Achieving Climate Stabilization in an Insecure World: Does Renewable Energy Hold the Key?

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Final Report

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RETD Notice

The RETD is comprised of ten countries: Canada, Denmark, France, Germany, Ireland, Italy, Japan, the Netherlands, Norway, and the United Kingdom. Hans Jørgen Koch, Deputy State Secretary, Ministry of Climate and Energy, Danish Energy Agency, serves as Chair of the RETD.

The RETD Implementing Agreement is one of a number of Implementing Agreements on renewable energy under the framework of the International Energy Agency (IEA). The creation of the RETD Implementing Agreement was announced at the International Renewable Energy Conference in Bonn, 2004.

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Foreword

More than ever, it is critical that we define pathways for the global energy system that lead to rapid reductions in greenhouse gas emissions, while simultaneously providing access to clean, modern energy sources for a growing world population. These pathways must also enhance nations' security of energy supply while avoiding the most severe impacts of climate change, which have the potential to cause instability on a wide scale.

I am pleased to present you with this report detailing the results of a recent scenario modeling project conducted by the RETD. It represents the culmination of nearly three years of work on the role of renewable energy in global energy scenarios. The project began as an examination of what others have been doing in the area of global energy system modeling, with an emphasis on the role of renewable energy. The effort evolved into the RETD taking on a more active role by providing direct input into the key modeling activities of the IEA – the *World Energy Outlook (WEO)* and *The Energy Technology Perspectives (ETP).* This report summarizes the next step in this project, in which the RETD conducted its own scenario modeling. With this report, the RETD hopes to add to this important field of research.

The scenario created by the RETD pursues aggressive greenhouse gas reduction targets consistent with achieving atmospheric concentrations of greenhouse gases of 400 parts per million ppm CO_2 equivalent (ppm CO_2-eq). This is more aggressive than the often cited target of 450 ppm CO_2-eq that is estimated to limit global average temperature rise to 2°C with 50% probability. The scenario also examines the issue of security, which is increasingly seen as inextricably linked to global climate change in a number of ways.

As the first attempt by the RETD at this type of modeling, there are surely improvements that can be made. Nevertheless, the key messages from this project and other similar work – such as the *WEO 2009*, the Greenpeace *Energy (R)evolution* and the *ETP 2008* – are remarkably consistent. First, the transition to a low-carbon energy economy is technically feasible. Second, while technically feasible, the transition is profound and must begin immediately. Third, energy efficiency and renewable energy are the most important means of achieving the climate change mitigation targets. Fourth, and perhaps most importantly, the direct economic impacts of the transition are small to none, and possibly even net positive, i.e., when considering both initial investments and ongoing energy cost savings, there is virtually no difference in total energy system costs between aggressive climate mitigation scenarios and so-called "Reference" scenarios that contain little or no mitigation measures. When you add in other economic benefits, such as reduced climate change adaptation costs, enhanced global security, reduced energy price volatility, and the economic development benefits of climate change mitigation, the logical conclusion is simple: aggressive climate change mitigation saves you money.

I hope you find this report, and the access to the detailed assumptions and results, useful.

Sincerely,

Hans Jørgen Koch
Deputy State Secretary, Ministry of Climate and Energy, Danish Energy Agency
Chair of the RETD

Acknowledgements

The authors wish to thank the following individuals:

From the RETD Executive Committee, we are grateful to Hans Jørgen Koch, RETD Chair, and Annette Schou, Senior Policy Advisor, for their ongoing commitment to this project, their guidance, and for the opportunity to present the results at the COP15 in Copenhagen. From the Operating Agent of the RETD, David de Jager, Ecofys, and Kristian Petrick, Factor CO_2 Ennova S.A for their invaluable support. From the Energy Technologies Systems Analysis Program (IEA-ETSAP), GianCarlo Tosato, ETSAP Operating Agent, Richard Loulou (KANLO), Amit Kanudia (KanORS), and Maryse Labriet (ENERIS), for their hard work in helping us translate the RETD ACES Scenario into assumptions for the TIAM model, for running the model, and for reviewing this report. Without their excellent collaboration and commitment to this project, it would not have been possible. From the Project Steering Group, Jan Hamrin, HMW International, Michael Liebreich, Bloomberg New Energy Finance, Angelo Amorelli, BP plc, Gustav Resch, Vienna University of Technology, Arthouros Zervos, EREC, and Ingrid Slungaard, Enova SF, for their valuable insights and ongoing guidance throughout the project. Last, but not least, from the IEA, Paolo Frankl, Head of the Renewable Energy Division, for his help and advice over the course of this project.

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[1] Except for Figure 1, all the graphs display results of ETSAP-TIAM scenario runs.

Acronyms and Definitions

BEV: Battery-electric vehicle

CCS: Carbon capture and sequestration

CHP: Combined heat and power

CO_2-eq: Carbon dioxide equivalent, which is a unit of measure that expresses total greenhouse gas emissions from all the individual greenhouse gases as an equivalent amount of carbon dioxide only. Each of the greenhouse gases has a climatic forcing potential (i.e., its Global Warming Potential) that can be compared to carbon dioxide, which has a Global Warming Potential of 1. The following Global Warming Potentials are used in this report: CH_4 = 25, N_2O = 298 (IPCC, 2007).

EE: Energy efficiency

EJ: Exajoule (10^{18} joules)

ETP: *Energy Technology Perspectives*, a biennial publication of the IEA

ETSAP: Energy Technology Systems Analysis Programme Implementing Agreement of the IEA

GHG: Greenhouse gas

Gt: Gigatonnes

HEV: Hybrid electric vehicle

IEA: International Energy Agency

IGCC: Integrated gasification combined cycle

kWh: Kilowatt-hour

MJ: Megajoule (10^{6} joules)

NPV: Net present value

O&M: Operations and maintenance

PHEV: Plug-in hybrid electric vehicle

ppm: Parts per million, used to measure GHG concentrations in the atmosphere

PV: Photovoltaic

RE: Renewable Energy

RETD: Renewable Energy Technology Deployment Implementing Agreement of the IEA

T&D: Transmission and distribution

TIAM: **T**IMES **I**ntegrated **A**ssessment **M**odel

TIMES: **T**he **I**ntegrated **M**ARKAL-**E**FOM **S**ystem, which is an economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon.

WEO: *World Energy Outlook*, an annual publication of the IEA

Executive Summary

Background and Introduction

In the ongoing evolution of the global energy system, the first decade of the 21st century will likely be remembered as the period when renewable energy (RE) technologies moved from niche to mainstream. RE market growth has been dramatic, and yet RE's vast potential remains largely untapped.

Computer models of the global energy system are important for understanding energy supply and demand issues over the long term. Increasingly, they are being used to assess how the energy system must evolve in order to meet the challenges posed by global climate change. The models were, for the most part, developed under assumptions of smooth demand growth met primarily with large, centralized infrastructure, and perform well under these conditions. However, these assumptions are being challenged by several changes that require a reevaluation of modeling algorithms, as the global energy system enters this period of dramatic change. This suite of changes has profound implications for how RE is modeled. The changes include: the need for rapid decarbonization of the energy system; the shift from centralized to decentralized infrastructure; accelerating technological change and the increasing potential for disruptive technological changes (e.g., deployment of the Smart Grid, expansion of plug-in hybrid vehicles (PHEVs) market penetration, and cost reductions in solar photovoltaics (PV) that result in grid price parity); and the convergence of energy security issues with climate change mitigation and adaptation.

In an effort to address these changes and better understand their impact on the evolution of the global energy system, which are currently not fully represented by existing scenarios, the Renewable Energy Technology Deployment (RETD) Implementing Agreement of the International Energy Agency (IEA) has defined its own scenario. It has developed and modeled this scenario in collaboration with the Energy Technology Systems Analysis Programme (ETSAP) Implementing Agreement, making use of an existing techno-economic, bottom-up computer model. This report presents the results of that work. The *RETD ACES Scenario* (**A**chieving **C**limate and **E**nergy **S**ecurity) targets reductions in greenhouse gas (GHG) emissions consistent with stabilizing GHG concentrations in the atmosphere at 400 ppm carbon dioxide equivalents (CO_2-eq) by 2100.[2] Of equal importance, the RETD ACES Scenario also places constraints on the global trade of energy commodities to reflect the rising importance of energy security and the linkages between energy security and climate change. The RETD ACES Scenario also seeks to better represent some of the unique characteristics of RE resources and technologies and to include the impacts of the Smart Grid.

The RETD ACES Scenario was modeled using the ETSAP-TIAM[3] model, a partial equilibrium, technology-rich, economic optimization model. It balances supply and demand for energy services by maximizing total (consumer + producer) economic surplus, subject to whatever additional constraints are applied (such as emissions limits or other specific policies).[4] TIAM represents the global energy system in a logical, transparent, and reproducible way, finding technically possible solutions to different scenarios. In order to evaluate the results of the RETD ACES Scenario, an internally consistent Reference Scenario was developed. Generally, the Reference Scenario can be considered a "policy free" scenario that does not contain any assumptions regarding future policy. Thus, within the methodologies applied in the TIAM model, it represents an economically optimal solution unconstrained by any of the drivers

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[2] In running the model, it was not possible to achieve this target. Rather, the model converged on a concentration of about 420 ppm by 2100, with concentrations falling at a rate of about 1 ppm per year in 2100.

[3] **T**IMES **I**ntegrated **A**ssessment **M**odel.

[4] The actual constraint in the TIAM model is that energy supply must be equal to or greater than demand. In order to satisfy other constraints that are imposed, the model may overproduce certain energy commodities.

that define the RETD ACES Scenario. It is very important to note that the Reference Scenario is not, and should not be interpreted as, a "business as usual" scenario, nor is it an extrapolation of current trends. Rather, it is simply a hypothetical baseline from which comparisons can be made.

Greenhouse Gas Emissions and Energy Supply & Demand

In the Reference Scenario, GHG emissions continue to grow, from about 40 gigatonnes (Gt) CO_2-eq to 70 Gt by 2060[5]. This growth represents a completely unsustainable pathway that would lead to destructive and irreversible climate change. In the RETD ACES Scenario, GHG emissions fall steadily, reaching just 9 Gt CO_2-eq by 2060, a roughly 75% reduction from 2010 levels. These emissions encompass the impact of all energy and non-energy sector emission sources and sinks contained in TIAM, which include land use change and reforestation (the latter acts as a sink). In 2060, net CO_2 emissions reach zero. The system is able to achieve carbon neutrality because of ongoing reforestation and other GHG mitigation options, even though the energy sector as a whole and land use change remain net CO_2 emitters through 2060 and beyond.

Despite these dramatic reductions in GHG emissions, GHG concentrations still do not reach 400 ppm CO_2-eq by 2100, instead reaching approximately 420 ppm, after peaking at approximately 490 ppm CO_2-eq in 2035. In 2100, GHG concentrations are falling at a rate of about 1 ppm per year, suggesting that the 400 ppm CO_2-eq target could be met in the first quarter of the next century, or perhaps by about 2150, if the rate of decrease were to slow moderately. One factor behind the challenge of reaching 400 ppm by 2100 is the GHG emissions contribution of agriculture, even though the RETD ACES Scenario includes relatively optimistic assumptions about the emissions of non-energy GHGs.

The GHG reductions are achieved primarily through reductions in CO_2 emissions from the energy sector. A decline in the energy intensity of the economy accounts for a large fraction of the reduction. Compared to the Reference Scenario, total final energy consumption in the RETD ACES Scenario is 22% lower in 2060. This difference is due to two factors: (i) increasing efficiency of energy transformation and use, and (ii) reduced demands due to higher energy prices and improved access by consumers to energy usage information via the Smart Grid.

In addition to greater efficiency, there is a rapid decarbonization of energy supply. Consumption of coal at plants that are not equipped with carbon capture and sequestration (CCS) technology is dramatically reduced. In terms of primary energy demand, total coal consumption falls by over 25% by 2060, but coal use without CCS falls by almost 85%.[6] The situation for oil is similar – its consumption for energy purposes falls by more than 65%. However, its use for non-energy purposes continues to rise from about 31 exajoules (EJ) in 2010 to 54 EJ by 2060. The result is still an overall reduction in total oil consumption,

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[5] In general, the results of the analysis are presented through the year 2060. In addition to providing a 50 year block of time for analysis (2010 to 2060), this year is significant because, as will be shown in the main report, it is the year in which net CO_2 emissions reach zero (this includes emissions from the energy sector and the other sources and sinks included in the TIAM model).

[6] Primary energy is an often reported metric for global energy modeling. It provides an indication of the relative importance of different energy resources to meeting overall energy demand, regardless of where it is used. For fuels that are transformed into electricity or other energy carriers – typically via combustion, such as coal, oil, natural gas, and biomass – it is relatively straightforward to measure the energy input (primary energy). However, for technologies that do not involve this type of transformation (nuclear power and all RE resources other than biomass), the notion of primary energy is less relevant, is not as readily measured, and is often misleading. For these resources, the energy output of the process (almost always electricity) is sometimes used as the primary energy. However, this understates their relative contribution to useful energy output by a factor of two to three because the efficiencies of combustion technologies in producing electricity are not factored into their primary energy values. Thus, when primary energy is reported in this paper for nuclear power and non-biomass RE, it is provided only after applying a fossil fuel substitution factor of 9 MJ/kWh (i.e. using the substitution principle). This value is consistent with a "typical" efficiency of electricity generation from fossil fuels (40%). Doing so does a better job at illuminating the relative contributions of all energy resources to total energy supply. Effectively, it measures the contribution of nuclear power and non-biomass RE by estimating how much fossil fuel is displaced.

even when non-energy uses are included, from about 147 EJ in 2010 to 93 EJ in 2060. The situation with natural gas is different, given its favorable GHG characteristics. For energy purposes, natural gas use rises from about 93 EJ in 2010 to 227 EJ in 2060, of which 74 EJ is equipped with CCS. Thus, consumption of natural gas rises for applications with and without CCS. Nuclear power generation roughly triples from 2010 to 2060. Such expansion would require the construction of roughly 530 1,000 MW nuclear power plants between 2010 and 2060, not including any additional plants needed to replace existing ones that might be retired. The net effect is that total primary energy demand for all non-RE resources rises modestly but the GHG emissions from these resources fall (See Figure ES 1). Simultaneous, RE becomes the most important energy source sometime between 2030 and 2040, when it passes 50% of all primary energy supplies, up from about 20% today.

One of the RE technologies included in the RETD ACES Scenario is biomass power with CCS. This technology becomes attractive as a "carbon negative" option, driven by the strict carbon constraint in the RETD ACES Scenario.[7] In order to satisfy this constraint, some biomass-CCS capacity is deployed only for its GHG mitigation potential, resulting in the production of electricity beyond the level required to meet demand. The TIAM model reduces electricity generation from other sources to the greatest extent possible, but due to other constraints, the result is still a slight overproduction. This result can be explained by the priority placed on GHG reductions in the RETD ACES Scenario, coupled with the fact that biomass-CCS is one of a very limited number of mitigation options in the model that acts as a carbon sink. The use of biomass-CCS primarily as a GHG mitigation option actually competes with these other mitigation options (e.g., reforestation) within the limits placed on overall bioenergy supplies (reforestation is also subject to limits on available land). Thus, based on that competition and the need for deep reductions in GHG concentrations, the TIAM model chooses to deploy some biomass-CCS solely for GHG mitigation purposes.[8] The amount of extra capacity represents about 48% of the total biomass-CCS capacity deployed by 2030 and 54% by 2060. The portion of biomass-CCS capacity that is deployed for GHG mitigation only is excluded from all primary energy, generation, and capacity tables and figures in this report since its deployment produces electricity beyond the quantity that is necessary to meet demand.

To the RETD's knowledge, there are no published reports where models like TIAM have been used to model a 400 ppm CO_2-eq target, and in cases where 450 ppm CO_2-eq targets are modeled, models often fail to converge. For example, see Clarke, et. al (2009), which highlights the difficulties and challenges of modeling strict climate targets with existing energy-economic models.

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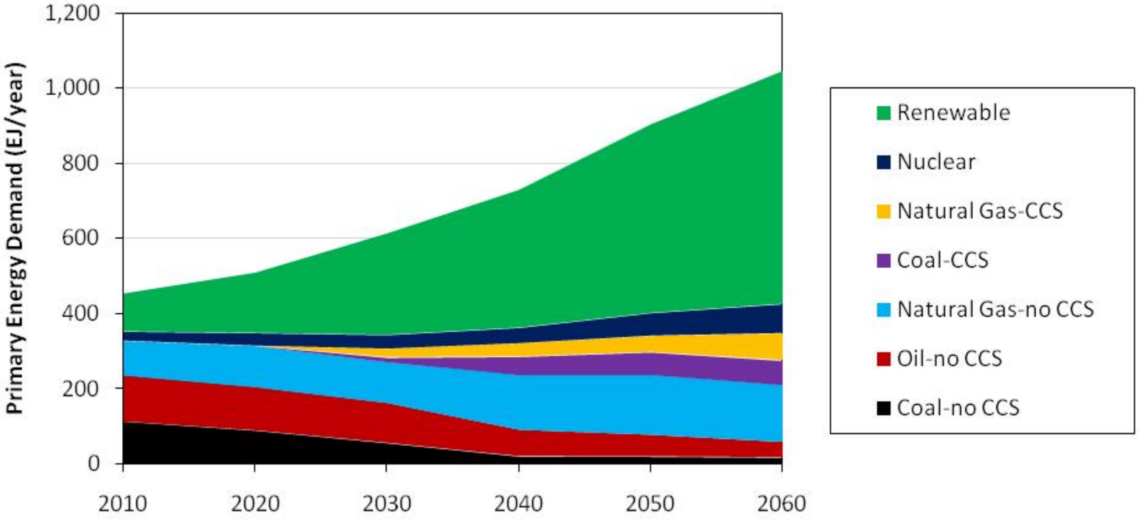
[7] The important, underlying assumption in the analysis is that biomass is grown and harvested on a sustainable basis. TIAM contains constraints on biomass availability, just as it does for other energy resources. In general, the importance of biomass with CCS, as well as reforestation, within the RETD ACES Scenario suggests that the whole issue of biomass availability and use is a very important topic for further analysis and for sound policy formulation. The RETD has been addressing this issue in a separate project, "Better Use of Biomass Energy". See http://www.iea-retd.org/page.aspx?idsection=62 for more details.

[8] While this result was unexpected, it is the result of applying a strict climate constraint. To the RETD's knowledge, there are no published reports where similar models have been used to model a 400 ppm CO2-eq target, and in cases where 450 ppm CO2-eq targets are modeled, models often fail to converge. For example, see Clarke, et. al (2009), which highlights the difficulties and challenges of modeling strict climate targets with existing energy-economic models.

Figure ES 1: Primary Energy Demand in the RETD ACES Scenarios Through 2060



Note: These values are for energy uses only. TIAM also calculates non-energy uses (e.g., petrochemicals). There are currently no technology options within TIAM for oil use with CCS. CCS plants include those for producing electricity and fuels. Biomass-CCS used only for the purpose of CO_2 removal is excluded. See Section 4 for additional details.

In the RETD ACES Scenario, no other sector is more transformed than electricity. There is a rapid reduction in the use of fossil fuels for power generation, except where this usage is also accompanied by CCS, which is assumed to be available commercially starting in 2020. As a result, electricity generation is virtually decarbonized by 2030. RE becomes the largest contributor to electricity generation and capacity sometime before 2030, with RE generation rising from about 22% in 2007 to 61% by 2030 (capacity percentages are higher due to lower average capacity factors for RE compared to other options). All RE technologies grow significantly, although wind and PV see the greatest growth in capacity through 2060 (see Figure ES 2). Other RE technologies that contribute less through 2060, see robust growth after 2060 (not shown), most notably solar thermal electricity. The lag in adoption for some RE technologies is most likely the result of both the assumed technology characteristics and the way in which policy is represented in the RETD ACES Scenario, which is largely technology neutral.[9]

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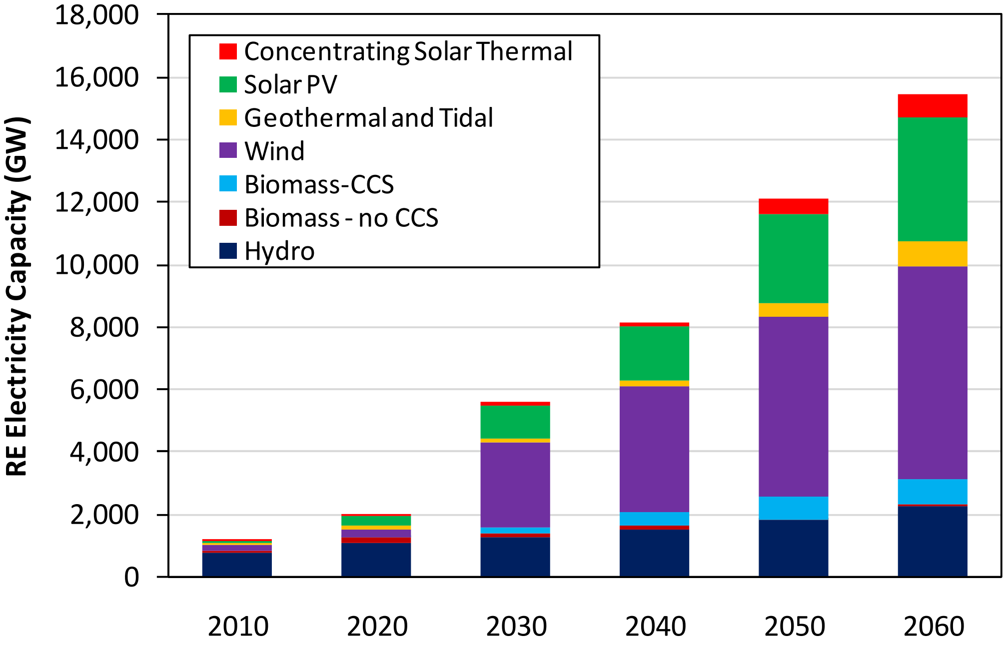
[9] See the main report for additional details on how climate policy was modeled.

Figure ES 2: Renewable Electricity Capacity in the RETD ACES Scenario Through 2060



Note: Biomass-CCS used only for the purpose of CO_2 removal is excluded. See Section 4 for additional details.

As fossil fuels (without CCS) are largely phased out in favor of carbon neutral and negative options, electricity generation as a whole becomes, on average, carbon negative. After 2030, the global electricity mix is composed mainly of (i) fossil fuels with CCS (still mildly carbon positive), (ii) nuclear power and RE (essentially carbon neutral) and (iii) biomass with CCS (quite strongly carbon negative).

The availability of carbon negative electricity results in significant fuel switching to electricity in all sectors of the economy where this is technically possible, driven by the strict GHG reduction targets of the RETD ACES Scenario. This switching drives demand for electricity higher, even as total energy consumption in the RETD ACES Scenario is substantially lower than total energy consumption in the Reference Scenario. In the RETD ACES Scenario, total electricity demand grows steadily at about 2% per year through 2060.

In the RETD ACES Scenario, transportation energy demand grows by about 25% from 2010 in 2060, to 110 EJ. However, growth in demand for transportation services (e.g., kilometers driven, tonnes of freight transported) is much more rapid. The implication of this is that the efficiency of the transport sector improves significantly. At the same time, consumption of oil products falls by about 75% from 2010 to 2060. The main substitutes are second generation biofuels (biofuels made from non-food sources of biomass), hydrogen, and electricity. Although electricity use only reaches about 16% of transportation energy demand by 2060, it is used much more efficiently than other transport fuels (i.e., electricity satisfies a higher percentage of transportation services than its 16% share of transportation energy use). As with electricity from biomass, second generation biofuel plants equipped with CCS are preferred over those without CCS in the RETD ACES Scenario.[10]

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[10] Second generation biofuel plants equipped with CCS are similar to biomass-CCS in that they have a carbon negative profile and therefore competes as a GHG mitigation option. However, unlike with electricity, the competition between mitigation options does not result in the deployment of second generation biofuel plants with CCS beyond what is necessary to meet transportation demand.

Energy Trade

The very real possibility that global trade in energy commodities would be reduced in an insecure world is part of the definition of the RETD ACES Scenario. In addition, the RETD ACES Scenario has lower total energy demand than the Reference Scenario. These two factors combined to help drive down overall trade in coal, oil and natural gas. Compared to the Reference Scenario, total energy trade is reduced by about 35% in the RETD ACES Scenario. The reduction in trade results in a preference for the consumption of domestic resources (in that context, demand for coal is partially maintained due to the security driver, given its wider geographic availability, even if trade is restricted, i.e., there will be more development of in-country coal resources). Looking at individual commodities, both oil and coal trade are reduced, but total natural gas trade increases, driven in part by slightly higher total demand. This higher demand is driven by the attractive carbon footprint of natural gas compared to other fossil fuels. Thus, even as the overall constraint on energy trade is maintained, trade of natural gas increases. It is, of course, important to realize that the amount of natural gas trade would be even higher in a scenario with the climate targets of the RETD ACES Scenario, but without the constraints on trade.

The situation is similar for exports from the Middle East (MEA). By 2060, oil exports from MEA drop by 75% in the RETD ACES Scenario compared to the Reference Scenario. However, natural gas exports rise over the same timeframe. Overall, total energy exports from MEA are about 15% lower by 2060 in the RETD ACES Scenario compared to the Reference Scenario. In other words, in a climate constrained scenario, natural gas dependence on MEA remains non negligible even under the constraint on trade (as it was defined in the RETD ACES Scenario), while oil dependence is considerably reduced. These results, particularly the importance of natural gas, suggest that this should be an area of further analysis in the future.

Costs and Benefits

The direct costs of the RETD ACES and Reference Scenarios have been estimated with TIAM. These costs include capital investments, fuel costs, and operations and maintenance (O&M) costs for energy exploration, production, transformation, transport, and end use, as well as the impacts of policies on energy costs. From a climate change perspective, the differences in these costs between the RETD ACES Scenario and the Reference Scenario can be understood as the direct costs of climate change mitigation. Yet in order to have a complete picture of the economics of a scenario, these mitigation costs must be compared to other economic costs, advantages and/or savings resulting from:

- Reduced climate change adaptation costs
- Job creation and rural economic development
- Reduced energy price volatility
- Enhanced security, including reduced military spending to protect fossil fuel supplies
- Reduced damages from other types of pollution that would be also be reduced (e.g., acid rain, particulates, mercury)

These additional economic considerations are harder to estimate and currently fall outside of traditional economic models of the global energy system. Yet they all have real economic value. Unfortunately, there is as of yet, no single model that can effectively estimate and optimize investment decisions around this full range of economic factors.

Nevertheless, the results of the RETD ACES Scenario, as well as recent work by others, strongly suggest that, even in the absence of concrete estimates for these additional economic benefits, the magnitude of the benefits are likely to exceed any direct mitigation costs. It is possible that the reduction of climate change adaptation costs, which have the potential to be very large, could offset a substantial portion, if not all, of the cost of mitigation. This possibility results partly from the fact that the estimated climate change mitigation costs, even for aggressive climate change mitigation scenarios, when measured on a lifecycle basis, turn out to be relatively small when compared to the total cost of running the energy system, and smaller still when compared to total gross domestic product (GDP). Thus, even if the benefits described above are modest in scope – on the order of 1% of total GDP or higher – they are likely to more than make up for any mitigation costs.

The total direct energy system costs of the RETD ACES Scenario are larger than the comparable costs resulting from the Reference Scenario by approximately $14.3 trillion (discounted) over the next 50 years[11]. While this value may appear large, it is not. Over this same timeframe, total, cumulative discounted global GDP is expected to be about $1,400 trillion.[12] Thus, the total incremental cost of the RETD ACES Scenario compared to the Reference Scenario is only about 1% of total cumulative GDP. Said another way, the total cost of mitigation for the RETD ACES Scenario over the next 50 years is less than four months of current global economic output. Given the wide range of benefits that will result from the RETD ACES Scenario, one can reasonably conclude that the value of these as-yet-to-be quantified benefits should exceed this comparatively modest incremental investment in climate change mitigation.

These results are largely consistent with those of other recent similar studies. In particular, in the *World Energy Outlook 2009* (WEO 2009), $10.5 trillion (undiscounted) in net incremental investments are required for the period 2010-2030 to put the energy system on a pathway to achieving the climate stabilization objectives of the 450 Policy Scenario (compared to the Reference Scenario of the WEO 2009). These investments result in $17.1 trillion (undiscounted) in reduced energy costs over the life of the investments. The WEO 2009 further reported that at a 3% discount rate, there are net savings of $3.6 trillion, while at a 10% rate, there are still net savings of $450 billion over the lifetime of the investments. Thus, the conclusion from the WEO 2009 is that working towards a climate target of 450 ppm CO_2-eq is economically superior to the inaction associated with its Reference Scenario. While the costs of continued aggressive mitigation are likely to climb beyond 2030, as suggested by the results of the RETD ACES Scenario, the message is still clear – that **aggressive climate change mitigation has minimal direct incremental costs, and may even be economically superior to inaction, even without factoring in the potentially substantial benefits beyond direct energy cost savings.**[13]

The "BLUE Map" scenario of the *Energy Technology Perspectives 2008* (ETP 2008) has a similar climate objective as the 450 Policy Scenario of the WEO 2009, but runs out to 2050. Specifically, it targets a 50% reduction in energy-related CO_2 by 2050 compared to 2005. This scenario requires incremental investments of $45 trillion (undiscounted) from 2005 to 2050, equal to about 1.1% of cumulative GDP over the same period. However, these investments yield $50.6 trillion in (undiscounted) fuel cost savings over the same period. At discount rates of 3% and 10%, the net incremental costs of the BLUE Map Scenario were reported to be $0.8 trillion and $2.1 trillion respectively. Thus here too, when compared to the size of the global economy, the direct incremental costs of aggressive climate mitigation are small – much less than 1% of cumulative global GDP. It is also worth noting that the ETP 2008 used energy prices that were much lower than the WEO 2009 – it assumed oil would reach just $65/bbl ($2006) by 2050, which was a reasonable assumption at the time.

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[11] Costs are measured on a net present value basis using a 5% discount rate.

[12] Global annual GDP is expected to grow in the model from approximately $54 trillion/yr in 2010 to $175 trillion/yr in 2060 (in constant dollars).

[13] It is important to note that these conclusions are based on achieving the assumed technology cost and performance characteristics in each of the scenarios.

Finally, in a similar study for the United States, the Union of Concerned Scientists (UCS, 2009) estimated that reducing GHG emissions by 56% below 2005 levels by 2030 would actually produce a cumulative net savings of $1.7 trillion for the U.S. economy.

Conclusions and Next Steps

The results of this project are both encouraging and sobering. The future as described by the RETD ACES Scenario is both technically and economically feasible, and may in fact be economically superior to a future characterized by inaction. Achieving this future will require immediate, sustained and concerted investment in technology development and infrastructure. EE and RE are the keys to achieving the climate and security goals of the scenario. These messages are consistent with several other similar independent analyses.

In order to achieve the goals of the RETD ACES Scenario, immediate steps must be taken to transform the energy sector from one dominated by large centralized fossil-fuel infrastructure, to one dominated by RE generation and characterized by a greater a mix of both centralized and distributed energy generation. The role of enabling technologies, including Smart Grid and CCS, will be critical to this transition. The success of this evolution will also depend on the sustainability of increased bioenergy utilization and the reversal of the trend of deforestation. The results of the modeling also point to the importance of non-energy GHG reductions and sinks.

Finally, a number of improvements to the assumptions of the RETD ACES Scenario and the TIAM model have been identified during the modeling process. The RETD intends to continue to develop these further in collaboration with ETSAP and others.

1. Introduction

The RETD Mission and Vision

The RETD is one of several independent bodies set up under the framework of the Technology Cooperation Programme of the IEA.[14] Implementing agreements bring together experts from research, government and industry to address common challenges in specific technology areas and to share the benefits of their combined efforts. The RETD was formed after the International Conference for Renewable Energies in Bonn, Germany, June 2004. It was created as a complement to the other RE Implementing Agreements, which are mainly focused on specific technology research, development and demonstration. In contrast, the RETD is cross-cutting and aims to bridge the gaps between technology development, market development and policy formulation.

The RETD's vision is to achieve significantly higher utilization of RE by promoting international cooperation and encouraging more effective, efficient and rapid deployment. The RETD's mission is to act as a catalyst for increased RE technology deployment by:

- Proposing solutions and options to maximize, (a) the share of RE technologies in the global, regional, and national energy systems, and (b) the contribution of RE to climate change mitigation, security of energy supply and economic growth; and
- Providing recommendations on how to overcome barriers for significantly increased RE deployment.

Building on the unique framework of the IEA, the RETD aims to disseminate information and enhance knowledge about RE technology deployment, thus supporting improved public and private sector decision making. RETD projects are intended to make transparent and demonstrate the impact of RE action and inaction, and provide the necessary facts and comparisons to aid in the formulation of sound public policy.

Project Background

In the ongoing evolution of the global energy system, the first decade of the 21st century will likely be remembered as the period when RE technologies moved from niche to mainstream. RE market growth has been dramatic, and yet RE's vast potential remains largely untapped. Under even the most conservative assumptions, RE market growth is expected to far outpace that of all other forms of energy for the foreseeable future. The transition of RE into the mainstream coincides with several other fundamental changes that are occurring in the larger energy system (see Section 2 below for more details).

Modeling the global energy system during such a period of fundamental change is a challenging undertaking. In order to understand the complexities, it is useful to break global energy system modeling into its two basic parts: global energy scenarios and the computer models used to simulate them. A scenario is created by developing a set of assumptions about how the energy system (and other aspects of the global economy) will evolve. The assumptions can relate to technologies, policies, geopolitics, and consumer and corporate behavior. A scenario is not a prediction of the future (i.e., it is

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[14] The IEA is an autonomous body which was established in November 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an international energy program. The IEA carries out a comprehensive program of energy cooperation on energy issues across 26 of the OECD's 30 member countries. More information about the IEA is available at the http://www.iea.org/.

not a forecast), but rather, it is a description of one possible pathway for the evolution of the global energy system.

Computer models of the global energy system are used to simulate how energy supply and demand can be met over the long term (current models typically extend through 2030 and beyond) using the assumptions of various scenarios. These models were, for the most part, developed under assumptions of smooth demand growth met primarily with large, centralized infrastructure, and perform well under these conditions. However, these assumptions are being undermined by several changes to the global energy system that require a reevaluation of modeling algorithms (see Section 2 for more details). The dramatic and dynamic growth of the RE market, as well as fundamental differences between RE technologies and traditional technologies further complicates the task of global energy system modeling. Since these RE technologies are likely to become the dominant source of new energy supplies, it is critically important to accurately incorporate the potential of RE in scenarios and models of the global energy system. For high-growth markets like those of RE technologies, what might seem like small differences in annual growth rates can add up to large variations in model results.[15] This issue is particularly important because current global energy models are known to be quite sensitive to technology assumptions. As such, even minor variations in technology assumptions can lead to large differences in model results, especially for methodologies that rely on the concept of technology learning as a basis for estimating future technology costs.

Project History

Since 2007, the RETD has undertaken a multi-phase project to better understand the role of RE in global energy scenarios. The initial phase was conducted by the Center for Resource Solutions (Hamrin, et. al, 2007). Subsequent phases have been conducted by Navigant Consulting, Inc. (NCI), in close collaboration with the RETD Executive Committee and with the valuable guidance of the Project Steering Group.

The project was motivated in part by the view that the official IEA scenarios – those of the *World Energy Outlook (WEO)* and *Energy Technology Perspectives (ETP)*[16] – have historically been too conservative with respect to RE deployment and technology learning rates. Some groups outside of the IEA have developed energy scenarios that have a much stronger uptake of RE (Hamrin, et. al, 2007), such as Greenpeace's *energy [r]evolution*[17] (Greenpeace, 2008). The RETD's initial work also found that the actual growth of the RE market was proceeding at a faster pace than was indicated by the results of the WEO and that the IEA's RE technology assumptions were conservative. However, the WEO and ETP are among the most important reports of their kind for guiding the development of energy policies and investment decisions, and are used by policymakers and the private sector to gain insights into the future evolution of the global energy system, including the role of RE technologies. Given this breadth of usage, the results of the WEO and ETP and how they are interpreted can have a strong influence on RE policy and investment decisions.

In light of the importance of these documents, the RETD has spent considerable effort in providing feedback to the IEA regarding the WEO and ETP, primarily in a peer review role. In this capacity, the RETD focused on scenario definitions, scenario development and the underlying technology

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[15] Consider the simple example of a 10% difference in estimated growth rates over a 25 year period: A market that grows at 22% per year versus one that grows at 20% per year will be 50% larger after 25 years. The same 10% percent difference for annual growth rates of 2.2% and 2% only results in a 5% difference after 25 years. The former is characteristic of PV or wind power whereas the latter is characteristic of fossil fuel demand growth.

[16] The *World Energy Outlook* is published annually. The *Energy Technology Perspectives* is published every two years. At the time of writing, the last edition of the ETP was for 2008.

[17] http://www.greenpeace.org/international/press/reports/energyrevolutionreport.

assumptions used in the models.[18] Throughout the project, the RETD has observed that the WEO (starting with the 2007 edition and ending with the 2009 edition) has undergone significant improvements with respect to the definition and framing of its scenarios and with respect to the analysis of RE technologies (IEA, 2007; IEA, 2008a; IEA, 2009).

Project Scope and Objectives

Over the course of the project, the RETD has developed a detailed understanding of the scenario development process and has articulated what it believes are the essential elements of energy scenarios for the future. In an effort to proactively apply these principles, the RETD has developed its own scenario and has modeled it in collaboration with ETSAP.[19] This report presents the results of that work. The project was also undertaken with the objective of disseminating the results at the United Nations Framework Convention on Climate Change Conference of the Parties 15 (COP 15), held on December 7-18, 2009, in Copenhagen, Denmark.

The RETD has developed the *RETD ACES Scenario* (**A**chieving **C**limate and **E**nergy **S**ecurity), a scenario that targets reductions in GHG emissions consistent with stabilizing GHG concentrations in the atmosphere at 400 ppm CO_2-eq with a target date of 2100. Of equal importance, the scenario also places constraints on the global trade of energy commodities to reflect the rising importance of energy security and the linkages between energy security and climate change. The RETD ACES Scenario also seeks to better represent some of the unique characteristics of RE resources and technologies.

Report Contents

Section 2 provides background information on the changing energy landscape and its impact on global energy scenarios and energy system modeling. The RETD ACES Scenario is described in Section 3 and the results are presented in Section 4. Because the energy system modeling activities of the IEA are of particular interest, some of the results of the RETD ACES Scenario are compared to the WEO 2009 and ETP 2008 in Section 4. Although it is difficult to make truly “apple-to-apples” comparisons between the results of different scenarios and models, this is done in order to illustrate some of the differences (and similarities) resulting from the different approaches taken. Section 5 provides some ideas for future modeling improvements, while Section 6 lists the references used in the report. Finally, in keeping with the RETD’s desire for increased transparency in global energy system modeling, this report contains an Annex of key technology assumptions. Detailed results of the modeling effort are available online at http://www.kanors.com/dcm/tiam.[20]

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[18] The RETD provided formal feedback for the WEO 2008, WEO 2009, forthcoming WEO 2010, ETP 2008, and forthcoming ETP 2010.

[19] For more information on ETSAP, go to http://www.etsap.org.

[20] Model documentation is also available. Access to the results requires registration (free).

2. The Energy Landscape and the Role of Global Energy Modeling

The Global Energy System in Transition

It is hard to overstate the pace and extent to which the energy system is changing, and to which it will continue to change in the coming decades. While the energy system is obviously complex, four key drivers are behind much of this change – drivers that are particularly relevant to modeling the global energy system in the context of climate change and energy security (Table 1).

Table 1. Changes Occurring To the Global Energy System

Driver	Historical Paradigm	Current Trends
The need for rapid decarbonization of the energy system	• Incremental demand growth met with existing technologies, mainly based on fossil fuels • Low retirement rates for existing capacity • Little concern for CO_2 emissions	• Rapid change to meet the challenge of climate change: decarbonization of incremental **and** existing demand • Accelerated retirement of existing fossil fuel capacity
The shift from centralized to decentralized infrastructure	• Large, centralized infrastructure • Economies of plant scale ("bigger is better")	• Mix of centralized, dispersed, and more remote infrastructure, including more customer-sited capacity • Economies of manufacturing scale ("small is beautiful", i.e., mass production of smaller systems, like wind and PV)
Accelerating technological change	• Gradual, predictable evolution of established technologies and gradual introduction of new technologies	• Multiple new technologies arise quickly • Technology cost & performance change rapidly • More potential for disruptive technology breakthroughs
From energy security to "everything" security	• Energy security focused on oil supply and price • Despite decades of good intentions on increasing energy independence, import dependence by major consuming nations continues to grow	• Multiple security considerations: oil and natural gas supply, infrastructure vulnerability, climate/weather impacts on energy infrastructure, geopolitical risk associated with oil dependence and climate change impacts • Linkages between climate change and security grow and become more apparent

The need for rapid decarbonization of the energy system

Many of the changes occurring to the energy system are a response to climate change concerns. Increasing consumption of fossil fuels is the main cause behind the changes occurring to the climate system (IPCC, 2007) and may push the climate system to a "tipping point", beyond which it will be impractical for humanity to mitigate further warming (Hansen, 2008; Lenton et al, 2008).[21] If one accepts this view, then it becomes imperative to achieve rapid and deep cuts in GHG emissions.[22] This type of aggressive reduction requires not only ensuring that incremental demand is met with energy technologies that produce little or no GHGs, but that existing energy demand must be rapidly decarbonized as well. Thus, the size of the problem is large and will require unprecedented shifts in how investments are made in the energy system (but not necessarily leading to larger overall energy costs, as is discussed later in the this report).

Despite the growing urgency to decarbonize and the rapid growth in markets for low- and zero-carbon technologies, the overall emissions trend is still in the opposite direction. This trend exists despite the "Great Recession", as some have called the 2008-2009 economic downturn.[23] The global economy must therefore rapidly shift to methods of production that are substantially more efficient and less carbon-intensive in order to lower emissions. Other mitigation options, such as reducing emissions from land use change, reforestation, and reductions in emissions of non-CO_2 GHGs, are also extremely important.

The shift from centralized to decentralized infrastructure

Distributed generation (DG) has long been talked about and analyzed as a potentially disruptive technology within developed countries and a "leapfrog" technology for developing countries, allowing them to avoid the need to invest in large-scale, centralized generation and transmission infrastructure. DG remains important in some developing countries, but overall its markets are small, indicating that this potential has not yet been realized. Centralized infrastructure, including power plants, electric transmission networks and petroleum refining, remains the dominant option today for meeting the majority of energy needs around the globe (district heating/combined heat and power in some countries is an important exception).

However, with the rise of new technologies, including RE, the landscape is changing in certain important ways. First, RE resources are dispersed and often remote. Even a large wind farm (200-300 MW) is small compared to a typical coal or nuclear power plant (500-1,000+ MW), leading to a larger number of smaller generation facilities. Similarly, a large biorefinery may produce 5,000-10,000 barrels per day of biofuels, about one tenth the size of a small petroleum refinery. Perhaps most notably, PV is also dispersed. As PV electricity approaches price parity with retail grid power, the shift to DG will accelerate, with profound implications for the electricity grid.

These shifts to more distributed and dispersed generation sources coincide with a decrease in the construction of large centralized facilities based on coal and nuclear power in the developed world. Natural gas-fired power plants, which can be of varying sizes, have largely supplanted traditional coal and nuclear power plants for new capacity.[24] China and other developing countries continue to build coal and nuclear plants, but a shift towards increased deployment of RE is underway there as well. In

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[21] NASA climate scientist Dr. James Hansen has championed research that suggests the world has already passed an atmospheric GHG concentration level beyond which positive feedback loops in natural systems are beginning to manifest themselves such that it "will become impractical to constrain CO_2… to a level that prevents the climate system from passing tipping points that lead to disastrous climate changes that spiral dynamically out of humanity's control" (Hansen, 2008). The term 'tipping point' is used to describe this critical threshold beyond which natural feedbacks in the climate system result in large, long-term changes to the Earth's climate system, even in the absence of additional anthropogenic climate forcing, e.g., see Lenton, et al. (2008).

[22] Even if one does not accept this view, it is important to recognize that the evidence points overwhelmingly towards human-induced warming. As such, taking more aggressive action now can be seen as an insurance policy to protect the world from potentially expensive adaptation costs later.

[23] The recession is expected to result in a projected 3% decline in worldwide CO_2 emissions for 2009, according to the IEA, as published in an early excerpt of the 2009 WEO. However once the global economy recovers, emissions are expected to continue to rise unless changes are made to energy production and use.

[24] For example, in 2009, natural gas and wind power each accounted for about 40% of new power generation capacity additions in the United States. This included 10 GW of wind power capacity additions, a record (AWEA, 2010).

2009, China's installed wind power capacity doubled for the fifth year in a row, and it has now become the single largest wind market in the world – larger than the United States and Europe (GWEC, 2010).

Decentralized infrastructure also addresses issues with access to energy in developing countries and transmission siting issues in both developing and developed countries. Transmission infrastructure is expensive and requires large amounts of capital for individual projects. Conversely, DG can be installed more easily and incrementally, and avoids the need for some of the transmission investments. The decentralized nature of these DG systems, coupled with the fact that they can be installed closer to the point of end use, mean that they can increase system efficiency – by decreasing transmission and distribution (T&D losses) – and enhance infrastructure security – by making the system more resilient in the event of outages at any one power plant or transmission line.

Accelerating technological change

Associated with the two issues discussed above is the fact that the pace of technological change in the energy sector is accelerating. New technologies are entering the marketplace, and the rate of growth in these markets is fast by any measure (exemplified especially by wind power and PV). The cost and performance for these technologies are changing rapidly and new business models are arising that may not fit well into established analysis methodologies.

Accompanying the rapid growth in deployment of these technologies is the increasing likelihood that one or more of them will cause disruptive changes to the energy system. Three examples are PV, electric transportation and the Smart Grid. PV is approaching price parity with retail grid power in major electricity markets (e.g., parts of North America and Europe). When this begins to occur, demand for PV will rise, leading to further cost reductions, which will further drive technology costs downward.[25] This is not some far off possibility. In areas with high retail electricity prices and available incentives (e.g., Hawaii in the United States), PV is already becoming cost competitive.

With electric transportation, the ongoing success of the hybrid-electric vehicle (HEV) has opened the door for the PHEVs. Several major automobile manufacturers have PHEVs in development, and some products are already being advertized. Without trying to understate the work required to bring PHEVs to market, it is fair to say that PHEVs require relatively little technology development beyond current hybrid vehicle technology, although battery price is a barrier today. Therefore, once commercially available, they could penetrate the market quickly. Since PHEVs are only being designed for moderate electric-only ranges (typically 10-40 miles), they could easily be charged at home without the need for special charging equipment. Also, they would have none of the drawbacks of battery-electric vehicles (BEVs). Since a large fraction of total miles driven is for short trips, the use of PHEVs would lead to significant fuel substitution in the transportation sector, from petroleum to electricity. As long as gasoline prices are $2-3/gallon or higher (excluding taxes),[26] these vehicles are likely to be economically attractive from a fuel cost perspective.

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[25] The year 2009 saw significant price declines for PV – on the order of 40%. While it is too early to say for sure, much of this drop is likely a permanent change, because this correction has actually returned the price of PV to levels consistent with its historical learning rate. Although continued volatility in prices is likely since supply and demand do not always balance well during periods of rapid growth, the overall trend should be towards continued declines in prices as PV technology improves, manufacturing scale increases and the supply chain matures.

[26] In rough terms, an oil price of about $75/barrel corresponds to a wholesale gasoline price of about $2/gallon. Retail prices are much higher than this in many countries, due mainly to taxes. It is fair to assume that if electricity is used as a transportation fuel that it too will eventually be subject to similar motor fuel taxes.

Given the cost competitiveness of electricity as a transportation fuel, as battery prices fall with increased investment, the potential exists for a major shift in the transportation sector to electric propulsion.[27] Such a change would have profound impacts on both the electricity and petroleum industries. Moreover, in the context of a low-carbon world, electrification is a very attractive way to decarbonize the transportation sector. Even at today's CO_2 intensity, electricity offers lower per mile emissions. Moreover, it is currently easier to decarbonize electricity than liquid transportation fuels. Electric transportation also has the potential to be more efficient than current options based on liquid petroleum fuels or renewable fuel substitutes.

The so-called Smart Grid represents a third area of technology development that could have profound impacts on the future of the energy system. The Smart Grid does not require much in the way of new technology development – it basically makes use of existing and emerging information technology solutions to provide a high-bandwidth, two-way communications infrastructure that would overlay the existing electricity T&D infrastructure. The Smart Grid would also extend beyond the meter, to appliances and other end-use equipment. This will provide utilities and consumers with the information necessary to do two basic things: (i) improve grid management and performance (specifically, manage energy use to reduce overall consumption, reduce peak demand via load response, and enhance system reliability); and (ii) integrate higher amounts of environmentally-friendly technologies than would otherwise be possible – including PV, wind, and electric transportation.

From energy security to "everything" security

Petroleum, and more recently, natural gas supply and pricing concerns have been at the forefront of international policy and national security planning for much of the 20th century. More recently, increases in prices and price volatility, growing concerns over the adequacy of supply, as well as supply disruptions of natural gas in Europe, have highlighted that this issue is likely to become even more important in the years to come. Remaining supplies of readily recoverable petroleum and natural gas are becoming increasingly concentrated in a few countries, some of which are politically unstable, while others exhibit outright hostility towards the major oil consuming nations. As a result, continued reliance on imports of fossil fuels is an ongoing vulnerability for many nations and a matter of national security. The implications of the security dimension include the need to devote significant resources to military expenditures, the need to use military force to maintain security of supply, and the long-term implications of massive wealth transfer to unstable, hostile and repressive regimes.

As if this were not worrisome enough, the issues surrounding energy security are becoming broader in scope. Energy infrastructure is seen as vulnerable, either to deliberate attack or to the elements, as weather patterns change and become more extreme and unpredictable. In London, for instance, winters are 10% wetter and summers are 10% dryer compared to historical data, leading to hundreds of floods per year in the London Underground. These increases are expected to be 20% and 40% respectively by 2050 (GLA, 2005). While high-income countries may consider their infrastructure robust, it has not been designed for these new weather conditions (IPPR, 2009). Given greater uncertainties in weather and security, countries will need more robust and flexible systems with improved resiliency to climatic changes. This need is one more reason why decentralized infrastructure is gaining traction, since it is generally better able to withstand disruptions, be they caused by natural phenomena, human error or deliberate attack.

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[27] If battery prices fall enough, BEVs with ranges up to 200 miles or more could become a viable addition to the fleet of electrified vehicles on the market further accelerating the electrification of transportation. These vehicles are also the subject of intense R&D and product development activities, with several products being introduced in the next 2-3 years by both established automobile companies and new entrants.

Even more significantly, other issues are emerging at the nexus of climate change and security. Specifically, climate change may initiate a range of adaptation-related crises with major security implications, including drought, famine and large migrations of so-called environmental refugees. There is a growing body of work on this topic, including for example: Ackerman (2008), Broder (2009), Campbell and Weitz (2007), and Cronin (2009). These events could lead to conflict over a variety of natural resources, as well as large disruptions to the global economic system. Thus, there is an emerging view that achieving security in the broadest sense is inextricably linked to mitigating climate change. These climate-security linkages are now considered serious enough that they will, for the first time, be part of the United States' Defense Department's 2010 Quadrennial Defense Review (DOD, 2009).

Energy System Modeling and Keeping up with Change

Current top-down global energy models were designed to model the "old" world; i.e., they were developed primarily to assess supply and demand for energy assuming that the basic structure of the energy economy does not change. In fact, as discussed above, energy markets are now changing quickly. Moreover, these models must include an increasingly complex set of policies (e.g., climate change policies) and must be able to model changing technologies and evolving consumer behavior. Said another way, when top-down models are applied to the "new" world, they are being used to answer different questions than in the past, and they may therefore underestimate the potential of new technologies. Despite ongoing updates and modifications to these models to meet these new requirements, they are limited in their ability to provide insights into the future. Conversely, techno-economic models are built upon the stock of existing technologies and explicitly model future technologies and policies. They are much more suitable to model the "new" world and explore radically different development paths, while maintaining economic equilibrium. Although the economic impacts of different policies can be modeled reasonably well with existing top-down and bottom-up global energy models, they all need to be further improved to adequately incorporate a wider range of economic costs and benefits, and not just consider the economics of energy supply and demand, even when policies are taken into account.

Just as models must evolve, new scenarios must also be able to adequately describe the new drivers of the energy economy in the context of a low carbon world. These include new technologies, business models, risks, policies, and security considerations. The RETD has developed a set of principles it believes global energy scenarios need to address in order to effectively adapt to the rapidly changing energy system (Table 2).

Table 2: RETD's Principles for Improving Global Energy Scenarios

Issues Affecting Global Energy Modeling	RETD Position
Energy System Drivers	Energy scenarios must consider all the drivers of the future energy system, which has expanded to include issues ranging from climate policy to energy supply security and economic development.
Climate Change	Climate change is now a key component of energy modeling. Scenarios should examine aggressive global actions sufficient to meet the most stringent targets with high probability.
Disruptive Technologies	Energy models need to examine disruptive technology developments that are becoming increasingly likely (e.g., Smart Grid, PHEVs, PV reaching grid parity).
Economic Analysis	Beyond modeling of direct energy infrastructure investments and fuel costs, scenario analyses should consider the other economic benefits (e.g., reduced climate change adaptation costs, job creation, rural economic development, reduced energy price volatility).
Fossil Fuel Prices	Scenario analysis should include sensitivity analysis of fossil fuel price and incorporate the impacts of price volatility, which favors the adoption of alternatives to fossil-based generation.
Infrastructure Development	Models need to allow for the development of distributed energy systems, particularly in developing economies where the drive for energy access in the face of capital constraints encourages their implementation. In developed countries, Smart Grid deployment could radically alter the generation, delivery and use of energy.
Transparency	Complete documentation of a model's methodology, assumptions, inputs, and results is critically important, especially as modeling techniques adapt to the changing energy system.

The RETD has begun to apply these principles in its work on global energy scenarios. Specifically, these principles have guided the feedback provided by the RETD on drafts of the ETP 2008, WEO 2008, WEO 2009, and the forthcoming publications of the WEO 2010 and ETP 2010. They were also the building blocks for the RETD ACES Scenario, as described below, although it was only possible to address some of these principles in the current work. Factors such as adaptation costs, jobs, and rural development, were not directly modeled in the RETD ACES Scenario.

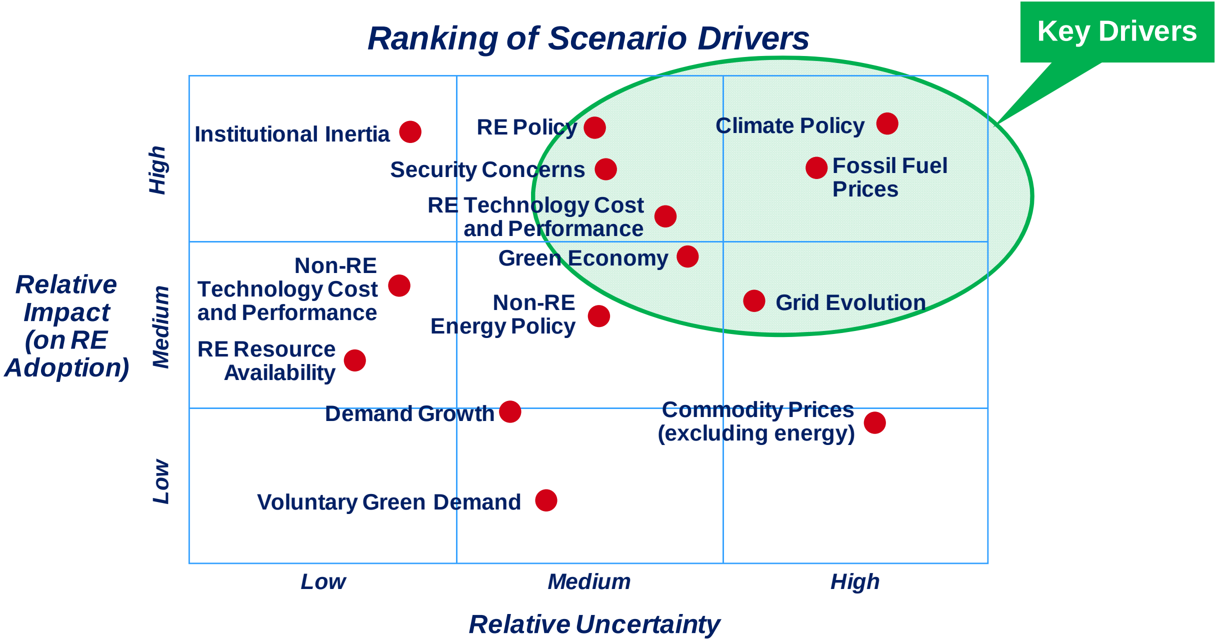
3. The RETD ACES Scenario

The Scenario Development Process

The development of the RETD ACES Scenario was done using a systematic Scenario Development Framework that Navigant Consulting has utilized and refined over more than 15 years with numerous public and private sector clients. It is based on the premise that a useful scenario is defined by drivers that have both high uncertainty and high impact, since it is this combination that can lead to dramatically different future end states.[28] For example, energy prices are both highly uncertain and highly impactful, and this impact can be felt if energy prices are either high or low.

The first step of this process was identifying and describing all the drivers affecting the global energy system. These were then ranked according to their uncertainty and impact as they relate to RE adoption (Figure 1). These key drivers were then used in different combinations to create a suite of six scenarios, each with different "settings" for the key drivers. The two key drivers that were deemed most important to model in the RETD ACES Scenario were climate policy and security concerns.[29] Global climate change policies are expected to undergo significant change over the coming decade, and a lack of agreement at the COP 15 only highlights the degree of uncertainty surrounding them. Security issues meanwhile have become much broader in scope than in the past, as discussed in Section 2, and are becoming increasingly linked to climate change.

Figure 1: Key Drivers Affecting Renewable Energy Adoption



The ETSAP-TIAM Model

Rather than develop its own model with which to represent the global energy system, the RETD decided to identify and collaborate with an organization that had already developed a suitable model. After considering several possibilities, the RETD decided to work with the ETSAP Implementing Agreement of the IEA. ETSAP has a long history of developing global energy models. ETSAP was created in 1976 following the first global oil crisis, and since then has developed a family of computer models, based

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[28] Although a scenario is fully described by many drivers, it is fundamentally defined by a small number of key drivers.

[29] The decision to model just one scenario was necessary given the time constraints of the project.

mainly on the MARKAL/TIMES[30] family of models. These models can be used for national, regional and global energy and environmental analyses. There are currently more than 200 MARKAL–TIMES users across the world.

The RETD ACES Scenario was modeled using the ETSAP-TIAM[31] model, which was considered the most appropriate one to use among the family of available models from ETSAP. It is a partial equilibrium, technology-rich economic optimization model. It balances supply and demand for energy services by maximizing total (consumer + producer) economic surplus, subject to whatever constraints are applied (such as emissions limits or specific policies). [32] TIAM represents the global energy system in a logical, transparent, and reproducible way, finding technically possible solutions to different scenarios. For example, TIAM distinguishes six time-slices – winter, summer, and intermediate seasons (spring and fall), each with a day (peak) and night (off-peak) – when calculating electricity production (and consumption). The electricity balance, including a peak reserve margin is satisfied by the model in each time slice. This means that electricity production matches demand in each time-slice. In meeting demand, the model thus recognizes that some technologies are baseload (like nuclear), other as fully flexible (like gas turbines), and still others as intermittent and not dispatchable (like solar and wind power). The technology assumptions include parameters that describe how each technology can contribute to meeting demand in each time slice. These parameters further allow for the application of assumptions about technologies such as thermal storage for concentrating solar thermal. The use of thermal storage is represented by adjusting both the capital cost and the ability of concentrating solar thermal to meet peak demand (since storage allows the technology to be dispatchable).

The ETSAP-TIAM model, like most long term-models based on equilibrium calculations, is an exploratory model, not a forecasting model. An exploratory model functions via scenario analysis, whereby assumptions about energy demands, resources, technologies and policies are clearly identified, and the model responds to these scenario assumptions by describing the equilibrium corresponding to this scenario. As described earlier, it is important to reiterate that this approach is not a forecast, mainly because there is no credible way of forecasting technological, policy and other inputs over the long-term, due to the many existing uncertainties. Thus, the results of the modelling represent one possible future outcome, based on the specific assumptions about energy demands, resources, technologies and policies, and the model response to these assumptions.

Other important characteristics of TIAM include the following:

- It can model the energy system out to the year 2100.
- It uses a set of exogenous assumptions about the development of key socio-economic drivers and policy decisions (e.g., GDP growth).[33]
- It includes 16 global regions and allows for energy and emissions trade between regions.
- Demand for energy services is divided into 42 separate categories across all sectors of the economy, including industry, residential, commercial, transportation, and agriculture (e.g., lighting, hot water, and vehicle-km by car, bus and rail).
- The level of demand for energy services is a function of price, and is elastic to it.
- A climate module is included in TIAM that estimates concentrations of the three main GHGs in the atmosphere (CO_2, CH_4 and N_2O). TIAM calculates GHG emissions from the energy sector

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[30] MARKAL stands for **<u>MARK</u>**et **<u>AL</u>**location and TIMES stands for **<u>T</u>**he **<u>I</u>**ntegrated **<u>M</u>**ARKAL-**<u>E</u>**FOM **<u>S</u>**ystem.

[31] **<u>T</u>**IMES **<u>I</u>**ntegrated **<u>A</u>**ssessment **<u>M</u>**odel.

[32] The actual constraint in the TIAM model is that energy supply must be equal to or greater than demand. In order to satisfy other constraints that are imposed, the model may overproduce certain energy commodities.

[33] In this long-term scenario analysis, there has been no attempt to reproduce the current economic slowdown or the subsequent recovery.

and uses exogenous inputs for non-energy GHG emissions, such as N_2O from agriculture and CO_2 from land use change and forestry.

- Past behaviors are not projected. Information about the past is embedded in the stock of plants, processes and devices existing in the start year, but after that year, the model is free to decouple the primary energy supply from the economy to the limit of technical feasibility defined in the model. Past patterns of dependence between economic growth and primary energy supply/prices are not projected into the future. Past macro-economic time series data do not influence future developments. Significant departures with the past are permitted.
- Decentralised and dispersed supply chains are simulated and compete with traditional centralised infrastructure in satisfying the demand for energy services. Electricity and heat are differentiated by season and by night/day/peak. Electricity and heat are generated by central plants, as well as decentralised and local plants, including several types of combined heat and power (CHP) plants.
- As soon as they become available (based on the assumptions provided in the scenario), new technologies compete with the existing ones in reaching the objectives of the scenario. This approach applies to both energy supply and end-use consumption.

General Description of the RETD ACES Scenario

The RETD ACES Scenario is the RETD's first effort at incorporating most of the principles listed Table 1 into a detailed scenario analysis, and it is designed as a meaningful next step in the evolution of global energy system modeling. A general description of the scenario is provided in this section, while specific assumptions are available in the section, "Specific Assumptions for the RETD ACES and Reference Scenarios".

A target frequently discussed for climate stabilization is 450 ppm CO_2-eq by the year 2100, which, according to the International Panel on Climate Change (IPCC), will limit the global average temperature rise to 2°C with approximately a 50% probability (Meinshausen 2006; IPCC, 2007). This CO_2-eq concentration corresponds roughly to a CO_2-only concentration of 400 ppm. However, this temperature estimate does not take into account non-linear responses from positive climate feedback loops, and recent research suggests that a 450 ppm CO_2-eq target is too high to avoid passing certain "tipping points" beyond which the climate system would continue to warm even if manmade climate forcings were drastically reduced (Hansen et al, 2008). A growing body of research suggests that a maximum limit of no more than 350 ppm CO_2 by the end of the century is required, corresponding roughly to 400 ppm CO_2-eq (Ackerman, et al, 2009).

Consistent with this emerging research, the RETD ACES Scenario targets a GHG concentration of 400 ppm CO_2-eq by the year 2100.[34] The RETD ACES Scenario implements this target explicitly via a constraint in the TIAM model. The model also calculates the trajectory of internal carbon prices resulting from such a target. It is important to understand that there are many combinations of policy instruments that could used to achieve the GHG target, such as taxes, financial incentives, emissions trading, and regulatory requirements such as RE obligations and efficiency standards. The manner in which the RETD ACES Scenario is modeled in TIAM does not presume the particular policy instruments used for its eventual implementation. Thus, the carbon price calculated by the model can be thought of as representing the combined impact of all the different policies that could be implemented. Therefore, it cannot and should not be compared directly to estimates of carbon prices in a specific country or region, either currently in place or contemplated for the future. For example, if a carbon price were implemented

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[34] As discussed in the results section, the model was not able to converge on this target. Rather a GHG concentration of about 420 ppm CO_2-eq was achieved by 2100, with concentrations dropping at about 1 ppm per year in 2100.

in a country that already had various support mechanisms for RE and energy efficiency (EE), that price would be lower than it would otherwise be if there were no RE or EE specific policies, all else equal. Thus, in the context of the results of the RETD ACES Scenario modeling presented later, what matters most is the total cost of the scenario relative to the Reference Scenario, not the specific carbon price.

The RETD ACES Scenario also includes constraints on global trade of energy commodities as a representation of the security driver. On the one hand, this reflects a desire among nations to enhance security by relying more on domestic resources. On the other, it reflects the likelihood that insecurity in the world would lead to a world in which unconstrained trade is simply not possible. This driver is implemented by imposing exogenous limits on global energy trade as a percentage of unconstrained energy trade, as detailed below.

The RETD ACES Scenario does not preclude the use of any particular technologies, such as nuclear power or CCS. Rather, it attempts to use reasonable, internally consistent assumptions for a wide range of existing and emerging technologies. In the context of an insecure world, where energy independence is seen as equally important, and linked, to climate change mitigation, it is reasonable to expect that all technologies would be "on the table", subject to the limits of resource availability.

In the RETD ACES Scenario, one would expect there to be extensive cooperation and convergence across industries and governments to drive rapid change in the energy system. In particular, the electricity grid is assumed to evolve quickly through investments that support the rapid deployment of RE, EE and other low-carbon options. In order for this to happen, regulators and policy makers would need to promote the necessary changes in rules and regulations to allow the investments to be made to accommodate rapid advancements in grid functionality (i.e., the so-called Smart Grid) and in transmission capacity. In developing countries, distributed energy is deployed, reducing the need for traditional infrastructure investments.

Although not modeled explicitly in the RETD ACES Scenario, one would also expect the green economy to thrive because of the emphasis on domestic, low-carbon technology development. Industry would naturally capitalize on the opportunities that arise from a rapidly changing energy system, further accelerating the transition to low-carbon technologies. Fossil fuel prices would be high because of security concerns, despite falling demand driven by decarbonization. In other words, supplies would remain constrained for reasons other than resource availability.[35]

Voluntary green demand is also likely to increase over time as continued emphasis on climate change and energy independence influences public opinion. Nevertheless, the dominant driving force is expected to be policy, so voluntary demand for low-carbon energy is not specifically modeled in the RETD ACES Scenario. There is however an estimate of the impact of the Smart Grid on consumer behavior in the model, assuming that the provision of better information about energy use and costs to consumers will encourage behavioral changes that reduce energy use.

Finally, in the RETD ACES scenario, reductions in emissions of non-energy GHGs play an important role in the overall strategy to mitigate climate change. The reductions cover mitigation of non-energy sources of CO_2 such as land-use change (LUC) and forestry, increased reforestation (which is a sink for CO_2) and mitigation of non-CO_2 GHG emissions.

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[35] Although this is part of the assumed characteristics of the RETD ACES Scenario, fossil fuel prices were not fixed as part of running the TIAM model. Rather, the model was used to calculate fossil fuel prices subject to supply, demand and the constraints placed on global energy trade.

The Reference Scenario

In order to analyze the results of the RETD ACES Scenario, it is necessary to have an internally consistent scenario that is run using the same model. The Reference Scenario[36] was developed for this purpose. Generally, the Reference Scenario can be considered a "policy free" scenario that does not contain any assumptions about future policies.[37] Thus, within the methodologies applied in the TIAM model, it represents an economically optimal solution unconstrained by any of the drivers discussed previously. Slightly different technology assumptions were used in a limited number of cases reflecting the fact that there will be slower technology development under the Reference Scenario, but the primary differences between this scenario and the RETD ACES Scenario are the core drivers that define the latter (i.e., climate change and security).

It is important to distinguish this Reference Scenario from a "business-as-usual" (BAU) scenario. A BAU scenario would need to contain many assumptions about policies already in place and assumptions about how these policies would change over time. Since the Reference Scenario does not contain such policy assumptions, it is, from a climate perspective, "worse" than a BAU scenario. This definition is reasonably consistent with how the WEO and ETP define their Reference Scenarios, but in fact is even less constrained because those analyses have a more detailed representation of existing policies in their Reference Scenarios. In the case of the WEO and ETP, the Reference Scenarios freeze policies in their current state. In the TIAM Reference Scenario, even existing policies are largely absent. Thus, it is critically important not to confuse the Reference Scenario with a scenario that is meant to predict the future. The Reference Scenario is only used to provide a datum with which to compare the results of the RETD ACES Scenario. It should not be considered a representation of the current evolution of the energy system. The same is true of the Reference Scenarios used by the WEO and ETP, even as their definitions differ somewhat from the TIAM Reference Scenario.

Specific Assumptions for the RETD ACES and Reference Scenarios

In order to model the RETD ACES Scenario, it was necessary to "translate" the scenario description into specific assumptions suitable for use in TIAM. While it is not possible to go into every detail in this report, this section provides a summary of the key assumptions, with an emphasis on changes made specifically for this project. Annex I also contains specific assumptions for power generation technologies.

Climate Policy

As mentioned above, the RETD ACES Scenario assumes that aggressive action is taken immediately to reduce GHG emissions, consistent with achieving atmospheric concentrations of GHGs of 400 ppm CO_2-eq by 2100[38]. For the purposes of modeling, this was implemented mainly via a price on CO_2. No specific policy mechanisms are assumed (i.e., a tax vs. cap and trade). Rather, the ETSAP-TIAM model calculates a CO_2 price necessary for driving changes in both energy supply and demand to achieve the climate target. The CO_2 price is assumed to be the same in all regions. Moreover, since specific policies are not explicitly modeled (like feed-in tariffs or renewable obligations), the CO_2 price effectively represents the combined impact of various incentives and policies. As such, the CO_2 price calculated by the TIAM model for this project cannot be directly compared to existing or proposed policies that place a price on carbon emissions, such as the European Union Emission Trading System (EU ETS) or the Regional Greenhouse Gas Initiative (RGGI) operating in the northeastern United States. The economic impacts of

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[36] We recognize that the term "Reference Scenario" is less than ideal in describing the purpose of this scenario. However, the modeling community has been struggling with this issue for decades without coming up with a better nomenclature.

[37] The Reference Scenario contains a small CO_2 price ($10-20/tonne) as a proxy for current policies.

[38] 400 ppm CO_2-eq by 2100 was the original target for the ACES Scenario. As we will discuss below in the section on results, the RETD ACES Scenario was only able to reach about 420 ppm by 2100.

the climate constraint are fully incorporated into the economic calculations of TIAM and can be thought of as an additional operating cost for technologies that emit GHGs.

Because a single economy-wide climate constraint cannot fully simulate the wide range of existing RE policies, some additional analysis was done for wind and PV markets, to ensure than the near-term results were reasonably in line with current and expected growth rates for these technologies. This is analogous to imposing a renewable obligation for these technologies in the near term. The TIAM model simply optimizes energy supply and demand around this additional constraint.

In the Reference Scenario, a minimal CO_2 price has also been imposed to represent to some degree the impacts of policies already in place today. It is assumed that CO_2 prices reach \$20/metric tonne (MT) in developed countries by 2050 and remain constant after that point. In developing countries, this price level is reached by 2100.

Security Concerns and Energy Trade

Since, to the RETD's knowledge, this is one of the first such modeling efforts to examine security, a simplified approach was taken to represent some of the security considerations discussed earlier. The most direct implications of security concerns on the global energy system will be the reduced trade of energy commodities. As nations are becoming increasingly concerned over the security of their energy supplies, they are placing greater emphasis on reducing energy imports by increasing the use of domestic resources. For the RETD ACES Scenario, the energy security driver was implemented by applying an across the board, 25% reduction in global trade of all energy commodities compared to a run of the RETD ACES Scenario without any constraints on trade. In addition, oil and natural gas exports from the Middle East were reduced by 40% relative to the run of the RETD ACES Scenario not containing any trade constraints. Note that these trade constraints are not relative to the Reference Scenario. In the Reference Scenario, there are no limits placed on global energy trade, except for the existing assumptions within TIAM for resource availability and the supply curves for these resources in the different regions.

Energy Demand

Energy demand in TIAM is based on GDP, the rate of technological change/substitution, and the sensitivity of consumers to energy prices, among others variables. GDP assumptions are fixed, but the rate of technological change and overall demand for energy services will vary in response to scenario assumptions. Thus, in the RETD ACES Scenario, there will be greater deployment of more efficient technologies as well as lower demand for certain energy services in response to the constraints of that scenario as compared to the Reference Scenario.

The TIAM model also allows for fuel substitution in many cases, such as for heating fuels and transportation fuels. As with energy demand, these changes are in response to the assumptions of the scenario. In general, this leads to substitution towards low-carbon energy carriers in the RETD ACES Scenario. The TIAM model currently does not include substitution between different energy demands, for example, between vehicles miles traveled by car versus public transit.

For the RETD ACES Scenario, the existing assumptions within TIAM served as the primary assumptions related to the demand for energy services. Some adjustments to electricity demand assumptions in the RETD ACES Scenario were made in connection with assumptions about the Smart Grid, as described in more detail below. For the Reference Scenario, the default TIAM assumptions were used for energy demand.

Technology Cost & Performance

A comprehensive review of all technology assumptions for electricity generation was undertaken to update them with the latest information available.[39] Since TIAM does not use learning rates, it was necessary to estimate technology costs and performance over time. In general, the same cost and performance assumptions were used in both the Reference Scenario and the RETD ACES Scenario, with the exception of discount rates and the ability of certain RE technologies to meet peak demand. Regarding discount rates, it was assumed that fossil fuel technologies that do not have CCS would be deemed riskier investments in the RETD ACES Scenario, so a higher discount rate was applied (see Table 3). Also, a higher discount rate was applied during an initial period after new technologies were first introduced. Regarding the ability of RE technologies to meet peak demand, it was assumed that deployment of the Smart Grid would increase the ability of PV and wind power to meet peak demand. The specifics for this assumption are provided below in the discussion of "Grid Evolution".

Table 3. General Approach To Power Generation Discount Rates

Discount Rate	Reference Scenario	RETD ACES Scenario
15%	• New technologies[1] for first 10 years of commercial availability	• New technologies[1] for first 10 years of commercial availability (including CCS options) • Coal and oil technologies without CCS[2]
10%	• Everything else	• Everything else

1. Includes technologies available today but still considered novel, such as gasification-based technologies and fuel cells. Some technologies were modeled with intermediate discount rates through c.2020 (i.e., between 15% and 10%), such as offshore wind and concentrating solar power.
2. Beyond 2030, the discount rate was reduced to 13%, reflecting the assumption of greater certainty in carbon prices after that date.

Fossil Fuel Prices

As noted above, the constraints imposed by security concerns in the RETD ACES Scenario limit the trade of energy commodities. For the purposes of modeling, fossil fuel prices were determined by TIAM according to the model's existing assumptions about price relative to supply from different regions. The same approach was taken in the Reference Scenario, but with no constraints on energy trade.

Grid Evolution

An important feature of the RETD ACES Scenario is the expectation that aggressive policies around climate change and security will lead to relatively rapid and complete deployment of the so-called Smart Grid. While the main drivers for RE and EE will be these fundamental issues, the Smart Grid will be necessary to enable high penetration levels of intermittent RE and electric transportation, as well as greater use of DG in general. Since it was not possible to make major changes to the TIAM model, the following alterations were made within the existing capabilities and assumptions:

Smart Grid Deployment Timeline. In developed countries, it was assumed that the Smart Grid would be deployed starting in 2015 and be completely deployed by 2030. For developing countries, deployment was assumed to occur over the period 2030-2045.

Smart Grid Investment Requirements. There is still quite a bit of uncertainty regarding mature costs for Smart Grid deployment. A conservative estimate of a one-time $400 investment per existing customer

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[39] See Annex I for the assumptions used and www.kanors.com/dcm/tiam for the description of the TIAM model itself.

was developed for the RETD ACES Scenario. This charge, which is a retrofit cost to existing infrastructure, would be recovered by utilities over a period of time as an incremental cost of providing service. It was assumed that ongoing investments for new distribution infrastructure would be the same as for a grid without Smart Grid functionality.

In TIAM, the Smart Grid cost adder was estimated by examining the number of customers and their average electricity consumption in the United States. The values arrived at were 0.5 ¢/kWh for residential customers and 0.1 ¢/kWh for commercial customers, based on amortizing the one-time investment over the same period in which the technology phase-in occurs. No additional costs were added for industrial customers, since they are not the focus of Smart Grid deployment efforts. Moreover, as large electricity consumers, they already have much of the key functionality (such as interval metering and time-of-use pricing), and because of their large energy use per metering point, the incremental cost per kWh is negligible. Moreover, the cost of overlaying the Smart Grid communications and information technology infrastructure on the distribution system would be mostly covered by bringing it to residential and commercial customers.

Smart Grid Benefits. Several benefits of Smart Grid deployment were modeled. First, by giving consumers better information about energy use and costs, and ways to manage energy use, these consumers are expected to change behaviors (e.g., turning off lights and lowering thermostats) that will lead to energy savings. Up to a 10% savings has been observed among residential customers. This reduction was phased-in for electricity consumption in the residential sector over the same period as the Smart Grid technology. For commercial customers, the reduction was set at 5%, assuming that they would have more limited ability to reduce energy use through behavior changes (i.e., they are more constrained by the nature of the business being conducted and therefore cannot modify behavior as easily).

The Smart Grid is also likely to make consumers more responsive to higher energy costs (i.e., the elasticity of demand would increase). This sensitivity would be in addition to the behavior savings described above, which is based simply on having better information and control with current energy prices. Since it is difficult to anticipate exactly the size of this effect, a small impact of 5% additional electricity savings was assumed. It was implemented through modifications to the price elasticity equations in TIAM.

The Smart Grid will also facilitate the integration of DG of all kinds, including intermittent resources. In TIAM, there is an assumption for each technology that defines it ability to meet peak demand in each of the different time slices. For the RETD ACES Scenario, these values were increased for PV and wind power to reflect this improved integration. For concentrating solar thermal, the technology assumptions were adjusted to model the incorporation of thermal storage, including an increase in its peak contribution. No further adjustment to this factor was made for solar thermal electric technology on account of the Smart Grid.

A major benefit of the Smart Grid will be the ability for the utility to shift and manage load. This capability will not directly result in energy savings by the end user (although it may result in small improvements in grid efficiency), but will mean that less investment will be needed in traditional generation, T&D infrastructure to meet overall electricity demand. This was modeled by shifting 15% of residential and commercial electricity demand from peak to off-peak time periods. Industrial demand, which was assumed to be dictated primarily by the needs of the industrial processes, was not modified. Cost savings resulting from this shift are automatically estimated by TIAM.

Expanding Connections Between Grids. For the RETD ACES Scenario, specific assumptions were developed for increasing the amount of electricity trade from North Africa to Europe.

Resource Availability

TIAM contains estimates for resource availability by region, for fossil fuels, RE and nuclear power. These default values were reviewed and the decision was made to use them in both the RETD ACES and Reference Scenarios. The only adjustments that were made were to nuclear power potential. Nuclear power resource potential is a function of fuel availability and assumptions about nuclear plant technology. Fuel can be supplied from natural uranium, uranium from dismantled nuclear weapons, spent fuel reprocessing, and from breeder reactors (if such technology is pursued). So-called Generation-IV nuclear reactor technology would likely require less fuel than current technology, and could therefore increase the technical potential, all else equal.

The role of nuclear power is of course a key consideration in many debates about future energy projections. It can contribute to achieving climate policies and energy security in a certain way. However, it is also associated with a range of negative impacts (e.g., risk of accidents, radioactive waste management, and nuclear weapons proliferation). Therefore, perhaps more than any other technology, decisions to invest in nuclear power plants are based on a range of non-economic factors that are not well-reflected in techno-economic models like TIAM. Thus, instead of relying exclusively on resource potential, TIAM instead applies lower and upper bounds for nuclear generation by region based on a range of factors. These bounds attempt to reflect these non-economic factors behind the implementation (or opposition to) nuclear power.

The resource inputs used in the RETD ACES Scenario assume that global generation by nuclear plants would be between 4,700 and 8,900 billion kWh by 2060 (it is around 2,700 billion kWh today). This range represents a reduction by half of the default assumptions in TIAM, and it is based on the likelihood that under the RETD ACES Scenario, security concerns about nuclear proliferation would trump other considerations.

Transportation Sector

The transportation sector includes a range of technologies for both personal transportation and freight, including PHEVs and BEVs. Fuel production options cover a range of traditional options, as well as the use of natural gas, either directly or to produce liquid fuels. Coal- and biomass-based options are also included, with and without CCS, for the production of both hydrogen and liquid fuels.

Non-energy GHG emissions

The TIAM model contains estimates for non-energy GHG emissions. Some are provided as exogenous assumptions (for example, non-energy related emissions from the agriculture sector), whereas others are calculated endogenously, namely certain CH_4 and N_2O emissions that are subject to various mitigation options that are modeled in TIAM. In addition, reforestation, which acts as a sink for CO_2, is endogenous to the model (i.e., the model can select varying levels of reforestation in response to the climate constraint imposed). For the RETD ACES Scenario, estimates for the exogenous components of CH_4 and N_2O emissions were developed that are lower than in the Reference Scenario. These were based on published estimates developed for aggressive climate change mitigation scenarios (van Vuuren et. al, 2007; Riahi, et al, 2007; Nakicenovic, et. al, 2006).

TIAM also includes exogenous estimates of the radiative forcing for the fluorinated gases covered by the Kyoto Protocol, fixed at 0.017 W/m^2 in 2005 and kept constant until 2100, and for the Montreal Protocol gases, fixed at 0.320 W/m^2 in 2005 and decreasing linearly to less than 0.1 W/m^2 in 2100.

4. Results and Discussion

The highlights of the modeling results are presented in this section. Additional details can be found at http://www.kanors.com/dcm/tiam (documentation is freely available; access to the results requires user registration, which is also free). In general, the results in this section are presented through the year 2060. In addition to providing a 50 year block of time for analysis (2010 to 2060), this year is significant because, as will be shown later in this section, it is the year in which net CO_2 emissions reach zero (this includes emissions from the energy sector and the other sources and sinks included in the TIAM model). It is also far enough into the future such that the key trends, based on the assumptions for technology cost and performance, become apparent and drive the results. Recall that from a policy perspective, the RETD ACES Scenario has been modeled primarily by placing a global constraint on GHG concentration, as opposed to a detailed set of policies that are designed to carefully mimic the current patchwork of policies around the globe. As such, the results of the analysis are more useful when taking a longer-term view. The results related to the two key drivers of the RETD ACES scenario – climate and security – are presented first in the sections below followed by additional details on energy production, use and costs.

Greenhouse Gas Emissions and Concentrations

In the Reference Scenario, GHG emissions continue to grow, from about 40 gigatonnes (Gt) CO_2-eq to 70 Gt by 2060 (Figure 2). Conversely, in the RETD ACES Scenario, GHG emissions fall steadily, reaching just 9 Gt by 2060, a roughly 75% reduction from 2010 levels. In both scenarios, the vast majority of GHG emissions are initially from the energy sector, which is dominated by CO_2. Although this continues to be the case in the Reference Scenario, in the RETD ACES Scenario, non-energy GHG emissions become a larger fraction of total GHG emissions, as the energy sector is decarbonized. This result highlights the importance of non-energy GHG emissions. In the RETD ACES Scenario, total emissions of CH_4 and N_2O are roughly the same in 2060 as in 2010, and experience modest declines after that (Figure 3). For comparison, Reference Scenario CH_4 and N_2O emissions rise between 60-65% through 2060, with additional increases thereafter.

The total emissions shown in Figure 2 and Figure 3 include emissions and sinks from the non-energy sectors contained in TIAM, which include land use change and reforestation. Land use change emissions are assumed to decrease steadily (but still remains a net GHG source) whereas reforestation acts as a sink. An additional GHG sink is electricity generation using biomass with CCS. Despite having a lower efficiency than comparable technology options without CCS, Biomass-CCS becomes attractive as a "carbon negative" option, driven by the strict carbon constraint in the RETD ACES Scenario.[40] In order to satisfy this constraint, some biomass-CCS capacity is deployed only for its GHG mitigation potential, resulting in the production of electricity beyond the level required to meet demand. The TIAM model reduces electricity generation from other sources to the greatest extent possible, but due to other constraints in the model, the result is a slight overproduction. This result can be explained by the priority placed on GHG reductions in the RETD ACES Scenario. The use of biomass-CCS primarily as a GHG mitigation option actually competes with the other mitigation options available in the model (e.g., reforestation) within the limits placed on overall bioenergy supplies (reforestation is also subject to limits on available land). Thus, based on that competition and the need for deep reductions in GHG concentrations, the TIAM model chooses to deploy some biomass-CCS solely for GHG mitigation purposes. While this result was unexpected, it is due to the strict climate constraint. To the RETD's knowledge, there are no published reports where similar models have been used to model a 400 ppm

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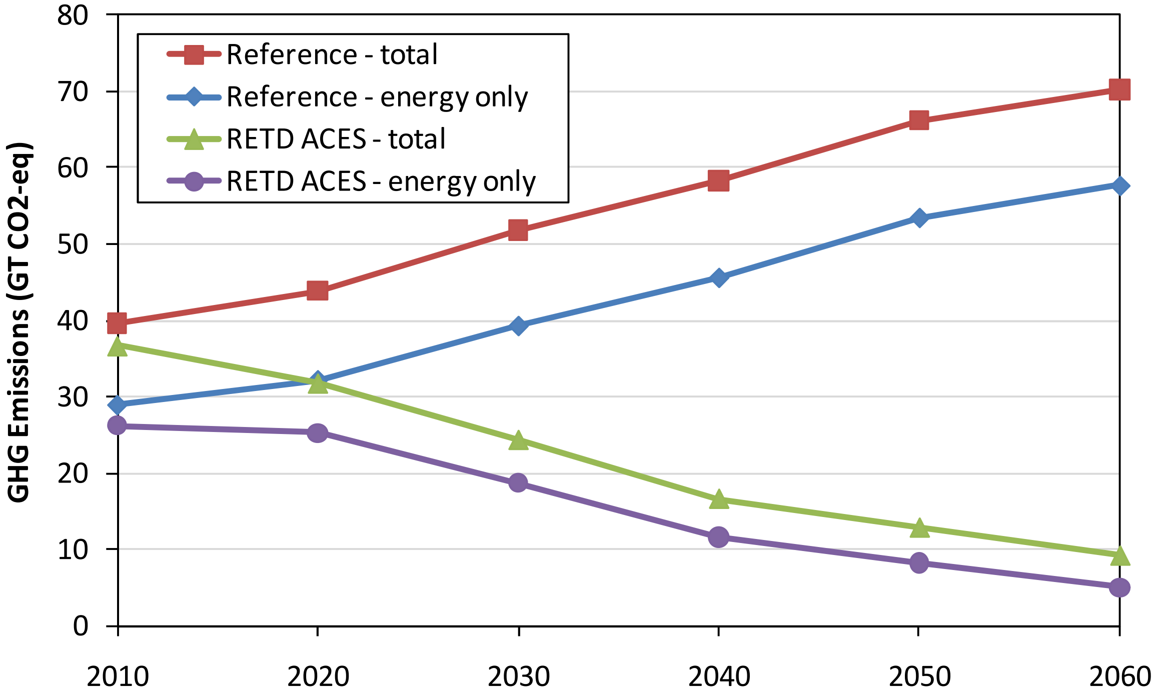
[40] The important, underlying assumption in the analysis is that biomass is grown and harvested on a sustainable basis. In general, the importance of biomass with CCS, as well as reforestation, within the RETD ACES Scenario suggests that the whole issue of biomass availability and use is a very important topic for further analysis and for sound policy formulation. The RETD has been addressing this issue in a separate project, "Better Use of Biomass Energy". See http://www.iea-retd.org/page.aspx?idsection=62 for more details.

CO_2-eq target, and in cases where 450 ppm CO_2-eq targets are modeled, models often fail to converge. For example, see Clarke, et. al (2009), which highlights the difficulties and challenges of modeling strict climate targets with existing energy-economic models.

The amount of extra capacity represents about 48% of the total biomass-CCS capacity deployed by 2030 and 54% by 2060. Unless noted, in reporting the results of the modeling, the portion of biomass-CCS capacity that is deployed for GHG mitigation only is excluded from all primary energy, generation, and capacity tables and figures in this report since the deployment produces electricity beyond the quantity that is necessary to meet demand.

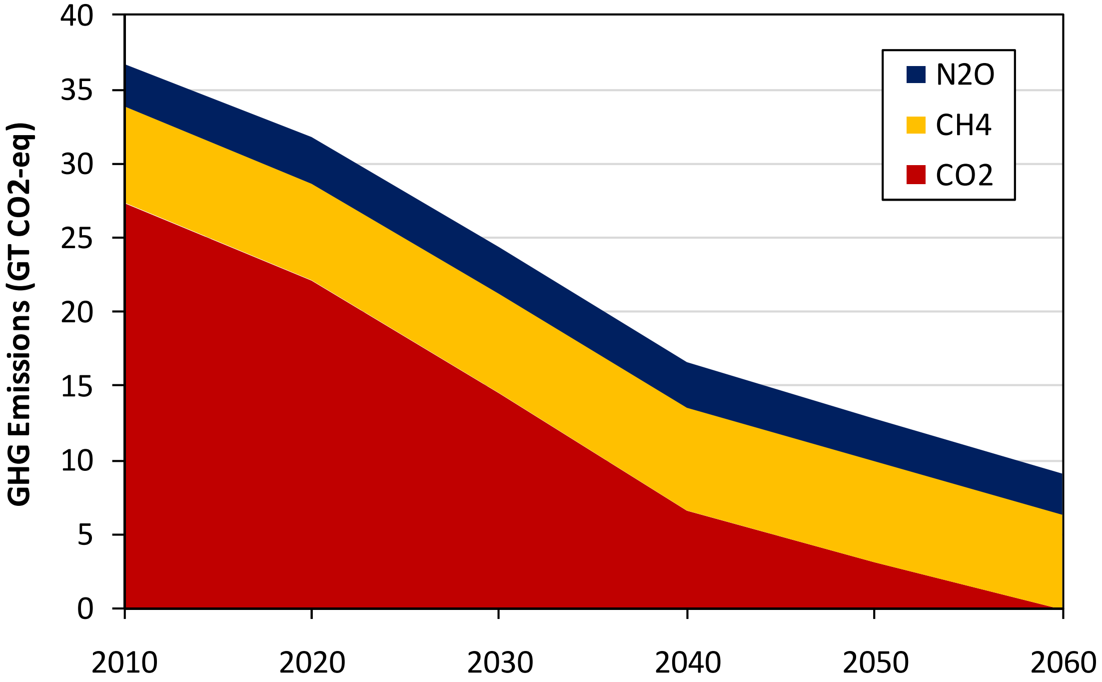
As the results show, there is indeed a rapid reduction in GHG emissions in the RETD ACES Scenario through 2060, when net CO_2 emissions (energy plus non-energy emissions) reach zero. The system is able to achieve carbon neutrality because of carbon reduction from ongoing reforestation and deployment of biomass-CCS plants, even though the energy sector as a whole and land use change remain net CO_2 emitters through 2060 and beyond. Reforestation provides, on average, a sink of about 4.3 Gt CO_2 per year in the analysis, and the biomass-CCS deployed solely for its GHG mitigation value adds another roughly 4.7 Gt CO_2 per year.

Figure 2. Total Net GHG Emissions in the RETD ACES and Reference Scenarios Through 2060



Note: “Energy only” includes all biomass-CCS capacity.

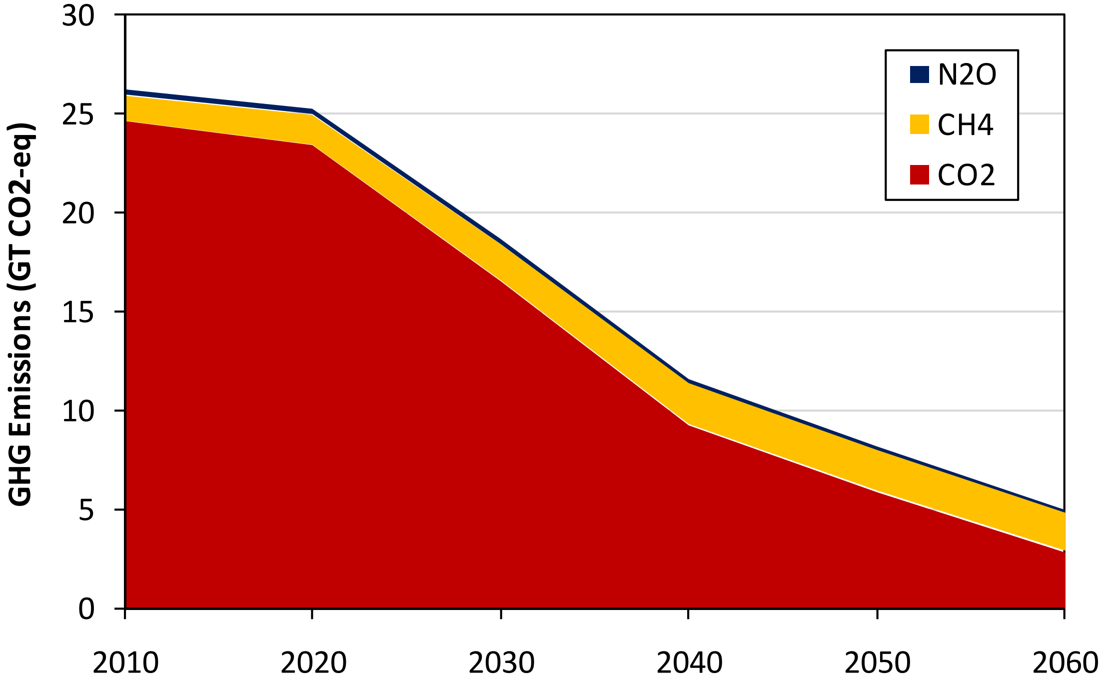
Figure 3. Total Net Emissions of CO_2, CH_4 and N_2O in the RETD ACES Scenario Through 2060



Note: Includes all sources and sinks of GHG emissions included in TIAM.

The breakdown of emissions for the energy sector alone for the RETD ACES Scenario is shown in Figure 4 indicating that CO_2 is the dominant GHG emanating from the energy sector, even in 2060, although its relative importance is reduced as the sector is decarbonized.

Figure 4. Energy Sector Emissions of CO_2, CH_4 and N_2O in the RETD ACES Scenario Through 2060

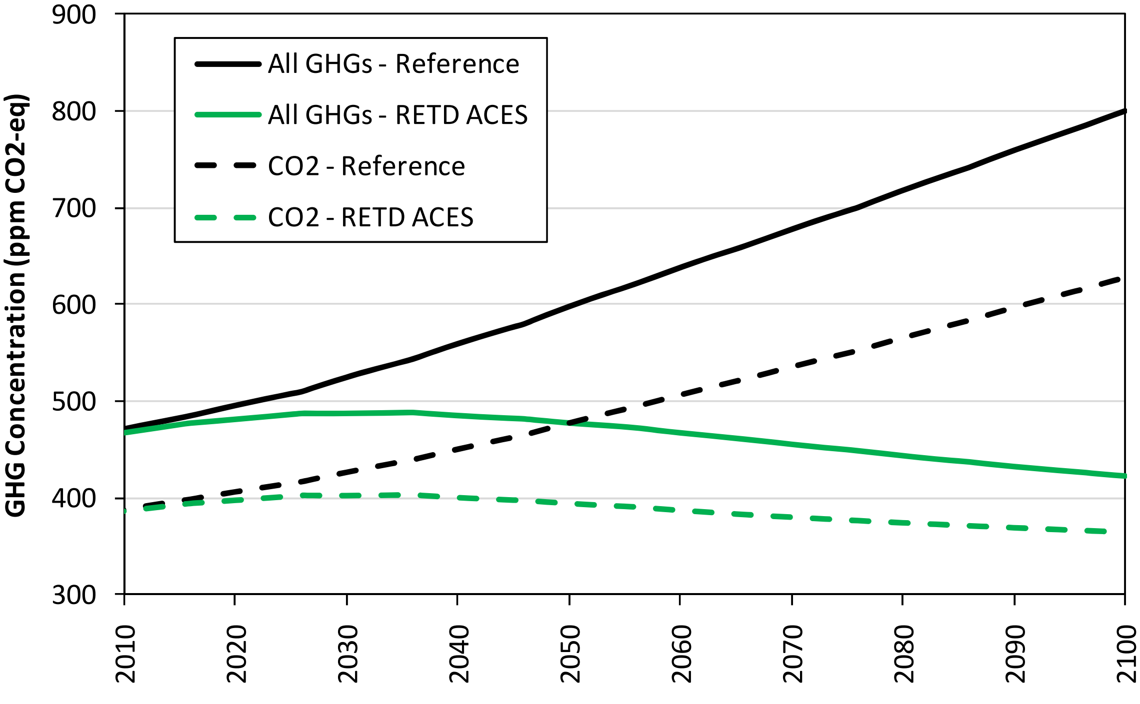


Note: Includes all biomass-CCS capacity.

Despite these dramatic reductions in GHG emissions, GHG concentrations still do not reach 400 ppm CO_2-eq by 2100, instead reaching approximately 420 ppm (Figure 5), after peaking at roughly 490 ppm CO_2-eq in 2035. A crucial factor behind the difficulties in reaching 400 ppm by 2100 is the GHG emissions contribution of agriculture, even though the RETD ACES Scenario contains relatively optimistic assumptions about GHG emissions from non-energy sources. This result, coupled with the importance of reforestation and biomass-CCS discussed above, highlights the need for a multi-sectoral approach to GHG emissions reductions in scenarios that are as aggressive as the RETD ACES Scenario. Clearly, the energy sector is key. But at the same time, the energy sector alone cannot achieve the overall climate target set in the RETD ACES Scenario. This highlights the need for further development of TIAM and other similar models, so that they can better handle scenarios that address deep GHG reductions. As has already been discussed, the RETD is not aware of other scenarios that have targeted GHG concentrations below 450 ppm CO_2-eq that have also been modeled with tools such as TIAM. The RETD expects that this will become more important in the future, as the consensus builds for GHG reductions targets that are below 450 ppm CO_2-eq.

Even though the desired climate target is not met, GHG concentrations are falling at about 1 ppm per year in 2100, suggesting that the 400 ppm CO_2-eq target could be met in the first quarter of the next century, or perhaps by about 2150, if the rate of decrease were to ease. The result is quite sobering and highlights the magnitude of the challenge, especially given the rapid rate of decarbonization already occurring within the energy sector in the RETD ACES Scenario, as well as the favorable assumptions about non-energy GHG emissions reductions, the rate of reforestation that is sustained over a period of many decades and the expansion of biomass-CCS.

Figure 5. GHG Concentrations in the RETD ACES and Reference Scenarios Through 2100

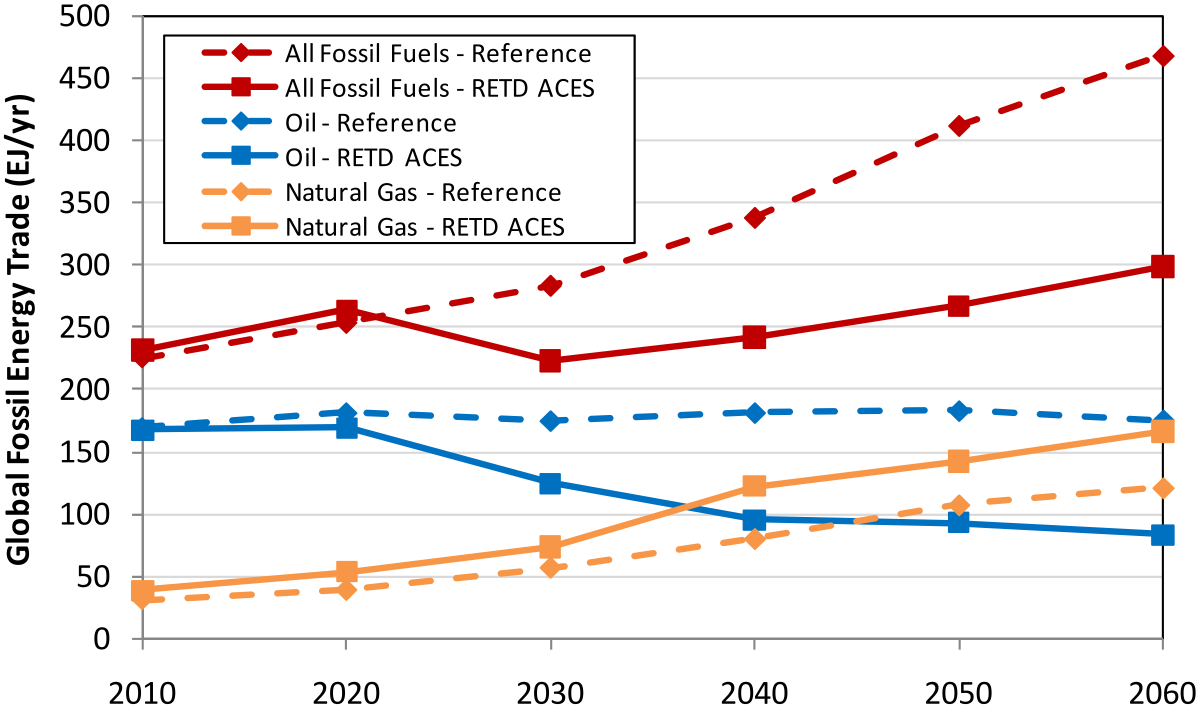


Note: Includes all sources and sinks of GHG emissions included in TIAM.

Global Energy Trade

The very real possibility that global trade in energy commodities would be reduced in an insecure world is part of the definition of the RETD ACES Scenario. In addition, the RETD ACES Scenario has lower total energy demand than the Reference Scenario. These two factors combined to drive down overall fossil fuel trade as is evident in the results of the analysis shown in Figure 6. Compared to the Reference Scenario, total fossil fuel energy trade is reduced by about 35% in the RETD ACES Scenario. Oil trade is also significantly reduced, as is coal trade (not shown), because of both lower total demand and the constraints on trade that are part of the definition of the RETD ACES Scenario. This situation results in a preference for the consumption of domestic resources (in that context, coal does benefit somewhat given its wide geographic availability). For natural gas, however, total trade increases in the RETD ACES Scenario, driven by slightly higher total demand for natural gas that results from the attractive carbon footprint of natural gas compared to other fossil fuels. Thus, even as the overall constraint on energy trade is maintained, trade of natural gas increases. It is important to note that natural gas usage in the scenario is subject to the assumptions about total resource availability embedded in the TIAM model and that the level of natural gas trade would be higher in a scenario with the climate targets of the RETD ACES Scenario but without the trade constraints.

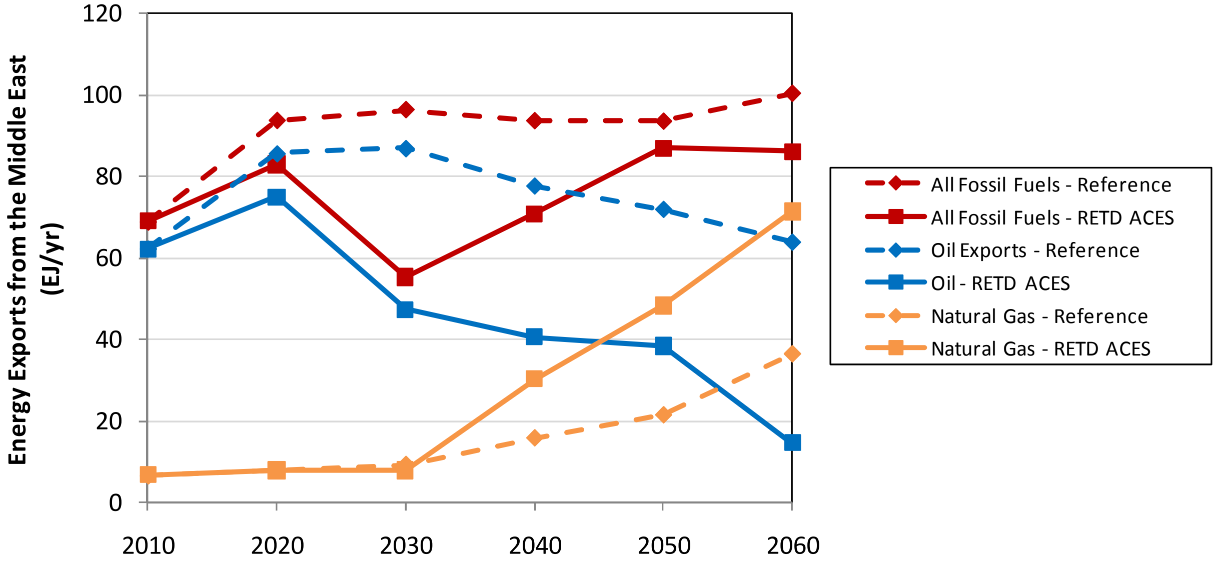
Figure 6. Total Fossil Energy Trade in the RETD ACES and Reference Scenarios Through 2060



Note: Includes trade in fossil fuels used for both energy and non-energy purposes. Oil includes petroleum and petroleum products.

The situation is similar for exports from the Middle East (MEA) (Figure 7). By 2060, oil exports from MEA drop by 75% in the RETD ACES Scenario compared to the Reference Scenario. However, natural gas exports rise considerably over the same timeframe. Overall, total energy exports from MEA are about 15% lower by 2060 in the RETD ACES Scenario compared to the Reference Scenario. In other words, in a climate constrained and unsecure world as described by the RETD ACES Scenario, natural gas dependence from MEA remains non negligible, while oil dependence is considerably reduced. These results, particularly the importance of natural gas, suggest that this should be an area of further analysis in the future, for example, by developing a more sophisticated view of potential energy trade constraints.

Figure 7. Energy Exports from Middle East in the RETD ACES and Reference Scenarios Through 2060



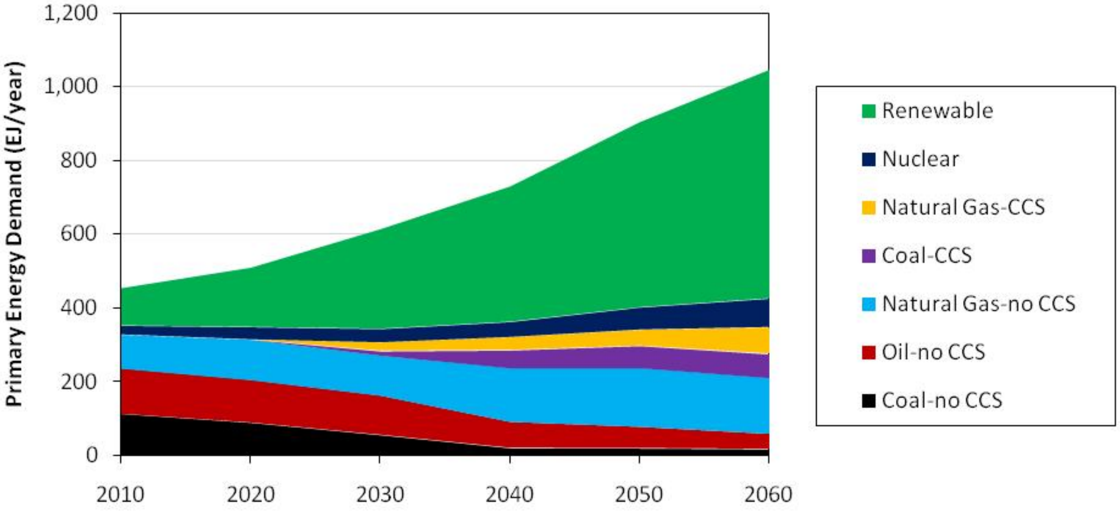
Note: Includes trade in fossil fuels used for both energy and non-energy purposes. Oil includes petroleum and petroleum products.

Energy Demand

Primary energy is an often reported metric for global energy modeling. It provides an indication of the relative importance of different energy resources for meeting overall energy demand, regardless of where or how it is used. For fuels that are transformed into electricity or other energy carriers – typically via combustion, such as coal, oil, natural gas, and biomass – it is relatively straightforward to measure the energy input (primary energy). It is simply the tonnes, cubic feet or gallons used, converted to energy units. However, for technologies that do not involve this type of transformation (nuclear power and all RE resources other than biomass), the notion of primary energy is less relevant, is not as readily measured, and is often misleading. For these resources, the energy output of the process, which is almost always electricity, is sometimes used as the primary energy. However, this understates their relative contribution to useful energy output by a factor of two to three because the efficiencies of combustion technologies in producing electricity are not factored into their primary energy values. Thus, when primary energy is reported in this paper for nuclear power and non-biomass RE, it is provided only after applying a fossil fuel substitution factor of 9 MJ/kWh. This value is consistent with a "typical" efficiency of electricity generation from fossil fuels of 40%. Doing so does a better job at showing the relative contributions of all energy resources to total energy supply. Effectively, it measures the contribution of nuclear power and non-biomass RE by estimating how much fossil fuel is displaced by these energy resources.

Figure 8 shows the primary energy demand for the RETD ACES Scenario through 2060 (energy use only – fossil fuels used for non-energy purposes are not included here). It shows the relatively rapid shift in coal use to technologies that only have CCS. Overall coal consumption falls by over 25% by 2060, but coal use without CCS falls by almost 85%. The situation for oil is similar – its consumption for energy purposes falls by over 65%. However, its use for non-energy purposes (not shown) continues to rise from about 31 EJ in 2010 to 54 EJ by 2060. The result is still an overall reduction in total oil use, even when non-energy uses are included, from about 147 EJ in 2010 to 93 EJ in 2060. The situation with natural gas is different, given its favorable GHG characteristics. For energy purposes, natural gas use rises from about 93 EJ in 2010 to a total of 227 EJ in 2060, of which 74 EJ is equipped with CCS. Thus, consumption increases for applications with and without CCS. Nuclear power generation roughly triples from 2010 to 2060. Such expansion would require the construction of roughly 530 1,000 MW nuclear power plants between 2010 and 2060, not including any additional plants needed to replace existing plants that might retire. Also evident from Figure 8 is that RE becomes the most important energy source sometime between 2030 and 2040, when it passes 50% of all primary energy supplies, up from about 20% today.

Figure 8. Primary Energy Demand in the RETD ACES Scenario Through 2060



Note: These values are for energy uses only. TIAM also calculates non-energy uses (e.g., petrochemicals). There are currently no technology options within TIAM for oil use with CCS. CCS plants include those for producing electricity and fuels. Biomass-CCS used only for the purpose of CO_2 removal is excluded. See discussion above for additional details.

Figure 9 shows similar primary energy data just for RE. Hydropower production grows modestly and steadily, almost tripling between 2010 and 2060, reflecting its relative maturity today. Biomass energy utilization grows more significantly to about 191 EJ/yr by 2050[41], after which point it levels off. This growth pattern reflects the fact that biomass has reached its maximum sustainable technical potential by about 2050, except for some small incremental increases after that time. Other RE technologies, comprised mainly of solar and wind power, show the greatest growth and continue to grow rapidly through 2060 and beyond.

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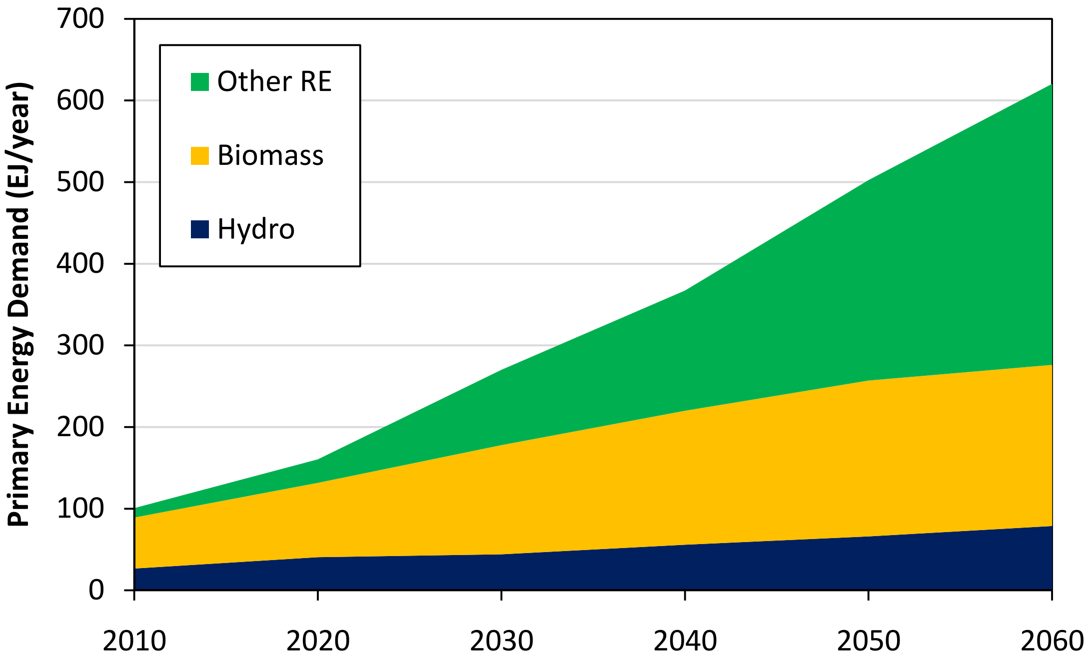
[41] The value excludes biomass-CCS for GHG mitigation only.

Figure 9. Primary Renewable Energy Demand in the RETD ACES Scenario Through 2060



Note: Biomass-CCS used only for the purpose of CO_2 removal is excluded. See discussion above for additional details.

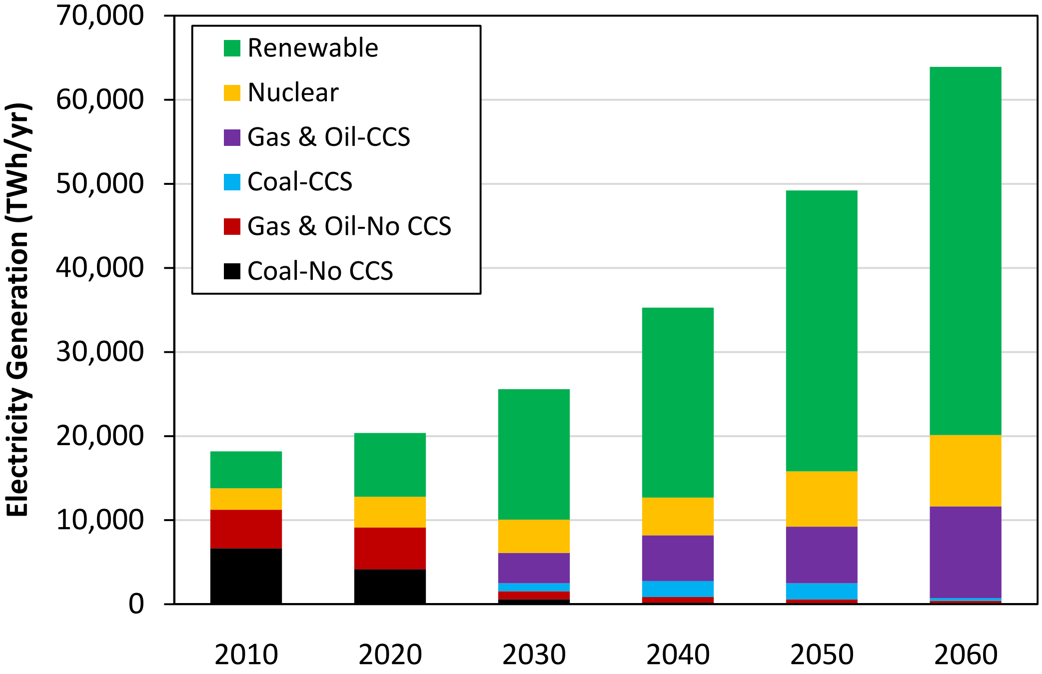
Another reporting metric used to characterize energy consumption by source is final energy demand, which represents the amount of energy consumed (i.e., the energy output). As such, it avoids the aforementioned drawbacks of the traditional primary energy calculation (i.e., that non-biomass RE and nuclear sources do not incur the same type of transformation losses as other fuels). Given that it represents the ultimate energy consumption, it also provides a useful metric for measuring the energy intensity/efficiency of scenarios. Compared to the Reference Scenario, total final energy consumption is significantly lower in the RETD ACES Scenario. By 2060, total final energy demand in the RETD ACES Scenario is 544 EJ, compared to 693 EJ in the Reference Scenario. The reduction, 22%, is due to the lower energy intensity of the economy, which is driven by two factors: (i) increasing efficiency of energy transformation and use, and (ii) reduced demands due to higher energy prices and improved access for consumers to energy usage information via the Smart Grid. One factor that prevents even steeper reductions in final energy demand when comparing the RETD ACES Scenario to the Reference Scenario is that many EE measures are implemented in the Reference Scenario, as they become cost effective over the course of the scenario timeframe.

In examining the energy demand figures discussed above, it is important to consider the total utilization of different energy resources compared to the estimated reserves available. In the RETD ACES Scenario through 2060, between 45-55% of conventional oil and natural gas reserves are consumed, but less than 5% of coal reserves are used. In the same timeframe, less than 2.5% of unconventional oil and natural gas reserves are used.

Electricity Production

In the RETD ACES Scenario, no other sector is more transformed than electricity. Several trends are apparent. First, as is evident in Figure 10, there is a rapid reduction in the use of fossil fuels for power generation, except where this usage is also accompanied by CCS, which is assumed to be available commercially starting in 2020. As a result, electricity generation is virtually decarbonized by 2030. This reflects the fact that it is relatively easier to decarbonize electricity generation compared to other types of energy (i.e., liquid transportation fuels and direct fuel use in buildings, agriculture and industry). Moreover, because of the strict GHG reduction targets, natural gas with CCS is preferred over coal with CCS. Even with CCS, these power plants still emit some CO_2 (about 90% of the CO_2 is captured), and as such, even coal with CCS is at a disadvantage in the RETD ACES Scenario, given the strict climate target and the fact that that there are other options with lower CO_2 emissions.

Figure 10. Electricity Generation by Fuel Type in the RETD ACES Scenario Through 2060



Note: TIAM reports natural gas and oil capacity together. However, the bulk of this is fueled with natural gas and all "gas & oil-CCS" is fueled with natural gas. Biomass-CCS used only for the purpose of CO_2 removal is excluded. See discussion above for additional details.

Collectively, RE becomes the largest contributor to electricity generation and capacity sometime before 2030, with RE generation rising from about 22% in 2007 to 61% by 2030 (capacity percentages are higher due to lower average capacity factors for RE compared to other options). All RE technologies grow significantly (Figure 11 and Figure 12). Wind and biomass see the largest increases in generation, whereas wind and PV see the greatest growth in capacity through 2060.[42] Other RE technologies that contribute less through 2060, see robust growth after 2060 (not shown), most notably solar thermal electric and solar PV. The lag in adoption for some RE technologies is most likely the result of both the assumed technology characteristics and the way in which policy is represented in the RETD ACES Scenario, which is largely technology neutral.

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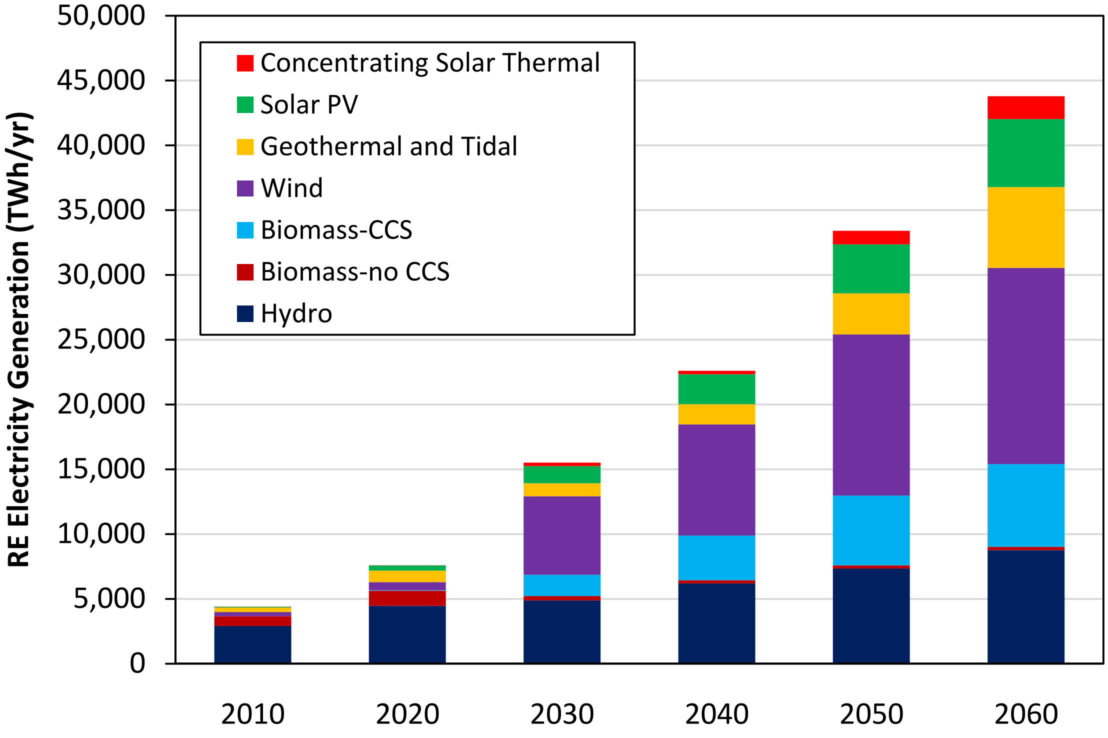
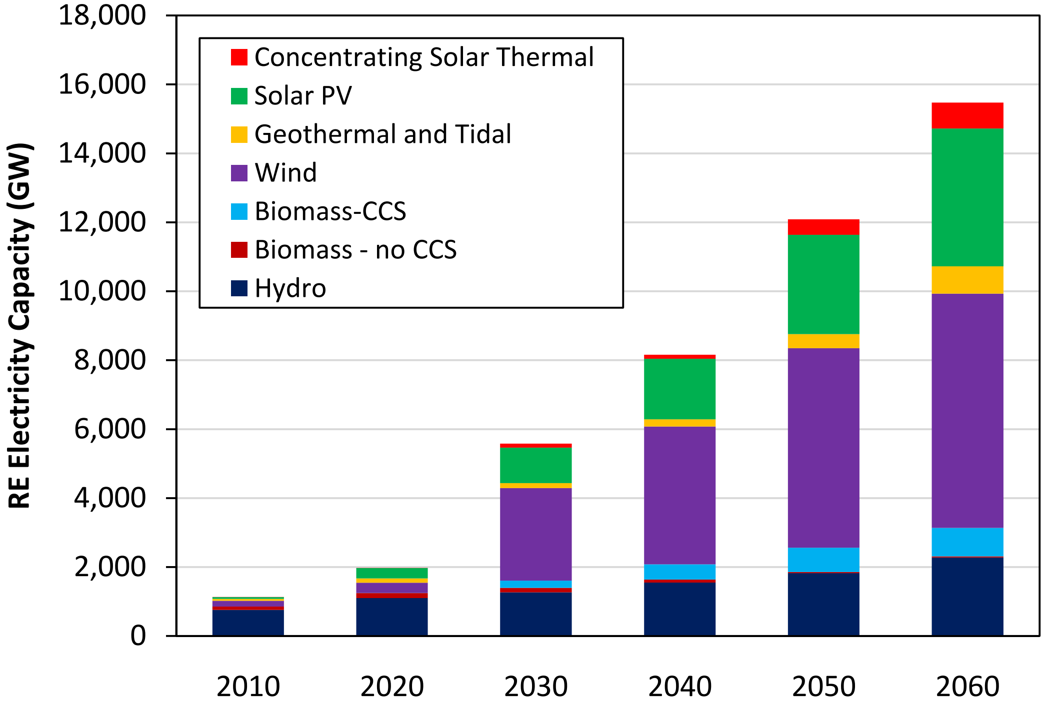
[42] PV has a lower capacity factor than other RE technologies. Thus, even though it is second only to wind in terms of installed capacity, other technologies with higher capacity factors produce more electricity.

Figure 11. Renewable Electricity Generation by Type in the RETD ACES Scenario Through 2060



Note: Biomass-CCS used only for the purpose of CO_2 removal is excluded. See discussion above for additional details.

Figure 12. Renewable Electricity Capacity in the RETD ACES Scenario Through 2060



Note: Biomass-CCS used only for the purpose of CO_2 removal is excluded. See discussion above for additional details.

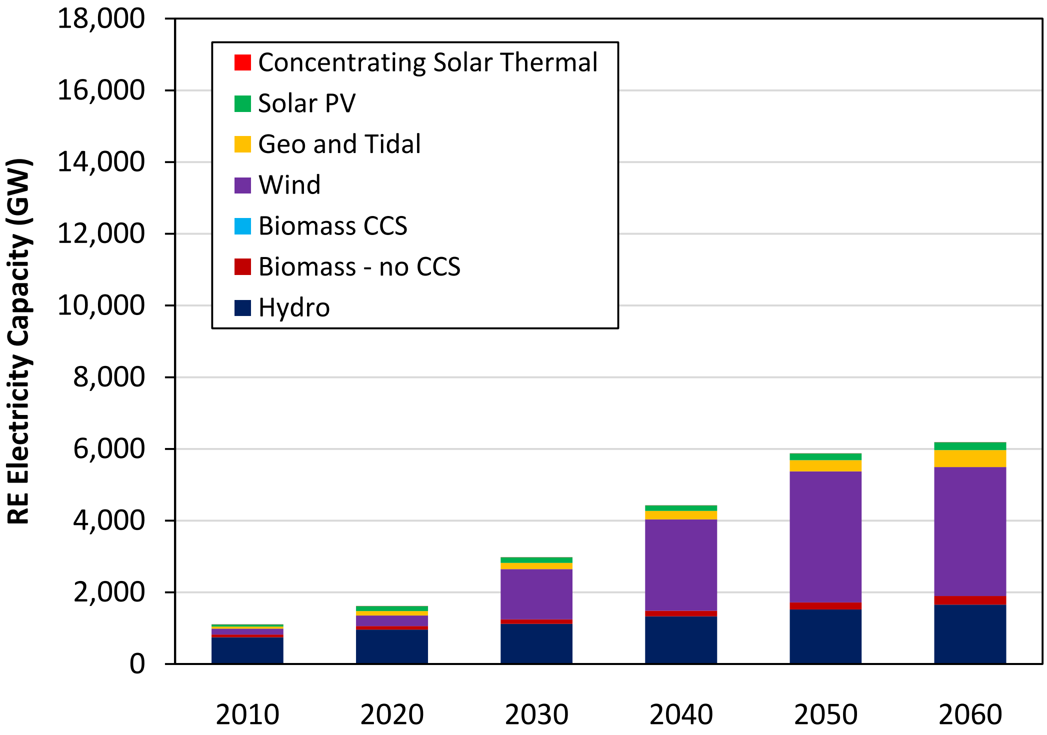
As fossil fuels (without CCS) are largely phased out in favor of carbon neutral and negative options, electricity generation as a whole becomes, on average, carbon negative. After 2030, the global electricity mix is composed mainly of (i) fossil fuels with CCS (still mildly carbon positive), (ii) nuclear power and RE (essentially carbon neutral) and (iii) biomass with CCS (quite strongly carbon negative).

An important, underlying assumption in the analysis is that biomass is grown and harvested on a sustainable basis. In general, the importance of biomass-CCS, as well as reforestation, within the RETD ACES Scenario suggests that the whole issue of biomass availability and use is a very important topic for further analysis and for sound policy formulation. The RETD recognized this even before developing the RETD ACES Scenario, and undertook a separate project entitled, "Better Use of Biomass Energy".[43]

The availability of carbon negative electricity results in significant fuel switching to electricity in all sectors of the economy where this is technically possible, driven by the strict GHG reduction targets of the RETD ACES Scenario. This switching drives demand for electricity higher, as seen in Figure 10, even as total energy consumption in the RETD ACES Scenario is lower than total energy consumption in the Reference Scenario. In the RETD ACES Scenario, total electricity demand grows steadily at about 2% per year through 2060. Thus, even though the growth in electricity production seems large, the rate of growth is similar to historical global growth rates for electricity generation.

The situation in the Reference Scenario differs dramatically from the RETD ACES Scenario results. RE electricity capacity is about half of what is achieved in the RETD ACES Scenario by 2060 (Figure 13). Wind power dominates, followed by hydropower. Other technologies only see incremental growth.

Figure 13. Renewable Electricity Capacity in the Reference Scenario Through 2060



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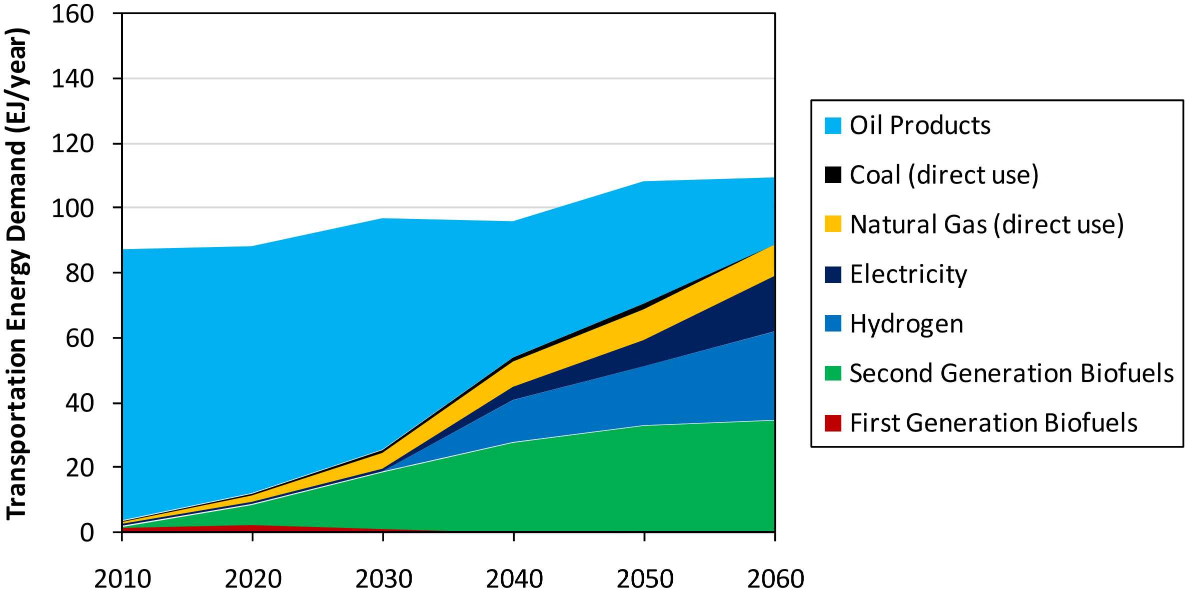
[43] More information on the RETD's "Better Use of Biomass Energy" project is available at http://www.iea-retd.org/page.aspx?idsection=62.

Transportation

In the RETD ACES Scenario, transportation energy demand grows by about 25%, from about 87 EJ in 2010 to 110 EJ in 2060 (Figure 14). Demand for transportation services (e.g., kilometers driven, tonnes of freight transported) grows much faster. The implication of this is that the efficiency of the transport sector improves significantly. At the same time, consumption of oil products falls by about 75% from 2010 to 2060. The main substitutes are second generation biofuels (biofuels made from non-food sources of biomass), hydrogen, and electricity. Although electricity use only reaches about 16% of transportation energy demand by 2060, it is used much more efficiently than other transport fuels, and as such, satisfies a much higher share of the demand for transportation services.[44] As with electricity from biomass, second generation biofuels plants equipped with CCS are preferred over those without CCS in the RETD ACES Scenario. It is important to note that for biofuels production, CO_2 removal is generally a required process step in fuel synthesis.[45] Thus, CO_2 capture does not result in significant additional costs or energy penalty, although the CO_2 would still need to be stored, transported and sequestered.

Figure 14. Transportation Energy Demand in the RETD ACES Scenario Through 2060 (All Uses)



The situation in the Reference Scenario is quite different (Figure 15). First, total transportation energy demand is higher, reaching about 140 EJ by 2060. The resource mix is also dramatically different. While first generation biofuels (those based on food crops) supply a larger share of the fuel mix compared to the RETD ACES Scenario, second generation biofuels supply much less. Moreover, the dominant technology option after petroleum is coal-to-liquids technology. This technology is the most cost effective option for replacing petroleum-based fuels, although petroleum remains the most important fuel through 2060.

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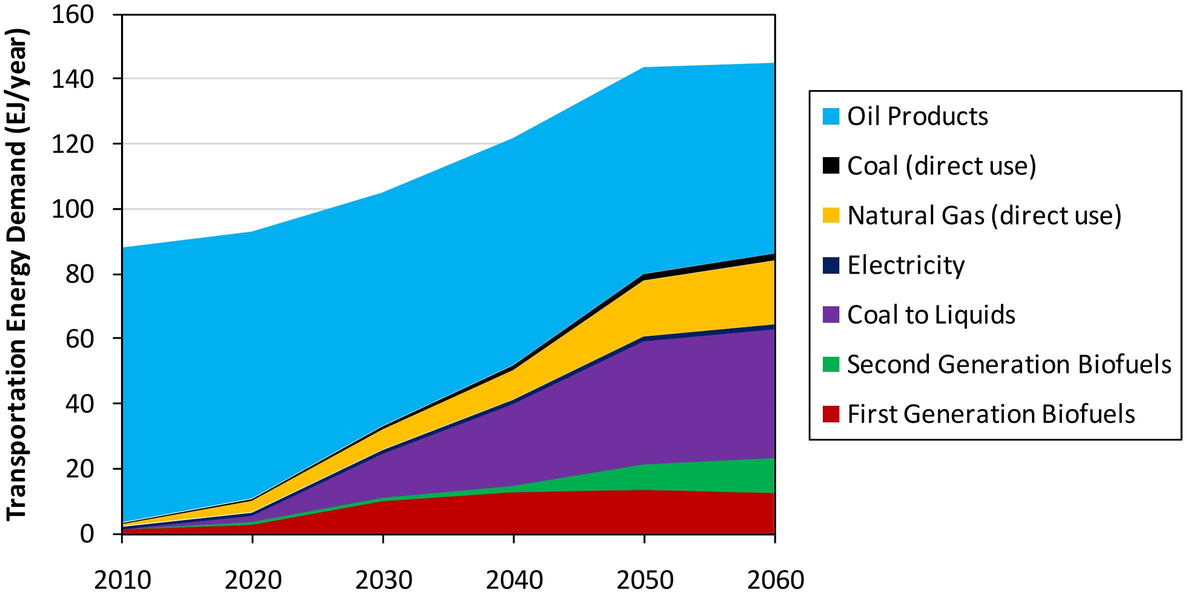
[44] Even at today's efficiencies, electric vehicles get the equivalent of about 140 miles per (U.S.) gallon of gasoline.

[45] Second generation biofuels plants equipped with CCS are similar to biomass-CCS in that they have a carbon negative profile and are allowed to compete with the mitigation options. However, unlike biomass-CCS for electricity, the competition between mitigation options does not result in the deployment of second generation biofuels plants with CCS beyond what is necessary to meet transportation demand.

Figure 15. Transportation Energy Demand in the Reference Scenario Through 2060 (All Uses)



Note: The TIAM model includes coal-to-liquids production for use in transport and non-transport applications. This chart assumes 50% of total coal-to-liquids output is used in transportation.

Costs and Benefits of the RETD ACES Scenario

The RETD ACES Scenarios presents a future that is dramatically different than the one of the Reference Scenario, at least as far as energy supply and demand are concerned. Arguably, the RETD ACES Scenario also represents a significant departure from "business as usual". Thus, a key question that arises is, "what is the cost of this scenario?" Said another way, is the RETD ACES Scenario also dramatically different from an economic point of view?

Table 2 laid out a range of principles that the RETD has identified as being essential for scenarios of the global energy system. One of these was to include the full range of economic costs and benefits of different pathways for the global energy system. The direct costs can be reasonably estimated using existing energy-economic models like TIAM, including capital investments, fuel costs, and O&M costs for energy exploration, production, transformation, transport, and end use. The captured costs would also include the costs of policies, such as imposing a price on GHG emissions. From a climate change perspective, the differences in these costs between the RETD ACES Scenario and the Reference Scenario can be understood as the costs of climate change mitigation. Yet, in order to have a complete picture of the economics of a scenario, these mitigation costs must be compared to other economic costs, advantages and/or savings resulting from:

- Reduced climate change adaptation costs
- Job creation and rural economic development
- Reduced energy price volatility
- Enhanced security, including reduced military spending
- Reduced damage from other types of pollution that would be reduced (e.g., acid rain, particulates, mercury)

These additional economic considerations are harder to estimate and typically fall outside of traditional economic models of the global energy system. Yet they all have real economic value. There is as of yet, no single model that can effectively estimate and optimize investment decisions around this full range of economic factors. Thus, it is necessary to continue primarily examining the direct costs and drawing reasonable conclusions from the data.

The results of the RETD ACES Scenario, as well as recent work by others strongly suggests that, even in the absence of concrete estimates for these additional economic benefits, the magnitude of the benefits is likely to exceed any direct mitigation costs. It is possible that the reduction of climate change adaptation costs, which have the potential to be very large, could offset a substantial portion, if not all, of the cost of mitigation.[46] This possibility results partly from the fact that the estimated climate change mitigation costs, even for aggressive climate change mitigation scenarios (like the RETD ACES Scenario, the 450 Policy Scenario of the WEO 2009 and the BLUE Map Scenario of the ETP 2008), measured on a lifecycle basis, turn out to be relatively small. Thus, even if the benefits described above are modest in scope, they are likely to more than make up for any mitigation costs. Of course, the mitigation costs are contingent on successfully achieving the technology cost and performance characteristics assumed for each of the scenarios.

With this in mind, climate change mitigation measures are better thought of as investments rather than costs, and instead of asking "what is the cost of this scenario?", the question one might ask is, "what is the cost of inaction?", or "what is the return on my investment in this scenario vs. another scenario?" (where this return includes traditional financial returns but also other economic benefits).

The TIAM model provides an estimate of the net present value (NPV) of all direct costs of the energy system, including costs associated with policies, such as a price on CO_2. The model uses a "social" discount rate of 5%.[47] The results are shown in Table 4.

Table 4. Estimated Economics of the RETD ACES Scenario Compared To Reference, 2010-2060

Incremental NPV over Reference ($2008 trillion, discounted)	$14.3
Incremental NPV (as % of total cumulative global GDP)	1%

Note: NPV calculations include the direct costs associated with the energy system only.

For the period 2010-2060, the RETD ACES Scenario has a total discounted cost associated with the energy system that is approximately $14.3 trillion higher than the Reference Scenario. However, over this same timeframe, total, cumulative discounted global GDP is expected to be about $1,400 trillion.[48] Thus, the total incremental cost of the RETD ACES Scenario compared to the Reference Scenario is only about 1% of total cumulative GDP for the period 2010-2060. Said another way, the total cost of mitigation for the RETD ACES Scenario over the next 50 years is less than four months of current global economic output. Given the wide range of benefits that will result from the RETD ACES Scenario, one can reasonably assume that the value of the as-yet-to-be quantified benefits will likely exceed this modest incremental investment in climate change mitigation, possibly by a wide margin. While achieving the

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[46] Just as there is no one pathway for mitigating climate change, there is no single pathway that describes potential climate change impacts and adaptation costs. Certainly, there is (at least) a small probability of very large adaptation costs. This possibility suggests that statistically, adaptation costs could amount to several percent of global GDP, and would therefore easily be larger than mitigation costs (Stern, 2008).

[47] The question of what discount rate to use is an interesting one. In this type of analysis, the purpose of discounting is not to perform a traditional financial analysis of an investment. If that were the case, then one would apply discount rates similar to those applied to energy technologies (see Table 3, for example). Here, one is actually using a discount rate to measure the costs of climate change mitigation investments now against benefits far into the future. Doing this is somewhat akin to asking a parent if they value their own wellbeing more than that of their children. In this context, one could therefore argue for a low discount rate, hence the choice of 5% as a suitable "social" discount rate. A parent might actually chose to apply a negative discount rate (if that were possible) since ensuring a bright future for one's children would trump any near-term costs that would need to be incurred.

[48] Global annual GDP in TIAM is expected to grow from about $54 trillion/yr in 2010 to $175 trillion/yr in 2060 (in constant dollars). This value is fixes and independent of the scenario.

technology development necessary to make the RETD ACES Scenario a reality will not be easy, it is important to note that many of the same assumptions were used in the Reference Scenario, and care has been taken to ensure that assumptions about fossil fuel and RE technologies are internally consistent. On balance, the results suggest that there is a strong economic motivation for pursuing climate change mitigation as aggressively as possible.

It is also helpful to compare these results to those of other recent similar studies (Table 5).[49] In particular, in the WEO 2009, they estimate the incremental costs and savings of the 450 Policy Scenario compared to their Reference Scenario (IEA, 2009). The results of that work are remarkably similar to the results of the RETD ACES Scenario. In the WEO 2009, $10.5 trillion in net incremental investments are required for the period 2010-2030 to put the energy system on a pathway to achieving the climate stabilization objectives of the 450 Policy Scenario. These investments result in $17.1 trillion in reduced energy costs over the life of the investments. The WEO 2009 further reported that at a 3% discount rate, there are net savings of $3.6 trillion, while at a 10% discount rate, there are still net savings of $450 billion over the lifetime of the investments. Thus, the conclusion from the WEO 2009 is that working aggressively towards a climate target of 450 ppm CO_2-eq is economically superior to the inaction associated with its Reference Scenario. While the costs of continued aggressive mitigation are likely to climb beyond 2030, as suggested by the results of the RETD ACES Scenario, the message is still clear – that aggressive climate change mitigation has negligible direct incremental costs, and may even be economically superior to inaction, even without factoring in the potentially substantial benefits beyond direct energy cost savings.

The ETP 2008 (IEA, 2008b) provides similar estimates of direct energy system costs and benefits. The BLUE Map scenario targets a similar climate objective as the 450 Policy Scenario of the WEO 2009 – specifically, it targets a 50% reduction in energy-related CO_2 by 2050 compared to 2005. The results of the BLUE Map Scenario are similar as well. The scenario requires incremental investments of $45 trillion from 2005 to 2050, equal to about 1.1% of cumulative GDP over the same period. However, these investments yield $50.6 trillion in (undiscounted) fuel savings over the same period. At discount rates of 3% and 10%, the net incremental costs of the BLUE Map Scenario are $0.8 trillion and $2.1 trillion respectively. Thus, here too, when compared to the size of the global economy, the direct incremental costs of aggressive climate mitigation are small – much less than 1% of cumulative global GDP.[50] It is also worth noting that the ETP 2008 used energy prices that were much lower than in the WEO 2009 – it assumed oil would reach just $65/bbl ($2006) by 2050.

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[49] It is worth pointing out that these scenario results are all presented relative to their own reference or baseline scenarios, each with its own assumptions. However, the TIAM Reference Scenario is arguably the most "pessimistic" with respect to existing policies for RE and other low-carbon technologies. Thus, all else equal, one would expect a larger cost differential for the RETD ACES Scenario. Said another way, the reference/baseline scenarios for the WEO and ETP, since they already include existing policies, already include some of the mitigation costs.

[50] Both the TIAM model and the model used for the ETP 2008 exclude upstream capital investments in the production and transportation of coal, oil and natural gas. Since demand for these fuels is lower in the BLUE Map and RETD ACES Scenarios compared to their respective reference scenarios, this would be a source of additional savings not included in the figures presented here. In the WEO 2009 450 Policy Scenario, it was reported that the investments in these upstream fuel supply chains for 2008-2030 is $2.1 trillion lower than for the WEO 2009 Reference Scenario.

Table 5. Estimated Economics of the WEO 2009 and ETP 2008

	WEO 2009	**ETP 2008**
Analysis timeframe	2010-2030	2005-2050
Incremental Investment over Reference ($ trillion)	$10.5	$45
Incremental fuel costs savings over reference ($ trillion)	$17.1	$50.6
Net costs (savings) ($ trillion)	($6.6) undiscounted ($3.6) @ 3% discount rate ($0.45) @ 10% discount rate	($5.6) undiscounted $0.8 @ 3% discount rate $2.1 @ 10% discount rate

Note: NPV calculations include the direct costs associated with the energy system only. Savings are over the life of the investments made through the analysis timeframe.

Finally, in a similar study for the United States, the Union of Concerned Scientists (UCS, 2009) estimated that reducing GHG emissions by 56% below 2005 levels by 2030 would actually produce a cumulative net savings of $1.7 trillion.[51]

A consistent message is emerging from these analyses – that aggressive climate change mitigation is not only economically feasible, but that it has minimal impact on GDP growth, and may actually be economically superior even when only direct costs and savings are considered. If one factors in the wide range of economic and security benefits that will result from the investments, a compelling case emerges for taking immediate and significant action to reduce GHG emissions.

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[51] The UCS used a modified version of the National Energy Modeling System, a detailed model of the U.S. energy system similar in scope and methodology to TIAM. It is maintained by U.S. Department of Energy, Energy Information Administration.

5. Conclusions

This report presents the results of the RETD's first effort at modeling the global energy system, in collaboration with the ETSAP Implementing Agreement. The RETD created a scenario that achieves dramatic reductions in GHG emissions in a world characterized by growing linkages between climate change and security.

The results of this project are both encouraging and sobering. The future as described by the RETD ACES Scenario is both technically and economically feasible, and the RETD believes it is likely to be economically superior to a future characterized by inaction on either climate change or security. The RETD ACES Scenario is achieved at an incremental cost of about 1% of cumulative global GDP for the period 2010-2060, during which global annual GDP is expected to more than triple. This result is consistent with several other similar independent analyses conducted with different models and assumptions.

Importantly, the economic analysis does not include benefits from reduced climate change adaptation costs, rural economic development, clean energy jobs, enhanced security and reduced energy price volatility. Although it is difficult to estimate the value of these benefits, it is also difficult to imagine that these benefits will be smaller than the modest incremental costs of the RETD ACES Scenario over the Reference Scenario. The result is a compelling argument for pursuing aggressive climate change mitigation.

In order to achieve the goals of the RETD ACES Scenario, immediate and dramatic steps must be taken to transform the energy sector from one dominated by large centralized fossil-fuel infrastructure, to one dominated by RE. The RETD ACES Scenario is also characterized by a more diverse mix of both centralized and distributed energy generation. Energy efficiency is also a key part of the solution, with the RETD ACES Scenario requiring about 22% less final energy consumption than the Reference Scenario in 2060. Moreover electricity becomes the most important energy carrier, since it is more easily decarbonized than other options. In the RETD ACES Scenario, electricity is essentially carbon free by 2030, which in turn drives demand for electricity at a faster pace than total energy demand, as other fuels are replaced by electricity in a range of end uses, including transportation.

The main driver for RE deployment in the RETD ACES Scenario is the climate constraint. However, the role of enabling technologies, including the Smart Grid and CCS, is also critical. The Smart Grid is necessary for integrating large amounts of intermittent RE generation (and DG more broadly). It also helps to reduce the cost of the RETD ACES Scenario by improving this integration. Sensitivity analysis conducted with the TIAM model showed that without a climate constraint, the Smart Grid helped increase the share of RE, whereas with a carbon constraint, the Smart Grid led to a lower carbon price and lower total cost. It is also expected to contribute to lower overall energy consumption by providing consumers with better information on energy use and the tools to manage that energy use.

CCS is important for both fossil fuels and biomass, and for both electricity generation and transportation fuel production. In particular, the attractiveness of biomass-CCS is a result of the strong climate constraint in the RETD ACES Scenario. If CCS technology is not commercialized, or is less successful than assumed in the RETD ACES Scenario, then to meet the same level of energy demand with the same GHG emissions reductions will require some combination of: higher levels of EE, greater use of other RE options (including biomass without CCS), greater use of nuclear power, greater levels of reforestation, greater use of other mitigation options (e.g. atmospheric scrubbing of CO_2), and greater reductions in non-energy GHGs. These results along with the particularly strong penetration of the biomass-CCS technology, make a strong case for developing a better understanding of the potential for CCS technology, especially at the smaller scale required for biomass applications compared to fossil fuel applications.

In the RETD ACES Scenario, the total amount of biomass required is at the upper end of what is assumed to be available on a sustainable basis. At the same time, reforestation also plays an important role in the scenario results. Thus, the overall role of biomass is quite important. It also highlights the importance of addressing the sustainability of increased bioenergy utilization in parallel to reversing the trend of deforestation.

Throughout the course of the project a number of improvements to both the RETD ACES Scenario and the TIAM model have been identified. The TIAM model is already a very flexible tool in that it can incorporate rapid changes in technology mix that is characteristic of very aggressive GHG reduction scenarios. Nevertheless, modeling such scenarios presents some unique modeling challenges (for TIAM and other global energy-economic models). To the RETD's knowledge, there are no published reports where similar models have been used to model a 400 ppm CO_2-eq target, and in cases where 450 ppm CO_2-eq targets are modeled, models often fail to converge. For example, see Clarke, et. al (2009), which highlights the difficulties and challenges of modeling strict climate targets with existing energy-economic models. Given these challenges, coupled with the need for additional analysis of scenarios with deep GHG reductions, potential improvements to TIAM include the following:

TIAM model enhancements

- Energy storage at the T&D levels could be added to the model along with a more detailed representation of the Smart Grid.
- Baseline assumptions about energy demand growth and the EE modeling methodology could be reassessed. More specifically, alternative macro-economic drivers and decoupling factors between the demands for energy services and these macro-economic drivers could be explored.
- Additional information about ocean energy resources and technologies and synthetic fuels technologies could be incorporated into the model.
- The expected penetration of electric vehicles could be further refined.
- The ability to substitute transport modes (e.g., public transit for personal vehicle travel) could be incorporated into the model.
- The methodology for nuclear power potential could be modified to replace the upper and lower bound approach with a fuel cycle approach, so that the technology is allowed to compete on a similar basis to the other technologies.
- Inclusion of additional GHG mitigation options and greater flexibility for fuel substitution in transport, agriculture and industry (to the extent that this is technically feasible). This could allow for greater penetration of electricity into these sectors, which appears to be necessary to meet aggressive GHG targets without running into issue of overproduction of electricity (as occurred with biomass-CCS).

Scenario improvements

- Probabilistic modeling methods could be used to allow for the incorporation of uncertainty in key variables (note that the TIAM model already has this capability).
- The scenarios could add a more detailed assessment of policy options for achieving the climate and security objectives.
- The representation of security constraints placed on the global energy system could be refined (e.g., examining restrictions on fossil fuel trade for each fuel rather than for fossil fuels as a single group and assessing the need for a security-based constraint on the export of natural gas from Russia to Europe).

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Annex I: Power Generation Technology Assumptions

While it is not possible to provide all the assumption used in the analysis, the assumptions used for power generation technologies are presented below. Additional documentation about the TIAM model can be found at http://www.kanors.com/DCM/TIAM/Docs/Index.aspx.

Technology Group	Technology	Year	Installed Costs (U.S. $2009/kW)*	O&M (U.S. $2009/kW)*	Efficiency (%)	Technology Lifetime (Years)	Year Available
Biomass	**Biomass Combustion - Biogas from Waste**	2010	$2,970	$180	30%	30	available now
		2020	$2,800	$180	32%	30	
		2060	$2,500	$180	35%	30	
Biomass	**Biomass Combustion - Solid Biomass**	2010	$3,470	$195	30%	30	available now
		2020	$3,300	$195	32%	30	
		2060	$3,200	$195	33%	30	
Biomass	**Biomass Gasification - Solid Biomass**	2010	$3,920	$301	36%	30	available now
		2020	$3,500	$285	38%	30	
		2060	$3,200	$261	40%	30	
Biomass	**Biomass Gasification - Solid Biomass - with CCS**	2010	n/a	n/a	n/a	n/a	2020
		2020	$5,250	$358	32%	30	
		2060	$4,200	$281	38%	30	
Biomass	**Biomass Gasification - Solid Biomass - Decentralized**	2010	$4,310	$282	33%	30	available now
		2020	$3,850	$267	36%	30	
		2060	$3,300	$245	38%	30	
Geothermal	**Geothermal - Conventional**	2010	$2,280-3,180	$45-64	n/a	40	available now
		2020	$2,190-3,070	$44-61	n/a	40	
		2060	$2,000-2,700	$40-54	n/a	40	
Geothermal	**Geothermal - Hot Dry Rock**	2010	$16,410	$328	n/a	40	available now
		2020	$13,320	$266	n/a	40	
		2060	$4,690	$94	n/a	40	

Technology Group	Technology	Year	Installed Costs (U.S. $2009/kW)*	O&M (U.S. $2009/kW)*	Efficiency (%)	Technology Lifetime (Years)	Year Available
Hydropower	**Conventional Hydropower - Impoundment**	2010	$1,110-4,070	$39-124	n/a	100	available now
		2020	$1,100-4,000	$39-121	n/a	100	
		2060	$1,060-3,780	$35-107	n/a	100	
Hydropower	**Conventional Hydropower - Run-of-River**	2010	$2,680	$76	n/a	100	available now
		2020	$2,680	$76	n/a	100	
		2060	$2,680	$76	n/a	100	
Municipal Solid Waste	**Waste Combustion - Municipal Solid Waste**	2010	$5,920	$236	25%	30	available now
		2020	$5,500	$236	25%	30	
		2060	$5,000	$236	25%	30	
Solar	**Solar Photovoltaic - Centralized**	2010	$4,560	$30	n/a	23	available now
		2020	$2,900	$19	n/a	26	
		2060	$1,950	$13	n/a	30	
Solar	**Solar Photovoltaic - Decentralized**	2010	$5,330	$30	n/a	21	available now
		2020	$3,710	$19	n/a	24	
		2060	$2,290	$14	n/a	25	
Solar	**Concentrating Solar Thermal**	2010	$4,940	$71	n/a	25	available now
		2020	$4,560	$70	n/a	25	
		2060	$2,931	$60	n/a	25	
Wind Power	**Wind - Onshore - Centralized**	2010	$1,690	$46	n/a	21	available now
		2020	$1,640	$43	n/a	22	
		2060	$1,430	$34	n/a	25	
Wind Power	**Wind - Onshore - Decentralized**	2010	$1,990	$58	n/a	21	available now
		2020	$1,940	$53	n/a	22	
		2060	$1,710	$39	n/a	25	
Wind Power	**Wind - Offshore - Centralized**	2010	$3,070	$99	n/a	20	available now
		2020	$2,920	$91	n/a	22	
		2060	$2,430	$68	n/a	25	
Coal	**Air-Blown IGCC**	2010	$2,940	$99	43%	30	available now
		2020	$2,700	$90	45%	30	
		2060	$2,700	$89	46%	30	
Coal	**Oxygen-Blown IGCC**	2010	$3,240	$113	43%	30	available now
		2020	$3,000	$104	45%	30	
		2060	$3,000	$103	46%	30	

Technology Group	Technology	Year	Installed Costs (U.S. $2009/kW)*	O&M (U.S. $2009/kW)*	Efficiency (%)	Technology Lifetime (Years)	Year Available
Coal	**Oxygen-Blown IGCC - with CCS**	2010	n/a	n/a	n/a	n/a	2020
		2020	$4,000	$153	39%	30	
		2060	$3,600	$126	43%	30	
Coal	**Atmospheric Fluidized Bed**	2010	$4,070	$124	n/a	30	available now
		2020	$4,000	$121	n/a	30	
		2060	$3,780	$107	n/a	30	
Coal	**Pressurized Fluidized Bed**	2010	$3,200	$106	40%	30	available now
		2020	$3,200	$106	42%	30	
		2060	$3,200	$106	45%	30	
Coal	**Fuel Cell (SOFC) - with CCS**	2010	n/a	n/a	n/a	n/a	2035
		2020	n/a	n/a	n/a	n/a	
		2060	$3,500	$254	41%	30	
Coal	**Pulverized Coal**	2010	$3,000	$97	44%	30	available now
		2020	$3,000	$93	45%	30	
		2060	$3,000	$89	47%	30	
Coal	**Pulverized Coal - with CCS (CO_2 Removal from Flue Gases)**	2010	n/a	n/a	n/a	n/a	2020
		2020	$4,000	$182	32%	30	
		2060	$3,500	$182	38%	30	
Coal	**Pulverized Coal - with CCS (Oxy-fueled)**	2010	n/a	n/a	n/a	n/a	2020
		2020	$4,000	$211	30%	30	
		2060	$3,300	$211	34%	30	
Natural Gas/Oil	**Natural Gas Fuel Cells**	2010	$5,400	$417	42%	30	available now
		2020	$2,800	$176	51%	30	
		2060	$2,000	$146	55%	30	
Natural Gas/Oil	**Natural Gas Fuel Cells - with CCS**	2010	n/a	n/a	n/a	n/a	2030
		2020	n/a	n/a	n/a	n/a	
		2060	$2,500	$154	47%	30	
Natural Gas/Oil	**Simple Cycle Gas Turbine - Centralized**	2010	$500	$28	36%	30	available now
		2020	$500	$26	38%	30	
		2060	$500	$26	38%	30	

Technology Group	Technology	Year	Installed Costs (U.S. $2009/kW)*	O&M (U.S. $2009/kW)*	Efficiency (%)	Technology Lifetime (Years)	Year Available
Natural Gas/Oil	**Combined Cycle Gas Turbine - Centralized**	2010	$1,000	$40	52%	30	available now
		2020	$1,000	$37	54%	30	
		2060	$1,000	$37	56%	30	
Natural Gas/Oil	**Natural Gas Combined Cycle - with CCS (CO_2 Removal from Flue Gases)**	2010	n/a	n/a	n/a	n/a	2020
		2020	$1,500	$74	46%	30	
		2060	$1,300	$63	52%	30	
Natural Gas/Oil	**Natural Gas Combined Cycle - with CCS (Oxy-fueled)**	2010	n/a	n/a	n/a	n/a	2030
		2020	n/a	n/a	n/a	n/a	
		2060	$1,270	$64	55%	30	
Natural Gas/Oil	**Natural Gas - Thermal Steam**	2010	$2,000	$59	35%	30	available now
		2020	$2,000	$59	35%	30	
		2060	$2,000	$59	35%	30	
Natural Gas/Oil	**Oil-Fired Baseload - Decentralized**	2010	$1,500	$159	36%	30	available now
		2020	$1,500	$159	38%	30	
		2060	$1,500	$159	40%	30	
Natural Gas/Oil	**Oil-Fired Peak Load - Decentralized**	2010	$1,200	$251	36%	20	available now
		2020	$1,200	$251	38%	20	
		2060	$1,200	$251	40%	20	
Natural Gas/Oil	**Oil - Thermal Steam**	2010	$2,000	$62	35%	30	available now
		2020	$2,000	$62	35%	30	
		2060	$2,000	$62	35%	30	
Nuclear	**Nuclear**	2010	$3,550-4,020	$152-172	n/a	40	available now
		2020	$3,550-4,020	$152-172	n/a	40	
		2060	$3,550-4,020	$152-172	n/a	40	

*Note: For technologies with multiple resource classes, ranges are presented.