ROLE OF ENERGY EFFICIENCY FOR SUSTAINABLE ENERGY FOR ALL: EXPLORING SYNERGIES WITH RENEWABLE ENERGY AND ENERGY ACCESS

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ABSTRACT

The global initiative Sustainable Energy for All (SEforALL) aims to ensure the global transition towards more sustainable energy services by 2030 through achievement of three interlinked objectives: 1) to ensure the universal access to modern energy services; 2) to double the global rate of improvement in energy efficiency; and 3) to double the share of renewable energy in the global energy mix. Very often energy access, energy efficiency and renewable energy are considered to be separate areas of the policy and technological development with quite isolated policy frameworks, stakeholders involvement processes and implementation efforts.

This paper investigates potential synergies between these areas through the framework and global indicators of SEforALL by means of the integrated assessment model ETSAP-TIAM and development of several scenarios for the period between 2010 and 2030.

The results demonstrate significant synergies between the outlined SEforALL objectives and their importance for ensuring sustainable energy future at the global level, as well as mitigation of the climate change impacts and global temperature rise. This calls for uniting efforts across these three areas of sustainable energy and elaboration of more holistic approaches to policy and technology development.

INTRODUCTION

This paper analyzes pathways for achieving the objectives under Sustainable Energy for All (SEforALL), a United Nations (UN) global initiative grounded on the three interlinked objectives: 1) to ensure the universal access to modern energy services (EA objective); 2) to double the global rate of improvement in energy efficiency (EE objective); and 3) to double the share of renewable energy in the global energy mix (RE objective) (SE4ALL, 2013).

The main hypothesis of this paper is that the synergies exist between large-scale renewable energy deployment and energy efficiency improvement, which can be utilized in the achievement of the SEforALL objectives. The verification of this hypothesis was conducted through development and comparison between the scenarios, which consider (1) achievement of EE objective in isolation from renewable energy deployment, (2) achievement of RE objective in isolation from energy efficiency improvement and (3) progress towards achievement of both these objectives at the same time. The effect of achieving EA objective is also modelled, but is not in the focus of the discussion presented in this paper. The positive verification of the hypothesis would demonstrate the importance of simultaneous actions in the field of energy efficiency improvement and renewable energy deployment, rather than separating them or giving a priority to either of them in the policy development and choices of technological solutions.

The integrated assessment model, ETSAP-TIAM, was used to compare developed scenarios for the energy system dynamics between 2010 and 2030 from the economic optimization point of view. The compound annual rate of reduction (CAGR) in the global primary energy intensity[1] (EIIR) was adopted as a proxy indicator for the SEforALL EE objective and the share of renewable energy in the global final energy consumption (RE share) – for the SEforALL RE objective, as suggested in the Global Tracking Framework (SE4ALL, 2013). ETSAP-TIAM gives the opportunity to analyze a large number of technologies with various levels of efficiency, which gives the flexibility to set different levels for energy efficiency and renewable energy ambitions under different scenarios.

METHODOLOGY

Base year

Global Tracking Framework determines the following global base values and targets by 2030 for the three SEforAll objectives (Table1).

Table 1. Progress in achieving the SEforALL 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 (%)	Global compound annual rate for EIIR (%)	Global RE share (%)
1990	76	47	-1.3	16.6
2010	83	59	-1.3	17.8
2030 (target)	100	100	-2.6	36

Table 2 presents regional rates for energy intensity reduction (EIIR), which were assumed in the model for the base year of calculations.

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%

[1] EIIR = primary energy consumption divided by GDP

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%

The 2010 statistical data was used in the model as the input data for the base year of calculations. Then SEforALL objectives were translated into the target constraints to be achieved by 2030. Such a constraint is set as a specific predefined outcome for 2030 for a specific attribute (i.e., energy intensity, renewable energy share, or energy access). From there, a scenario is created by linearly interpolating targets for each time step between 2010 and 2030. In the model, a scenario is linked to the minimum constraint for each time step (i.e., that the conditions of the target must be met, and may be exceeded), applied at the global level.

Scenarios

The model distinguishes between a reference and several alternative scenarios linked to the investigation of the linkages between the SEforALL objectives. A reference scenario was created based on the historical EIIR rates, a default energy system constructed in the model under its default settings. Alternative scenarios were created in order to reflect progress towards achievement of different SEforALL objectives, as described below. The analysis is based on the comparison of each alternative scenario to the reference scenario, in order to see how the structural development of the energy system changes when different combinations of the SE4forALL objectives are achieved.

The following scenarios were constructed:

(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). 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 sets a global minimum constraint on the global energy intensity reduction rate between 2010 and 2030 of at least 2.6% per year. No constraints are placed on renewable energy share.

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

(iv) ***EE+RE Scenario***: The Energy Efficiency and Renewable Energy Scenario combines the constraints for EE and RE scenarios, so that the global energy intensity is reduced by at least 2.6% per year, and the renewable energy share in the global final energy use reaches at least 36% of 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 puts the condition of phasing out the use of traditional biomass, and meets an assumed minimum electricity demand, thus, potentially achieving all three SEforALL objectives.

Time Frame and Regions

The model is set up to explore the development of the global energy system from the year 2010 to the SEforALL target year of 2030 with 5-year time steps using the framework of ETSAP-TIAM. The model places the focuses on the global results, based on the aggregation of estimates from 15 regions presented in Figure 1.

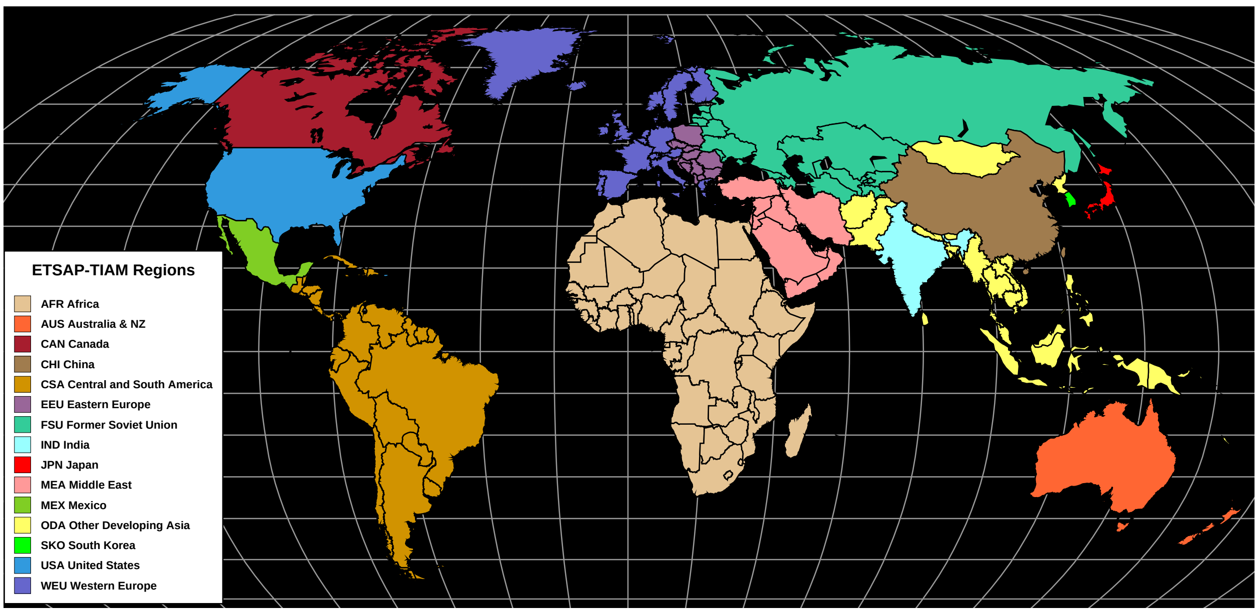

Figure 1. Fifteen regions of the Energy Technology System Analysis Program TIMES Integrated Assessment Model (ETSAP-TIAM).

The historic average rate of annual change in energy intensity is calculated using the data from the Global Tracking Framework (SE4ALL, 2015) for years 1990-2013 for each ETSAP-TIAM region and for the world. For the Reference scenario, the average reduction rate in global energy intensity for the years 1990-2030 was extrapolated to the years between 2010 and 2030. By multiplying these energy intensity projections with the OECD (2014) GDP PPP projections, a total primary energy constraint was created for the world. The SEforALL target constraint for global reduction rate in energy intensity 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. In a similar manner, using OECD (2014) GDP PPP projections for the world, the 2030 global total primary energy targets were calculated and used as constraints for EE objective under the EE+RE and EE+RE+EA scenarios.

Renewable energy constraints were constructed to set a target share of 36% of renewable energy share in the global total final energy consumption by 2030. Due to the fact that 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 in order 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.

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. Lacking any detailed literature on pathways to phase out traditional biomass by 2030, this rate 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 well-known 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 technological options allow for distinguishing between the usage of traditional biomass from modern bioenergy production. It is assumed that all solid biomass consumed in the residential sub-sector for hot water, cooking, and heating is traditional biomass.

Model logic and structure

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.

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[2] 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.

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[3] of the total surplus[4] for the entire world. 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 CO_2 storage and region-specific demand developments. The region and sector-specific demands for end-use energy and industrial products are driven by socio-economic parameters. 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. Such technological detail allows precise tracking of optimal capital turnover, and provides a precise description of 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,

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

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

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

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, assuming that the costs of technologies generally decrease in future time periods (Loulou, R., etc. 2009).

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).

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).

Input Data

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 means of a set of exogenous demand drivers. 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 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.

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. In this paper, the analysis is conducted for the following end-use sectors: agriculture, buildings, transport, industry.

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. Some technologies have an increasing level of energy efficiency for each future time step, representing an evolution in design for a given technology. 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. 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).

RESULTS

Energy efficiency objective

In Figure 2 presents the EIIR for Reference, RE, and EE-based scenarios (i.e. the results are the same for EE, EE+RE, EE+RE+EA scenarios and presented under one line) for the years 2010 to 2030. Reference scenario has an EIIR of -1.3% CAGR, and the EE-based scenarios have EIIR set to -2.6% CAGR. In the RE scenario, the reduction in energy intensity is larger than that under the Reference scenario, reaching almost half of the 2030 target value for EIIR for the energy efficiency objective. This demonstrates a synergetic effect between the two objectives, as the deployment of renewable energy technologies reduced primary energy consumption and, therefore, had a notable impact on the EIIR.

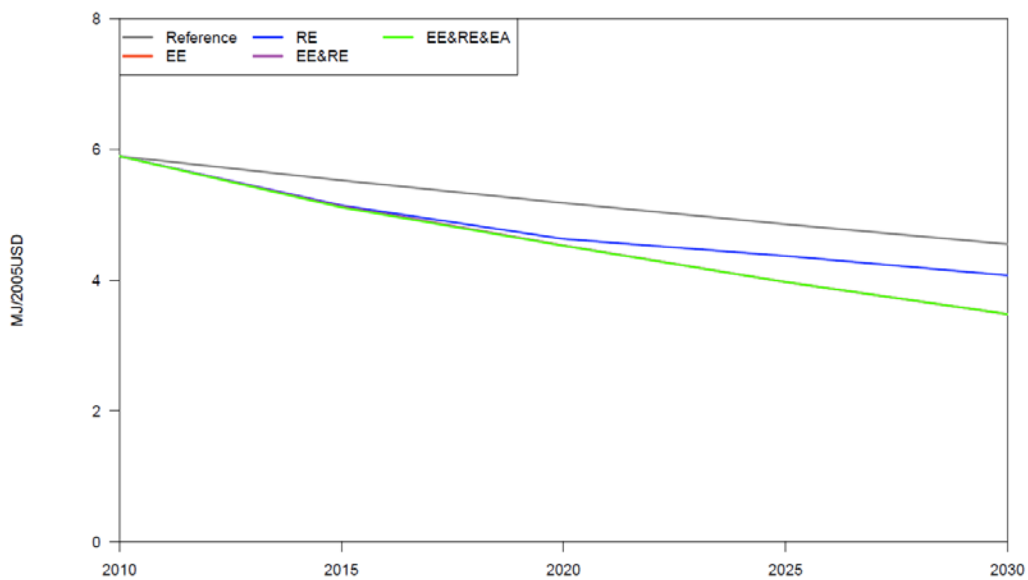

Figure 2. Global Energy Intensity by year and scenario

Note: EE&RE&EA, EE&RE and RE scenarios are under the same line marked 'EE&RE&EA'

In Figure 3, the RE scenario, where no constraints are placed on energy efficiency improvement, and the SEforALL's objective on doubling the global renewable energy share is achieved, the result for the global EIIR is estimated at the level of 1.8% CAGR. As noted above, achieving the SEforALL renewable energy objective is synergistic with meeting the SEforALL energy efficiency objective. Results for India, Japan, the Middle East, and Western Europe show a more significant reduction in energy consumption under the EE+RE scenario versus the EE scenario, suggesting that these regions have a have a greater synergy between energy efficiency and renewable energy among other ones.

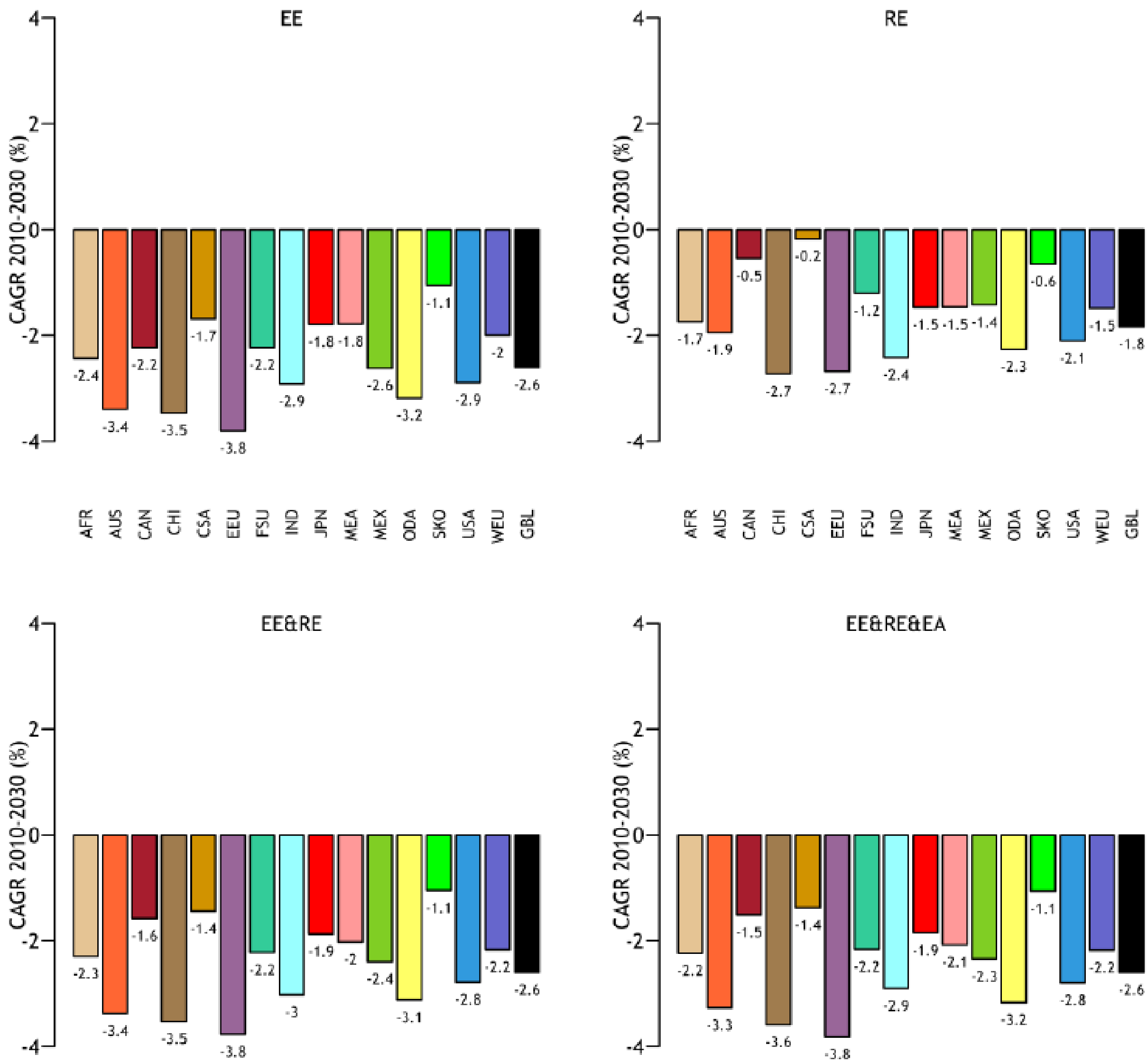

Figure 3. Compound Annual Change in Energy Intensity 2010-2030, by region, alternative scenarios

Renewable energy objective

In Figure 4, the global RE share for 2030 is compared between the Reference, EE and the RE scenarios (shares of renewable energy are similar between the RE, EE+RE and EE+RE+EA scenarios). 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 achievement of RE objective in comparison to the reference scenario.

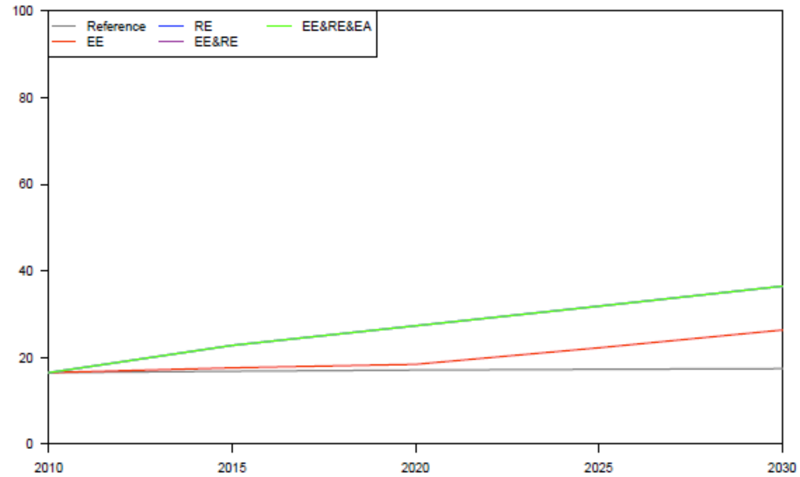

Figure 4. Global renewable energy share (%) of total final energy consumption by scenario

Note: EE&RE&EA, EE&RE and RE scenarios are under the same line marked 'EE&RE&EA'

Climate change targets

The model also gives the opportunity to estimate the CO2 emissions for 2010-2030 for the developed scenarios. Figure 5 presents the results for the scenarios discussed in this paper compared to the CO2 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/m2 radiative forcing over pre-industrial times and is the most ambitious of the RCPs (Moss, 2010). The RCP4.5 represents 4.5 W/m2 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). As can be seen from Figure 5, the scenarios developed for this paper fall between these two pathways, meaning that they are consistent with limiting global warming to 2° C with the probabilities to stay below this threshold estimated in the range between 50% and 66%.

Under the reference scenario, keeping global warming to under 2° C is unlikely. In isolation from other two SEforALL objectives, the scenario with the focus on energy efficiency objective (EE) reduces emissions more than the scenario pursuing the achievement of the renewable energy objective (RE). However, the scenario, which combines the achievement of the both of them (EE+RE) reduces more emissions than either of them alone, offering the ground to conclude that there are beneficial synergies of simultaneous improvement of energy efficiency and large-scale deployment of renewable energy technologies for mitigating the global temperature rise caused by the anthropogenic climate change. Achieving the SEforALL energy access objective (EE+RE+EA), however, increases emissions in comparison to the previous case (EE+RE), because electricity consumption increases in the developing regions in order to ensure the universal access to modern energy services, and because some of the traditional biomass is replaced by fossil fuels within ETSAP-TIAM.

These results demonstrate that ambitious and effective policies are required in all three areas of SEforALL (energy access, energy efficiency and renewable energy) in order to achieve the global transition toward a more sustainable energy system and limit the global temperature rise under 2° C. Such policies should not be developed in isolation in order to exploit potential synergies and take into account the trade-offs (e.g. if the energy access is increased, the global emissions are likely to increase) between these interlinked areas. However, even the complete achievement of the SEforALL objectives might not guarantee the achievement of the climate change targets (the probability is between 50 and 66%), which means that even more ambitious efforts are needed in order to ensure the sustainable energy future for the world.

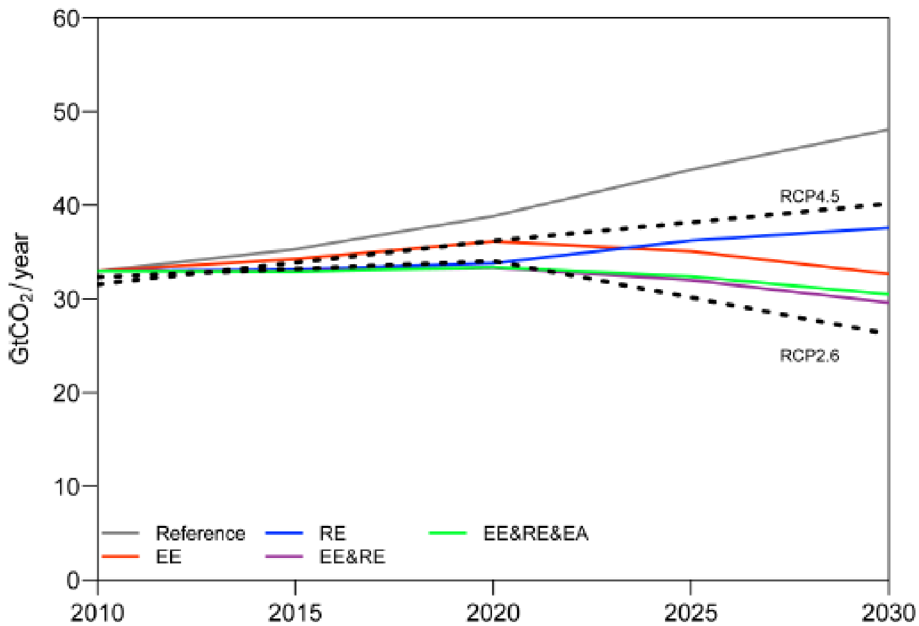

Figure 5. Emissions under various scenarios in comparison to the RCP 2.6 and RCP 4.5

CONCLUSIONS

There are notable synergies between the SEforALL 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. When the SEforALL renewable energy objective is modelled to be achieved within the ETSAP-TIAM framework, the changes in the global energy system resulting from implementation of this constraint lead to the increased rate of the global energy intensity reduction. Likewise, a scenario that achieves the SEforALL energy efficiency objective results in a solution that achieves the SEforALL renewable energy objective halfway, i.e. increasing the global renewable energy share in the total final energy from 18% in the base year to 26% in 2030. On the global scale, the renewable shares in every sector increase if the SEforALL energy efficiency objective is achieved. The results from ETSAP-TIAM suggest that the SEforALL 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, which decreases the renewable energy share.

The results for different regions show that 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 SEforALL energy efficiency objective will require ambitious global efforts. According to the ETSAP-TIAM results, Eastern Europe, China, Australia & NZ, Other Developing Asia and India have the 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.

The SEforALL universal energy access objective, on the other hand, is more difficult to achieve. 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 SEforALL energy efficiency objective of 2.6% EIIR CAGR 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 Reference 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 SEforALL 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.

Achieving the SEforALL objectives would require many regions to make drastic improvements relative to their historic trends in energy efficiency improvement and renewable energy deployment. 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.

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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.