved and fixed for all model runs in order to avoid optimization of the past. Therefore, though 2010 is not a calibrated year in ETSAP-TIAM, it functions as a de facto base year for this study.

3.4.1.1 Population

The default exogenous population data within ETSAP-TIAM were updated with more recent data from the World Bank (2014), which provides population projections up until year 2050. These project population growth in Africa, and India, and a plateau in China's population around 2020. Only Japan and Eastern Europe have decreasing populations. In ETSAP-TIAM, the population data are expressed as indices referenced to 2005, thus new population coefficients were created by dividing the World Bank population 2010-2030 projections with the World Bank 2005 population data (Figure 6).

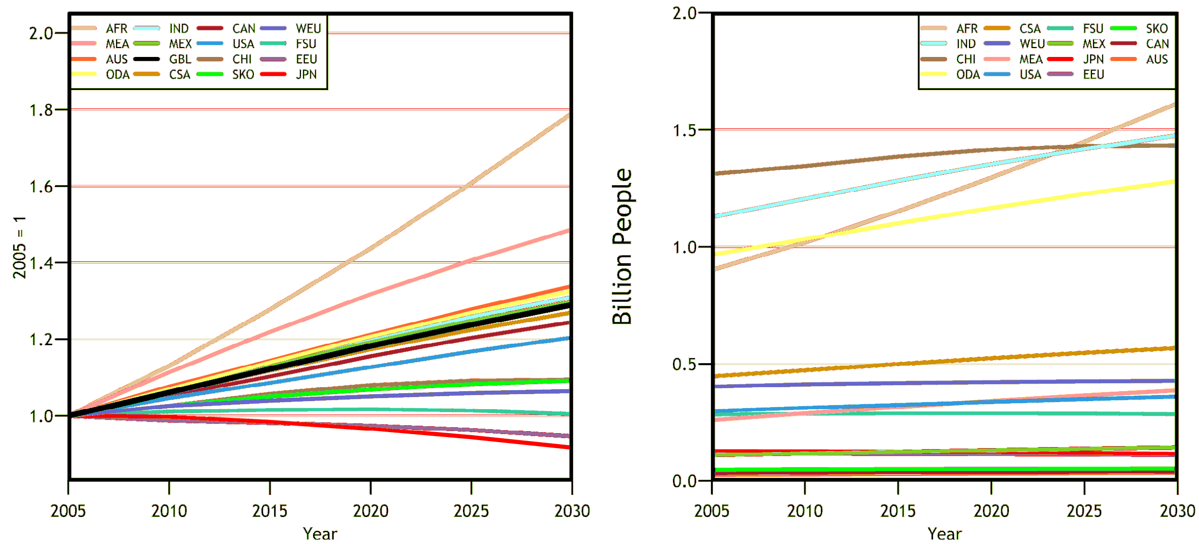

Figure 6. Population indices as inputs into ETSAP-TIAM and corresponding projected values

3.4.1.2 GDP

The 2010 ETSAP-TIAM GDP indices were updated using historical per capita GDP in PPP (constant 2011 international dollars) data from the World Bank (2014). The regional GDP were calculated by multiplying the per capita GDP estimates by the World Bank (2014) population data.

The OECD (2014) provides GDP projections per capita in PPPs (in constant 2005 dollars) from 2010 until 2060 for its 34 member countries, and for Russia, Brazil, India, China, Indonesia and South Africa. Together these 40 countries cover over 98% of the current world GDP. Countries not covered by the OECD (2014) dataset retained the default ETSAP-TIAM coefficients in 2030 (corresponding to their respective region). Coefficients for 2015-2025 were extrapolated between the 2030 coefficients and the coefficients from 2010. New GDP coefficients were calculated by dividing the GDP (PPP) projections with the GDP (PPP) in 2005.

Using this estimates, the global GDP is exogenously projected to double by 2025 (relative to 2005), and all regions are projected to have growing economies. Much of the global growth in GDP is projected to be in China and India, where the 2030 GDP projections are respectively 5 and 4.5 times larger than in 2005 (Figure 7).

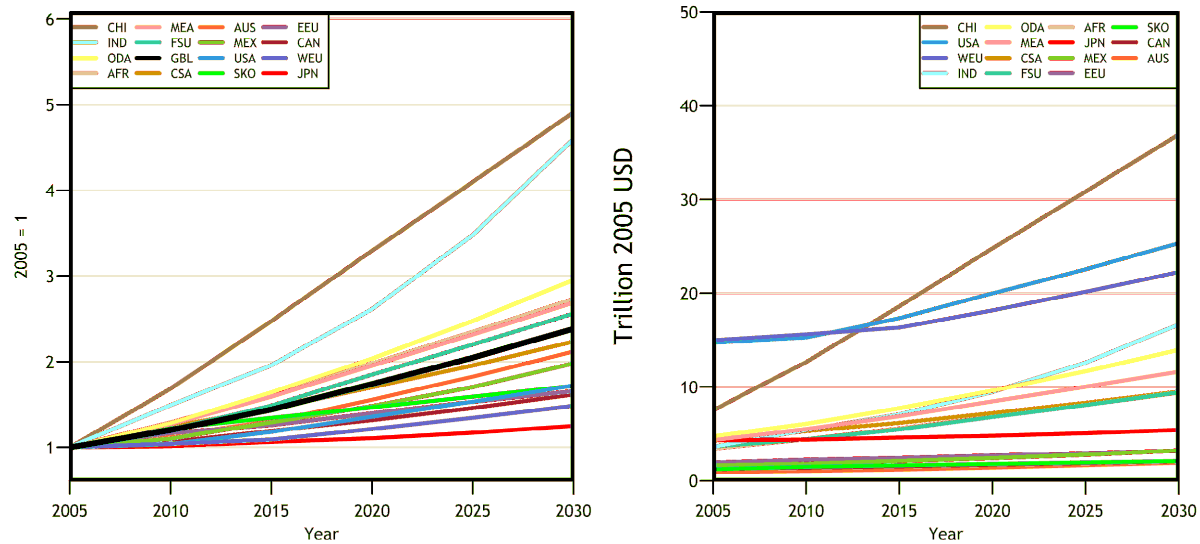

Figure 7. GDP PPP index projections as inputs into ETSAP-TIAM and corresponding projected values

3.4.1.3 Per Capita GDP

Per Capita GDP indices were computed by dividing the GDP indices by the population indices. Globally, 2030 per capita GDP is projected to increase by 85% in relation to 2005. Again, large growth is anticipated in China (450%) and India (350%) over this period (Figure 8).

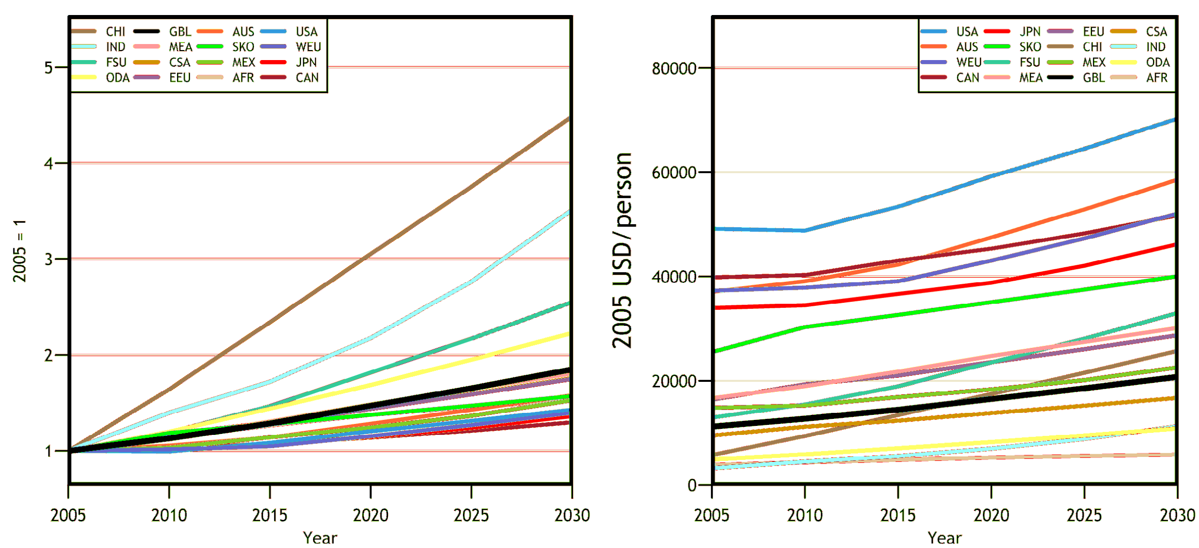

Figure 8. Per Capita GDP PPP index projections as inputs into ETSAP-TIAM and corresponding projected values

3.4.1.4 Number of Households

Data were taken from TekCarta (2015) on average household size from 2000-2012. Metadata from TekCarta (2015) indicates that these data come from the UN, Eurostat, World Bank, national census reports, and various other sources. Not all of the world's countries are included in the TekCarta (2015) database. For the countries included, the population was divided by the household size (TekCarta, 2015), to obtain the number of households. From here, the sum of all the households was divided by the sum of all the household sizes for each region, in effect, computing a weighted average household size for each ETSAP-TIAM region. This assumes that the included countries in a region are representative of the entire region. The total number of households per region was computed by multiplying the household size by the population for each region. To create a projection, a linear regression was used to extrapolate the trend to 2030. These were then indexed to 2005, by region (Figure 9). The largest growth in the number of households occurs in Africa and India, both of which are projected to have twice the number of households in 2030, relative to 2005.

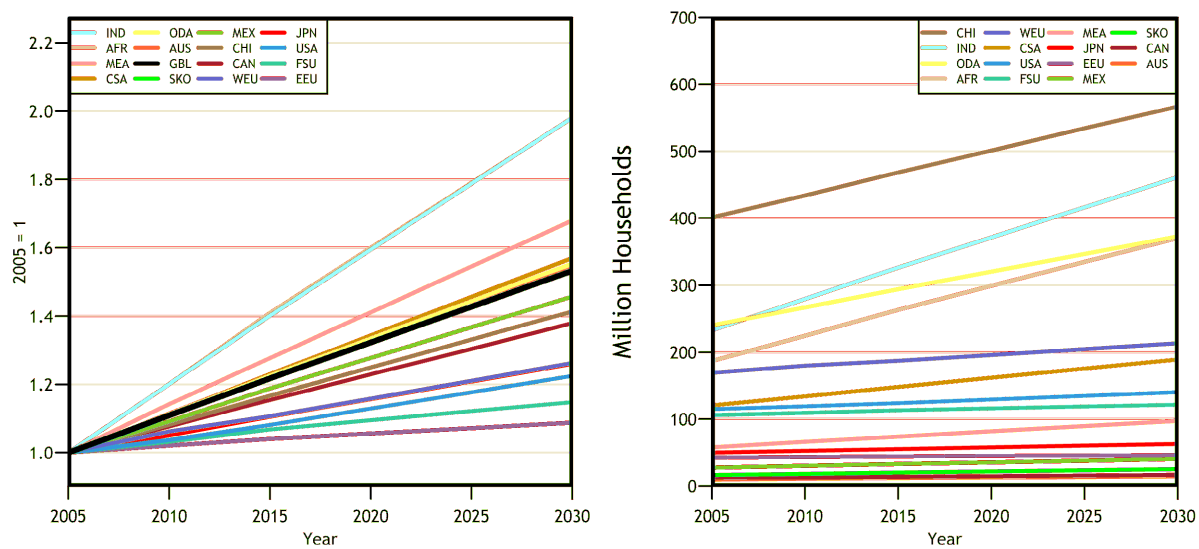

Figure 9. Number of households index as inputs into ETSAP-TIAM and corresponding projected values

By dividing the regional population by the number of households, an estimate is created for aggregate average household size for the ETSAP-TIAM regions (Figure 10). Though not a specific input in ETSAP-TIAM, it demonstrates the input assumptions that ultimately drive energy service demand. In general, it is projected that household size will continue to decrease over the future, resulting in more households globally. The largest reduction in household size is projected to occur in India.

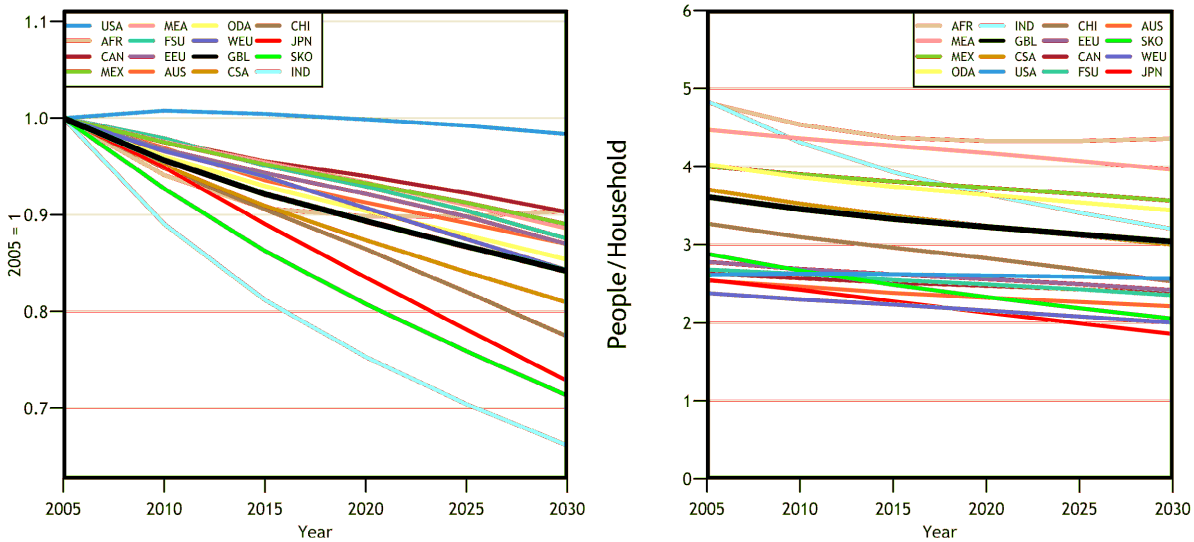

Figure 10. Size (number of people) of households by region, indices and projected values

3.4.1.5 GDP Per Household

GDP per household is computed by dividing the regional indices for GDP by the indices for the number of households (Figure 11). There is generally an increasing trend in most regions except for Japan and South Korea, and lower growth rates for Western Europe and other developed regions.

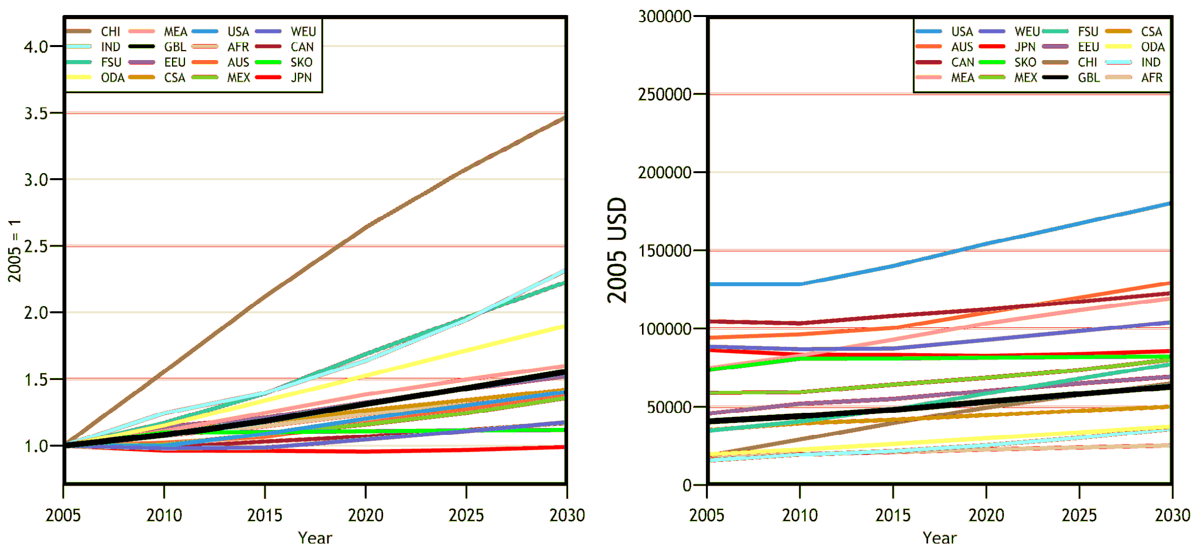

Figure 11. GDP per households index as inputs into ETSAP-TIAM and corresponding projected values

3.4.1.6 Other Sectoral Drivers

The remaining demand drivers are related to specific sectors, and thus can be interpreted as growth rates for the respective sectors in each region, indexed to 2005 (see Table 33. Demand Driver Description

POP	Population
GDP	Gross Domestic Product
GDPP	Per Capita GDP
HOU	Number of Households
GDPPHOU	GDP per Household
PAGR	Driver for Agriculture
PCHEM	Driver for Chemicals and Petrochemical
PISNF	Driver for Iron, Steel, and Non-Ferrous Metals
POEI	Driver for Other Energy Intensive Industries
POI	Driver for Other Industry
PSER	Driver for Services

Table 34 in the appendix). In general, these sectoral projections are based on other general equilibrium models, such as the global General Equilibrium Model (GEM-E3)[7] and GEMINI-E3[8]. These models produce a set of coherent drivers for each region, including population, households, GDP, sector outputs (commodities and services), and technical progress[9].

3.4.2 Sectors

ETSAP-TIAM also includes several measures and technologies to reduce energy intensity of fuel transformation of both energy supply and energy demand, including different types of power plants, transport technologies, industrial applications and energy appliances for the residential and commercial sectors. For the purpose of this project, the analysis focuses on the following end-use sectors (red boxes in Figure 5):

- Agriculture
- Building
- Transport
- Industry

In ETSAP-TIAM, agriculture is represented simplistically, and energy consumption in this sector is exogenously defined. Residential and commercial sub-sectors comprise the building sector, and include lighting, heating, cooling, cooking, appliances, and other electrical end-uses. Transport covers both personal and freight in the form of air, rail, shipping, and road vehicles. The industry sector consists of seven sub-sectors: iron & steel, chemicals, non-metallic minerals, non-ferrous metals, pulp and paper, other industries, and energy consumption for non-energy use (mainly feedstocks for chemical industry). Note, the power sector covers upstream fuel conversion and electricity generation and is not generally associated directly with end-use demand.

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[7] See http://www.gem-e3.net/
[8] See http://gemini-e3.epfl.ch
[9] See http://www.kanors.com/TIAM/Docs/Index.html

The main technology sectors and sub-sectors are outlined below. In general, the model's technology database contains both standard technologies to cover the industrial demand but also advanced technologies with higher efficiencies, and can be categorized as conventional/existing, improved/advanced, and best available. Not every technology, however, is categorized as such. Some technologies have an increasing level of energy efficiency for each future time step, representing an evolution in design for a given technology.

Conventional technological options are the most commonly present and widely used technologies on the current market, and may include old and outdated technologies that require replacement in accordance with current standards and/or regulations in a given region. This varies by the region, depending on the local conditions, market availability, energy resources, climate, etc.

Advanced technologies have higher energy performance than the conventional technologies and therefore require lower energy input. These technologies may be in compliance with the newly established standards in the region or even go beyond them in terms of performance. This category includes relatively new technologies currently being developed on the market.

Best available technologies are the regional 'best practices', i.e. the technology with the best possible performance available on the regional market. They are, therefore, a special subset of the advanced technology category. This category may include innovations and emerging technologies with small current market shares. In the industrial sub-sectors, the model also can shift between fuels (within pre-determined ranges to account for the technical feasibility to produce the corresponding final industry goods), which implies an adjustment of the energy chain and processes. ETSAP-TIAM is calibrated to energy statistics provided by the IEA (2007) and other public statistical databases. Subsectors, their units and associated demand drivers are given in Table 35.

In ETSAP-TIAM, energy efficiency is parameterized through different fuel conversion efficiencies in upstream processes and in end use technologies, defined as service output (e.g., light, heat, etc.) over energy input. Each technology has corresponding fixed (capital) and variable (operations and management) costs. In general, more efficient technologies have higher capital costs.

Each technology in ETSAP-TIAM also has a specified discount rate which shows how much corresponding energy efficiency improvements are implicitly valued by consumers (or investors) over time (Gillingham, Kotchen, Rapson, & Wagner, 2014). These discount rates are implicit since consumers do not base their decisions on life cycle cost calculations. High implicit discount rates for energy efficiency technologies have been found, at least 10% and sometimes much higher (Allcott, Mullainathan, & Taubinsky, 2014). High discount rates are not barriers themselves but a way to represent these in models or calculations. A study by Newell and Siikamäki (2015) on how US homeowners treat energy efficiency investments showed that people in a lower income group tend to have higher discount rates. However it is not clear if the same observations are true for low-income countries as it is with high-income countries in this regard. We speculate that there is some degree of regional differentiation of discounting with respect to efficiency investments, in particular, an argument could be made that low-income countries would likely have higher discounting, but we are aware of no studies that have examined this as of yet.

3.4.2.1 Agriculture

In contrast to the other end-use sectors, agriculture is represented simplistically within ETSAP-TIAM. Food production and demand is not represented in ETSAP-TIAM, but emissions are exogenously estimated from food production. Land competition or various alternative crop management techniques are not part of ETSAP-TIAM, so no adjustments in energy consumption are done to the agriculture sector in ETSAP-TIAM.

Biomass potential in ETSAP-TIAM is exogenously defined, and is given by industrial wastes, municipal wastes, energy crops, biogas, bioliquids (biofuels) and solid biomass. Solid biomass represents three types of biomass energy sources: dedicated bioenergy crops, agricultural and forestry residues and waste, and forest growth (Smeets, Faaij, & Lewandowski, 2004) and is defined for three different prices (low, medium and high). These different types of biomass are introduced in ETSAP-TIAM by the interregional exchange (IRE) process. These processes are defined by an activity bound, stating the resource potential, as well as an 'extraction' cost (IRE price). Stepwise cost curves are exogenously defined for each region. Data on the biomass potential (the activity bound) is based on a study by Smeets et al. (2004), which used the Quickscan model to calculate bioenergy potentials in 2050. In the study by Smeets et al. (2004), biomass potential is calculated based on assumptions of a mixed animal production system (i.e. a mix of pastoral and landless), high feed conversion efficiency, a very high level of technology for crop production, and rain fed water supply for agriculture.

By default ETSAP-TIAM does not distinguish between traditional biomass use and modern bioenergy production. This is problematic in renewable energy calculations because while modern bioenergy is considered a source or renewable energy in our analyses, traditional biomass is not, because we assume it is not in accordance with the SE4ALL objective of providing universal access to modern energy services.

Because traditional biomass is not generally a marketable good, there is no price data as such. Nevertheless, prices are required in the ETSAP-TIAM architecture. The modeling strategy is therefore to set a low price so that traditional biomass is consumed as a basic energy resource, but then place a constraint on the amount available per region and not allowing international trade of the resource. Price data were taken from TIAM-ECN (Kober, 2014).

It is not clear how much traditional biomass is currently being consumed in the world. For example, the IEA approach assumes all biomass consumption in non-OECD countries is traditional biomass whereas other researchers estimate that only half of the biomass consumption in non-OECD countries is traditional biomass (REN21, 2015). To produce the total amount of available traditional biomass for each region, results were taken from a reference scenario model run from the Global Change Assessment Model (GCAM 3.2) (Wise & Calvin, 2011). Per capita consumption estimates were created for the GCAM regions and years by dividing the traditional biomass consumption output by the GCAM population data. These per capita numbers were multiplied by the population in ETSAP-TIAM. In GCAM, Mexico is included in the Latin America region (analogous to Central and South America in ETSAP-TIAM), so the same per capita consumption rate was used for both Central and South America and Mexico regions in ETSAP-TIAM. To determine the share of biomass used for different service demands, the relative proportions (between water heating, cooking, and space heating) were computed from TIAM-ECN (Kober, 2014) and multiplied by total traditional biomass consumption estimates. Traditional biomass consumption is projected to decline by 2030 in all regions except for Africa (Figure 12). The traditional biomass amounts were subtracted from the ETSAP-TIAM biomass potentials for the respective regions.

In scenarios that include energy access, traditional biomass is assumed to be phased out at a rate of 7.5% per year for the ETSAP-TIAM regions using traditional biomass (Figure 12). Lacking any detailed literature on pathways to phase out traditional biomass by 2030, this rate of decrease was chosen to create a roughly linear decline to 2030. It is noted that complete phase out of traditional biomass is a very ambitious goal, as traditional biomass is still a part of ambitious climate mitigation scenarios, e.g. IEA World Energy Outlook 450 Scenario.

To address the issue of traditional biomass, three new technologies were added to ETSAP-TIAM. These technologies consume traditional biomass for hot water, cooking, and space heating in the following regions:

Africa, China, Central and South America, India, Mexico, and Other Developing Asia. These were added to distinguish traditional biomass usage from modern bioenergy production. In our analysis, we assume that all solid biomass consumed in the residential sub-sector for hot water, cooking, and heating is traditional biomass.

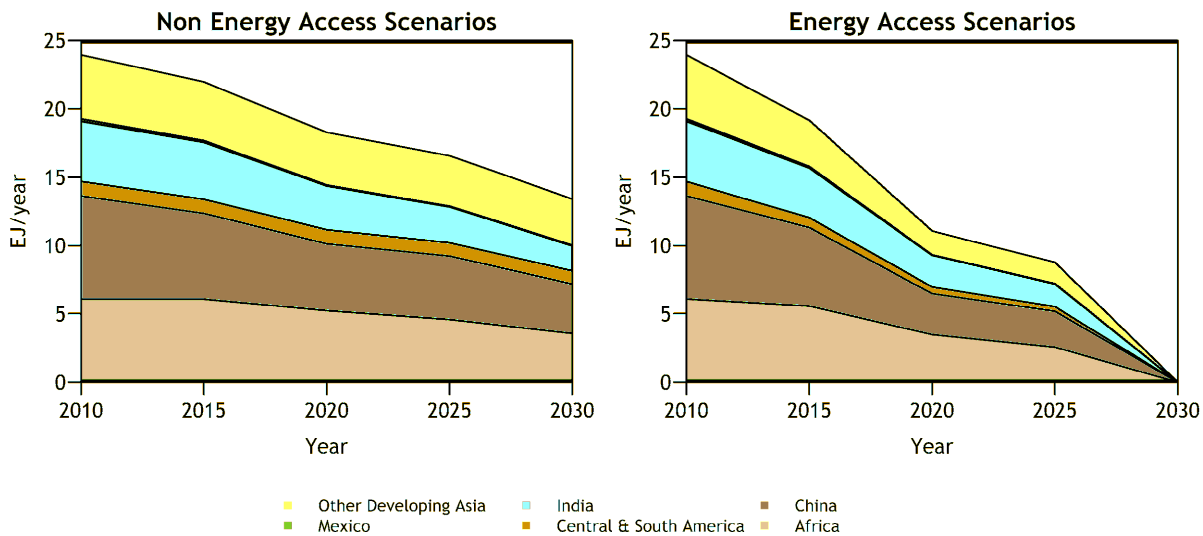

Figure 12. Traditional Biomass Consumption

3.4.2.2 Buildings

The building sector has more end-use technologies than any other sector in ETSAP-TIAM. For developing regions, new technologies were added that consume traditional biomass, so they could be distinguished from modern bioenergy consumption. This was done to allow a better accounting of renewable energy consumption, and also to analyze universal access to modern energy.

For the residential and commercial sub-sectors, ETSAP-TIAM distinguishes among different types of end-use energy, such as space heating, water heating, cooking, cooling and energy for other end-use applications (divided into electric and non-electric appliances). To satisfy end-use demand the model can choose between different technologies (e.g. boilers, heat pumps, electric heaters, etc.), including different levels of energy intensity and different fuels.

3.4.2.3 Transport

The transport sector entails both personal and freight transport in the form of air, rail, shipping, and road vehicles with a fixed distribution of the different transport modes over time, which is determined through the demand projections of the transport types covered by ETSAP-TIAM. Modal shift is not handled explicitly; i.e. there is no optimization of transportation modes; rather, the service demand for each transport type is modeled exogenously based on the demand drivers. Urbanization factors are handled implicitly with these demand drivers. Energy efficiency measures for road transport based on internal combustion engines (ICEs) are parameterized according to the IEA (2014b). Different levels of fuel conversion efficiency measures to reduce fuel consumption correspond to different transport technologies (Kober, 2014). For cars with gasoline or diesel ICE, the maximum improvement of fuel transformation efficiency is assumed to be 46% (compared to the standard car technology) and can be deployed at an additional cost of 3344 USD for gasoline engines and 3966 USD for diesel engines (Kober, 2014). For heavy duty diesel trucks, the maximum improvement is 42%, which comes with an additional cost of 38,504 USD (compared to the standard truck technology) (Kober, 2014). In order to reflect different levels of fuel conversion efficiency measures to reduce fuel consumption are clustered for the corresponding car and truck technologies (Kober, 2014). As a result the model contains five steps for energy efficiency improvements for gasoline cars and diesel trucks and six steps for diesel cars (Kober, 2014). These are summarized in Table 10, whereat cost figures are given for North American market conditions. Costs applicable to other world regions may differ from those costs by a factor of up to 25%.

In addition to ICE technology, ETSAP-TIAM covers alternative engine systems, electric engines as hybrid or pure electric drives as well as hydrogen combustion engines and fuel cell technology. An overview of selected car technologies is provided in Table 11. It should be noted, that from an energy system perspective competitiveness of alternative transport technologies not only depends on the costs and performance of the transport technologies itself but also on the costs associated to the upstream fuel production and the fuel transport infrastructure. This applies to electricity and in particular to hydrogen for which infrastructure costs could play a significant role. The associated costs are implemented in ETSAP-TIAM according to the approach suggested and demonstrated in Rösler, Bruggink, and Keppo (2011) and Rösler, van der Zwaan, Keppo, and Bruggink (2014).

Table 10. Efficiency and investment costs for various vehicles (Kober, 2014)).

Technology	Reduction of Fuel Consumption compared to standard technology (%)	Additional investment costs compared to standard technology (US$)
Gasoline Cars		
Advanced car with improvements up to 25 US$ per %-point of fuel reduction, including low rolling resistance tires, low friction design and material, improvement of aerodynamics	8	168
Advanced car with improvements up to 35 US$ per %-point of fuel reduction, including additionally lightweight components and variable valve actuation and lift	20	619
Advanced car with improvements up to 50 US$ per %-point of fuel reduction, including additionally start and stop technology and direct injection	33	1350
Advanced car with improvements up to 100 US$ per %-point of fuel reduction, including additionally starter-alternator, lightweight steel components, auxiliary systems improvements and dual clutch transmission.	44	2765
Advanced car with improvements up to 170 US$ per %-point of fuel reduction, including additionally lightweight aluminum.	46	3344
Diesel Cars		
Advanced car with improvements up to 25 US$ per %-point of fuel reduction, including low rolling resistance tires, low friction design and material, improvement of aerodynamics	8	168
Advanced car with improvements up to 35 US$ per %-point of fuel reduction, including additionally lightweight components	10	225
Advanced car with improvements up to 50 US$ per %-point of fuel reduction, including additionally start and stop technology and advanced combustion technology	19	632
Advanced car with improvements up to 75 US$ per %-point of fuel reduction, including additionally variable valve actuation and lift	34	1972
Advanced car with improvements up to 100 US$ per %-point of fuel reduction, including additionally starter-alternator, lightweight steel components, auxiliary systems improvements and dual clutch transmission.	44	3387
Advanced car with improvements up to 170 US$ per %-point of fuel reduction, including additionally lightweight aluminum.	46	3966
Diesel Trucks (Heavy Duty)		
Advanced truck with improvements up to 100 US$ per %-point of fuel reduction, including eco roll freewheel function and driver support systems	6	350

Advanced truck with improvements up to 200 US$ per %-point of fuel reduction, including additionally controllable air compressor, low rolling resistance tires, variable valve actuation, sequential turbo/downsizing, speed control (injection) and vehicle platooning	18	2628
Advanced truck with improvements up to 550 US$ per %-point of fuel reduction, including additionally acceleration control, smart alternator, battery sensor, electric accessory drive, pneumatic booster – air hybrid, active aerodynamics and single wide tires	29	7359
Advanced truck with improvements up to 1050 US$ per %-point of fuel reduction, including additionally aerodynamic fairings, predictive cruise control, lightweight materials and automated manual transmission	38	18354
Advanced truck with improvements up to 4500 US$ per %-point of fuel reduction, including additionally aerodynamic trailers, turbo-compound bottoming cycles/waste heat recovery	42	38504

Table 11: Overview of selected alternative car technologies using electricity or hydrogen, based on Rösler et al. (2011)

Technology	**Reduction of fuel consumption compared to standard gasoline car technology**[10]	**Additional investment costs compared to standard gasoline car technology (USD)**
High efficient gasoline electric plug-in hybrid car	43%	8627
Long-distance electric car	75%	20694
High efficient hydrogen ICE car (2020)	43%	8002
High efficient hydrogen fuel cell car (2020)	61%	18168

3.4.2.4 INDUSTRY

In the industry sector, energy efficiency improvement measures are specific to the industry branch and the processes applied to produce a certain product. In ETSAP-TIAM, modeling of energy intensity of industrial production not very detailed, and thus there is not much flexibility to determine different energy efficiency levels of industrial production. Because of the simplifications regarding industry production in ETSAP-TIAM, this leads to a strong decline of energy intensity even under absence of policies promoting energy efficiency improvements. Therefore, it is necessary to enhance ETSAP-TIAM to increase its flexibility regarding representation of different energy intensive production processes in the industry sector and to better reflect impacts of energy and climate policy measures with respect to promotion of energy efficiency in industry.

By default, ETSAP-TIAM specifies an AEEI for each of the industry sub-sectors as a fixed coefficient in the industrial energy demand processes in the base year templates. This results in a strong decline of energy intensity of industrial production regardless the energy/climate policy conditions. Therefore ETSAP-TIAM was enhanced by

[10] Upstream conversion efficiency to produce electricity or hydrogen is not considered for the calculation of fuel reduction.

introducing new energy demand processes for five industry sub-sectors, which represent shift in production processes and/or improvements of the energy consumption in industrial production processes itself.

Model structure and data in ETSAP-TIAM were updated for the following industry sub-sectors: non-metallic minerals, chemicals, non-ferrous metals, pulp and paper, and other industries. No changes have been made for the iron and steel sub-sector, because a detailed technology-oriented structure was already developed during an ETSAP-TIAM collaboration project, funded by ETSAP.

3.4.2.4.1 NON-METALLIC MINERALS

Energy efficiency improvements are introduced for different kiln types and conversion from one kiln type to another. Data for regional distribution are based on WBCSD (2015) (Table 12). It is assumed that the 2012 distribution remains constant throughout 2030. Energy efficiency improvements are introduced according to kiln type specific best available technology (BAT). Therefore WBCSD's (2015) 2012 average of thermal energy consumption has been used to calculate BAT and current regional energy intensity by kiln type (Table 13). In order to apply WBCSD's (2015) figures to the ETSAP-TIAM model simplifications or general assumptions have been made where regional data from WBCSD (2015) does not exactly match the model regions. For instance, Latin America energy consumption data was used for the native model regions 'Mexico' and 'Central and South America', and EU28 data for both 'Eastern Europe' and 'Western Europe'. The energy efficiency improvement potential is given in Table 14. With the first option, conversion of wet kiln processes to dry kiln processes, highest efficiency improvements can be achieved. This option, however, is only applicable in a few regions where this transformation has not been fully deployed so far. For instance, India has modernized its cement production over the past decades and shifted from 97% wet kiln based processes in the 1950s to 100% dry kilns by today (Sathaye et al., 2010).

Table 12. Cement kiln types by region, based on WBCSD (2015)

Region	**Wet, semi-wet and semi-dry kilns**	**Mixed (wet/dry) kilns and dry kilns without pre-heater**	**Dry kilns with pre-heater and without pre-calciner**	**Dry kilns with pre-heater and with pre-calciner**
Africa	2%	0%	12%	86%
Australia/ New Zealand	5%	14%	15%	66%
Canada	0%	0%	50%	50%
China	0%	0%	0%	100%
Central and South America	0%	16%	24%	60%
Eastern Europe	11%	13%	29%	46%
Former Soviet Union	0%	0%	0%	100%
India	0%	0%	12%	88%
Japan	5%	14%	0%	81%
Middle East	0%	0%	0%	100%
Mexico	0%	16%	27%	57%
Other Developing Asia	0%	0%	0%	100%
South Korea	0%	0%	11%	89%
USA	2%	15%	11%	72%
Western Europe	11%	13%	29%	46%

Table 13. Average of thermal energy consumption (excluding drying of fuels) on global level and of selected world regions WBCSD (2015)

Region **(MJ / t clinker)**	**Wet kilns**	**Dry kilns without pre-heater**	**Dry kilns with pre-heater and without pre-calciner**	**Dry kilns with pre-heater and with pre-calciner**
World average	5005	3731	3672	3402
Regional minimum	5005	3623	3488	3028
Regional maximum	7029	4930	3950	4057
EU28	5230	3822	3695	3587
USA	7029	4930	3950	3675
CIS (Commonwealth of Independent States)	-	-	-	4057
India	-	-	-	3028
China	-	-	-	3300
Asia (excl. China, India, CIS)	-	-	3493	3302
Latin America	5357	3623	3679	3499
Africa	5842	-	3885	3692

Table 14: Energy efficiency improvements for cement industry, based on Worrell and Galitsky (2008), Worrell, Kermeli, and Galitsky (2013) and WBCSD (2015)

Technology shift	**energy efficiency improvement**	**Cost (USD/GJ fuel saved)**
Conversion cement wet process to standard to dry multi	40 – 57%	29.7
Conversion cement wet process to BAT wet process	4-34%	0.9
Conversion cement dry single stage process to multi-stage process with preheater and pre-calciner	16 – 39%	22.5
Conversion cement dry multi stage process with pre-heater to multi with preheater and pre-calciner	13 – 23%	13.5

3.4.2.4.2 Chemicals

Energy efficiency improvements in the chemical subsector are introduced mainly for the energy-intensive chemical branches (CIEC, 2015). Three typical products (Methanol, Ammonia and Ethylene) are used as indicators in order to determine the regional distribution of the production of energy-intensive chemical products (Table 15). For each product, two levels of energy efficiency improvement (medium and very high) are applied based on fuel saving and cost data from the IEA (2009) (Table 16) which are then converted to region-specific cost-potential-curves for energy efficiency improvements for energy-intensive chemical industry in ETSAP-TIAM.

Table 15: Regional shares of global production of three energy-intensive products of the essential chemical industry (CIEC, 2015). Statistics for methanol and ethylene estimated for 2013 based on Brelsford (2014), Berggren (2013)and Methanex (2014), and statistics for ammonia derived from the USGS (2015).

Region	**Methanol**	**Ammonia**	**Ethylene**
Africa	3%	4%	1%
Australia/ New Zealand	3%	1%	0%
Canada	1%	3%	4%
China	51%	31%	10%
Central and South America	11%	6%	4%
Eastern Europe	0%	3%	7%
Former Soviet Union	3%	13%	3%
India	0%	9%	2%
Japan	0%	1%	5%
Middle East	17%	8%	17%
Mexico	0%	1%	1%
Other Developing Asia	3%	8%	9%
South Korea	0%	0%	0%
USA	3%	6%	20%
Western Europe	3%	7%	17%

Table 16: Energy efficiency improvements for the chemical industry, based on IEA (2014a)

Chemical sector/level of improvement	**energy efficiency improvement**	**Investment cost (USD/GJ annual fuel capacity)**
High value chemicals: medium energy efficiency improvements	0.05	69
High value chemicals: very high energy efficiency improvements	0.33	433
Ammonia: medium energy efficiency improvements	0.05	29
Ammonia: very high energy efficiency improvements	0.33	180
Methanol: medium energy efficiency improvements	0.05	14
Methanol: very high energy efficiency improvements	0.33	84

Table 17: Shares of sub-sectors of the chemical industry for the deployment of energy efficiency measures by region

Region	High value chemicals	Ammonia	Methanol
Africa	10%	66%	6%
Australia/ New Zealand	13%	50%	19%
Canada	39%	42%	1%
China	13%	58%	11%
Central and South America	26%	46%	11%
Eastern Europe	50%	32%	0%
Former Soviet Union	13%	67%	2%
India	14%	69%	0%
Japan	68%	14%	0%
Middle East	47%	28%	8%
Mexico	44%	38%	0%
Other Developing Asia	37%	43%	2%
South Korea	82%	0%	0%
USA	56%	24%	2%
Western Europe	52%	29%	2%

3.4.2.4.3 NON-FERROUS METALS

The sector 'non-ferrous metals' encompasses production of metal other than iron and steel. With regards to production quantities and associated energy consumption aluminum and copper represent the most important products of this sector. China dominates primary aluminum and copper production in the world (Table 18). Primary aluminum production is very electricity intensive and energy efficiency improvements mainly refer to improved/changed smelter technologies (incl. enhanced anodes and cathodes) and better process control (Table 19). In India for example, average smelter electricity consumption is at 14.8MWh/t of aluminum, with a range between 14.2 and 18.1 MWh/t (Sathaye et al., 2010), while best-practice primary aluminum production consumes about 13.6 MWh/t of Aluminum (Worrell & Galitsky, 2008). An even higher efficiency improvement in the long-run is expected from inert anodes which could bring down energy requirement to 11 MWh/t of aluminum (IEA, 2009). However costs for this technology have not yet been thoroughly assessed in the literature and are thus highly uncertain. For the model implementation of the defined energy efficiency improvements for aluminum production it was taken into account, that aluminum production has different relevance of total production of non-ferrous metals across regions. The region's aluminum shares have been calculated based on Table 18, and are assumed to remain constant over time.

Table 18: Production of primary aluminium and copper in 2010 (USGS, 2015)

Region	Aluminium (Mt)	Copper (Mt)
Africa	1.73	0.88
Australia/ New Zealand	2.27	0.42
Canada	2.96	0.32
China	16.20	4.67
Central and South America	2.29	3.88
Eastern Europe	0.64	0.79
Former Soviet Union	4.55	1.31
India	1.61	0.66
Japan	0.05	1.55
Middle East	3.00	0.29
Mexico	0.00	0.25
Other Developing Asia	0.31	0.56
South Korea	0.00	0.57
USA	1.73	1.10
Western Europe	3.89	1.89
Global	*41.20*	*19.10*

Table 19: Energy efficiency improvements for aluminium production based on IEA (2009)

	energy savings	Investment cost (USD/GJ fuel saved)
Conversion Søderberg smelter to pre-baked anode smelter	10%	850
Pot control and point feeder improvements for pre-baked anode smelters	3%	600
New cathodes in addition to pot control and point feeders	6%	1600
Inert anodes and cathodes	28%	3200

3.4.2.4.4 Pulp and paper

In ETSAP-TIAM, pulp and paper are treated as an aggregate and are not modeled as separate products. However, energy intensities of paper production are typically lower than those of pulp production. Among pulp production two general process classes can be distinguished: mechanical pulping and chemical pulping; where mechanical pulping requires mainly mechanical energy and chemical pulping mainly thermal energy. Both production processes are not fully substitutable, because they provide different product qualities, or even different products. Hence their historic shares of total production (Table 20) are assumed to remain constant over the whole model time horizon. In order to determine the extent to which an energy efficiency measure applies to the aggregate of pulp and paper, shares of the different process types based on statistical data from the FAO (2015) and the IEA (2009) have been used.

In consequence, the first measure of Table 21 applies to mechanical pulping only and the second and third measure to chemical pulping. The fourth measure can only be deployed to the extent of paper production. The costs and energy savings are estimated based on the IEA (2007, 2009, 2014b).

Table 20: Production of pulp and paper in 2010 (FAO 2015) and shares of mechanical and chemical pulping, based on 2004 data from the IEA (2007)

	Pulp production				**Paper production**	
Region	**Quantity (Mt)**	**Share of world production**	**Share of mechanical pulping**	**Share of chemical pulping**	**Quantity (Mt)**	**Share of world production**
Africa	0.5	(0%)	22%	78%	1.3	(0%)
Australia/ New Zealand	2.8	(2%)	22%	78%	4.1	(1%)
Canada	18.6	(10%)	47%	53%	12.8	(3%)
China	20.1	(11%)	24%	76%	92.9	(24%)
Central and South America	22.5	(12%)	5%	95%	17.6	(4%)
Eastern Europe	2.9	(2%)	20%	80%	8.3	(2%)
Former Soviet Union	7.6	(4%)	20%	80%	7.6	(2%)
India	4.0	(2%)	22%	78%	10.1	(3%)
Japan	9.4	(5%)	12%	88%	27.4	(7%)
Middle East	0.4	(0%)	22%	78%	4.9	(1%)
Mexico	0.2	(0%)	5%	95%	4.7	(1%)
Other Developing Asia	9.1	(5%)	0%	100%	34.5	(9%)
South Korea	0.1	(0%)	22%	78%	0.1	(0%)
USA	50.3	(27%)	8%	92%	77.7	(20%)
Western Europe	36.6	(20%)	35%	65%	90.5	(23%)
Global	*185.0*	*(100%)*	*20%*	*80%*	*394.5*	*(100%)*

Table 21: Energy efficiency improvements for pulp and paper industry, based on the IEA (2007, 2009, 2014b)

	Energy intensity per unit of production (GJ/t)	**Cost per unit of production (US$/t)**
Conversion mechanical pulping to BAT technology	7.50	29
Conversion to integrated chemical pulping BAT technology	11.83	74
Integrated chemical pulping with black liquor gasification	9.83	1595
Conversion to paper production BAT technology	6.87	195

3.4.2.4.5 Other industries

For Other industries, which represents various mining and manufacturing subsectors, five energy efficiency improvement steps are estimated based on fuel saving costs for cross-cutting technologies from the IEA (2014b). Energy efficiency improvements covered in this category refer to steam piping, boilers, furnaces, refrigeration, fans, pumps and compressed air systems. The original data source of IEA (2014b) lists 72 energy saving measures- these have been clustered into the five cost categories (Table 22). In clustering the measures, it is assumed that the measure with the highest fuel saving is representative for corresponding cost cluster. It is also assumed that measures resulting in a smaller fuel savings need to be combined in order to reach the cluster's determined energy efficiency improvement level. Across all five steps, a maximum fuel saving of up to 42% has been estimated. This estimate assumes that multiple energy saving measures over all energy efficiency improvement levels can be combined leading to a least energy consumption across all applications in this sector. Given the variety of applications in the sector 'other industries' the levels defined here represent a rough simplification of regional capabilities and costs to reduce energy consumption in this sector. To provide a benchmark of energy savings for other industries we compare the maximum energy saving of 42% with the reduction of the final energy consumption of 'other industries' between the 6 degree Celsius scenario and the 2 degree Celsius scenario of IEA's Energy Technology Perspectives (2015), which amount on global level to 36 EJ in 2050 corresponding to 39% of the final energy consumption of the 6 degree Celsius scenario.[11] More regional data and a disaggregated model structure would allow an investigation of energy efficiency improvements in more detail.

Table 22: Energy efficiency improvements for other industries based on IEA (2014a)

	energy savings	**Cost (USD/GJ fuel saved)**
Improvements other industry: stage 1	13%	4
Improvements other industry: stage 2	19%	8
Improvements other industry: stage 3	26%	17
Improvements other industry: stage 4	34%	42
Improvements other industry: stage 5	42%	85

3.5 Calculations

3.5.1 Ranking Metrics

The high level of detail in the technologies, fuels, sectors, and subsectors within ETSAP-TIAM, coupled with 15 regions and a global sum, across 11 scenarios, results in a large amount of output data. Detailed figures for the results of all these permutations will therefore be relegated to an appendix. In order to identify key sectors (those with the greatest growth rate between two scenarios or those that have the largest net difference in 2030 between the two scenarios), two metrics are used: a growth rate metric and a net growth metric.

First, to determine which (sub)sectors in which regions have the greatest growth rates, scores are calculated for all (sub)sectors in all regions based on the ratio of the rates of growth from 2010-2030 between a reference and an alternative scenario (Equation 2).

$$growth\ rate\ metric_{region,sector} = \frac{(2030\ Value_{Alt\ Scenario} - 2010\ Value)_{region,sector}}{(2030\ Value_{Ref\ Scenario} - 2010\ Value)_{region,sector}}$$

[11] When comparing to IEA's ETP 2015, we associate final energy consumption of the sector 'other industries' with the total final energy consumption of the industry sector, reduced by the consumption for the production of cement, chemicals and petrochemicals, iron and steel, pulp and paper, and aluminium.

Equation 2. Metric for ranking (sub)sectors based on growth rates relative to a reference scenario.

Equation 2 essentially calculates the ratio between the 2030 versus 2010 increase in the alternative scenario versus the 2030 versus 2010 increase in the reference scenario. The drawback to the growth rate metric is that it does not take into account the scale of the actual growth amounts, and therefore can give high rankings to subsectors that change a lot in relative terms, but in fact, start from a very low value and grow very little in absolute terms. Additionally, if the amount of growth in the reference scenario is greater than the amount of growth in the alternative scenario, then the metric will produce an absolute value less than unity, and this will not be ranked high, even if the difference between the two scenarios is substantial. To address these drawbacks, a second metric is also employed that looks at the net growth within a (sub)sector in Equation 3.

$$net\ growth\ metric_{region,sector} = \left(2030\ Value_{Alt\ Scenario} - 2030\ Value_{Ref\ Scenario}\right)_{region,sector}$$

Equation 3. Metric for ranking (sub)sectors based on net growth relative to a reference scenario.

Equation 3 computes the difference in the 2030 values between the alternative and reference scenarios. The drawback to the net growth metric is that it can give high rankings to (sub)sectors that have a high initial value but that have low growth rates.

As both metrics have strengths and weaknesses, these two metrics are qualitatively considered together to assess which (sub)sectors which have the highest potential for change: the scores for the two metrics are then ranked, with the top rankings representing the (sub)sectors with the greatest rate of change between the two scenarios. Depending on the parameter of interest, one metric may be more intuitively meaningful than the other. In (sub)sectors where the largest change in either direction is of interest, the metrics are ranked by their absolute value, yet, in such cases, the arithmetic signs of the metrics are retained to determine the direction of change.

3.5.2 Economic Metrics

Net Present Value (NPV) is used to summarize all costs into present day, using a discount rate. Because ETSAP-TIAM operates on a 5-year time step, intermediary years are assigned to model output thusly (Table 23):

Table 23. Allocation between calendar years and ETSAP-TIAM model years

Calendar Year (index)	Year number	ETSAP-TIAM model year (time step)
2010	0	2010
2011	1	2010
2012	2	2010
2013	3	2015
2014	4	2015
2015	5	2015
2016	6	2015
2017	7	2015
2018	8	2020
2019	9	2020
2020	10	2020
2021	11	2020
2022	12	2020
2023	13	2025

2024	14	2025
2025	15	2025
2026	16	2025
2027	17	2025
2028	18	2030
2029	19	2030
2030	20	2030

NPV is calculated as the sum of a given value over the years, subject to the discount rate (Equation 4).

$$NPV = \sum_{i=2010}^{2030} value_t \times (1 - dr)^{i-2010}$$

Equation 4. NPV calculation

For economic cost efficiency ranking, and discounted investment cost is used over discounted energy savings is used, and is given in Equation 5.

$$cost\ efficiency\ of\ energy\ savings_{region,sector} = \frac{\sum_{i=2010}^{2030}\left(investment_{Alt} - investment\ _{Ref}\right)_t \times (1 - dr)^{i-2010}}{\sum_{i=2010}^{2030}\left(Energy\ Consumption_{Ref} - Energy\ Consumption_{Alt}\right)_t \times (1 - dr)^{i-2010}}$$

Equation 5. Cost efficiency of energy savings

In Equation 4 and Equation 5, *i* is the year index, for every year between 2010 and 2030, where the t is the ETSAP-TIAM time step that corresponds to the value of *i*, given in Table 23.The discount rate, *dr*, is taken to be 5%

3.5.3 Greenhouse Gas Accounting

ETSAP-TIAM computes output emissions for three greenhouse gases: CO_2, CH_4 and N_2O. To compare and display emissions on a single scale, CH_4 and N_2O are converted to CO_2e by their respective 100-year Global Warming Potentials (GWP) from the IPCC 5th Assessment Report (Myhre et al., 2013) (Table 24). We employ the GWP values that include the carbon feedback, as they provide a more consistent methodology for calculation (Trottier, 2015).

Table 24. 100-year Global Warming Potentials of greenhouse gases (Myhre et al., 2013)

Gas	**GWP without climate carbon feedback**	**GWP with climate carbon feedback**
CO_2	1	1
CH_4	28 (fossil methane); 30 (non-fossil methane)	34
N_2O	265	298

4 Results

4.1 SE4ALL Key Objectives

4.1.1 Energy Intensity

In Figure 13, the EIIR are given for the Ref, RE, and EE-based scenarios (EE, EE+RE, EE+RE+EA) for the years 2010 to 2030. By design, the Ref scenario has an EIIR of -1.3% CAGR, and the EE-based scenarios have EIIR set to -2.6% CAGR. In the RE scenario (which meets the SE4ALL renewable energy objective), the reduction in energy intensity is approximately half way to the SE4ALL energy efficiency objective. This gives evidence that the two objectives have a synergetic effect.

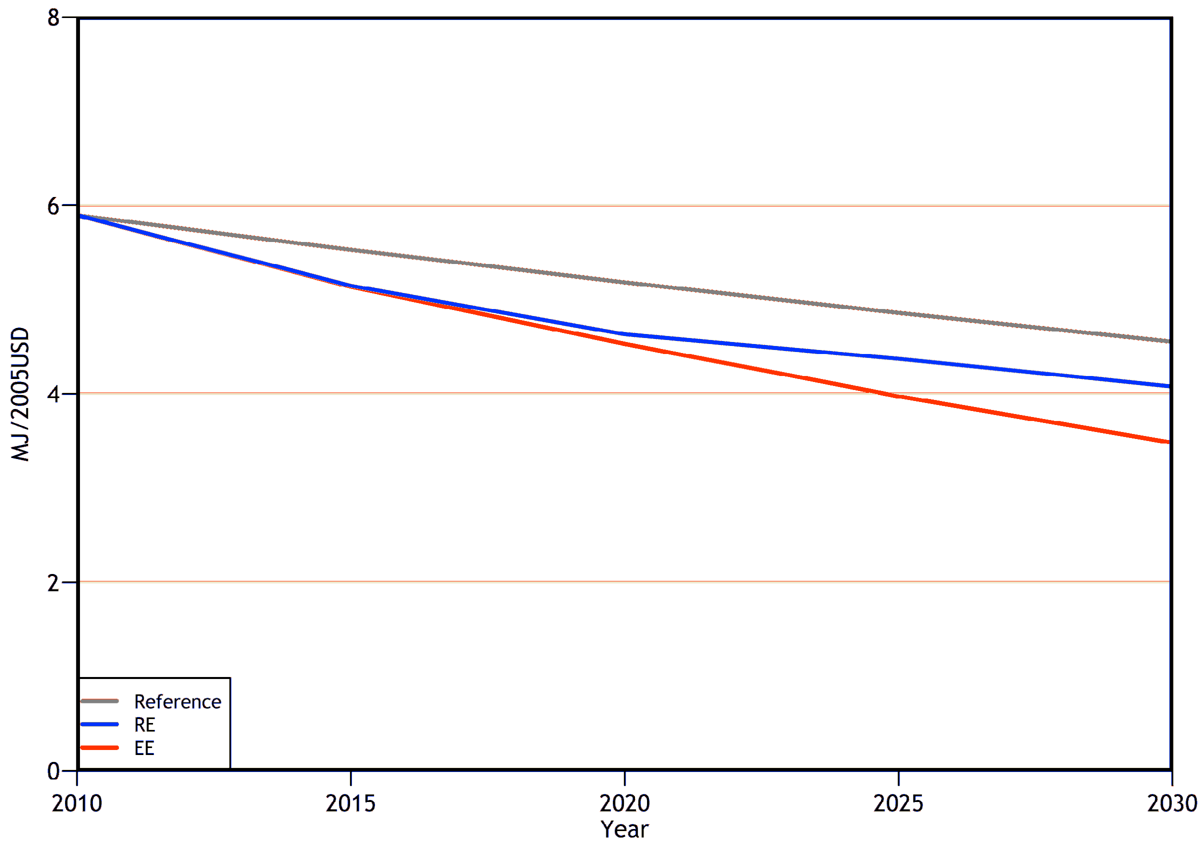

Figure 13. Global Energy Intensity, by year and scenario.

Figure 14 displays regional energy intensity for the EE+RE+EA scenario, which is designed to achieve the three SE4ALL objectives. The largest rates of reduction in energy intensity are projected in many of the historically least efficient regions, such as the Former Soviet Union and China. However, South Korea and Canada, relatively developed regions, have relatively high energy intensities and are not projected to improve much.

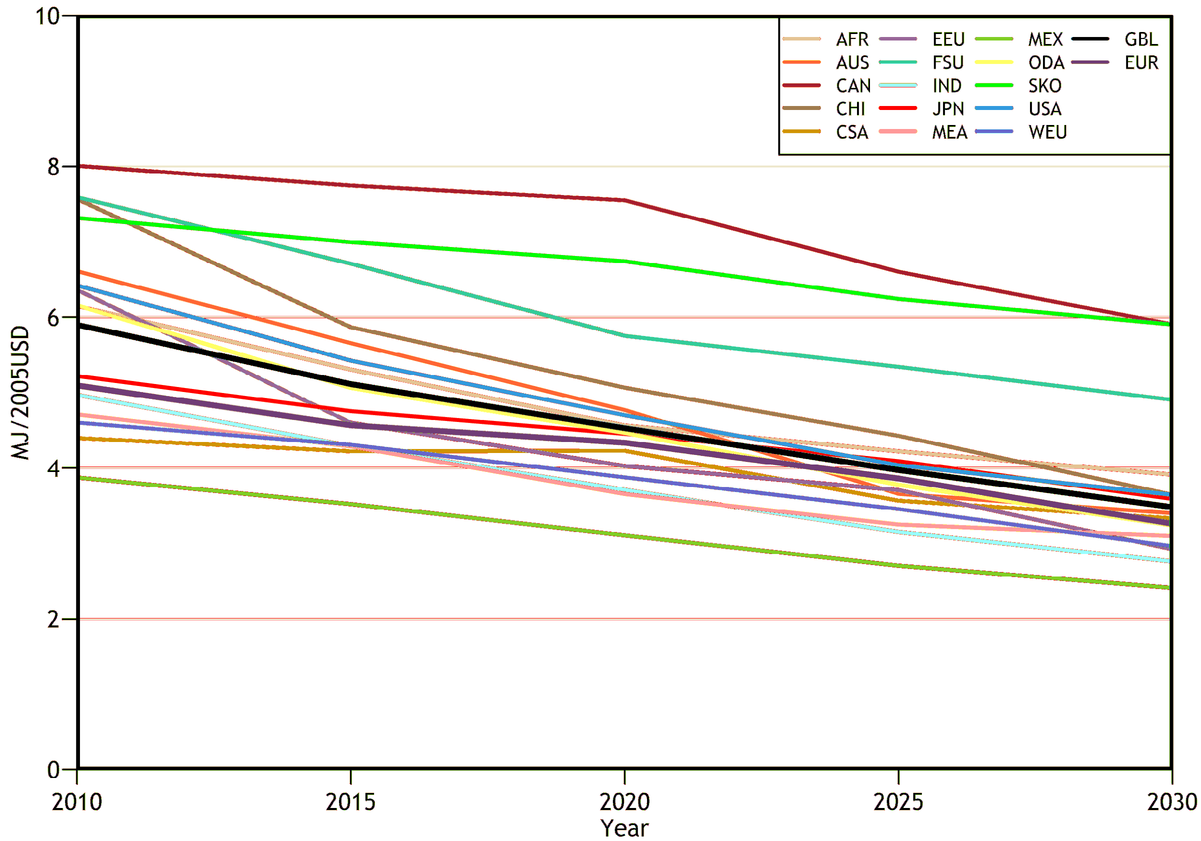

Figure 14. EIIR from the EE+RE+EA scenario.

In Figure 15, the RE scenario, where no constraint is placed on energy efficiency yet the SE4ALL doubling of renewable energy objective is achieved, has a global EIIR is 1.8%. As noted above, achieving the SE4ALL renewable energy objective is synergistic with meeting the SE4ALL energy efficiency objective. India, Japan, the Middle East, and Western Europe are projected to reduce energy consumption slightly more in the EE+RE scenario versus the EE scenario, suggesting that these regions have a have a greater synergy between energy efficiency and renewable energy than the other regions.

In the EE+RE+EA scenario in Figure 15, the most cost optimal way of achieving all three SE4ALL objectives would be to focus on Eastern Europe, China, Australia, Other Developing Asia, and India. The introduction of the universal energy access objective translates into a slightly lower reduction rate in energy intensity for some of the regions currently consuming traditional biomass (China, India, Africa, Mexico) and a slightly higher in others consuming traditional biomass (Other Developing Asia, Central and South America).

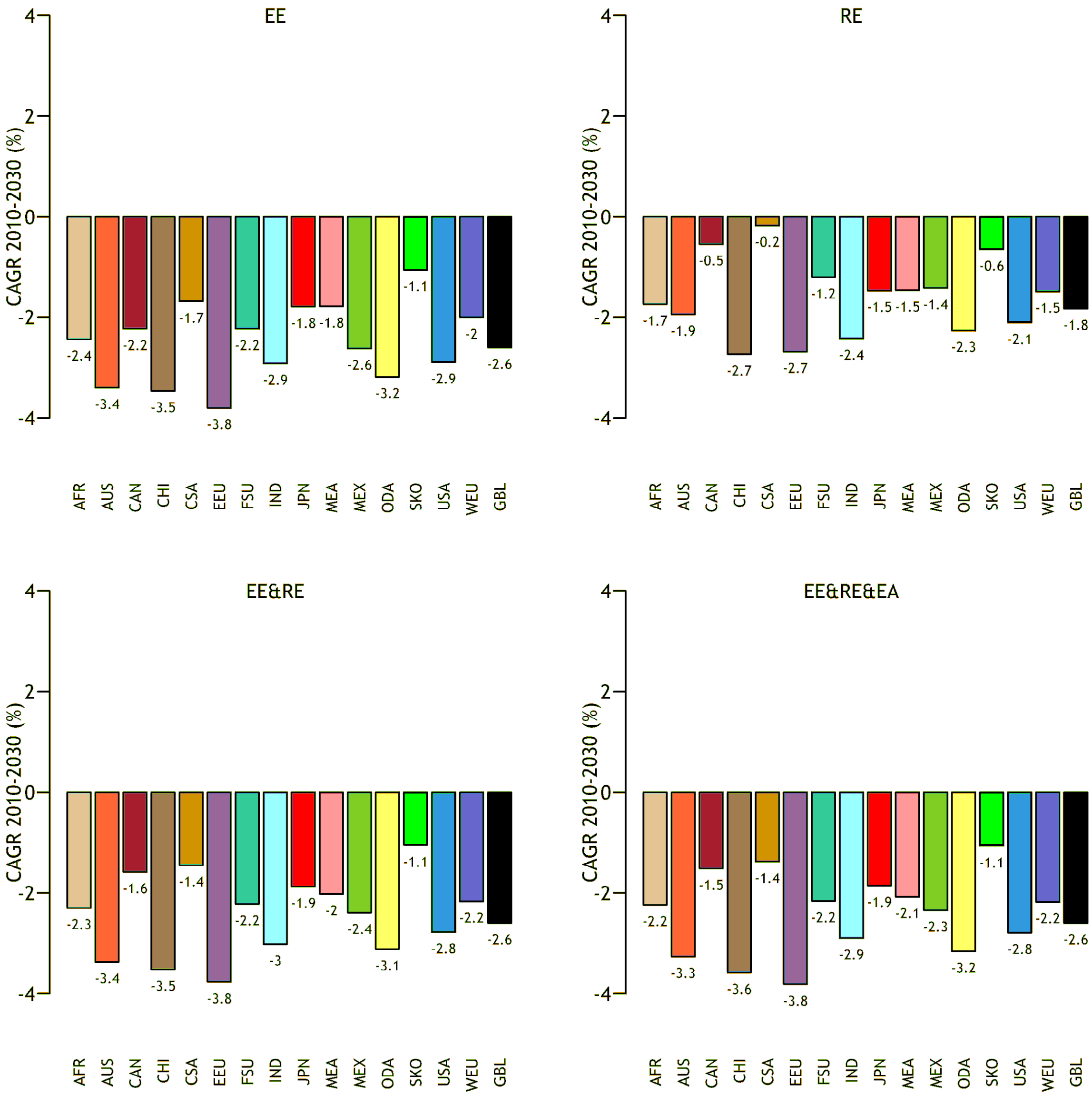

Figure 15. Compound Annual Change in Energy Intensity 2010-2030, by region, alternative scenarios

4.1.2 Renewable Energy

In Figure 16, the renewable energy for the year 2030 is compared between the reference, the EE and the RE scenarios (shares of renewable energy are similar between the RE, EE+RE and EE+RE+EA scenarios). Without any constraints (targets) for renewable energy and no constraints (targets) for energy intensity, the percentage of renewable energy in final energy consumption does not increase much.

In Figure 16, Adding the energy intensity constraint produces a solution where it is economically optimal to also increase the deployment of renewable energy, such that by 2030, it is approximately half way to the RE scenario level in comparison to the reference scenario.

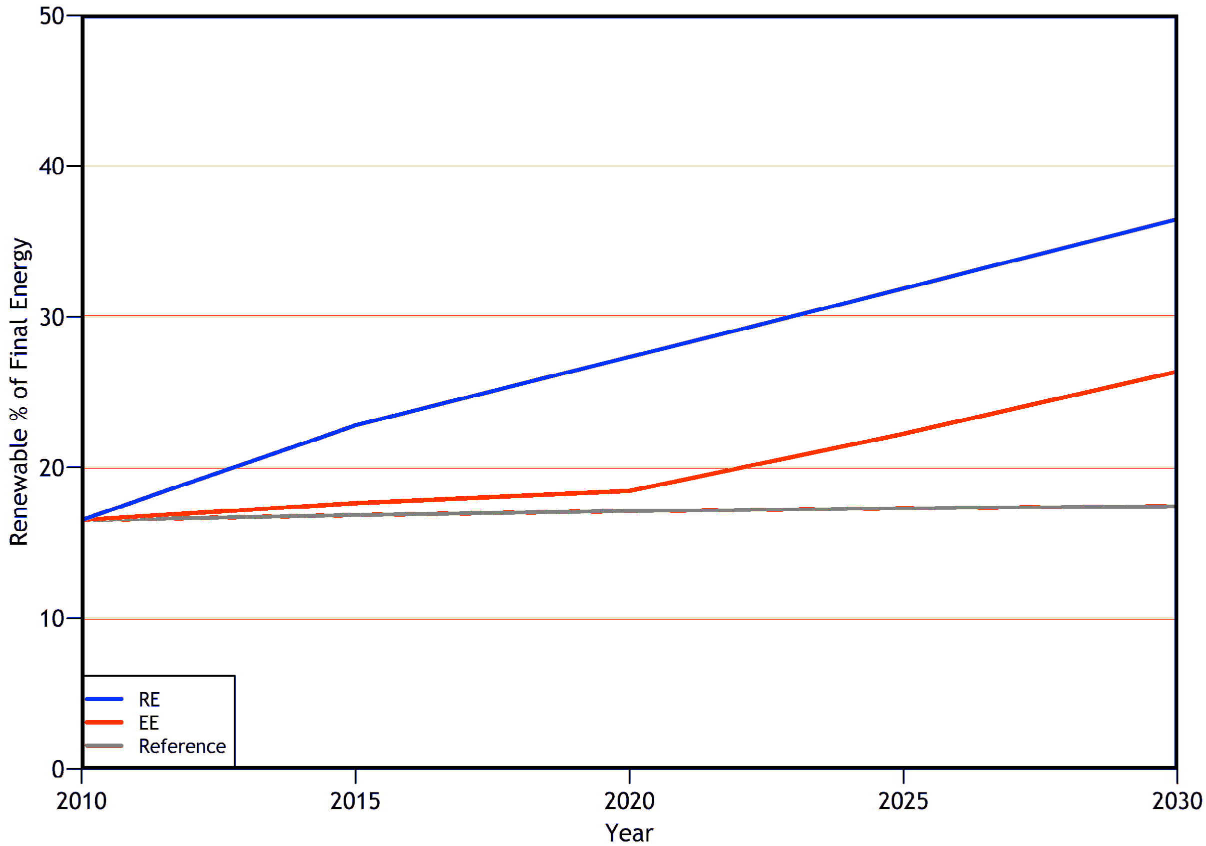

Figure 16. Renewable share of total final global energy consumption by scenario

This is seen in more detail in Figure 17, where the Ref scenario is compared to the EE and RE scenarios by region. Results are shown only for the year 2030. Meeting the energy efficiency objective encourages more deployment in renewable energy, particularly in Africa, China, and India and Developing Asia. It has less effect in South Korea, Western and Eastern Europe, where the economically optimal solution actually results in a lower percentage of renewable energy in comparison to the reference case.

From a global perspective, the energy intensity targets bring about more renewable energy in the commercial and residential sectors (i.e. building) and less so in industry (Figure 18). The renewable energy share within transport is actually lower in the EE scenario than the reference scenario. Again, this shows the synergy between the SE4ALL energy efficiency and renewable energy objectives.

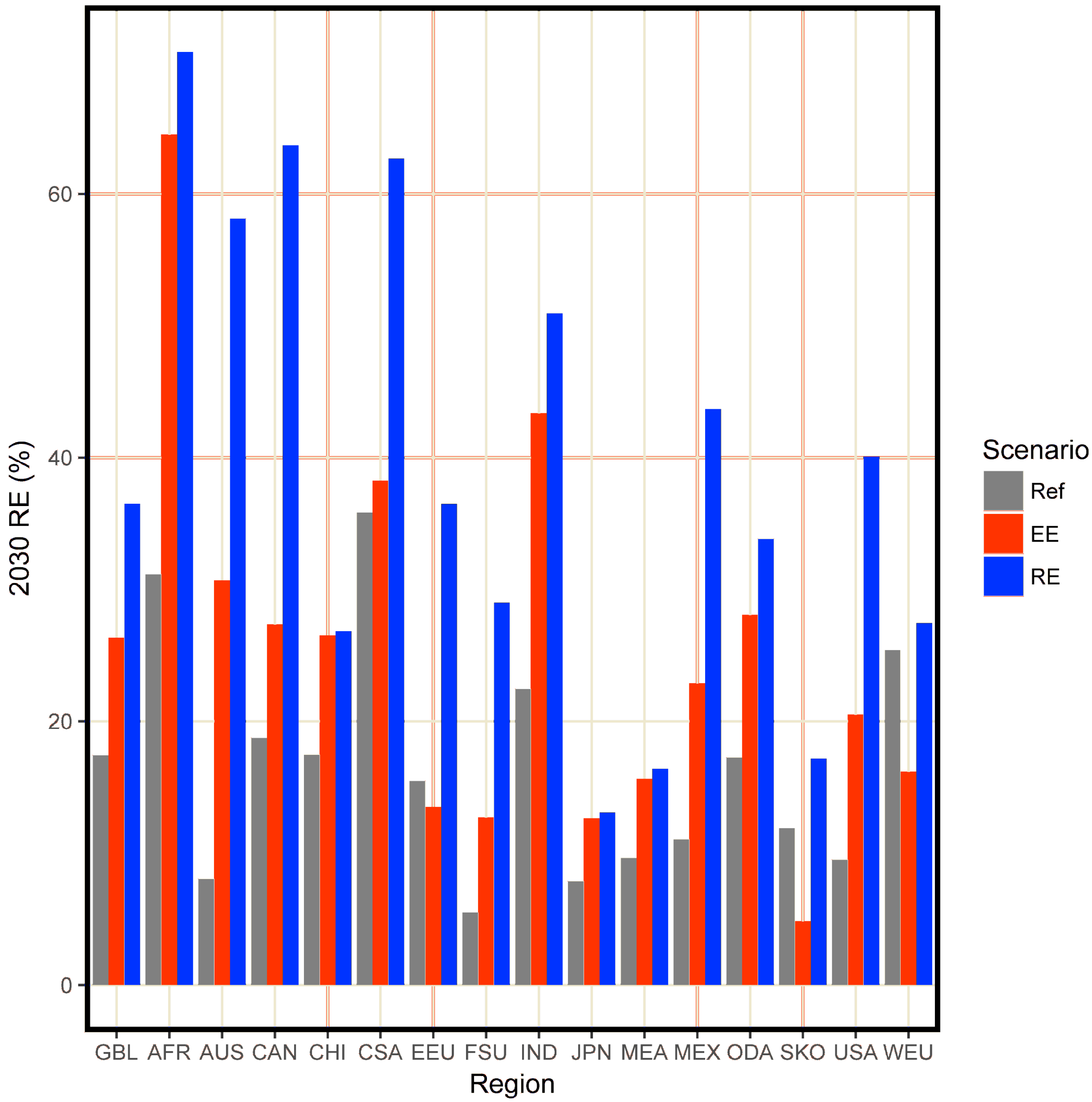

Figure 17. 2030 Renewable shares of global final energy, by region

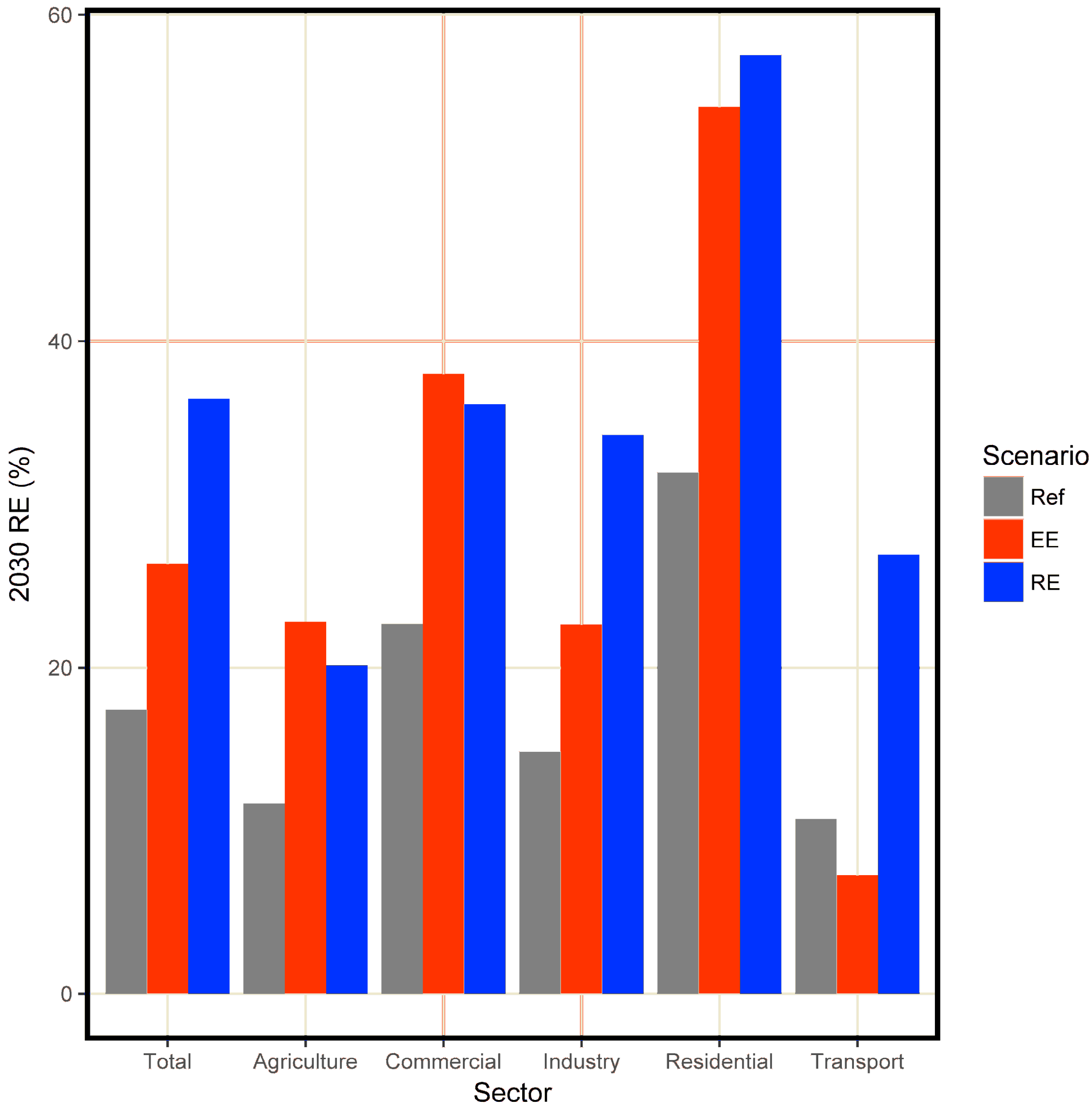

Figure 18. 2030 global renewable energy shares of final energy, by sector.

Traditional Biomass is counted as renewable in our calculations of renewable energy shares. However, in the scenarios where the SE4ALL Energy Access objective is achieved, use of traditional biomass is phased out. When comparing the EE+RE scenario with the EE+RE+EA scenario in Figure 19, there is a large difference between developing and developed regions in how they develop through time within the modeled scenarios. In both scenarios, the SE4ALL renewable energy objective is achieved, but with the Energy Access objective (EE+RE+EA scenario), the renewable energy shares do not increase as much in the developing regions, and increase more in the developed regions in order to reach the global target. This occurs because when traditional biomass is phased out in the EE+RE+EA scenario, not all of the energy demand is replaced by renewable energy; it is more economically optimal to expand renewable energy in developed regions to meet the global target. For example, the renewable energy shares decrease through time in Africa in the EE+RE+EA scenario, and at the same time, there is a larger increase in Canada and USA.

This is also seen in the global sectoral results: in the EE+RE+EA scenario, the renewable energy share within the residential sector decreases, while in the EE+RE scenario it increases. The reduction in renewable energy in the residential sector within the EE+RE+EA scenario is compensated by steeper increases in the industrial and transportation sectors.

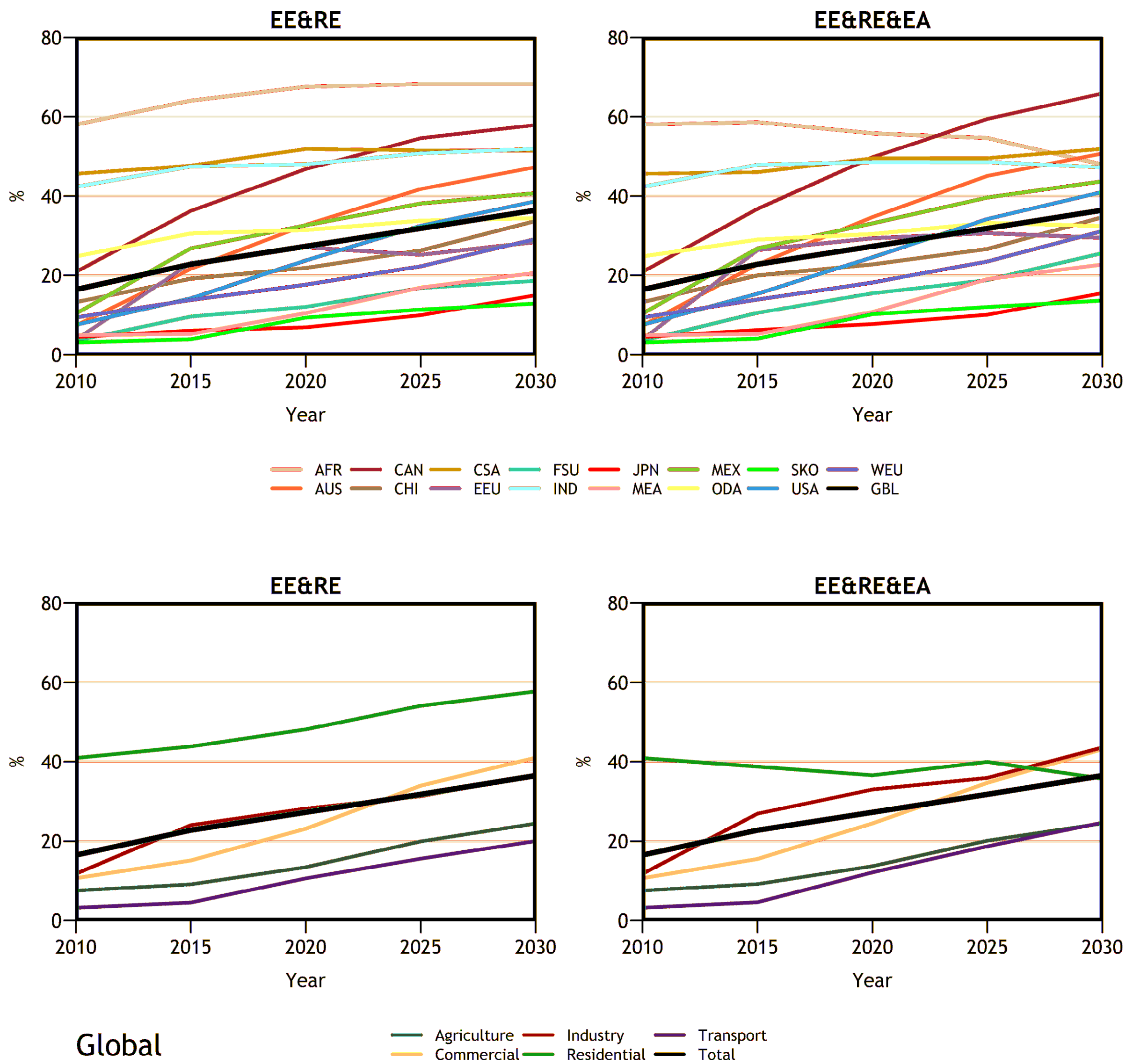

Figure 19. Renewable energy shares by region and global sector, 2010-2030, EE+RE and EE+RE+EA scenarios.

The top-10 results of ranking regions and their sectors according to the growth rate metric (Equation 2) and the net growth metric (Equation 3) are given in Table 25. Sectors within the Australia & NZ region rank high by both metrics, with 4 of the top 10 sectors. The commercial sector of Australia & NZ would also be ranked highly by the growth rate metric, except the renewable energy shares decrease in the Ref scenario, making the metric negative (it *is* highly ranked by the net growth metric, however). Therefore, the development of the sectoral renewable energy shares for Australia & NZ is displayed more in depth in Figure 20. In this region, the renewable energy shares grow dramatically in all sectors within the EE+RE+EA scenario; the residential and commercial sectors in particular. This suggests there is a large potential for renewable energy in the Australia and New Zealand building sector.

Sectors in Canada are also ranked highly by the metrics, and the renewable shares are given in Figure 21. Similar to the commercial sector in Australia & NZ, the renewable energy shares decline in the Ref scenario for the commercial and industrial sectors in Canada, so they do not make the growth rate ranking metric. In the EE+RE+EA scenarios, there is considerable growth in renewable energy in these sectors in Canada. Canadian transport and residential sectors show the highest rates of growth however.

Table 25. Regional sectors with the most change in renewable energy percent between the Ref and the EE+RE+EA scenarios, ranked by assessment metrics.

Growth Rate Metric Ranking	**Region**	**Sector**	**2010 (%)**	**2030 Ref (%)**	**2030 EE+RE+EA (%)**	**Growth Rate Metric (dimensionless)**
1	AUS	Residential	22.1	22.1	74.2	divide by 0
2	AUS	Agriculture	1.2	1.2	9.4	divide by 0
3	AFR	Industry	40.7	41.1	71.7	87
4	MEX	Industry	10.1	10.6	54.5	86
5	FSU	Agriculture	6.4	6.5	20	71.3
6	JPN	Industry	7.2	7.3	17.8	60.8
7	FSU	Industry	3.2	3.8	35.2	47.3
8	AUS	Transport	0.1	1	38.4	44.3
9	AUS	Industry	9.4	11.2	58.9	28.5
10	ODA	Transport	0	0.5	13.7	27.7
Net Growth Metric Ranking	**Region**	**Sector**	**2010 (%)**	**2030 Ref (%)**	**2030 EE+RE+EA (%)**	**Net Growth Metric (Δ%)**
1	AUS	Commercial	9.4	8.2	67.8	59.6
2	CAN	Transport	2.2	7.7	66.4	58.7
3	CAN	Residential	29.9	29.9	87.8	57.9
4	USA	Industry	13.9	7.2	59.8	52.6
5	AUS	Residential	22.1	22.1	74.2	52.2
6	AUS	Industry	9.4	11.2	58.9	47.7
7	ODA	Commercial	8.8	23.7	69.6	45.9
8	MEX	Industry	10.1	10.6	54.5	44
9	CAN	Industry	32	22	61.6	39.7
10	AUS	Transport	0.1	1	38.4	37.4

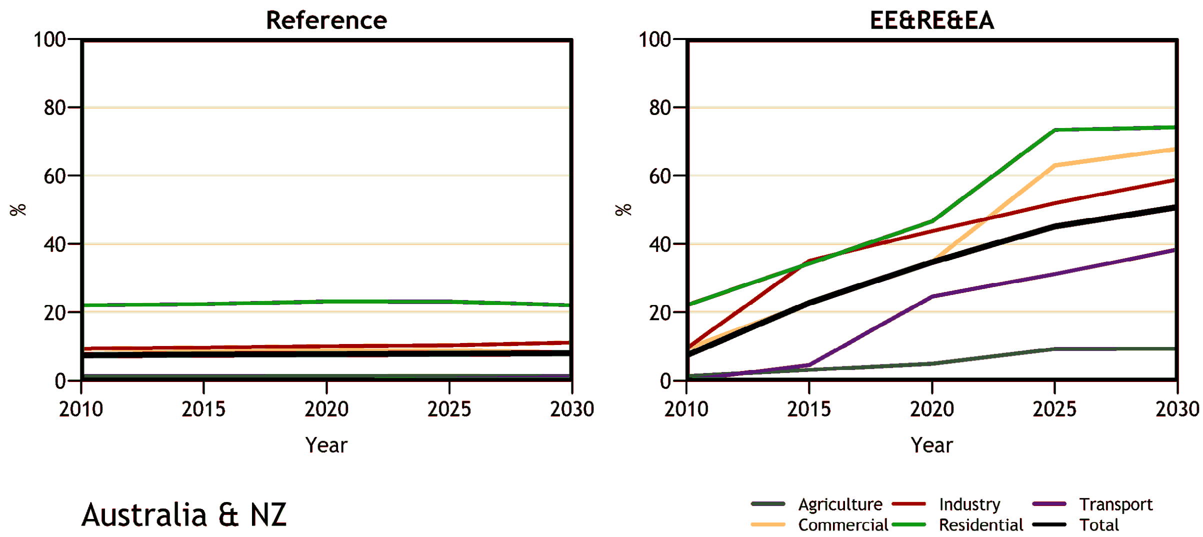

Figure 20. Sectoral renewable energy shares for Australia & New Zealand.

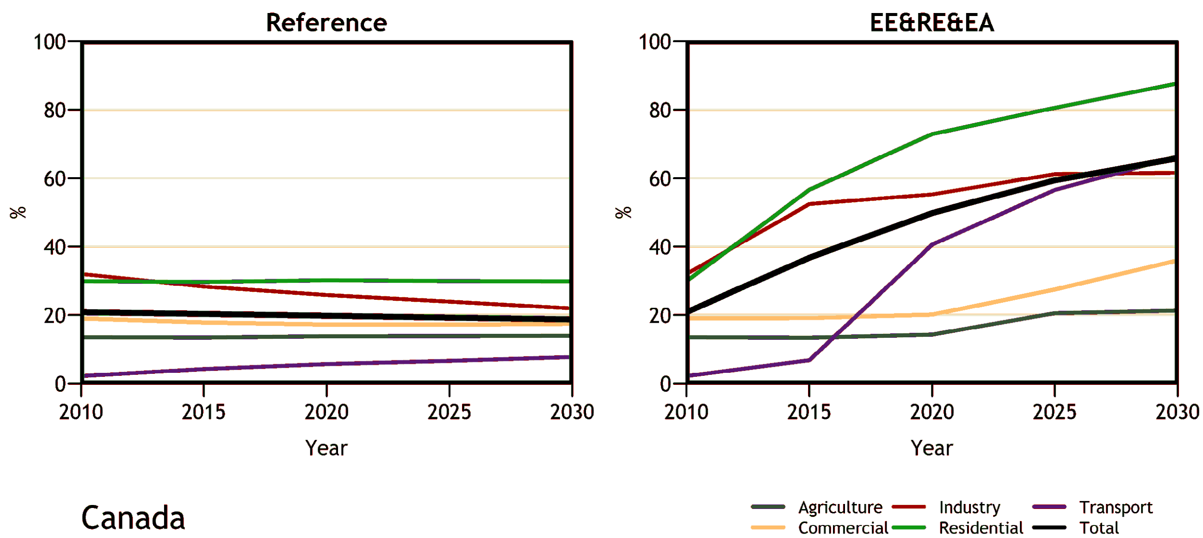

Figure 21. Sectoral renewable energy shares for Canada.

4.2 Primary Energy

4.2.1 Global Primary Energy

In Figure 22 and Figure 23, global primary energy is shown by resource and by region for four scenarios: Ref, RE, EE, and EE+RE+EA. In the Ref primary energy supply is constrained such that the global energy intensity is reduced

1.3% per annum between 2010 and 2030. In the EE and EE+RE+EA scenarios, the global primary energy supply is constrained in such a way that energy intensity is reduced 2.6% per annum between 2010 and 2030. No constraint energy efficiency is placed on the RE scenario.

In Figure 22, primary energy production is generally expected to increase from 2010-2030, and fossil energy is still expected to dominate the global energy portfolio by 2030. Increasing the rate of reduction in energy intensity reduces the amount of fossil energy, especially coal. In the EE scenario, much of this is replaced with natural gas. I the RE+EE+EA scenario, much of this is made up with an increase in biomass consumption and other renewables (traditional biomass is phased out globally in this scenario). Contrarily, in the RE scenario, primary energy production from coal increases as well as primary energy production from biomass. There is not much change in nuclear power across these various scenarios. In Figure 23, the largest reductions in primary energy consumption between the Ref scenario and the alternative scenarios are seen in the Former Soviet Union and in China, as also seen in Figure 14.

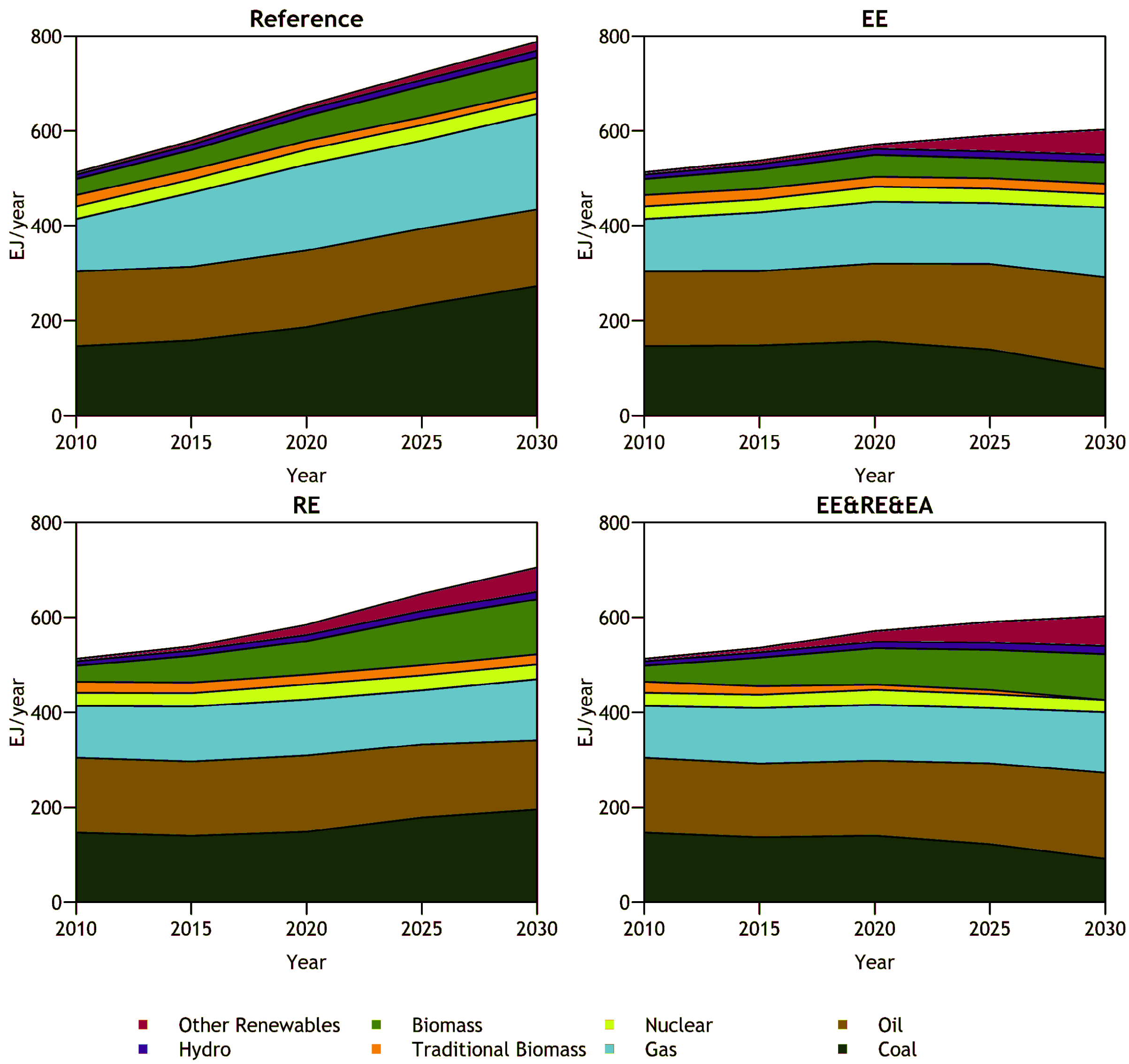

Figure 22. Global primary energy supply, by resource.

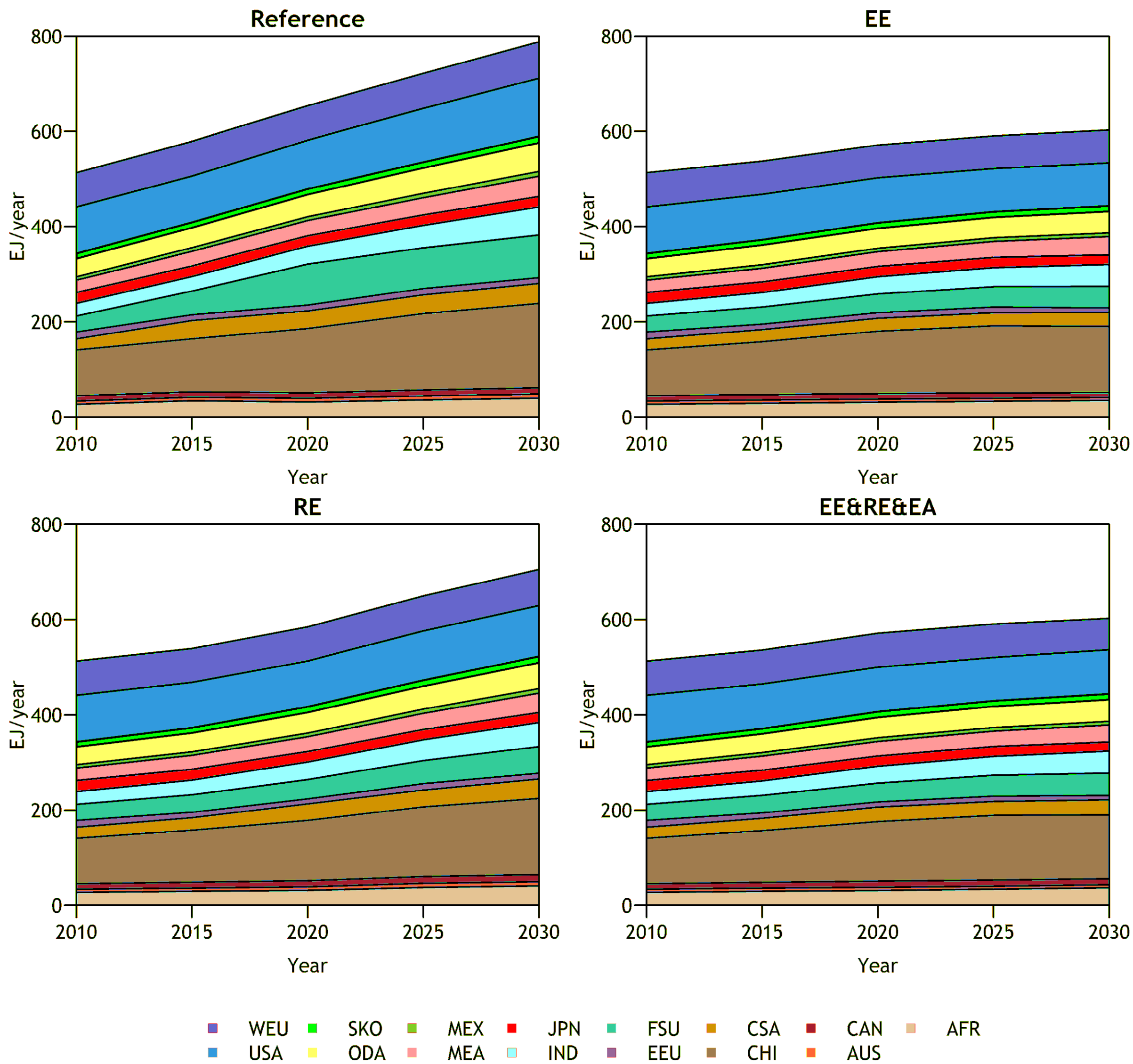

Figure 23. Global primary energy supply by region.

4.2.2 Regional Primary Energy

China and the Former Soviet Union, as well as the USA, have the largest net changes in the resources going into primary energy supply when the SE4ALL objectives are achieved (Table 26). The EE+RE+EA scenario produces in a reduction of coal and natural gas in the global energy portfolio. The growth rate metric is dominated by renewable energy resources; in general, this energy source shows the greatest percentage change across the scenarios, though it the impact in net changes is much smaller. The largest absolute changes in renewable energy production between the Ref and EE+RE+EA scenarios are in China and the USA, 13, and 11.5 EJ, respectively, for the 2030 values.

As a resource, oil does not appear in the top-10 by either metric in Table 26. China and Africa are the only regions to reduce oil consumption in the EE+RE+EA scenario relative to the Ref scenario, and only slightly: respectively in 2030 by 1.6 EJ and 0.8 EJ. On the other hand, USA and the Former Soviet Union actually increase oil consumption by 2030 between the EE+RE+EA and reference scenarios, by 6.8 EJ and 5.5 EJ, respectively. This indicates that replacing oil is one of the least cost effective measures for reducing energy consumption and thereby meeting the SE4ALL energy efficiency objective.

Table 26. Regions with the greatest change in primary energy production by resource, between the Ref and the EE+RE+EA scenarios, ranked by assessment metrics.

Growth Rate Metric Ranking	Region	Resource	2010 (EJ)	2030 Ref (EJ)	2030 EE+RE+EA (EJ)	Growth Rate Metric (dimensionless)
1	FSU	Renewable	0	0.1	3.4	144
2	MEX	Hydro	0.1	0.1	0.1	-81.2
3	CAN	Renewable	0	0	0.9	-63.2
4	USA	Renewable	1.9	1.6	13.1	-36.2
5	IND	Renewable	0.1	0.4	6	18.6
6	EEU	Renewable	0	0	0.2	18.1
7	JPN	Hydro	0.3	0.3	0.3	-11.3
8	CSA	Trad. Bio.	1.1	1	0	10.3
9	AUS	Renewable	0	0.1	1.1	8.4
10	WEU	Nuclear	8.3	8.6	5.5	-8
Net Growth Metric Ranking	**Region**	**Sector**	**2010 (EJ)**	**2030 Ref (EJ)**	**2030 EE+RE+EA (EJ)**	**Net Growth Metric (ΔEJ)**
1	CHI	Coal	63.9	96.7	36.3	-60.4
2	FSU	Gas	19.5	62.3	17.4	-44.9
3	USA	Coal	26.2	45.3	2.5	-42.7
4	IND	Coal	11.1	28	9.9	-18.1
5	ODA	Coal	7.1	23.5	7.5	-16.1
6	CHI	Renewable	0.4	7.1	20.1	13
7	USA	Renewable	1.9	1.6	13.1	11.5
8	FSU	Coal	5	15.5	5.8	-9.7
9	MEA	Coal	0.9	11.9	2.3	-9.7
10	CSA	Gas	4.3	14.7	6	-8.8

Figure 24, Figure 25, and Figure 26 show the primary energy supply by resource for China, the Former Soviet Union, and USA, respectively, for the Ref and the EE+RE+EA scenarios. In the EE+RE+EA scenario of Figure 24, coal consumption declines dramatically in China and at the same, the amount of renewable energy generation increases. In the Former Soviet Union, natural gas consumption triples between 2010 and 2030 in the Ref scenario, yet remains rather stable in the EE+RE+EA scenario (Figure 25). In the EE+RE+EA scenario, total primary energy supply in 2030 in the Former Soviet Union is nearly half that in the Ref Scenario: 46 EJ/year versus 89 EJ/year (Figure 25). With the large reduction overall primary energy supply in the Former Soviet Union in the EE+RE+EA scenario, the energy intensity is reduced significantly (Figure 15). In Figure 26, coal consumption in the USA is nearly phased out completely by 2030 in the EE+RE+EA scenario. Similar to China, there is a large expansion in renewable energy and biomass energy between 2010 and 2030 in the USA in the EE+RE+EA scenario (Figure 26).

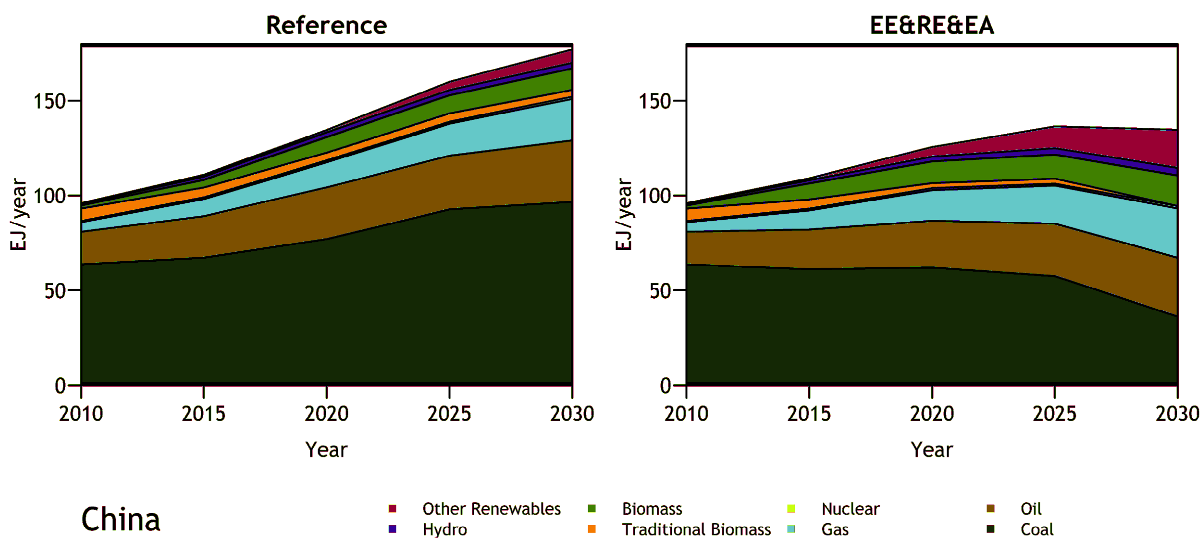

Figure 24. Primary energy by resource, China.

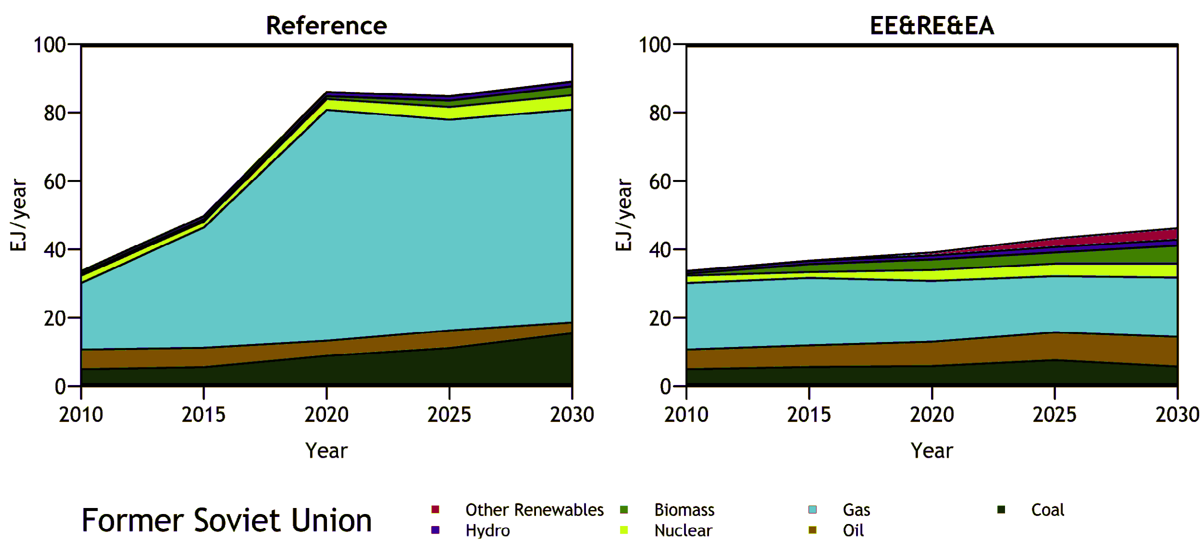

Figure 25. Primary energy by resource, Former Soviet Union.

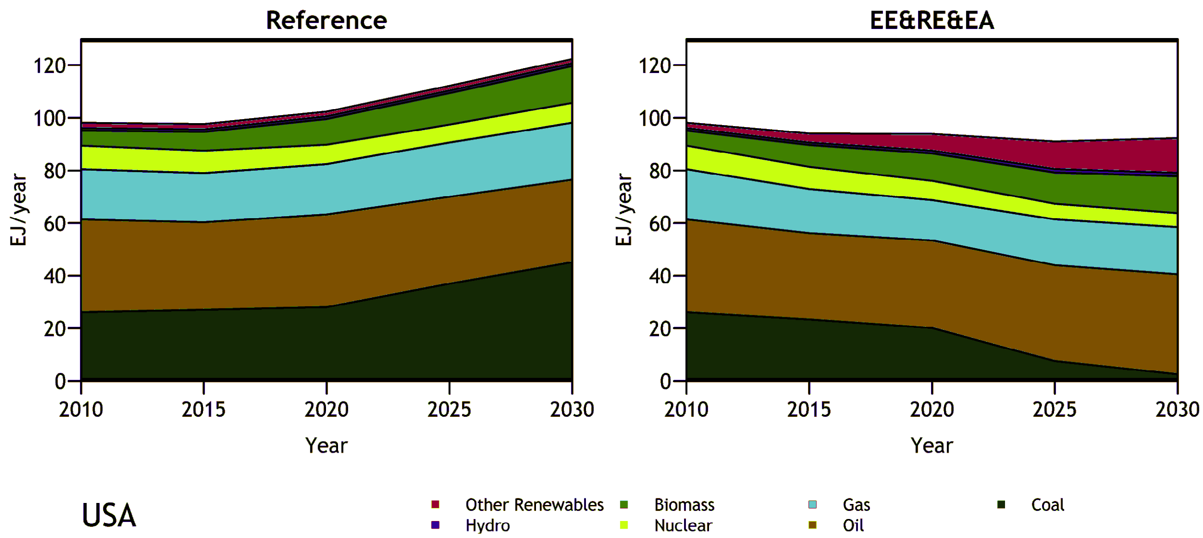

Figure 26. Primary energy by resource, USA.

4.3 Final Energy

4.3.1 Global Final Energy

Figure 27, Figure 28, and Figure 29 display the global final energy for four scenarios, broken down by fuel, region, and sector, respectively. In Figure 27, the scenarios where the SE4ALL energy efficiency objective is achieved (EE and EE+RE+EA) have reduced coal consumption in global final energy, though natural gas is higher in the EE scenario than in the EE+RE+EA scenario. There is more biomass, alcohol fuels and hydrogen in 2030 global final energy portfolio in the RE scenario, and also in the EE+RE+EA scenario where traditional biomass is phased out.

Regional shares of total global final energy demand remain rather constant across scenarios; differences are nearly imperceptible in Figure 28. In the EE+RE+EA scenario, final energy consumption in China is reduced by about 9 EJ/year by 2030 relative to the Ref scenario. Likewise, in the EE+RE+EA scenario, final energy consumption in Other Developing Asia is reduced by about 5 EJ/year by 2030, relative to the Ref scenario. In terms of regional shares of final energy consumption, the Ref scenario and the RE scenario are similar to each other, as are the EE and EE+RE+EA scenarios.

Sectoral distributions do not change much across scenarios in Figure 29. The absolute change is in the industrial sector: globally, the 2030 final energy consumption in is approximately 18 EJ less in the EE+RE+EA scenario versus the Ref scenario. Again, in terms of sectoral shares of final energy consumption, the Ref scenario and the RE scenario are similar to each other, as are the EE and EE+RE+EA scenarios.

Figure 27. Total global final energy, by fuel.

Figure 28. Total global final energy, by region.

Figure 29. Total global final energy, by sector.

Figure 30 shows the subsector composition of global final energy consumption under the Ref and EE+RE+EA scenarios. The differences between these two scenarios are summarized in Table 27. As with the sectoral breakdown, the differences between the two scenarios with regard to the subsector decomposition of final energy consumption are not that large.

Figure 30. Global final energy consumption by subsector.

Table 27. Global subsectors have the greatest change in final energy supply between the Ref and the EE+RE+EA scenarios, ranked by assessment metrics (absolute value).

Growth Rate Metric Ranking	Global Subsector	2010 (EJ)	2030 Ref (EJ)	2030 EE+RE+EA (EJ)	Growth Rate Metric (dimensionless)
1	Residential Hot Water	15	14.7	13.7	5
2	Transport Trucks Light	12.3	15.9	19.1	1.9
3	Residential Miscellaneous Electric Energy	4.8	6.7	7.3	1.4
4	Commercial Lighting	4.5	4.1	4.1	1.2

Net Growth Metric Ranking	Global Sector	2010 (EJ)	2030 Ref (EJ)	2030 EE+RE+EA (EJ)	Net Growth Metric (ΔEJ)
1	Industrial Other Industries	46.3	95.6	91.2	-4.4
2	Industrial Iron and Steel	29.9	32.3	28.2	-4.1
3	Industrial Non-Metal Minerals	14.9	34.3	31	-3.4
4	Residential Heating	28.7	31.1	27.7	-3.4
5	Transport Trucks Light	12.3	15.9	19.1	3.2
6	Transport Cars	20.1	29	26.1	-3
7	Transport Trucks Heavy	12.9	14.8	12.8	-2
8	Industrial Pulp and Paper	8.2	15.3	14.1	-1.3
9	Commercial Heating	9	10.5	9.2	-1.3
10	Residential Hot Water	15	14.7	13.7	-1
11	Transport Trucks Medium	7	9	8.1	-0.9
12	Commercial Cooking	3.4	6.2	5.3	-0.9
13	Residential Miscellaneous Electric Energy	4.8	6.7	7.3	0.7
14	Transport Trucks Commercial	5.7	7.3	6.9	-0.4
15	Industrial Chemicals	39.8	81	81.3	0.3

Transport and residential subsectors tend to have the highest growth rates, while the top absolute net changes are dominated by reductions in final energy consumption in the industrial subsectors. Final energy consumption by fuel type in global industry is given in Figure 31. Coal consumption is reduced, bioenergy is increased, and overall final energy is reduced in 2030 when comparing the EE+RE+EA scenario to the Ref scenario.

Light Trucks in the transport sector rank high by both metrics in Table 27, and therefore, final energy consumption by fuel type in this sector is shown in Figure 32. The EE+RE+EA scenario includes substantially more hydrogen- and methanol-powered light trucks, while gasoline is replaced, in comparison to the Ref scenario.

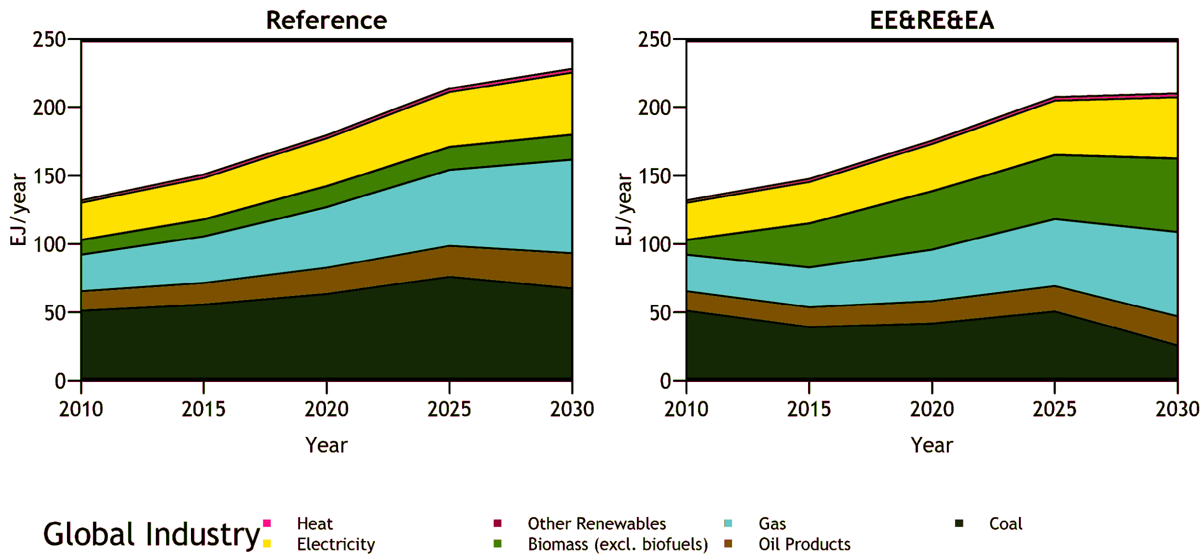

Figure 31. Global industry final energy consumption: Ref and EE+RE+EA scenarios.

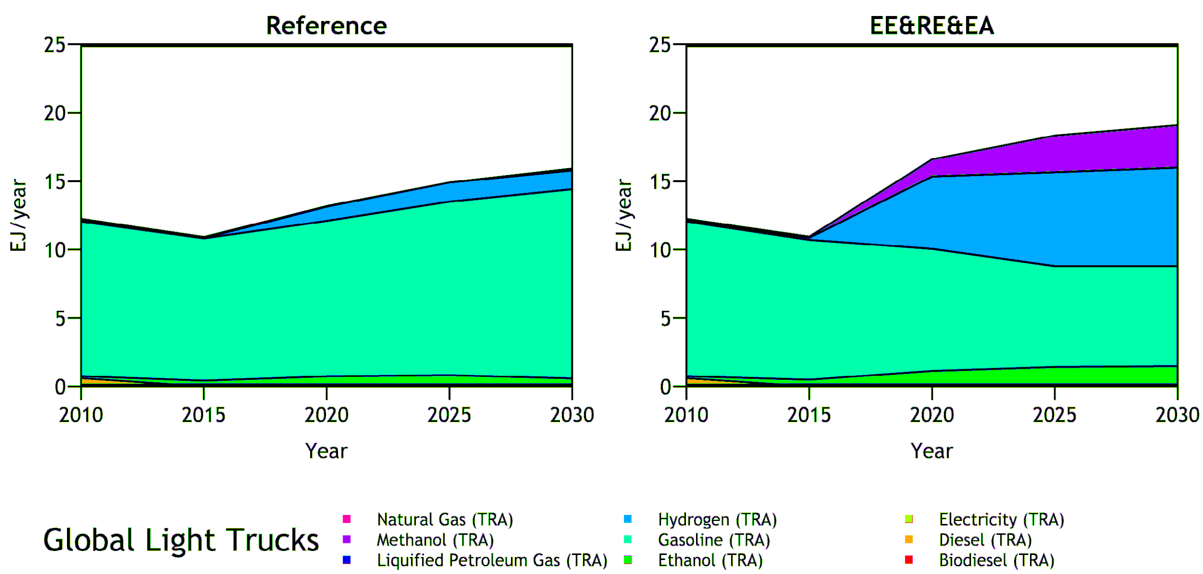

Figure 32. Final energy consumption by fuel type for global light trucks: Ref and EE+RE+EA scenarios.

4.3.2 REGIONAL FINAL ENERGY

Table 28 ranks the regions by the amount of change in final energy consumption between 2010 and 2030 in the EE+RE+EA scenario, relative to the Ref scenario. The two metrics produce very different rankings. In the growth rate metric, only Japan is negative: for the 2010 to 2030 period, it is the only region to increase final energy consumption in the reference scenario and decrease final energy consumption in the EE+RE+EA scenario. Eastern Europe is the only other region besides Japan with lower final energy consumption in 2030 versus 2010 in the EE+RE+EA scenario, but this also occurs in the reference scenario. Canada is unique in that is the only region where final energy consumption increases between 2010 and 2030 in the Ref and EE+RE+EA scenarios, and where it increases to at a greater rate in the EE+RE+EA scenario. Achieving the SE4ALL objectives has the effect of reducing the rate of energy consumption between 2010 and 2030 in all regions except Canada and Eastern Europe. The net growth metric gives insight into which regions reduce final energy consumption to achieve the optimal economic solution for achieving the SE4ALL objectives. In this case, all regions reduce final energy consumption except Canada, with China, Other Developing Asia, and India the regions with the greatest amount of final energy consumption reduction between the EE+RE+EA and Ref scenarios.

Table 28. Regions having the greatest change in final energy consumption between the Ref and the EE+RE+EA scenarios, ranked by assessment metrics.

Growth Rate Metric Ranking	Region	2010 (EJ)	2030 Ref (EJ)	2030 EE+RE+EA (EJ)	Growth Rate Metric (dimensionless)
1	CAN	7.5	8.7	10.8	2.7
2	JPN	13.1	13.5	12.5	-1.3
3	EEU	11.6	8	7.2	1.2
4	FSU	23.6	36.3	35.3	0.9
5	MEA	18.1	28.6	27.8	0.9
6	AFR	20.5	31.9	30.4	0.9
7	IND	17.5	38	35.2	0.9
8	CHI	65	121.8	112.7	0.8
9	USA	58.9	73.7	71.1	0.8
10	CSA	15.2	24.6	22.8	0.8
11	MEX	4.4	6.7	6.2	0.8
12	SKO	5.2	7.1	6.7	0.8
13	WEU	45.3	52.7	50.9	0.8
14	AUS	4.5	5.7	5.4	0.7
15	ODA	26.3	41.1	36.4	0.7
Net Growth Metric Ranking	**Region**	**2010 (EJ)**	**2030 Ref (EJ)**	**2030 EE+RE+EA (EJ)**	**Net Growth Metric (ΔEJ)**
1	CHI	65	121.8	112.7	-9.1
2	ODA	26.3	41.1	36.4	-4.8
3	IND	17.5	38	35.2	-2.8
4	USA	58.9	73.7	71.1	-2.6
5	CAN	7.5	8.7	10.8	2.1

6	WEU	45.3	52.7	50.9	-1.8
7	CSA	15.2	24.6	22.8	-1.8
8	AFR	20.5	31.9	30.4	-1.4
9	JPN	13.1	13.5	12.5	-1.1
10	FSU	23.6	36.3	35.3	-1
11	MEA	18.1	28.6	27.8	-0.9
12	EEU	11.6	8	7.2	-0.9
13	MEX	4.4	6.7	6.2	-0.5
14	SKO	5.2	7.1	6.7	-0.4
15	AUS	4.5	5.7	5.4	-0.3

In Table 28, China is projected to reduce 2030 final energy demand by over 9 EJ/year when the SE4ALL objectives are achieved (the EE+RE+EA scenario versus the Ref scenario). Moreover, the 2030 total final energy consumption in China under the EE+RE+EA scenario is larger than the total final energy consumption in other regions. In fact, the 2030 final energy consumption in the industrial sector alone for China (72 EJ/year) exceeds the total energy consumption in all other regions in the EE+RE+EA scenario.

Figure 33 shows the final energy consumption by fuel and sector for China for the Ref and the EE+RE+EA scenario. Under the EE+RE+EA scenario, there is a phase out of traditional biomass and a reduction in coal, yet, increased biomass consumption, and more deployment of alcohol fuels and hydrogen when compared to the Ref scenario. The industrial and residential sectors have lower final energy consumption and the transport has slightly higher energy consumption when making the same comparison across the two scenarios pictured in Figure 33 .

As noted above, Canada is unique in that it increases total final energy consumption in both the Ref and EE+RE+EA scenarios, and does so at a greater rate in the later. Thus, it is the highest ranked region by the growth rate metric and still relatively high by net growth metric in Table 28. Final energy in terms of fuel and sector are displayed in Figure 34. The growth in final energy consumption comes from an expansion of biomass and hydrogen production, allowing for more energy consumption in the residential and transport sectors (in the EE+RE+EA scenario relative to the reference scenario).

Figure 33. China final energy consumption by fuel and by sector: Ref and EE+RE+EA scenarios.

Figure 34. Canada final energy consumption by fuel and by sector: Ref and EE+RE+EA scenarios.

The final energy difference among regional subsectors is assessed with the net growth metric in Table 29, and only those subsectors with at least 1 EJ of difference between the EE+RE+EA and Ref scenarios are shown. The growth rate metric is overly sensitive to subsectors with very small levels of energy consumption and therefore is not used for the comparison purposes here. Developing regions dominate the list, with the exception of Light Trucks in Canada and Cars in the USA. The list is also populated by industrial and transport subsectors. There are 607 distinct regional subsectors in ETSAP-TIAM. Of those, only 109 show a change between the Ref and EE+RE+EA scenarios, and only 10 have a change greater than 1 EJ/year in final energy consumption Table 29.

Table 29. Regional subsectors with the greatest change in final energy consumption between the Ref and the EE+RE+EA scenarios, ranked by the net growth metric.

Net Growth Metric Ranking	Region	Regional Subsector	2010 (EJ)	2030 Ref (EJ)	2030 EE+RE+EA (EJ)	Net Growth Metric (ΔEJ)
1	CHI	Industrial Other Industries	9.9	25	21.9	-3.1
2	IND	Industrial Iron and Steel	2.5	6.7	4.4	-2.4
3	CHI	Residential Heating	5.5	5.7	3.9	-1.8
4	CHI	Industrial Non-Metal Minerals	7.9	21.3	19.5	-1.8
5	CSA	Industrial Pulp and Paper	0.6	2.4	0.7	-1.7
6	ODA	Industrial Other Industries	5.6	11.9	10.2	-1.6
7	CAN	Transport Trucks Light	0.4	0.5	2	1.6
8	CHI	Transport Trucks Light	0.2	0.5	1.6	1.1
9	USA	Transport Cars	7.8	9.7	8.7	-1.1
10	MEA	Industrial Iron and Steel	0.8	0.5	1.6	1.1

Using the ranking in Table 29, regional sectoral and sub-sectoral results are shown in Figure 35 through Figure 40. Achieving the SE4ALL objectives coincides in a reduction of oil and coal in the China's industrial sector, and more reliance on bioenergy (Figure 35). In the subsector of 'other industries' in China (which include the mining and manufacturing subsectors), overall final energy is lower in the EE+RE+EA scenario versus the Ref scenario, suggesting improvements in efficiency (Figure 36). The 'other industries' in China become more reliant on electricity and less on coke when the SE4ALL objectives are achieved (Figure 36). Heat consumption is also reduced in this subsector with the SE4ALL objectives are achieved (Figure 36). In India's iron and steel industrial subsector, the EE+RE+EA scenario results in less hard coal, more biomass consumption, and slightly more hydrogen consumption (after 2025) than in the Ref scenario (Figure 37). In China's residential heating subsector, the phase out of traditional biomass is met with an increase in natural gas consumption in the EE+RE+EA scenario (Figure 38), and overall energy consumption in this sector declines, suggesting efficiency gains in the building sector within the EE+RE+EA scenario. Figure 39 displays final energy consumption by fuel resource in China's industrial non-metal minerals. There are no large changes in the fuel shares between the Ref and EE+RE+EA scenarios in this subsector, but the total final energy consumption in this subsector decreases in the EE+RE+EA scenario (Figure 39). The pulp and paper industry in Central and South America is fifth in the rankings shown in Table 29 and is displayed in Figure 40. The EE+RE+EA scenario results in a large reduction in hard coal consumption and more biomass consumption versus the Ref scenario (Figure 40).

Figure 35. China industry final energy consumption by fuel.

Figure 36. China industrial other industries final energy fuel consumption.

Figure 37. India iron and steel final energy consumption by fuel.

Figure 38. China residential heating final energy consumption by fuel.

Figure 39. China industrial non-metal minerals final energy consumption by fuel.

Figure 40. Central and South America pulp and paper industry final energy consumption by fuel.

4.4 Greenhouse Gas Emissions

4.4.1 Global CO_2 Emissions

Figure 41 summarizes the 2010-2030 annual emissions for the different scenarios. These are compared to the CO_2 emissions from two Representative Concentration Pathways (RCPs): RCP2.6 and RCP4.5. The RCP 2.6 describes the Earth's climate in the year 2100 with 2.6 additional W/m^2 radiative forcing over pre-industrial times and is the most ambitious of the RCPs (Moss, 2010). The RCP4.5 represents 4.5 W/m^2 additional radiative forcing in 2100 (Moss, 2010). RCP2.6 is likely to limit warming to 2° C global warming over pre-industrial times, whereas the RCP4.5 is more likely than not to exceed it (Moss, 2010). In Figure 41, the alternative scenarios developed for this report fall between these two pathways, meaning that they are consistent with limiting global warming to 2° C; the probabilities to stay below this threshold are estimated in the range between 50% and 66%.

Under the reference scenario, keeping global warming to under 2° C is unlikely. Taken alone, the SE4ALL energy efficiency objective reduces emissions more than the SE4ALL renewable energy objective. They reduce more emissions together (EE+RE) than either alone. Achieving the SE4ALL energy access objective (EE+RE+EA scenario), however, increases emissions in comparison to when this objective is not achieved (EE+RE scenario), because electricity consumption increases in the developing regions, and because some of the traditional biomass is replaced by fossil fuels within ETSAP-TIAM.

Figure 41. Comparison of emissions between 2010 and 2030 across the various scenarios. The RCP 2.6 and RCP 4.5 are shown for comparison purposes.

4.4.2 Sectoral GHG Emissions

In Figure 42, the total sectoral emissions (including CO_2, CH_4 and N_2O) are presented by sector. Agricultural emissions remain constant between 2010 and 2030 across all scenarios by default in ETSAP-TIAM. Achieving the SE4ALL energy efficiency objective reduces over emissions, particularly so in the upstream sector. Emissions associated with electricity production are reduced in all alternative scenarios and to a greater degree in the scenarios where the SE4ALL energy efficiency objective is achieved. However, electricity and to a lesser extent, industry, become much less GHG-intensive in the EE+RE+EA scenario.

Figure 42. Global GHG emissions, by sector

Figure 43. Global CO_2 emissions, by region.

Figure 43 presents CO_2 emissions by region across four different scenarios. Overall, total emissions are higher when the energy efficiency objectives are not achieved. Under all the scenarios, the largest amount of emissions is attributed to China. China is also the region with the greatest potential for the emissions reduction under the EE+RE+EA scenario. This scenario also results in substantial reductions in Western Europe and the USA.

Table 30 ranks the regions by the change in regional CO_2 emissions from 2010 to 2030 in the EE+RE+EA scenario relative to the Ref scenario. Japan and Canada have high rankings in the growth rate score and this is due to the 2010 and 2030 emissions remaining roughly equal in under Ref scenario. In terms of absolute emissions reductions, however, China, and US have the greatest potential for emissions reductions when the SE4ALL objectives are achieved.

Table 30. Ranking of regions by change in CO_2 emissions between Ref and EE+RE+EA scenarios

Growth Rate Metric Ranking	**Region**	**2010 (Gt CO_2)**	**2030 Ref (Gt CO_2)**	**2030 EE+RE+EA (Gt CO_2)**	**Growth Rate Metric (dimensionless)**
1	JPN	1.3	1.3	1	222.6
2	CAN	1	1	0.7	-5.6
3	AUS	0.6	0.7	0.3	-2.2
4	WEU	3.6	3.8	3.2	-2.1
5	EEU	1.2	0.8	0.6	1.4
6	USA	5.8	7.8	3.8	-1
7	AFR	1.6	2.6	2.1	0.5
8	SKO	0.6	0.7	0.6	0.4
9	MEA	1.8	3	2.2	0.4
10	MEX	0.4	0.6	0.4	-0.3
11	FSU	2.4	4.1	2.9	0.3
12	CSA	1.6	2.1	1.7	0.3
13	IND	1.6	3.8	2	0.2
14	CHI	7.3	12	6.4	-0.2
15	ODA	2.2	3.9	2.4	0.1
Net Growth Metric Ranking	**Region**	**2010 (Gt CO_2)**	**2030 Ref (Gt CO_2)**	**2030 EE+RE+EA (Gt CO_2)**	**Net Growth Metric (Δ Gt CO_2)**
1	CHI	7.3	12	6.4	-5.6
2	USA	5.8	7.8	3.8	-4
3	IND	1.6	3.8	2	-1.7
4	ODA	2.2	3.9	2.4	-1.5
5	FSU	2.4	4.1	2.9	-1.1
6	MEA	1.8	3	2.2	-0.8
7	WEU	3.6	3.8	3.2	-0.6
8	AFR	1.6	2.6	2.1	-0.5
9	AUS	0.6	0.7	0.3	-0.4
10	CAN	1	1	0.7	-0.3
11	CSA	1.6	2.1	1.7	-0.3
12	JPN	1.3	1.3	1	-0.3
13	MEX	0.4	0.6	0.4	-0.2
14	EEU	1.2	0.8	0.6	-0.2
15	SKO	0.6	0.7	0.6	-0.1

Total GHG emissions from China and the US across the Ref and EE+RE+EA scenarios are shown in Figure 44 and Figure 45, respectively. For both regions, achievement of the SE4ALL objectives translates into a reduction in upstream emissions (1.64 to 0.74 $GtCO_2e$/year by 2030 in China and 1.42 to 0.55 $GtCO_2e$/year by 2030 in USA) and the near elimination of emissions from electricity generation. This results in changes mainly in CO_2 emissions, and does not significantly affect CH_4 and N_2O emissions.

Figure 44. Emissions from China, by sector and by greenhouse gas type

Figure 45. Emissions from USA, by sector and by greenhouse gas type

4.5 Investment Costs

4.5.1 Global Investment Costs and Emissions

The overall trend in the analysed scenarios is that increased total investments are accompanied by higher emissions reductions (Figure 46). The Ref scenario has the highest emissions, as a scenario with low ambition for energy efficiency improvement and renewable energy deployment by 2030. The EE and RE scenarios are roughly equivalent in terms of total cumulative emissions. Meeting the SE4ALL renewable energy objective requires less investment than meeting the energy efficiency objective, however, the latter results in less global emissions (EE scenario versus RE scenario). Meeting these two objectives together requires only a little more investment than either alone, and reduces emissions to a greater extent (mass of CO_2/USD) than meeting either objective separately (EE+RE scenario versus EE scenario and RE scenario). Finally, the energy access objective requires a lot more investment and actually increases emissions slightly due to increased electricity production and substitution of bioenergy with fossil resources in developing regions (EE+RE scenario versus the EE+RE+EA scenario).

Figure 46. NPV of Total Investment Costs versus total CO_2 Emissions. NPV calculations use a 5% discount rate.

4.5.2 Regional and Sectoral Investment Costs

Figure 47 shows the difference in the net present value of the total investments between each of alternative scenarios and Ref scenario by region, between the years 2010 and 2030, while Figure 48 shows such a difference by sector. In the alternative scenarios, additional investment occurs consistently in USA and Western Europe, relative to the Ref scenario (Figure 47). In the EE scenario, additional investment (relative to the Ref scenario) occurs in China, USA and Western Europe (Figure 47). Globally this additional investment is largely in the transport sector (Figure 48). In the RE scenario, largest additional regional investments occur in the US, Canada, China, and Western Europe to meet the SE4ALL renewable energy objective (Figure 47). As with the EE scenario, the largest additional investments occur in the transport sector globally in the RE scenario (Figure 48). The investment differences between the EE+RE scenario and the Ref Scenario follow the investment patterns of the EE and RE scenarios (Figure 47 and Figure 48)

In Africa, India, and Other Developing Asia, investment decreases in all the alternative scenarios (relative to the Ref scenario) except the EE+RE+EA scenario, where additional investment is needed in to meet the SE4ALL energy access objective (Figure 47). This result is also seen in the global residential sector in Figure 48, where the EE, RE, and EE+RE scenarios have lower investment relative to Ref scenario, and the EE+RE+EA scenario has a higher level of investment relative to the Ref scenario.

Figure 47. Additional total regional investment (NPV) relative to Ref. NPV calculations use a 5% discount rate. Negative values represent regions with less investment in the alternative scenario versus the reference scenario.

Figure 48.Additional Global investment (NPV) relative to Ref, by sector. NPV calculations use a 5% discount rate. Negative values represent sectors with less investment in the alternative scenario versus the reference scenario.

4.5.3 Subsector Investment Costs

The NPV of subsector investment and the discounted energy savings are compared between the EE+RE+EA scenario and the Ref scenario. The subsectors are ranked by additional cost per energy saved. Figure 49 and Figure 50 respectively show the globally and regionally ranked subsectors by cost efficiency of energy saved (Equation 5).

Globally, industrial subsectors have the lowest cost for energy efficiency improvements (Figure 49). Large potentials exists in the global residential heating subsector, as well as the global residential hot water heating subsector, with the former cheaper per unit of energy saved. The transportation sector also has potential for reductions in energy consumption, with heavy and medium trucks having the lowest cost per unit of energy reduced. Finally, the commercial sector, among which commercial cooling has the largest potential and the greatest cost for reducing energy consumption.

The same general trend exists regionally, with the majority of the least expensive energy savings occurring in the industrial subsectors, residential and transport subsectors are mixed in terms of ranking of NPV cost per (discounted) energy saved, and the commercial subsectors tend to have the highest cost per (discounted) unit of energy saved (Figure 50). A detailed list of the regional subsectors by discounted energy savings can be found in the appendix, in Table 36.

Figure 49. Discounted energy savings by global subsector, ranked by cost efficiency of energy saved. Discount rate is assumed to be 5%.

Figure 50. Discounted energy savings by regional subsector, ranked by cost efficiency of energy saved. Discount rate is assumed to be 5%.

4.5.4 Policy Targets

In most regions, achieving the objectives of SE4ALL will require substantial increase in the current rate of energy efficiency improvements (Table 31). Only China has a historical rate of EIIR that would reduce energy consumption enough to achieve the SE4ALL regional results modeled by ETSAP-TIAM. Achieving the SE4ALL energy efficiency objective, or all three SE4ALL objectives, will require accelerating the rates of this reduction in most regions to the extent that it would exceeds the EIIR previously achieved over any 5-year period between 1990 and 2010. Such reductions are economically and technically possible, according to ETSAP-TIAM, though may be limited by other political and social barriers not considered in the model.

*Table 31. Historic annual energy intensity improvement rates (EIIR), and target reduction rates to achieve the SE4ALL energy efficiency objective in an economically efficient way. Results are shown for the EE scenario in column 4, and the EE+RE+EA scenario in column 5. *These two scenarios are compared to the 1990-2010 historic data; if the answers are different for the two scenarios, they are separated with a slash.*

Region	Average Annual EIIR, 1990-2010 (%)	Historic Max EIIR, 1990-2010 (5-year rolling average) (%)	Average Annual EIIR to achieve SE4ALL EE objective (%)	Average Annual EIIR to achieve all SE4ALL objectives (%)	Greater reduction than (1990-2010) historic average?	Greater than historic max reduction (5-year rolling average)?*
AFR	-0.9	-2.3	-2.4	-2.2	YES	YES/NO
AUS	-1.3	-2.5	-3.4	-3.3	YES	YES
CAN	-1.4	-3.0	-2.2	-1.5	YES	
CHI	-4.3	-6.5	-3.5	-3.6		
CSA	-0.6	-1.4	-1.7	-1.4	YES	YES/equal
EEU	-3.0	-4.8	-3.8	-3.8	YES	
FSU	-1.9	-5.5	-2.2	-2.2	YES	
IND	-2.4	-3.4	-2.9	-2.9	YES	
JPN	-0.3	-1.8	-1.8	-1.9	YES	equal/YES
MEA	1.0	-0.9	-1.8	-2.1	YES	YES
MEX	-0.7	-2.4	-2.6	-2.3	YES	YES/NO
ODA	-1.1	-2.3	-3.2	-3.2	YES	YES
SKO	-0.1	-2.4	-1.1	-1.1	YES	
USA	-1.7	-2.4	-2.9	-2.8	YES	YES
WEU	-1.2	-2.0	-2.0	-2.2	YES	equal/YES
Global	-1.3	-2.0	-2.6	-2.6	YES	YES

5 Limitations

5.1 Model Limitations

At its core, ETSAP-TIAM is a large linear equation, and the results presented are an algebraically optimal solution to a set of input data and constraints. However, ETSAP-TIAM does have its limitations. As a linear model it cannot handle feedback effects, such as Jevons Paradox (an economic phenomenon where efficiency gains reduce energy prices thus increase demand), structural changes in the economy, or economic growth as a result of technological development. Thus, ETSAP-TIAM, as with all integrated assessment models, should not be considered as a prediction machine and the results contained herein are not forecasts, but rather solutions to the preset scenarios with their associated constraints. The results represent an economically optimal solution for the entire world, which may not be an economically attractive option at the national and/or regional scales. Furthermore, the solutions represent a theoretical possibility, but do not capture sociological and cultural barriers to development.

IAMs with large databases such as ETSAP-TIAM quickly become obsolete; this is a particular challenge, as naturally, results are only as good as the input assumptions. While the demand drivers were updated for this analysis, updating the thousands of technology parameters is an on-going process. Therefore, there is some uncertainty stemming from outdated input data. On the other hand, with internally consistent data, ETSAP-TIAM is nevertheless useful in determining where the largest potentials for energy efficiency lie, both regionally, and technologically. This can aid in crafting efficient policies to meet targets for energy efficiency, renewable energy, and energy access.

5.2 Statistical Uncertainty

As a proxy for analyzing energy efficiency improvements at a high level, energy intensity of GDP has limitations as an indicator. Energy intensity of GDP incorporates uncertainties in both energy consumption and the economy. Economic uncertainty is compounded by uncertainties in purchasing power parity, which depends on the relative buying power across economies. Globalization trends dilute the interpretation of energy intensity, as production and consumption of goods are geographically separated. Furthermore, given the vicissitude of the economy, energy intensity can vary widely year to year without any discernable change in the energy technology or conservation. This is problematic when establishing future targets for energy intensity reduction.

In the calculation of energy intensity (GDP per year divided by primary energy consumption per year), the year cancels algebraically, but tacitly, it still understood to be there. Efficiency ultimately concerns the rate of production over the rate of consumption, and greater efficiency can be attained while increasing both, so long as the rate of production increases at a greater rate than the rate of consumption. When using energy intensity of GDP as a metric, an economic boom could give achieve the SE4ALL energy efficiency objective even without any real technological improvements in energy efficiency. Likewise, an economic recession could give the opposite false impression: ambitious technological progress in improving energy efficiency without achieving the SE4ALL energy efficiency objective.

In summary, though widely used, energy intensity of GDP as a metric and a target is highly uncertain, difficult to forecast, and does not necessarily guarantee that development or environmental goals are achieved. On the other hand, one principle advantage of energy efficiency is that it is a “no regrets” option and has many co-benefits in climate mitigation and sustainable development.

Concerning renewable energy, ETSAP-TIAM regional results may not coincide with the REMap 2030 scenario from IRENA (International Renewable Energy Agency) (2014). The REMap 2030 scenario covers only selected countries, while ETSAP-TIAM operates using large, aggregated regions. Some regions do match between ETSAP-TIAM and IRENA, but for other regions it would require making the assumption that selected countries in the REMap 2030 scenario are representative of entire ETSAP-TIAM regions. This is not always a good assumption: particularly for the regions of Eastern Europe (where only Poland is included) and Africa (only South Africa and Ethiopia are included). Fundamentally, there is a difference of scale between the ETSAP TIAM model structure and the REMap

2030 scenario. Nevertheless, it is hoped that the contrasting methodologies give good insights into the different ways of looking at the potential for renewable energy and the assumptions inherent in each approach.

6 CONCLUSIONS

There is synergy between the SE4ALL energy efficiency and renewable energy objectives. Achieving either of these objectives alone results in economically optimal solutions where the other objective is easier to achieve. Investing in both renewable energy and energy efficiency has cost benefits in terms of emissions as well; the additional cost of meeting both objectives is small (in terms of mass of avoided emissions per USD invested) in relation to the additional emissions reduced versus a scenario when only one objective is achieved.

The SE4ALL universal energy access objective, on the other hand, is more difficult to achieve and demonstrates lower synergetic effect with the other two objectives. It is a very ambitious assumption to phase out traditional biomass by 2030, and the most economic near-term option to replace this fuel is likely to be fossil-based. This reduces the share of renewable energy in these regions, and also requires additional investment in the residential sectors. Achieving the energy access objective requires significantly higher level of investments, and slightly increases emissions. Phasing out traditional biomass, modernizing the residential energy sector, and increasing electricity consumption would likely coincide with rapid economic development. This would also potentially have an effect on energy intensity, as the distribution and availability of fossil fuels would likely increase fossil energy consumption, thus affecting GDP. Further research is needed to better understand such non-linear feedbacks.

According to the exogenous economic projections used in this analysis, achieving the SE4ALL energy efficiency objective of 2.6% EIIR by 2030 (EE Scenarios) will result in global primary energy production of 603 EJ/year by 2030. This is a reduction of nearly 185 EJ/year in 2030 versus the historic 1.3% EIIR (the Ref Scenario). Yet, this will still mean an absolute increase in global primary energy production of nearly 90 EJ/year relative to 2010, where primary energy production is 513 EJ. Meeting the SE4ALL objectives, however, changes the primary energy portfolio. Coal use is reduced in the USA and China, and natural gas use declines in the Former Soviet Union. Biomass energy increases, and, in the case of the energy access objective, traditional biomass is replaced by more modern fuels. In terms of final energy, the largest changes are in electricity generation, and in the industrial subsectors, particularly in China. Final energy consumption does not change as much as primary energy production between the scenarios: the EE scenarios result in global final energy consumption of approximately 460-470 EJ/year by 2030 while the Ref Scenario shows nearly 500 EJ/ year of global final energy consumption. This is because the final energy service demands, which are calculated from the demand drivers in ETSAP-TIAM and do not change across scenarios.

Yet, the results from ETSAP-TIAM show different sources of the energy consumed in the different scenarios, as well as different levels of energy consumption within the different sectors of the economy. The regions with the largest reduction in final energy are predominately in the developing world: China, Other Developing Asia, India, Central and South America, and Africa. USA and Western Europe also has a lot of potential for reducing energy consumption in terms of absolute numbers. Many of the industrial subsectors and the residential heating subsector in China have large potential for reduction in energy consumption. The iron and steel production subsector in India also is an area with a high potential for reduction in final energy consumption and fuel switching.

When discounted energy savings are considered, the largest reductions are in the industrial sector, the residential heating subsector, and trucks in the transport sector. Commercial cooling also has a large potential for energy efficiency improvements, particularly in Western Europe, though this option will require a higher level of investment than other options.

The EE scenario reduces emissions slightly more than the RE energy scenario, suggesting that the SE4ALL energy efficiency objective is more in line with meeting a climate target than the SE4ALL renewable energy objective. Together, these two SE4ALL objectives, energy efficiency and renewable energy, are more effective than separately at reducing emissions. The energy access objective results in increased emissions with the EE+RE+EA scenario in ETSAP-TIAM, but would have other sustainable development benefits such as bringing modern energy services to more people of the world. While achieving the SE4ALL objectives reduces emissions in comparison to the Ref scenario, it is not enough to reduce carbon emissions to the level of the RCP2.6 pathway. Scenarios that achieve the SE4ALL energy efficiency objective approach the RCP2.6 pathway. Achieving either the SE4ALL renewable energy objective or the SE4ALL energy efficiency objective puts keeps global emissions below the pathway of the RCP4.5. Therefore, the SE4ALL initiative is at least compatible with keeping global warming below 2° C with a probability between 50 and 66%. Additional climate policies may still be necessary to remain below 2° C global warming, such as a price on carbon or other climate policy mechanisms.

China is the most important region when it comes to reducing emissions, but large reductions are also seen in the ETSAP-TIAM results in USA and Western Europe when the SE4ALL objectives are achieved. When the SE4ALL objectives are achieved, most of the greenhouse gas emissions reductions are CO_2 in the power and industrial sectors.

The global industry and transport sectors, followed by the commercial sector, are the most cost effective sectors for investment into energy efficiency, in terms of discounted energy saved versus increased investment (NPV). Residential heating also is also an inexpensive solution with large potential globally, though, regionally, it is least expensive in Central and South America, Africa, Australia, and India. Regionally, other industries in China and heavy trucks in the US, Western Europe, and China are relatively inexpensive for energy efficiency improvements, and have rather large potentials. Commercial cooling in Western Europe also has high potential, but it is also relatively more expensive than many other regional subsector improvements in industry and transportation.

Achieving the SE4ALL objectives is an ambitious goal. It would require many regions to make drastic improvements relative to their historic trends in energy efficiency and renewable energy. The SE4All objective on energy access is particularly ambitious, and would require significant additional investment. Nevertheless, the goals are feasible, and in many ways synergetic. They are also compatible with addressing climate change and preventing global warming from exceeding 2° C.

7 References

ABB. (2012a). Japan energy efficiency report. https://library.e.abb.com/public/4a34976258d9db4bc12579e600391cf7/Japan%20Energy%20efficiency%20Report.pdf

ABB. (2012b). Russia energy efficiency report. https://library.e.abb.com/public/1112256e3dbeb710c12579e6003937a3/Russia%20Energy%20efficiency%20Report.pdf.

ABB. (2013a). Brazil energy efficiency report. https://library.e.abb.com/public/c6d0b52cc84505a2c1257be80052c5a7/Brazil.pdf.

ABB. (2013b). China energy efficiency report. http://new.abb.com/docs/librariesprovider46/EE-Document/china-report-en.pdf?sfvrsn=2.

ABB. (2013c). South Korea energy efficiency report. https://library.e.abb.com/public/557d50223ed20a76c1257beb0044f3bc/South%20Korea.pdf?filename=South%20Korea.pdf.

ABB. (2013d). Turkey energy efficiency report. https://library.e.abb.com/public/a2c92d1d4f7f2405c1257be9002c5060/Turkey.pdf.

Akimoto, H., Ohara, T., Kurokawa, J., & Horii, N. (2006). Verification of energy consumption in China during 1996–2003 by using satellite observational data. *Atmos. Environ., 40*, 7663– 7667.

Allcott, H., Mullainathan, S., & Taubinsky, D. (2014). Energy policy with externalities and internalities. *Journal of Public Economics, 112*(72-88).

Asafu-Adjaye, J. (2000). The relationship between energy consumption, energy prices and economic growth: time series evidence from Asian developing countries. *Energy Economics 22*(615-625).

Babonneau, F., Vielle, M., Haurie, A., & Loulou, R. (2010). *Uncertainty and Economic Analysis of Energy and Climate Policies using TIAM and GEMINI-E3 models*. White paper under the FP7 European Research Project PLANETS. http://gemini-e3.epfl.ch/page-54870-fr.html.

Bataille, C. G. F. (2005). *Design and application of a technologically explicit hybrid energy-economy policy model with micro and macro-economic dynamics* Doctoral dissertation, School of Resource and Environmental Management, Simon Fraser University.

Bazilian, M., & Pielke, R. (2013). Making energy access meaningful. *Issues in Science and Technology, 29*(4), 74-78.

Berggren, M. (2013). *Global Methanol Outlook: Capacity Calling*. Paper presented at the 16th IMPCA Asian Methanol Conference, Singapore.

Boden, T., Andres, B., & Marland, G. (2010). Ranking of the world's countries by 2010 total CO2 emissions from fossil-fuel burning, cement production, and gas flaring. Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, Oak Ridge, Tennessee http://cdiac.ornl.gov/trends/emis/top2010.tot.

Brelsford, R. (2014). Rising demand, low-cost feed spur ethylene capacity growth. *Oil & Gas Journal, 112*(7), 90-98.

Chakravarty, S., & Tavoni, M. (2013). *Would Universal Energy Access Boost Climate Change?* . Review of Environment, Energy and Economics (Re3), Forthcoming. Available at SSRN: http://ssrn.com/abstract=2255974.

China Carbon. (2015). Trading data. http://chinacarbon.net.cn.

Cho, M. (2015). Trading dries up in South Korea's new carbon market. *Reuters*. Retrieved from http://www.reuters.com/article/2015/02/05/emission-southkorea-idUSL4N0VF1QN20150205

CIEC (The Essential Chemical Industry). (2015). Basic Chemicals. University of York, York, UK, http://www.essentialchemicalindustry.org/chemicals.html.

Dayton, L. (2014). Australia scraps carbon tax. *Sciencemag*. Retrieved from http://news.sciencemag.org/asiapacific/2014/07/australia-scraps-carbon-tax

Dean, A., & Hoeller, P. (1992). Costs of reducing CO2 emissions - Evidence from six global models *OECD Economic Studies 19 (Winter)*.

Environment Canada. (2015). Greenhouse gas emissions by province and territory, Canada, 1990, 2005 and 2013. http://open.canada.ca/data/en/dataset/9a673fa1-22af-41c1-9ae5-de38de714c83.

EPA (Environmental Protection Agency). (2014). State Energy CO2 Emissions. http://epa.gov/statelocalclimate/resources/state_energyco2inv.html.

FAO (United Nations Food and Agricultural Organization). (2015). FAOSTAT. http://faostat.fao.org/.
Gillingham, K., Kotchen, M. J., Rapson, D. S., & Wagner, G. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy, 8*(1), 18-38.
Global Carbon Project. (2014) Global Carbon Atlas. http://www.globalcarbonatlas.org/.
Gregg, J. S., Andres, R., & Marland, G. (2008). China: Emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production. *Geophysical Research Letters 35*, L08806.
ICAP. (2015). ETS Map. https://icapcarbonaction.com/ets-map.
IEA (International Energy Agency). (2007). Tracking industrial energy efficiency and CO2 emissions. Paris, France.
IEA (International Energy Agency). (2009). Energy technology transitions for industry. Paris, France.
IEA (International Energy Agency). (2014a). Energy Efficiency Indicators: Essentials for Policy Making. Paris, France, https://www.iea.org/publications/freepublications/publication/IEA_EnergyEfficiencyIndicators_EssentialsforPolicyMaking.pdf.
IEA (International Energy Agency). (2014b). World Energy Investment Outlook. Paris, France.
IEA (International Energy Agency). (2015). Energy Technology Perspectives- Mobilising Innovation to Accelerate Climate Action. Paris, France, https://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives2015ExecutiveSummaryEnglishversion.pdf.
Ilskog, E., Kjellström, B., Gullberg, M., Katyega, M., & Chambala, W. (2005). Electrification co-operatives bring new light to rural Tanzania. *Energy Policy, 33*(10), 1299-1307.
IRENA (International Renewable Energy Agency). (2014). A Renewable Energy Roadmap. Abu Dhabi, http://irena.org/remap/REmap_Report_June_2014.pdf.
Kazakhstan Energy Charter Secretariat & Kazenergy. (2014). Review of the National Policy of The Republic of Kazakhstan in the Area of Energy Saving and Energy Efficiency. http://www.encharter.org/fileadmin/user_upload/Publications/Kazakhstan_EE_2014_ENG.pdf
Kober, T. (2014). Impact of Energy Efficiency Measures on Greenhouse Gas Emission Reduction *(ECN-E–14-038)*. Energy research Centre of the Netherlands (ECN), Petten, The Netherlands, http://www.ecn.nl/docs/library/report/2014/e14038.pdf.
Labriet, M., Kanudia, A., & Loulou, R. (2012). Climate mitigation under an uncertain technology future: A TIAM-World analysis. *Energy Economics, 34*, S366-S377.
Lee, C. C. (2006). The causality relationship between energy consumption and GDP in G-11 countries revisited. *Energy Policy, 34*(9), 1086–1093.
Loulou, R., Labriet, M., & Kanudia, A. (2009). Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. *Energy Economics 31*, S131-S143.
Markandya, A., Halsnæs, K., Lanza, A., Matsuoka, Y., Maya, S., Pan, J., . . . Taylor, T. (2001). Summary for Policy Makers. In E. Jochem (Ed.), In Climate Change 2001: Mitigation, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
Methanex. (2014). Global Methanol Production Facilities. https://www.methanex.com.
Moss, R. H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T. and Meehl, G.A. (2010). The next generation of scenarios for climate change research and assessment. *Nature, 463*(7282), 747-756.
Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., . . . Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
New Zealand Ministry of Economic Development. (2011). New Zealand Energy Strategy 2011–2021: Developing our energy potential. http://www.med.govt.nz/sectors-industries/energy/pdf-docs-library/energy-strategies/nz-energy-strategy-lr.pdf.
Newell, R. G., & Siikamäki, J. (2015). Individual Time Preferences and Energy Efficiency. *American Economic Review: Papers & Proceedings, 105*(5), 196-200.

NHTSA (National Highway Traffic Safety Administration). (2011). President Obama Announces Historic 54.5 mpg Fuel Efficiency Standard. http://www.nhtsa.gov/About+NHTSA/Press+Releases/2011/President+Obama+Announces+Historic+54.5+mpg+Fuel+Efficiency+Standard

Nordhaus, W. D., & Boyer, J. (1999). *Roll the DICE Again: Economic Models of Global Warming*: manuscript edition, http://www.econ.yale.edu/~nordhaus/homepage/web%20pref%20102599.PDF.

Nussbaumer, P., Bazilian, M., & Modi, V. (2012). Measuring energy poverty: Focusing on what matters. *Renewable and Sustainable Energy Reviews, 16*(1), 231-243.

OECD. (2014). Economic Outlook No 95 - May 2014 - Long-term baseline projections. http://stats.oecd.org/OECDStat_Metadata/ShowMetadata.ashx?Dataset=EO95_LTB&ShowOnWeb=true&Lang=en

OTC-X. (2015). CO2-Emissionsrecht CHU. https://www.otc-x.ch/markt/instrument/valor/999999.html.

Ozturk, I. (2010). A literature survey on energy-growth nexus. *Energy Policy, 38*(1), 340-349.

Planning Commission Government of India. (2013). Twelfth Five Year Plan (2012–2017) Economic Sectors Volume II. http://planningcommission.gov.in/plans/planrel/12thplan/pdf/12fyp_vol2.pdf.

REN21. (2015). Renewables 2015 Global Status Report. Paris, REN21 Secretariat, http://www.ren21.net/status-of-renewables/global-status-report/.

Rösler, H., Bruggink, J. J. C., & Keppo, I. J. (2011). Design of a European sustainable hydrogen model - Model structure and data sources *ECN-E-11-041*. Energy research Centre of the Netherlands (ECN), Petten, The Netherlands, https://www.ecn.nl/docs/library/report/2011/e11041.pdf.

Rösler, H., van der Zwaan, B., Keppo, I., & Bruggink, J. (2014). Electricity versus hydrogen for passenger cars under stringent climate change control. *Sustainable Energy Technologies and Assessments, 5*(0), 106-118.

Sathaye, J., de la Rue du Can, S., Iyer, M., McNeil, M., Kramer, K. J., Roy, J., . . . Roy Chowdhury, S. (2010). Strategies for Low Carbon Growth in India: Industry and Non Residential Sectors. Ernest Orlando Lawrence Berkeley National Laboratory, https://ies.lbl.gov/sites/all/files/low-co-growth-india-2011_1.pdf.

Scheper, E., & Kram, T. (1994). *Comparing MARKAL and MARKAL-MACRO for The Netherlands.* Paper presented at the May 1994 ETSAP Meeting, ECN Policy Studies.

SE4ALL (Sustainable Energy for All). (2013). Global Tracking Framework United Nations, Vienna, Austria, http://www.iea.org/publications/freepublications/publication/global_tracking_framework.pdf.

SE4ALL (Sustainable Energy for All). (2015). Progress Toward Sustainable Energy United Nations, Vienna, Austria, http://www.se4all.org/wp-content/uploads/2013/09/GTF-2105-Full-Report.pdf.

Shiu, A., & Lam, P.-L. (2004). Electricity consumption and economic growth in China. *Energy Policy, 32*(1), 47-54.

Sinton, J. E. (2001). Accuracy and reliability of China's energy statistics. *China Economic Review, 12*(373-383).

Smeets, E. M. W., Faaij, A. P. C., & Lewandowski, I. (2004). A quickscan of global bio-energy potentials to 2050: an analysis of the regional availability of biomass resources for export in relation to the underlying factors *Report NWS-E-2004-109* Universiteit Utrecht, Copernicus Institute, Department of Science Technology and Society, http://www.bioenergytrade.org/downloads/smeetsglobalquickscan2050.pdf

TekCarta. (2015). Households: Average Household Size (68 countries) http://www.generatorresearch.com/tekcarta/databank/households-average-household-size/.

Trottier, S. (2015). Understanding the Changes to Global Warming Potential (GWP) Values. http://ecometrica.com/assets/Understanding-the-Changes-to-GWPs.pdf: ecometrica.

USGS (US Geological Survey). (2015). Historical Statistics for Mineral and Material Commodities in the United States *Data Series 140*. http://minerals.usgs.gov/minerals/pubs/historical-statistics/#nitrogen.

Wang, H., Zhang, R., Liu, M., & Bi, J. (2012). The carbon emissions of Chinese cities. *Atmospheric Chemistry and Physics, 12*(14), 6197-6206.

WBCSD (World Business Council for Sustainable Development) Cement Sustainability Initiative. (2015). Getting The Numbers Right Project – Emissions Report 2013. http://www.wbcsdcement.org/GNR-2013/index.html.

Wise, M., & Calvin, K. (2011). GCAM 3.0 Agriculture and Land Use: Technical Description of Modeling Approach *PNNL-20971 Technical Report for the United States Department of Energy*. https://wiki.umd.edu/gcam/images/8/87/GCAM3AGTechDescript12_5_11.pdf.

Wolde-Rufael, Y. (2006). Electricity consumption and economic growth: A time series experience for 17 African countries. *Energy Policy, 34*(10), 1106-1114.

World Bank. (2014). Health Nutrition and Population Statistics: Population estimates and projections Washington, D.C., http://databank.worldbank.org/data/home.aspx
World Bank. (2015a). Carbon Pricing Watch 2015. Washington, D.C., http://documents.worldbank.org/curated/en/2015/05/24528977/carbon-pricing-watch-2015-advance-brief-state-trends-carbon-pricing-2015-report-released-late-2015.
World Bank. (2015b). Least developed countries: UN classification. Washington, D.C., http://data.worldbank.org/region/LDC.
World Bank. (2015c). World Bank Open Data. Washington, D.C., http://data.worldbank.org/.
Worrell, E., & Galitsky, C. (2008). Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making *LBNL-54036-Revision*. U.S. Environmental Protection Agency, Ernest Orlando Lawerence Berkeley National Laboratory, Berkeley, California https://www.energystar.gov/ia/business/industry/LBNL-54036.pdf.
Worrell, E., Kermeli, K., & Galitsky, C. (2013). Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making *Document Number 430-R-13-009* US Environmental Protection Agency, Washington, D.C., https://www.energystar.gov/sites/default/files/tools/ENERGY%20STAR%20Guide%20for%20the%20Cement%20Industry%2027_08_2013_Rev%20js%20reformat%2011192014.pdf.

8 APPENDICES

8.1 ABBREVIATIONS USED

AEEI	Autonomous Energy Efficiency Improvement
ASEAN	Association of Southeast Asian Nations
ATM	Automatic Teller Machine
BAT	Best Available Technology
BAU	Business as Usual
BUENAS	Bottom-Up Energy Analysis
CAFE	Corporate Average Fuel Economy
CAGR	Compound Annual Growth Rate
CDIAC	Carbon Dioxide Information Analysis Center
CIEC	The Essential Chemical Industry
DOE	Department of Energy (USA)
EBPD	Energy Building Performance Directive
EIA	Energy Information Administration (USA DOE)
EIIR	Energy Intensity Improvement Rate
EMF	Energy Modeling Forum
EPA	Environmental Protection Agency (USA)
ESCO	Employing Energy Services Company
ETS	Emissions Trading Scheme/System
ETSAP-TIAM	Energy Technology System Analysis Program TIMES Integrated Assessment Model
EU / EU27 /EU28	European Union
FAO	Food and Agriculture Organization of the United Nations
GDP (PPP)	Gross Domestic Product (Purchasing Power Parity)
GEM-E3	Global Equilibrium Model- Economy, Energy and the Environment
GEMINI-E3	A General Equilibrium Model of International-National Interactions between Economy,

Energy and the Environment

GHG	Greenhouse Gas
GTF	Global Tracking Framework
IAM	Integrated Assessment Model
ICE	Internal Combustion Engine
IEA	International Energy Agency
IESG	International Energy Study Group
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
MAGICC	Model for Greenhouse gas Induced Climate Change
MARKAL	MARket Allocation model
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
NHTSA	National Highway Traffic Safety Administration
OECD	The Organisation for Economic Co-operation and Development
PESTLEG	Political, Economic, Social, Technological, Legal, Environmental, and Governmental
R&D	Research and Development
REMap	Roadmap for a Renewable Energy Future (IRENA)
SE4ALL	UN Sustainable Energy for All
TFEC	Total Final Energy Consumption
TIAM-ECN	Times Integrated Assessment Model at the Energy Research Centre of the Netherlands
TIMES	The Integrated MARKAL-EFOM System
UN	United Nations
USA	United States of America
USGS	US Geological Survey
WBCSD	World Business Council for Sustainable Development

Table 32. ETSAP-TIAM Regions

Region	**Abbreviation**
Africa	AFR
Australia & NZ	AUS
Canada	CAN
China	CHI
Central & South America	CSA
Eastern Europe	EEU
Former Soviet Union	FSU
India	IND
Japan	JAP
Middle East	MEA
Mexico	MEX
Other Developing Asia	ODA
South Korea	SKO
United States	USA
Western Europe	WEU
Global	GBL

8.2 DRIVERS

Table 33. Demand Driver Description

POP	Population
GDP	Gross Domestic Product
GDPP	Per Capita GDP
HOU	Number of Households
GDPPHOU	GDP per Household
PAGR	Driver for Agriculture
PCHEM	Driver for Chemicals and Petrochemical
PISNF	Driver for Iron, Steel, and Non-Ferrous Metals
POEI	Driver for Other Energy Intensive Industries
POI	Driver for Other Industry
PSER	Driver for Services

Table 34. Regional sectoral demand drivers in ETSAP-TIAM

Drivers: Sectoral growth rate indices	Driver Abbreviation	2005	2010	2015	2020	2025	2030
Africa (AFR)							
Agriculture	PAGR	1.00	1.31	1.63	2.00	2.37	2.79
Chemicals	PCHEM	1.00	1.33	1.65	2.09	2.56	3.09
Industry Metals	PISNF	1.00	1.22	1.41	1.77	2.11	2.47
Industry Non-Metals	POEI	1.00	1.30	1.64	2.04	2.46	2.92
Other Industry	POI	1.00	1.24	1.53	1.87	2.20	2.58
Services	PSER	1.00	1.28	1.60	1.96	2.33	2.74
Australia & New Zealand (AUS)							

Agriculture	PAGR	1.00	1.14	1.25	1.42	1.53	1.64
Chemicals	PCHEM	1.00	1.14	1.26	1.41	1.52	1.62
Industry Metals	PISNF	1.00	1.20	1.36	1.57	1.73	1.87
Industry Non-Metals	POEI	1.00	1.15	1.28	1.44	1.57	1.69
Other Industry	POI	1.00	1.31	1.64	2.02	2.42	2.89
Services	PSER	1.00	1.16	1.30	1.47	1.60	1.73
Canada (CAN)							
Agriculture	PAGR	1.00	1.13	1.24	1.38	1.44	1.49
Chemicals	PCHEM	1.00	1.12	1.23	1.35	1.38	1.41
Industry Metals	PISNF	1.00	1.09	1.17	1.33	1.35	1.35
Industry Non-Metals	POEI	1.00	1.16	1.27	1.37	1.40	1.45
Other Industry	POI	1.00	1.16	1.33	1.51	1.62	1.75
Services	PSER	1.00	1.16	1.30	1.46	1.54	1.63
China (CHI)							
Agriculture	PAGR	1.00	1.61	2.21	3.00	3.91	5.15
Chemicals	PCHEM	1.00	1.63	2.37	3.32	4.41	5.90
Industry Metals	PISNF	1.00	1.63	2.34	3.24	4.30	5.75
Industry Non-Metals	POEI	1.00	1.64	2.29	3.13	4.13	5.51
Other Industry	POI	1.00	1.57	2.06	2.73	3.52	4.56
Services	PSER	1.00	1.57	2.07	2.76	3.58	4.67
Central and South America (CSA)							
Agriculture	PAGR	1.00	1.23	1.50	1.80	2.08	2.39
Chemicals	PCHEM	1.00	1.25	1.53	1.83	2.14	2.49
Industry Metals	PISNF	1.00	1.18	1.40	1.66	1.93	2.26
Industry Non-Metals	POEI	1.00	1.26	1.53	1.83	2.15	2.52
Other Industry	POI	1.00	1.22	1.47	1.74	2.01	2.32
Services	PSER	1.00	1.23	1.48	1.76	2.05	2.37
Eastern Europe (EEU)							
Agriculture	PAGR	1.00	1.16	1.16	1.18	1.19	1.20
Chemicals	PCHEM	1.00	1.17	1.17	1.20	1.23	1.25
Industry Metals	PISNF	1.00	1.10	1.07	1.04	1.04	1.05
Industry Non-Metals	POEI	1.00	1.16	1.15	1.14	1.14	1.15
Other Industry	POI	1.00	1.19	1.26	1.29	1.34	1.40
Services	PSER	1.00	1.18	1.21	1.23	1.26	1.29
Former Soviet Union (FSU)							
Agriculture	PAGR	1.00	1.34	1.81	2.26	3.01	3.78
Chemicals	PCHEM	1.00	1.24	1.64	2.04	2.72	3.40
Industry Metals	PISNF	1.00	1.33	1.83	2.31	3.15	4.05
Industry Non-Metals	POEI	1.00	1.37	1.83	2.26	3.05	3.84
Other Industry	POI	1.00	1.30	1.75	2.26	3.05	3.80
Services	PSER	1.00	1.33	1.77	2.19	2.98	3.75
India (IND)							
Agriculture	PAGR	1.00	1.51	2.20	3.25	4.53	6.29
Chemicals	PCHEM	1.00	1.56	2.30	3.40	4.93	7.00
Industry Metals	PISNF	1.00	1.53	2.36	3.81	5.71	8.29
Industry Non-Metals	POEI	1.00	1.55	2.33	3.51	5.05	7.09
Other Industry	POI	1.00	1.49	2.14	3.10	4.24	5.83
Services	PSER	1.00	1.50	2.17	3.20	4.44	6.17

Japan (JPN)							
Agriculture	PAGR	1.00	1.06	1.14	1.23	1.21	1.20
Chemicals	PCHEM	1.00	1.12	1.20	1.28	1.30	1.33
Industry Metals	PISNF	1.00	1.13	1.21	1.29	1.31	1.35
Industry Non-Metals	POEI	1.00	1.11	1.19	1.27	1.29	1.32
Other Industry	POI	1.00	1.13	1.23	1.33	1.37	1.43
Services	PSER	1.00	1.12	1.21	1.30	1.33	1.38
Middle East (MEA)							
Agriculture	PAGR	1.00	1.39	1.78	2.15	2.55	2.94
Chemicals	PCHEM	1.00	1.42	1.76	2.09	2.57	3.00
Industry Metals	PISNF	1.00	1.31	1.59	1.72	1.95	2.12
Industry Non-Metals	POEI	1.00	1.36	1.73	2.07	2.49	2.90
Other Industry	POI	1.00	1.25	1.41	1.67	1.91	2.23
Services	PSER	1.00	1.30	1.59	1.94	2.27	2.66
Mexico (MEX)							
Agriculture	PAGR	1.00	1.22	1.53	1.88	2.25	2.69
Chemicals	PCHEM	1.00	1.24	1.52	1.87	2.27	2.72
Industry Metals	PISNF	1.00	1.20	1.47	1.81	2.22	2.67
Industry Non-Metals	POEI	1.00	1.23	1.53	1.89	2.30	2.78
Other Industry	POI	1.00	1.21	1.53	1.86	2.25	2.67
Services	PSER	1.00	1.21	1.52	1.85	2.25	2.67
Other Developing Asia (ODA)							
Agriculture	PAGR	1.00	1.24	1.53	1.86	2.16	2.47
Chemicals	PCHEM	1.00	1.21	1.54	1.90	2.24	2.62
Industry Metals	PISNF	1.00	1.26	1.58	1.90	2.23	2.59
Industry Non-Metals	POEI	1.00	1.27	1.56	1.89	2.22	2.56
Other Industry	POI	1.00	1.25	1.56	1.89	2.21	2.55
Services	PSER	1.00	1.26	1.54	1.84	2.15	2.48
South Korea (SKO)							
Agriculture	PAGR	1.00	1.16	1.30	1.48	1.58	1.68
Chemicals	PCHEM	1.00	1.13	1.32	1.52	1.64	1.78
Industry Metals	PISNF	1.00	1.17	1.35	1.52	1.63	1.76
Industry Non-Metals	POEI	1.00	1.18	1.34	1.51	1.62	1.74
Other Industry	POI	1.00	1.17	1.33	1.51	1.61	1.73
Services	PSER	1.00	1.17	1.31	1.47	1.57	1.69
USA							
Agriculture	PAGR	1.00	1.16	1.33	1.53	1.73	1.93
Chemicals	PCHEM	1.00	1.20	1.38	1.60	1.81	2.02
Industry Metals	PISNF	1.00	1.23	1.42	1.64	1.85	2.05
Industry Non-Metals	POEI	1.00	1.19	1.38	1.61	1.82	2.03
Other Industry	POI	1.00	1.19	1.40	1.63	1.85	2.08
Services	PSER	1.00	1.19	1.39	1.62	1.83	2.04
Western Europe (WEU)							
Agriculture	PAGR	1.00	1.12	1.22	1.33	1.44	1.56
Chemicals	PCHEM	1.00	1.14	1.25	1.38	1.50	1.62
Industry Metals	PISNF	1.00	1.13	1.25	1.37	1.50	1.64
Industry Non-Metals	POEI	1.00	1.14	1.27	1.41	1.55	1.71

Other Industry	POI	1.00	1.16	1.31	1.47	1.64	1.82
Services	PSER	1.00	1.15	1.29	1.44	1.59	1.76

*Table 35. Sectors and subsectors in ETSAP-TIAM, *Driver is GDPPHOU for AFR, CHI, CSA, EEU, FSU, IND, MEA, MEX, ODA and SKO*

Sector	**Units**	**Driver**
Transportation segments (15)		
Autos	Bv-km	GDPP
Buses	Bv-km	POP
Light trucks	Bv-km	GDP
Commercial trucks	Bv-km	GDP
Medium trucks	Bv-km	GDP
Heavy trucks	Bv-km	GDP
Two wheelers	Bv-km	POP
Three wheelers	Bv-km	POP
International aviation	PJ	GDP
Domestic aviation	PJ	GDP
Freight rail transportation	PJ	GDP
Passenger rail transportation	PJ	POP
Internal navigation	PJ	GDP
International navigation (bunkers)	PJ	GDP
Non-energy uses in transport	PJ	GDP
Commercial segments (8)		
Space heating	PJ	PSER
Space cooling	PJ	PSER
Water heating	PJ	PSER
Lighting	PJ	PSER
Cooking	PJ	PSER
Refrigerators and freezers	PJ	PSER
Electric equipment	PJ	PSER
Other energy uses	PJ	GDP
Residential segments (11)		
Space heating	PJ	HOU
Space cooling	PJ	HOU/GDPPHOU*
Hot water heating	PJ	POP
Lighting	PJ	GDPP
Cooking	PJ	POP
Refrigerators and freezers	PJ	HOU/GDPPHOU*
Clothes washers	PJ	HOU/GDPPHOU*
Clothes dryers	PJ	HOU/GDPPHOU*
Dish washers	PJ	HOU/GDPPHOU*
Miscellaneous electric energy	PJ	HOU/GDPPHOU*
Other energy uses	PJ	GDP

Industrial segments (6)		
Iron and steel	Mt	PISNF
Non-ferrous metals	Mt	PISNF
Chemicals	PJ	PCHEM
Pulp and paper	Mt	POEI
Non-metal minerals	PJ	POEI
Other industries	PJ	POI
Agriculture segment (1)		
Agriculture	PJ	PAGR
Other segment (1)		
Other non-specified energy consumption	PJ	GDP

Table 36. Discounted energy savings by regional subsector, ranked by cost efficiency of energy saved. Discount rate is assumed to be 5%.

Region	Subsector	Additional Investment NPV (Billion USD)	Discounted Energy Savings (PJ)	Discounted Cost of Energy Savings (USD/GJ)
JPN	Industrial Iron and Steel	0.06	2609.2	0.02
AFR	Industrial Non-Ferrous Metals	0.00	35.6	0.04
AUS	Transport Trucks Heavy	0.08	559.9	0.14
MEA	Industrial Non-Ferrous Metals	0.01	33.8	0.23
CAN	Transport Trucks Heavy	0.25	954.0	0.27
AUS	Industrial Iron and Steel	1.12	4007.0	0.28
EEU	Industrial Iron and Steel	4.67	16503.3	0.28
FSU	Industrial Iron and Steel	0.27	834.9	0.32
USA	Industrial Iron and Steel	1.29	3489.5	0.37
CAN	Industrial Non-Ferrous Metals	0.00	7.8	0.42
SKO	Industrial Other Industries	0.20	452.3	0.44
ODA	Industrial Non-Ferrous Metals	0.00	4.6	0.52
IND	Industrial Iron and Steel	5.06	8432.1	0.60
ODA	Industrial Iron and Steel	2.96	4311.4	0.69
USA	Industrial Non-Ferrous Metals	0.09	131.3	0.70
CSA	Residential Heating	0.54	574.2	0.95
MEA	Industrial Chemicals	0.03	34.0	1.02
AFR	Transport Trucks Heavy	0.38	311.8	1.22
AFR	Industrial Iron and Steel	2.58	2109.0	1.22
CSA	Industrial Non-Metal Minerals	1.11	759.8	1.46
FSU	Industrial Non-Metal Minerals	7.34	3852.9	1.91

CHI	Industrial Other Industries	8.20	4206.7	1.95
USA	Industrial Non-Metal Minerals	5.16	2455.1	2.10
EEU	Industrial Non-Ferrous Metals	0.01	3.8	2.22
CAN	Commercial Heating	0.42	179.1	2.34
CHI	Commercial Heating	0.45	185.3	2.40
AUS	Industrial Non-Metal Minerals	0.04	15.3	2.45
SKO	Transport Trucks Medium	0.25	98.2	2.54
EEU	Industrial Non-Metal Minerals	0.43	163.3	2.66
FSU	Transport Trucks Heavy	1.75	650.8	2.70
AFR	Industrial Non-Metal Minerals	0.52	190.4	2.71
AUS	Commercial Heating	0.05	16.3	2.82
WEU	Industrial Non-Metal Minerals	3.06	1065.0	2.88
MEX	Transport Trucks Heavy	1.24	408.7	3.03
IND	Industrial Non-Metal Minerals	0.01	1.8	3.23
SKO	Transport Trucks Heavy	0.94	279.1	3.38
MEX	Industrial Non-Metal Minerals	0.25	72.4	3.41
CAN	Transport Trucks Commercial	0.16	46.5	3.47
USA	Commercial Heating	3.41	952.6	3.58
CAN	Transport Trucks Medium	0.12	33.4	3.59
USA	Transport Trucks Medium	0.78	216.3	3.59
WEU	Transport Trucks Commercial	2.03	558.1	3.64
CHI	Transport Trucks Heavy	9.54	2582.0	3.70
ODA	Industrial Non-Metal Minerals	1.18	312.7	3.77
CHI	Industrial Non-Metal Minerals	12.94	3400.3	3.81
WEU	Transport Trucks Medium	1.70	440.4	3.86
USA	Transport Trucks Heavy	19.19	4887.3	3.93
SKO	Commercial Heating	0.29	71.0	4.08
SKO	Industrial Non-Metal Minerals	0.41	96.0	4.29
JPN	Industrial Non-Metal Minerals	0.61	138.1	4.40
CHI	Transport Trucks Medium	1.76	397.8	4.42
AUS	Transport Trucks Medium	0.17	38.4	4.48
JPN	Transport Trucks Heavy	1.62	353.7	4.58
AFR	Residential Heating	15.91	3441.2	4.62
EEU	Transport Trucks Heavy	2.31	486.0	4.75
JPN	Transport Trucks Commercial	0.70	146.1	4.77
AFR	Transport Trucks Medium	0.23	47.6	4.80
AUS	Residential Heating	0.00	0.6	4.81
IND	Transport Trucks Medium	0.67	139.7	4.82
EEU	Transport Trucks Medium	0.34	70.4	4.90
MEX	Transport Trucks Medium	0.24	49.8	4.92
MEA	Transport Trucks Heavy	8.26	1629.9	5.07

IND	Transport Trucks Heavy	1.64	316.6	5.17
SKO	Transport Trucks Commercial	0.48	89.1	5.35
WEU	Transport Trucks Heavy	0.15	26.1	5.56
AUS	Transport Trucks Commercial	0.15	26.2	5.56
WEU	Industrial Non-Ferrous Metals	0.23	40.0	5.80
CAN	Transport Cars	2.53	433.6	5.82
MEX	Transport Trucks Commercial	0.09	15.2	6.11
EEU	Transport Trucks Light	0.42	68.5	6.13
ODA	Transport Trucks Heavy	7.44	1209.6	6.15
WEU	Transport Cars	13.14	2115.8	6.21
JPN	Transport Trucks Light	1.22	192.0	6.38
CSA	Transport Trucks Medium	0.69	107.6	6.38
ODA	Residential Heating	26.49	4143.2	6.39
SKO	Transport Cars	0.45	70.2	6.40
FSU	Transport Trucks Medium	0.22	34.0	6.49
USA	Transport Trucks Commercial	2.17	334.1	6.50
MEX	Transport Trucks Light	1.97	301.6	6.53
CHI	Transport Cars	1.51	228.4	6.61
USA	Transport Cars	8.27	1214.5	6.81
AUS	Transport Cars	0.53	77.2	6.81
CHI	Transport Trucks Commercial	7.83	1089.6	7.18
CSA	Commercial Heating	0.07	9.4	7.31
MEX	Transport Cars	0.87	118.3	7.35
ODA	Transport Cars	1.77	237.3	7.46
MEA	Transport Trucks Light	3.90	509.8	7.65
FSU	Transport Trucks Light	1.32	172.4	7.66
ODA	Transport Trucks Light	3.73	484.5	7.69
AFR	Commercial Heating	0.05	6.5	8.15
CSA	Transport Trucks Light	2.63	321.0	8.20
IND	Residential Heating	11.37	1301.1	8.74
WEU	Commercial Heating	2.24	249.1	9.01
AFR	Commercial Lighting	4.76	505.8	9.42
AFR	Transport Trucks Light	1.43	151.6	9.46
ODA	Transport Trucks Medium	1.40	147.7	9.49
CHI	Industrial Chemicals	10.04	1017.0	9.87
AUS	Industrial Non-Ferrous Metals	0.05	4.8	9.99
IND	Transport Cars	1.04	95.4	10.93
JPN	Commercial Heating	0.20	18.5	10.95
SKO	Commercial Hot Water	0.02	1.9	11.69
EEU	Commercial Heating	0.09	8.0	11.82
IND	Commercial Heating	0.00	0.3	11.99

ODA	Industrial Chemicals	0.85	66.8	12.76
FSU	Transport Trucks Commercial	0.55	40.7	13.51
FSU	Transport Cars	0.09	6.6	13.81
CHI	Residential Hot Water	11.03	793.8	13.90
CSA	Transport Cars	0.19	12.9	14.97
MEX	Residential Hot Water	0.68	44.1	15.41
IND	Residential Hot Water	14.74	936.3	15.74
AFR	Transport Trucks Commercial	0.90	55.1	16.37
ODA	Residential Hot Water	20.12	1044.8	19.26
CSA	Residential Hot Water	3.87	201.0	19.27
JPN	Industrial Non-Ferrous Metals	0.01	0.4	21.06
AFR	Residential Hot Water	28.95	1329.8	21.77
ODA	Transport Trucks Commercial	2.70	120.9	22.33
CAN	Industrial Chemicals	0.02	0.8	23.75
CSA	Transport Trucks Commercial	0.92	26.3	34.86
WEU	Commercial Cooling	34.78	866.0	40.16
USA	Residential Heating	0.84	20.7	40.32
FSU	Industrial Non-Ferrous Metals	0.03	0.6	43.63
JPN	Industrial Other Industries	2.18	27.5	79.26

8.3 Supplementary Files

Figures.pdf	Compendium containing 11438 graphs of the ETSAP-TIAM output
Contents.csv	List of the titles for each of the graphs in Figures.pdf
Output	Folder containing .csv files of data for Figures.pdf
ETSAP-TIAM Raw Output	Folder containing raw ETSAP-TIAM model output
R code.docx	Computer script in R for converting raw ETSAP-TIAM output to Figures.pdf, output data files, and report figures and tables.
Technology Drivers.xlsx	ETSAP-TIAM input technology parameter assumptions