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Article

A Sustainable Energy Scenario for the United States: Year 2050

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Abstract: This paper presents a scenario depicting life in the United States in the year 2050. The scenario is designed to achieve energy sustainability: fossil fuels and corn ethanol have been replaced by other sustainable and inexhaustible energy sources. The scenario describes the disappearance of the suburbs, replaced by a mix of high density urban centers and low density eco-communities. A suite of advanced technologies and significant social changes underpin the scenario. Analysis of the energy implications inherent in the scenario suggest that total US energy consumption would be around 100 quads in 2050, approximately the same as in the year 2010 despite a forecasted population increase of 130 million.

Keywords: sustainable energy systems; national energy portfolios; scenario analysis; futures methods; obligations to future generations

1. Introduction

> "*Energy sustainability is of great importance to overall sustainability given the pervasiveness of energy use, its importance in economic development and living standards, and its impact on the environment.*" [1]

This paper explores this question: is it possible for the United States to meet its energy needs sustainably without fossil fuels and corn ethanol? It can be argued that energy is one of the most pressing policy issues facing the United States today [2,3]. Current rates of fossil fuel use are unsustainable [4]. Emissions of greenhouse gases from the burning of fossil fuels is the leading cause of global climate change, which could have catastrophic consequences for human civilization and the earth's biosystem [5]. Dependence on imported oil and natural gas places enormous burdens on the nation's economy [6]. In addition to the familiar environmental impacts of fossil fuel use, which include emissions of criteria pollutants and toxics into the air, the US now realizes the environmental costs associated with deep-water drilling in the Gulf of Mexico.

Below is presented a scenario which describes one plausible sustainable energy future for the United States. There is no agreed upon definition of sustainability. The most notable definition of sustainable development was put forth by the Bruntland Commission: "Development that would meet the needs of the present without compromising the ability of future generations to meet their own needs" [7]. According to William Clark, the National Research Council's position is that sustainability initiatives should "meet the needs of a much larger but stabilizing human population…, sustain the life support system of the planet…, and substantially reduce hunger and poverty." [8] Herman Daly, in proposing a more operational and actionable definition of sustainability, posits that:

- Non-renewable resources should not be depleted at rates higher than the development rate of renewable resources,
- renewable resources should not be exploited at a rate higher than their regeneration level, and
- the absorption and regeneration capacity of the natural environment should not be exceeded [9].

To conclude this brief review of sustainability definitions is this comprehensive and provocative statement from Donella Meadows: "Our rational minds tell us that a sustainable world has to be one in which renewable resources are used no faster than they regenerate; in which pollution is emitted no faster than it can be recycled or rendered harmless; in which population is at least stable, maybe decreasing; in which prices internalize all costs; in which there is no hunger or poverty; in which there is true enduring democracy. But what else?" [10].

The approach to sustainability that motivated this research is based upon an amalgam of definitions of sustainability proposed by others. The foundation of the approach described below is an explicit futures-orientation toward the concept of sustainability. That is, any energy system toward which the US could transition ought to be able to function into the indefinite future without suffering risks related to the long-term supply of any inputs. This research considers the indefinite future to extend many centuries if not several millennia into the future.

Any new energy system also ought to satisfy obligations that current generations have toward future generations. For example, new energy systems ought not expose future generations to risks not tolerated by current generations [11], constrict options available to future generations [12], or threaten the ability of humanity to complete its unfinished business [13]. In this vein, any new energy system ought to be compatible with a high quality of life, affordable within the context of obligations to future generations and current generation imperatives, foster different types of life styles, and facilitate the achievement of other important social policy objectives. One can infer that any new energy system should not impose additional risks to human and ecological health. Thus, any new energy system should produce fewer emissions of toxic substances, reduce rates of species extinction, and reduce emissions of greenhouse gases, among many worthy environmental goals.

This research is based upon an exploratory scenario that depicts a plausible US energy system that emerges by the year 2050. Scenarios are widely used in futures analyses conducted for business, military and government decision makers [14-16]. The use of scenarios in environmental, planning and sustainability contexts has been more limited. In this special issue, Mulvihill and Kramkowski-Epner [17] present an excellent review of the scenario literature with respect to the use of scenarios to support sustainability research. Normally, scenario analyses entail the development of multiple scenarios that depict disparate visions of possible future worlds [18]. This is the approach followed by two other papers in this special issue, by Raskin *et al.* [19], which presents four global scenarios, and Olabisi *et al.* [20], which present scenarios describing potential futures for the State of Minnesota. It is also the approach adopted by the Intergovernmental Panel on Climate Change, which developed a set of global scenarios to drive emission estimates that then were fed into computationally-intensive global climate change models [21]. Only one *exploratory* scenario is presented because a great deal of effort was expended to thoroughly quantitatively assess its implications for a future national energy portfolio of the United States, although the scenario's impacts upon land use and water sustainability were also qualitatively assessed. The scenario presented herein differs from the others presented in this special issue because it explicitly incorporates emerging technologies and substantial changes in the built environment and society.

Scenarios have frequently been used in energy contexts [22]. For example, scenarios have been used to envision energy futures for Colombia [23]. Scenario work done for the Pew Center on Global Climate Change by the Global Business Network resulted in these three scenarios:

- Awash in Oil and Gas—assumes that these energy resources are available and cheap;
- Technology Triumphs—commercialization of climate friendly energy technologies is accelerated through a combination of state policy, technological breakthroughs, public and private investment, and consumer interest; and
- Turbulent World—supply disruptions and energy security concerns lead to aggressive federal energy policy promoting domestic, low-risk resources [24].

United Nations University's Millennium Project has been quite active in developing a comprehensive set of world scenarios. Their latest 2020 Global Energy Scenarios have these titles:

- Business as usual—the Skeptic-no surprises or much change in energy sources and consumption patterns;
- Environmental Backlash—International environmental movement becomes much more organized; some groups lobby for legal actions and new regulations and sue for action in the courts, while others become violent and attack fossil energy industries;
- High-Tech Economy—Technological innovations accelerate beyond current expectations; and
- Political Turmoil—Increasing conflicts and wars, with several countries collapsing into failed states, leading to increasing migrations and political instabilities around the world [25].

Several other energy-related scenario projects should be noted. The International Energy Agency developed two versions of the energy future: one that is underinvested, vulnerable, and dirty and another that is clean, clever, and competitive [26]. The World Energy Council developed four scenarios at the ends of two axes: high or low engagement by governments; and high or low cooperation and integration among nations and regions, and among the public and private sectors [27]. The European Commission has developed a reference projection for the world energy system and two variant scenarios, a carbon constraint case and a hydrogen case [28]. Finally, Jacobson and Delucchi [29] explore a worldwide energy scenario that is driven by wind, solar, geothermal, tidal, and hydroelectric energy sources. Like the scenario presented below, fossil fuels and corn ethanol are eliminated (although unlike the scenario presented below, so are nuclear and all other forms of ethanol).

This research builds upon previous scenario-based research conducted by Tonn *et al.* [30] that explored how different 'perspectives' could shape US national energy portfolios. Seven perspectives were explored, given labels such as Environmentalist, Technophile, Individualist, and Low-Cost Bottom-Liner. Each Perspective was distinguished by a specific set of values related to concerns about greenhouse gas emissions, energy independence, energy security, energy costs, and safety. These values translated into different preferences for various sources of energy (e.g., coal, nuclear power, wind, energy efficiency) and policies to support the attainment of their preferred portfolios (e.g., carbon taxes, federal energy R&D). It was found that different perspectives yielded significantly different portfolios. Probably most unlike were the Environmentalist and Low-Cost Bottom-Liner portfolios. The former emphasized reduction of greenhouse gas emissions and consequently favored a portfolio heavy on renewable and sans coal. The latter, representing industry, favored low-cost coal and low-cost foreign imports of energy.

This paper extends this research through its representation of an eighth perspective, one which focuses on long-term sustainability. Like the Environmentalist Perspective, the perspective adopted by this research eschews unsustainable, non-renewable fossil fuels. This eighth perspective also assumes that corn ethanol is unsustainable over the long-term because of its minimal energy input-to-output gains and strains on farmland, water supplies and water quality. Thus, this paper explores a scenario where the US meets its energy needs over the very long-term without fossil fuels and corn ethanol.

Before presenting the scenario, analytical approach, quantitative results, and support for various key assumptions, it needs to be emphasized that our scenario is in line with long-held US public opinion, attitudes and perspectives about energy [31-36]. The transition to a portfolio that encompasses an abundance of renewable energy resources is also consistent with other research on US energy system transition [37,38]. The scenario encompasses significant roles for both state and local governments, both of which are taking on increasing responsibilities for achieving sustainability and climate change goals [32,39-42]. The scenario envisions great strides towards self-sufficiency in low-density human settlements, a goal which Sorrell [43] states is very important for achieving sustainability. Lastly, as is seen below, the scenario simultaneously tackles energy security and climate change, which is one key to achieving policy gains in both areas [44].

2. The Scenario

Across the United States, people from all walks of life are attending 'Mid-Century' parties. Residents of mega-urban cities like New York, Atlanta, and Minneapolis are enjoying elaborate, colorful, and amusing parades of holographic images that swiftly move through avenues and quiet residential streets alike. The images portray scenes from their deep past, the heady present, and their almost unimaginable future. Laser shows intermingle with traditional fireworks to light up the evening skies. Those who live in the low density, self-sufficient eco-communities are also celebrating, albeit in less ostentatious ways.

America in the year 2050 is scarcely recognizable to those who were alive forty years earlier. The population of the United States has increased to 430 million. The population is much older. Now, over 21% of the population is 65 years old or older, up from 12% in the year 2000. The population is much more diverse. In 1900, 88% of the American population was Caucasian. It took one hundred years for this percentage to drop to 81%. In 2050, the percentage of the population reporting race as white has dropped to 46%. Conversely, the Hispanic population has increased to 30% in this world [45].

At the turn of the century, the US landscape was dominated by sprawling suburbs. Suburbanites loved their single family detached homes, their lawns, their SUVs, and not having to interact with their neighbors. Large numbers of workers commuted long distances to work. Suburbanites shopped at big box retailers and thought nothing of driving 15–20 miles for a meal or soccer practice.

Many analysts decried the American lifestyle from several decades back. Clearly, it was unsustainable with respect to almost every conceivable measurement, from energy to water, from biodiversity to food. Analysts today are amazed that the US avoided a catastrophic social, economic and environmental meltdown but on closer examination, the seeds for the stunning transition were sown decades ago.

Once the societal gestalt settled on the understanding that the suburbs were completely unsustainable, their days were numbered. Now, in 2050, the suburbs are no more. They have been absorbed into mega-cities or have been transformed into highly self-sufficient eco-communities. About half of the population lives in each type of settlement.

The mega-cities combine a futures vision right out of that historical 2-D animated cartoon show the Jetsons with a very traditional, but high population density vision of livable cities described by Jane Jacobs in her famous book *The Death and Life of Great American Cities* [46]. Neatly arranged throughout the mega-cities are very high density cores, think of Manhattan, Shanghai, and Hong Kong replicated in Minneapolis and Dallas. Neighborhoods of attractive multi-family residences and well integrated commercial, educational and other buildings fill out the rest of the urban landscape. Each community has its collection of vertical farms, which are multi-story structures designed specifically to grow vegetables, fruits, fish, and poultry [47]. Seeds of these changes were noticeable at the turn of the century as long-downtrodden communities such as Harlem were quickly gentrifying, New Urbanism in planning and use was taking hold, and community sustainability and gardening/farming were in resurgence.

The buildings are heated by electricity, solar thermal heating systems, district steam systems, and boilers burning bio-fuels. Appliances in homes are all electric and about 25% more energy efficient than their ancestors from several decades ago. Most buildings are equipped with closed-loop water systems. The homes are also smaller than the average from forty years ago. Urban dwellers in the year 2050 are very cosmopolitan. They rarely stay home and advanced, local production systems make products and food readily available, inexpensive and immediately recyclable, decreasing needs for storage space for food, clothes, *etc*. Most residents have custom-made ‘carts’ that they take shopping. The carts hold their reusable food containers they take to the stores and can transport most anything else bought locally. Sidewalks, stores, homes and transportation systems are designed to accommodate the ubiquitous carts.

The transportation systems in the mega-cities are completely electrified and highly intelligent. A visitor from the early 21st century might find these mega-cities eerily quiet, as electric taxis and buses smoothly traverse the traffic calmed streets. Of course, the mega-cities now have the densities and resources to invest in underground subways that connect the high-density cores. While some citizens still own their own electric cars (whose weight is now limited by law), most residents travel around the city via on-demand public transit. Computers whose speeds and capabilities are even beyond those envisioned by Ray Kurzweil many years ago [48] route and re-route thousands of small 'jitneys', large buses and numerous highly fuel efficient vehicles of all designs [49] based on the current, indicated, and forecasted transportation needs of the city's inhabitants.

Despite the high density settlements, the environment is much improved. The transportation sector does not consume any fossil fuels. Additionally, fossil fuels are also no longer used to produce electricity. In their place is an amalgam of nuclear, concentrated solar, geothermal, wind, and unconventional hydro plants. Therefore, emissions of nitric oxides, sulfur dioxides, mercury, carbon monoxide, and particulates from vehicles and power plants have been eliminated. Tropospheric ozone is also no longer a public and ecological health concern. Buildings are topped with green roofs and streets are decorated with urban forestry. Thus, the cities are cooler in the summer and greener. Wildlife has returned to the trees, roofs, pocket parks, planters, and restored rivers and creeks.

Of course, the 'environments' of the urban centers take a back seat to the 'environments' of the ecological communities. Suburbanites of the turn of the century would not recognize the 'suburbs' of today. One way to appreciate today's eco-communities is to compare and contrast them against suburban subdivision developments of the past. A typical American subdivision was almost completely unsustainable. All energy and water were imported. Waste water was whisked away to treatment plants miles away. The immaculately landscaped subdivisions consisted of inedible grasses, and 'invasive' bushes and trees. As mentioned above, most residents used automobiles to drive to work and school and all other destinations that composed daily life outside of the home. Typical subdivision ordinances restricted and/or prohibited drying clothes outside on clothes-lines and any renovations to homes that could be deemed unaesthetic and therefore impact property values of nearby homes. Thus, residents were prohibited from installing roof top photovoltaics and hot water tanks or using the sun to dry their clothes!

The American subdivisions were transformed in the following manner. Instead of growing grass, lawns were substituted with bio-fuel and agricultural crops and/or indigenous grasses and other indigenous plants. Treeless expanses of manicured turf have been replaced by oases of indigenous flower beds, garden plots, trees, and water gardens. Residents now farm these resources themselves or allow others to grow and harvest the resources for a fee. Ponds for fish, birds and other species replaced backyard pools. Instead of being governed by ordinances restricting farm animals, these settlements now have central areas for chickens and other animals. Roofs on single family attached and detached houses, as well as on mobile homes, are green as well. If not green, the roofs host photovoltaic panels and solar hot water heater systems. Like homes in the urban areas, most energy consumed is in the form of electricity, although biomass and biofuels are also used for space and water heating.

Residents in the low density settlements make heavy use of telecommunications technology for work, school, education, shopping, *etc*. In this way, their demand for transportation is greatly reduced as compared to the ancestral American suburban drivers. If a household owns a vehicle or two, they are either electric cars or ones that use bio-fuels. The impervious roads and driveways that dominated suburbs of yesteryear have given way to pervious roads and driveways. Water tables have recovered to levels not seen in many years. Water quality has also improved dramatically because fertilizers and herbicides needed to care for traditional lawns are no longer needed.

Advances in nano-technology have not yet reached levels envisioned by Eric Drexler in his famous book *The Engines of Creation* [50]. Society presently does not enjoy the fruits of self-replicating nano-machines, which the famous science fiction author Charles Stross in his first book, *Singularity Sky,* called cornucopia machines [51]. However, 3-D printing is now quite ubiquitous. Most homes have 3-D printing machines that produce common materials and products, from clothing materials to cleaning rags, from dishes and glasses to pieces for tables, chairs, beds and toys (some assembly required!). Mom and pop 3-D shops are licensed to produce more complex and controlled substances and products, from electronics to medicines. Gone from the landscapes in both types of human settlements are the big box retailers, although attractive urban malls are popular hangouts for the urban dwellers. To its credit, Walmart transitioned from being a big box retailer to the world's leading 3-D printer, having converted all its stores and warehouses to on-demand production of everything from all the pieces needed for new homes to climbing walls, carbon fiber toilets, and taxis.

The low-density settlements, contrary to expectation, are blossoming with a virtual Cambrian explosion of new sub-cultures. One reason is because many of the eco-communities have organized themselves into collectives of 150 or so individuals, where 150 seems to be a magic number associated with a group where everyone knows each other and can keep track of the myriad number and combinations of interpersonal interactions and obligations [52]. Many of these communities have deep environmental themes. In these communities, homes may have grass floors, carbon-nano walls, niches for various bugs and plants that live in the home while dealing with wastes and indoor air quality, and specially designed pathways and systems to allow mega-fauna and humans to better interact. Many of the electric appliances are human-powered [53]. Some communities feature artists of various persuasions. There are also research communities, religious communities, sporting communities, *etc*. Also, it should be mentioned that those who want to be left completely alone, we call them Home Dwellers, flourish in the decentralized environments. Lastly, a highly specialized set of communities, collectively known as the Stewardship Institution, has been established to administer and protect high-level nuclear waste repositories. These totally self-sufficient communities are specifically designed to weather both political and economic turmoil so that they can meet their responsibilities over the next several millennia [54].

3. US National Energy Portfolio in the Year 2050

Tonn *et al.* [30] developed a tool for constructing future energy portfolios. This tool was used to construct a US national energy portfolio for the year 2050 that is consistent with the scenario presented above. The analytical approach consisted of these steps: defining a 2050 base case; distilling the important energy-related assumptions from the scenario (see Table 1); operationalizing the assumptions for input into the tool; and iterating among assumptions to produce a sound national energy portfolio.

Technical literature that supports the key assumptions is both referenced in this section and contained in extended discussions of several key assumptions in the next section of this paper.

Table 1. Scenario design and supporting technological and social change assumptions.

Scenario Design Assumptions	**Technology and Social Change Assumptions**
Liquid Petroleum, Coal, Natural Gas production/ consumption in the US are eliminated by 2050.	Electricity transmission losses will decrease by 25% by 2050 due to advancements in high temperature superconducting lines and smart grid designs.
By 2050, approximately 50% of the population will live in super-urban high density areas and 50% will live in low-density, semi-self sufficient areas.	Transportation energy efficiency will increase by 40% by 2050 due to more efficient vehicles, and reductions in trip demand and trip length due to life style and land use changes.
Transportation energy consumption by 2050 will be 70% electricity and 30% biofuels.	Energy consumption in the residential, commercial and industrial sectors will decrease by 25% by 2050 due to improvements in energy efficiency.
Energy consumed by the US petroleum industry will fall to zero by 2050.	Energy consumption in the pulp and paper sector will decrease by another 20% by 2050 due to decreased demands for paper and packaging.
Nuclear power production to ~26 quads by 2050.	Energy consumption in the food sector will decrease by another 20% by 2050 due to more local production.
Wind power production to ~17 quads by 2050	Energy consumption in the commercial sector will decrease by another 20% by 2050 due to decrease need for commercial space
Geothermal power production to ~5 quads by 2050.	Energy consumption in the residential sector will decrease by another 20% by 2050 due to a decrease in the average size of homes and an increase in average household size (which will increase by 20%)
Solar power production to ~36 quads by 2050.	Requisite advances will be made in electric battery technologies, power storage technologies, and smart grid technologies.
Unconventional Hydro to ~3 quads by 2050.	
Increase in biofuels production, multiple sectors, to ~17 quads by 2050.	

The first step was to create a 'base case'. In the previous research, Tonn *et al.* [30] used as a base case the US national energy production and consumption forecasts for 2030 produced by the US Energy Information Administration (EIA) [55]. This research also started with the EIA base case, which needed to be extrapolated to the year 2050. The extrapolation was based upon a simple assumption that consumption will grow proportionally to population at a fixed rate. The 2030 consumption predictions and the projected population growth rate were used to predict the fraction by which consumption would grow and then applied that across the board to every energy consuming sector. Then the production of electricity from fossil fuels and other fossil fuel production was increased proportionally.

Table 2 presents the EIA 2030 forecasts and the extrapolations to the year 2050. By the year 2050, the base case suggests that US energy consumption could reach almost 132 quadrillion BTUs (quads), up from just over 100 quads in 2007. Liquids (defined to include petroleum), natural gas, and coal continue to dominate the US national energy portfolio. At the bottom of this table is the calculated independence gap (*i.e.*, the difference between US consumption and production). The independence gap increases by 50% over this time period, rising to over 46 quads.

Table 2. EIA base case summary.

	Component	2007	2010	2020	2030	2040	2050
Consumption	1. Liquids	39.56	39.33	40.29	41.82	44.44	47.05
	2. Natural Gas	23.58	23.93	24.01	23.39	24.53	25.67
	3. Coal	22.70	23.03	27.07	31.40	33.44	35.59
	4. Nuclear	8.34	8.31	9.05	9.57	9.57	9.57
	5. Hydropower	2.61	2.92	3.00	3.00	3.00	3.00
	6. Biomass	2.33	2.33	3.01	3.20	3.20	3.20
	7. Biofuels	1.03	1.80	3.44	4.48	4.48	4.48
	7A. Biofuels (Biodiesel)	0.06	0.08	0.13	0.16	0.16	0.16
	7B. Biofuels (Corn Ethanol)	0.54	0.95	1.26	1.26	1.26	1.26
	7C. Biofuels (Cellulosic Ethanol)	0.00	0.01	0.23	0.58	0.58	0.58
	7D. Biofuels (Other Ethanol)	0.00	0.00	0.01	0.01	0.01	0.01
	7E. Biofuels (Industrial)	0.40	0.67	1.49	2.31	2.31	2.31
	8. Wind	0.38	0.74	1.02	1.24	1.24	1.24
	9. Geothermal	0.34	0.37	0.58	0.80	0.80	0.80
	10. Waste	0.45	0.50	0.51	0.51	0.51	0.51
	11. Solar	0.01	0.01	0.03	0.03	0.03	0.03
	12. Unconventional Hydro	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity Imports	0.09	0.05	−1.10	−0.73	0.17	0.74
	TOTAL US CONSUMPTION	101.40	103.34	110.90	118.71	125.41	131.88
Production	**Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	13.36	15.03	15.54	15.71	15.16	14.15
	2. Natural Gas	19.55	19.85	20.08	20.24	20.17	20.00
	3. Coal	23.76	23.97	24.48	25.20	26.85	28.63
	4. Nuclear	8.34	8.31	8.41	9.05	9.50	9.57
	5. Hydropower	2.61	2.92	2.99	3.00	3.00	3.00
	6. Biomass	2.33	2.33	2.60	3.01	3.14	3.20
	7. Biofuels	1.00	1.71	2.37	3.12	4.29	4.33
	7A. Biofuels (Biodiesell)	0.06	0.08	0.17	0.13	0.14	0.16
	7B. Biofuels (Corn Ethanol)	0.54	0.95	1.18	1.26	1.26	1.26
	7C. Biofuels (Cellulosic Ethanol)	0.00	0.01	0.03	0.23	0.58	0.58
	7D. Biofuels (Other Ethanol)	0.00	0.00	0.00	0.01	0.02	0.01
	7E. Biofuels (Industrial)	0.40	0.67	1.00	1.49	2.28	2.31
	8. Wind	0.38	0.74	0.87	1.02	1.13	1.24
	9. Geothermal	0.34	0.37	0.48	0.58	0.70	0.80
	10. Waste	0.45	0.50	0.50	0.51	0.51	0.51
	11. Solar	0.01	0.01	0.02	0.03	0.03	0.03
	12. Unconventional Hydro	0.00	0.00	0.00	0.00	0.00	0.00

Table 2. *Cont.*

	TOTAL US PRODUCTION	72.11	75.76	78.36	81.46	84.48	85.45
	INDEPENDENCE GAP	**29.29**	**27.58**	**32.54**	**37.25**	**40.93**	**46.43**

Table 3 indicates that the model estimates energy consumption by four sectors: residential, commercial, industrial and transportation. Electricity is treated separately. In the base case, it is seen that coal still dominates electricity production and liquids dominate the transportation sector.

Table 3. Detailed forecasts for EIA base case (Quad Btus).

Residential (less Electricity)	**By Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	1.37	1.31	1.33	1.29	1.37	1.45
	2. Natural Gas	4.87	4.95	5.30	5.32	5.66	5.99
	3. Coal	0.01	0.01	0.01	0.01	0.01	0.01
	6. Biomass	0.46	0.44	0.40	0.38	0.38	0.38
	Total Residential	6.71	6.71	7.05	7.00	7.41	7.83
Commercial (less Electricity)	**By Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	0.68	0.63	0.68	0.68	0.72	0.77
	2. Natural Gas	3.11	3.04	3.47	3.78	4.02	4.26
	3. Coal	0.07	0.08	0.08	0.08	0.09	0.09
	6. Biomass	0.13	0.13	0.13	0.13	0.13	0.13
	Total Commercial	3.99	3.89	4.36	4.68	4.96	5.25
Industrial (less Electricity)	**Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	9.74	9.67	9.27	9.25	9.83	10.41
	2. Natural Gas	7.97	8.37	8.39	8.35	8.87	9.39
	3. Coal	1.94	1.93	2.11	2.26	2.40	2.54
	5. Hydropower	0.03	0.03	0.03	0.03	0.03	0.03
	6. Biomass	1.56	1.48	1.65	1.83	1.83	1.83
	7. Biofuels	0.40	0.67	1.49	2.31	2.31	2.31
	10. Waste	0.15	0.15	0.15	0.15	0.15	0.15
	Total Industrial	21.79	22.31	23.11	24.18	25.42	26.66
Transportation (Less Electricity)	**Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	27.22	27.15	28.42	29.98	31.85	33.72
	2. Natural Gas	0.66	0.68	0.76	0.80	0.85	0.90
	7. Biofuels	0.63	1.13	1.95	2.17	2.17	2.17
	7A. Biofuels (Biodiesell)	0.06	0.08	0.13	0.16	0.16	0.16
	7B. Biofuels (Corn Ethanol)	0.54	0.95	1.26	1.26	1.26	1.26
	7C. Biofuels (Cellulosic Ethanol)	0.00	0.01	0.23	0.58	0.58	0.58
	7D. Biofuels (Other Ethanol)	0.00	0.00	0.01	0.01	0.01	0.01
	7F. Biofuels (Ethanol Import)	0.03	0.09	0.31	0.15	0.15	0.15
	Coal to Liquids	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity	0.02	0.02	0.02	0.03	0.03	0.03
	Total Transportation	28.53	29.03	31.20	33.03	34.96	36.89

Table 3. *Cont.*

	Component	2007	2010	2020	2030	2040	2050
Electricity	1. Liquids	0.55	0.56	0.59	0.63	0.67	0.71
	2. Natural Gas	6.97	6.89	6.09	5.13	5.13	5.13
	3. Coal	20.68	21.01	24.87	29.05	30.95	32.95
	4. Nuclear	8.34	8.31	9.05	9.57	9.57	9.57
	5. Hydropower	2.58	2.89	2.97	2.97	2.97	2.97
	Component	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	6. Biomass	0.18	0.28	0.82	0.86	0.86	0.86
	8. Wind	0.38	0.74	1.02	1.24	1.24	1.24
	9. Geothermal	0.34	0.37	0.58	0.80	0.80	0.80
	10. Waste	0.30	0.35	0.36	0.36	0.36	0.36
	11. Solar	0.01	0.01	0.03	0.03	0.03	0.03
	12. Unconventional Hydro	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity Imports	0.09	0.05	−1.10	−0.73	0.17	0.74
	Total Electricity	40.40	41.46	45.26	49.91	52.74	55.35

With this base case set, the key assumptions distilled from the scenario were applied. The two most significant assumptions are that fossil fuels and corn ethanol are eliminated both in production and in use. The production end of the model allowed the elimination of these sources with no real difficulty. The next step was to move into the consumption end of the model and eliminate fossil fuels there. This required a few additional assumptions. The first was that fossil fuels can be replaced used to produce electricity 1:1 with an equal amount of pre-loss electricity from non-fossil fuel sources (losses will in practice make the amount of electricity consumed significantly larger). The second was that anything else can be replaced with other biofuels, again on a 1:1 basis. At this point the model meets an energy demand of 132 quads with large increases in nuclear, wind, geothermal, solar and biofuels. However, the scenario posits a substantial decrease in energy demand and other significant changes in the structure of the portfolio itself.

As noted above, the model breaks energy consumption into residential, commercial, industrial, and transportation sectors. The next step was to go through these one by one and consider how the scenario will impact the energy consumed within them. Based on current trends with respect to increasing building envelop, HVAC, lighting, and appliance energy efficiencies, it was conservatively assumed, all else being equal, that residential energy use decrease by 25% (recently energy efficiencies have increased about 1% per year [56]). On top of this reduction, a further decrease in the energy used within residential areas is predicted due to two other key assumptions. The first is that the size of the average residential unit will decrease to be more in line with what would today be considered an ‘apartment’. Most of the energy consumed within a residential unit ends up being proportional to its size (for example, heating and lighting), so a reduction in size implies a reduction in energy consumed. Moving up to the societal level, it is also predict that on average there will be more incentive for extended families to live together in the future, which would overall decrease the number of households, the number of housing units needed per capita and thus the energy used in the residential sector. These two assumptions are discussed more in the next section.

The commercial sector in many ways mirrors the residential sector in assumptions. Similar improvements in energy efficiency can be expected. Also, it is suggested that overall commercial space will reduce in size. The 'big box' stores that are so prevalent now will either cease to exist entirely or be reduced in numbers by changes in shopping demand and patterns suggested by the scenario. As with residential space most of the energy consumed is directly proportional to space, so an overall reduction in commercial space is necessarily an overall reduction in energy consumed.

In order to analyze the industrial sector, what products may or may not exist in the future needed to be considered. As the scenario is predicated around the elimination of petroleum fuels, substantial reductions in the current petrochemical industry can be envisioned (and given time and research into alternatives to petrochemicals for products such as plastics, its eventual elimination). Also easily envisioned is a future where usage of pulp and paper has actually been reduced by a meaningful degree (e.g., due to further inroads of information technology and decreases in demand for packaging for products), which would further reduce industrial energy consumption. Also added in is a small factor that assumes the agricultural system will use more sustainable, energy efficient techniques. Agricultural energy demand will also decrease because food will be grown more locally in both the urban and eco-community contexts.

Today energy used for transportation is the largest and fastest growing sector, and the EIA base case projects this to be the case long into the future. This is a problem, as the overwhelming majority of the energy used in transportation comes in the form of liquid fuels that are distilled into gasoline and diesel, for example. Over half of the transportation liquids consumed by the US is imported.

The basic transportation-related assumption is that about 70% of the energy used in transportation will be electrical (produced by non-fossil fuels), and liquid biofuels will make up the rest. It is then assumed that the same amount of total energy will be consumed overall by transportation regardless of the source. This gives a starting point to apply the scenario assumptions. The scenario assumes that people on average will travel substantially shorter distances, since more people will live in higher density urban areas. Mode choices in these areas will dramatically move away from personal vehicles to transit, biking, walking, *etc*. It is assumed that the number of personal trips made by those living in eco-communities will be less than those who live in suburbs today because these communities will substitute tele-commuting, *etc*. for trips and because these communities will be highly self-sufficient. All of these changes result in decreases in consumption of energy for transportation. It is also assumed that technological advances will act to make future vehicles more energy efficient than modern ones. There is also an assumption that through regulation vehicle sizes in general can be trended down, and further that large vehicles can be eliminated as much as possible in urban and residential areas. This allows vehicles in those areas to be smaller, lighter, and more efficient without compromising the safety of drivers and passengers.

It is, of course, impossible to eliminate long-range travel. Commercial transit and travel between cities still need to be possible. Pure electric vehicles may not be ideal for this, as their weight increases substantially as a function of range [57]. Clearly an alternative fuel technology is needed, though on a more limited basis. The scenario assumes a liquid biofuel-based system, though a hydrogen fuel-cell system could potentially be used instead if that technology proves more viable in the future. Hybridized electric-fuel cell vehicles are envisioned by many to provide the appropriate range to augment battery electric vehicles for long distance travel [58,59]. In the case of either a liquid fuel- or hydrogen-based transportation system, the fuel is merely a carrier of energy that has to be produced by some sustainable method. Which system is eventually implemented depends on the technical and economic barriers to be overcome, as well as the long term sustainability of the system.

Once all the assumptions listed in Table 1 were operationalized in the model, energy demands were balanced against energy production in the United States. The results are found in Tables 4 and 5. The future world depicted by the scenario would be expected to consume approximately 103 quads of energy in 2050, substantially less than the 130 quads the extension of the EIA forecast suggests but a still considerable amount. As can be seen in comparing the sector results in the base case (Table 3) to the scenario (Table 5), direct energy consumption in the residential, commercial, industrial, and transportation sectors is much reduced in the latter. However, because the transportation system is electrified, electricity demand actually increases by over 30 quads in the scenario.

Table 4. Scenario case summary.

	Component	2007	2010	2020	2030	2040	2050
Consumption	1. Liquids	39.61	38.45	38.68	31.89	15.21	0.00
	2. Natural Gas	23.58	23.60	23.28	22.30	14.46	0.00
	3. Coal	22.70	20.62	21.07	19.89	15.48	0.00
	4. Nuclear	8.34	8.33	12.00	18.00	25.36	26.36
	5. Hydropower	2.61	3.03	3.09	3.09	3.12	3.12
	6. Biomass	2.33	2.33	2.60	3.01	3.14	3.20
	7. Biofuels	0.98	1.88	2.58	6.22	14.77	13.45
	7A. Biofuels (Biodiesel)	0.06	0.34	0.41	0.46	0.60	0.62
	7B. Biofuels (Corn Ethanol)	0.54	0.00	0.00	0.00	0.00	0.00
	7C. Biofuels (Cellulosic Ethanol)	0.00	0.95	1.18	2.71	4.46	5.03
	7D. Biofuels (Other Ethanol)	0.00	0.00	0.00	0.01	0.02	0.01
	7E. Biofuels (Industrial)	0.35	0.50	0.86	2.72	9.49	7.63
	8. Wind	0.38	2.13	6.09	10.77	12.50	17.00
	9. Geothermal	0.34	0.65	0.80	0.99	2.67	5.33
	10. Waste	0.45	0.67	0.84	1.02	1.03	1.03
	11. Solar	0.01	1.33	6.00	10.40	27.36	36.36
	12. Unconventional Hydro	0.00	0.00	0.00	1.50	2.75	3.12
	Electricity Imports	0.09	−1.49	−14.63	−26.90	−29.73	−5.69
	TOTAL US CONSUMPTION	101.40	101.55	102.40	102.17	108.11	103.27
Production	**Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	13.36	12.42	9.32	6.21	3.11	0.00
	2. Natural Gas	19.55	18.19	13.64	9.09	4.55	0.00
	3. Coal	23.76	22.10	16.57	11.05	5.52	0.00
	4. Nuclear	8.34	8.33	12.00	18.00	25.36	26.36
	5. Hydropower	2.61	3.03	3.09	3.09	3.12	3.12
	6. Biomass	2.33	2.33	2.60	3.01	3.14	3.20
	7. Biofuels	0.95	1.79	2.44	5.91	14.58	13.29

Table 4. *Cont.*

	Component	2007	2010	2020	2030	2040	2050
Production	7B. Biofuels (Corn Ethanol)	0.54	0.00	0.00	0.00	0.00	0.00
	7C. Biofuels (Cellulosic Ethanol)	0.00	0.95	1.18	2.71	4.46	5.03
	7D. Biofuels (Other Ethanol)	0.00	0.00	0.00	0.01	0.02	0.01
	7E. Biofuels (Industrial)	0.35	0.50	0.86	2.72	9.49	7.63
	8. Wind	0.38	2.13	6.09	10.77	12.50	17.00
	9. Geothermal	0.34	0.65	0.80	0.99	2.67	5.33
	10. Waste	0.45	0.67	0.84	1.02	1.03	1.03
	11. Solar	0.01	1.33	6.00	10.40	27.36	36.36
	12. Unconventional Hydro	0.00	0.00	0.00	1.50	2.75	3.12
	TOTAL US PRODUCTION	72.06	72.98	73.39	81.03	105.68	108.80
	INDEPENDENCE GAP	**29.34**	**28.57**	**29.01**	**21.14**	**2.43**	**−5.54**

Table 5. Detailed forecasts for scenario case (Quad Btus).

	By Component	2007	2010	2020	2030	2040	2050
Residential (less Electricity)	1. Liquids	1.37	1.30	1.31	1.25	0.66	0.00
	2. Natural Gas	4.87	4.85	5.09	5.00	2.60	0.00
	3. Coal	0.01	0.01	0.00	0.00	0.00	0.00
	6. Biomass	0.46	0.44	0.40	0.38	0.38	0.38
	Total Residential	6.71	6.60	6.81	6.64	3.64	0.38
Commercial (less Electricity)	**By Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	0.68	0.62	0.65	0.64	0.33	0.00
	2. Natural Gas	3.11	2.98	3.33	3.56	1.85	0.00
	3. Coal	0.07	0.08	0.08	0.08	0.04	0.00
	6. Biomass	0.13	0.13	0.13	0.13	0.13	0.13
	Total Commercial	3.99	3.81	4.19	4.40	2.35	0.13
Industrial (less Electricity)	**Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	9.79	9.63	9.48	8.15	0.00	0.00
	2. Natural Gas	7.97	8.20	8.06	7.85	4.08	0.00
	3. Coal	1.94	1.90	2.03	2.12	1.10	0.00
	5. Hydropower	0.03	0.03	0.03	0.03	0.03	0.03
	6. Biomass	1.56	1.48	1.65	1.83	1.83	1.83
	7. Biofuels	0.35	0.50	0.86	2.72	9.49	7.67
	10. Waste	0.15	0.15	0.15	0.15	0.15	0.15
	Total Industrial	21.79	21.90	22.25	22.85	16.69	9.68

Table 5. *Cont.*

	Component	2007	2010	2020	2030	2040	2050
Transportation (Less Electricity)	1. Liquids	27.22	26.35	27.19	22.00	14.87	0.00
	2. Natural Gas	0.66	0.68	0.71	0.76	0.80	0.00
	7. Biofuels	0.63	1.38	1.72	3.50	5.28	5.82
	7A. Biofuels (Biodiesell)	0.06	0.34	0.41	0.46	0.60	0.62
	7B. Biofuels (Corn Ethanol)	0.54	0.00	0.00	0.00	0.00	0.00
	7C. Biofuels (Cellulosic Ethanol)	0.00	0.95	1.18	2.71	4.46	5.03
	7D. Biofuels (Other Ethanol)	0.00	0.00	0.00	0.01	0.02	0.01
	7F. Biofuels (Ethanol Import)	0.03	0.09	0.14	0.31	0.19	0.15
	Coal to Liquids	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity	0.02	0.09	0.16	0.83	2.60	9.85
	Total Transportation	28.53	28.49	29.79	27.09	23.55	15.66
Electricity	**Component**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
	1. Liquids	0.55	0.56	0.59	0.63	0.67	0.00
	2. Natural Gas	6.97	6.89	6.09	5.13	5.13	0.00
	3. Coal	20.68	18.64	18.95	17.69	14.33	0.00
	4. Nuclear	8.34	8.33	12.00	18.00	25.36	26.36
	5. Hydropower	2.58	2.99	3.06	3.06	3.09	3.09
	6. Biomass	0.18	0.28	0.41	0.67	0.80	0.85
	8. Wind	0.38	2.13	6.09	10.77	12.50	17.00
	9. Geothermal	0.34	0.65	0.80	0.99	2.67	5.33
	10. Waste	0.30	0.52	0.69	0.87	0.88	0.88
	11. Solar	0.01	1.33	6.00	10.40	27.36	36.36
	12. Unconventional Hydro	0.00	0.00	0.00	1.50	2.75	3.12
	Electricity Imports	0.09	−1.49	−14.63	−26.90	−29.73	−5.69
	Total Electricity	40.40	40.84	40.05	42.80	65.80	87.30

To meet this demand, several energy production sectors will need to ramp up significantly. Nuclear power increases production from about eight quads to around twenty-six quads. Technically, despite considerable lead times in developing new nuclear power plants, this ramp-up is feasible within the forty-year analysis horizon of this research [60-63]. Some legislators and policy makers in Washington, DC are already advocating for one-hundred new nuclear reactors by 2030, which would substantially meet the scenario's requirements. Economic, siting, licensing, waste disposal, and social issues, not necessarily technological issues, are the significant barriers to the expansion of nuclear power, issues that one could argue are not insurmountable within the socio-economic context described in the scenario presented above.

The US national energy portfolio consistent with the scenario relies very heavily on solar energy. Indeed, Table 4 calls for over 36 quads of energy to be provided by solar facilities. The US has ample solar resources [64] and this contribution is within reason, according to Fthenakis *et al.* [65], though as a downside the solar facilities would consume a substantial amount of land. Recent advances in reducing the cost of producing solar arrays is bringing this technology close to grid parity [66].

Another major source of power in the scenario must come from wind. The potential for wind energy in the US is as high as 527 quads [67], massive in comparison to the seventeen quads demanded from it in the model. Much like solar power, the potential for wind power does vary significantly depending on the location. The east and west coasts have relatively low potential for onshore wind, while the Midwest has very high potential [68]. It should be noted that a whole host of new wind technologies, such as kites floating in the jet-stream and floating power plants, are on the drawing boards [69].

To continue, geothermal technology and unconventional hydroelectric power (such as tidal power) also need to advance beyond their current levels of contribution. It is suggested that unconventional hydro increase to the levels that conventional hydro produces today. It is further suggested that geothermal power could reach about five quads by 2050. While geothermal has not yet taken off substantially in the US, the US has significant geothermal resources [70] and geothermal power is seen by many countries as a solution to their energy concerns [71].

Lastly, the scenario's energy resource portfolio for the year 2050 features a substantial increase in biomass/biofuels. Currently, biomass is primarily used to produce steam and heat in the paper industry and electricity from forest products residue and municipal solid waste (paper and wood) with a small additional amount as biofuels. The scenario assumes that biomass and biofuels will provide over 20 quads of energy to the transportation and industrial sectors by the year 2050. This represents a significant increase over current supply; in 2007, just over 3 quads total were supplied by biomass and biofuels. The biomass/biofuels increase assumption is based partly on the 2005 joint Department of Energy and US Department of Agriculture report, "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply" [72]. This study cites the year 2030 goals set by the Biomass Research and Development Technical Advisory Committee [73] which established benchmarks of 4.8 quads in the industrial sector and 8 quads in the transportation sector. These combined totals are nearly the same as those required by the scenario by the year 2050. This would require the harvest of approximately 1 billion dry tons of biomass feedstock per year. The report concluded that this demand could be met without diminishing current food, animal feed, export or forest products production capacity. The report also concluded that US forests have the potential to produce 368 million dry tons per year from forestlands. The report further concludes that an additional approximately 1 billion dry tons can be produced from agricultural lands, which include crop residue perennial crops (such as switch grass), dry grain, and animal manure and process residues. In the scenario, the elimination of corn-derived ethanol was assumed, which was included in the so-called "billion ton study". However, only 87 million tons of grain was assumed to be included in the approximately 1 billion tons of biomass derived from agricultural lands, or only about 9% of the agricultural biomass or only about 6.3% of the total biomass. It should be mentioned that with respect to the scenario, these estimates of biomass/biofuel production are conservative because they do not take into account the conversion of substantial portions of land now considered 'developed' into biomass producing resources.

4. Additional Key Scenario Assumptions

As noted above, intertwined within the scenario presented above are numerous assumptions that would impact future energy use in the United States. This section discusses additional technological assumptions and the key social change assumptions listed in Table 1.

5. Key Technology Change Assumptions

5.1. Lowering Electrical Losses

The scenario assumes a 25% increase by 2050 in the efficiency associated with the transmission of electricity. This is an important assumption since the scenario envisions a highly electrified transportation system. Currently, electrical transmissions losses over high voltage lines can be reduced by using shorter transmission cables, using higher voltages in the transmission cables, and reducing the amount of power being transmitted. With increased population density in urban centers and planning of the lower density population centers, the length of the network of lower voltage lines distributing power to suburban areas will decrease, which will decrease the total length of transmission lines. In addition to these anticipated improvements in losses, there are also new technologies close to implementation that could lead to significant improvements in transmission efficiency. A recent report from the Electric Power Research Institute [74] describes the use of currently available technology to implement a high temperature superconducting DC transmission line. While AC power transmission has traditionally been the favored mode of delivering electrical power, DC transmission is now used for long-distance, high-power transmission lines. The transmission lines would be cooled with liquid nitrogen and super-insulated. The authors of the report estimate that including the energy consumed by the liquid nitrogen system, the energy loss associated with transmission would be reduced by 50%. Thus, it can be argued that the assumption of a 25% increase in the efficiency of delivering electricity is reasonable.

5.2. Grid Improvements

The U.S electricity transmission grid needs to be significantly expanded and improved to meet the needs of this scenario. In many places in the US, grid capacities have already been reached (e.g., Manhattan is a good example). Additionally, current grid technology is designed to wheel power generated from reliable power sources, such as coal and nuclear plants. It is estimated that the systems could only draw maybe 10–20% of its power from intermittent renewable sources like solar and wind [75]. Major research projects are being undertaken to improve grid technology [76]. Progress is also being made on a plethora of energy storage technologies, which include flywheels, compressed air systems, capacitors, and massive batteries.

5.3. Electric Batteries

Electrification of the transportation system requires vehicle batteries that are durable, quickly-rechargeable, and provide vehicles with an acceptable range between recharges [77]. Progress has been made on lithium ion batteries; these are the power source for the currently available Tesla Roadsters [78], and the Chevy Volt and Nissan Leaf, both slated for availability in December, 2010. This battery technology has already been rapidly adopted in ultra-lightweight electric vehicles such as electric bicycles and scooters, due to its significant advantage in energy density over other battery technologies such as lead acid and nickel metal hydride batteries. Industry reports place the available lithium reserves at over 30 million tons [79]. With approximately 250 million total motor vehicles currently in use in the US [80], it would require roughly 1.35 million tons of lithium to electrify US transportation, assuming an average battery capacity of 30 kWh/vehicle (the Nissan Leaf has a 24 kWh battery), or around 4.5% of the current known reserves. While very little lithium is currently recycled from batteries, as its use increases, it is likely that recycling processes will be developed.

There are many reasons to be optimistic that over the next forty years battery technology will make significant advances. For example, MIT researchers are working on nanoball batteries that could, theoretically, charge electric cars in five minutes [81] and nanotube springs that would provide an entire new paradigm on energy storage [82]. Other researchers are working on a digital quantum battery that could boost energy densities up to ten times beyond that of lithium ion batteries [83].

6. Key Social Change Assumptions

6.1. Reduction in Household Size

Overall, it is envisioned that in both types of settlements household size will increase by around 20% (from about 2.56 persons/hhd now to about 3.00 persons per/hdd) and the size of homes will drop significantly. With respect to the former assumption, household sizes have dramatically decreased in the US over the past 100+ years. In 1900, the average housing unit was home to 4.76 residents. In 2007, this had dropped to 2.56 persons. Only 5% of homes in 1900 contained a single person. This rose to 27% by 2007. Beyond the qualitative changes in American society that these changes represent, the decrease in household size means that more housing units and everything that is in the units are needed to meet demands of a population of any size. More units means more space to heat and cool and light, which in turns requires more energy per capita to meet demands in the residential sector. It is assumed that increases in household size would result in decreases in the number of housing units per capita and therefore result in decreases in residential energy demand.

It is assumed that household sizes will begin to increase for the following reasons. First, an assessment of recent changes in average household size indicates that the rate of decrease has dramatically decreased. An assessment of the long-term trends suggests that average household size will bottom-out within a decade or so.

Second, many social trends could lead to increases in household size. Historically, the United States has experienced high-levels of internal migration due to economic considerations. Simply put, people move to take new jobs, from the south to the north over a century ago, from the northeast to the sun-belt more recently. Moves can break-up families and may also delay marriage commitments and household formation, all leading to smaller household sizes. It is also common for college age students also move away from home to attend school.

The scenario depicts a future world where economic imperatives to move would be greatly reduced. Two reasons are that increases in self-sufficiency and tele-commuting in the low density settlements will reduce the need for families to move and disintegrate due to employment concerns. The mega-urban centers will provide residents with full menus of educational and employment options. Efficient transportation systems will convey them to their destinations. So, although home sizes will be smaller, the need to move to find just the right job or school will be greatly reduced in the scenario, which it can be argued will help to increase household size. It should be noted that the rate of non-movers in the US increased from 83% in 1981 to 86% in 2001.

The social character of the United States is also changing. Immigrant and minority populations tend to have higher household sizes and these populations could compose more than 50% of the population in many regions of the US by 2050. Tolerance for diverse types of households is continuing to increase, from racially mixed couples to same sex couples. Forces that may have kept people from living together are now diminishing. As the population continues to age (12% was 65+ years in age in the year 2000, forecast to be 21% by 2050), more US citizens as a percentage of the population will live in assisted living situations where they often share rooms. As a last point, as the US population continues to increase and as populations become concentrated in high density urban settlements, one can imagine that land prices and housing prices will increase substantially. Increases in mortgages and rents would be another factor leading to higher household sizes.

6.2. Reduction in Home Size

An aging population and higher home prices could also lead to smaller home sizes. So could an increase in apartment living. One can already see a shift in house size. In 2008, the median square feet of a new single-family home decreased for the first time in at least thirty-five years. The median size dropped from 2,277 sq ft to 2,215 sq ft. The median size further dropped to 2,135 sq ft in 2009. In 1973, as a reference point, the median was 1,525 sq ft.

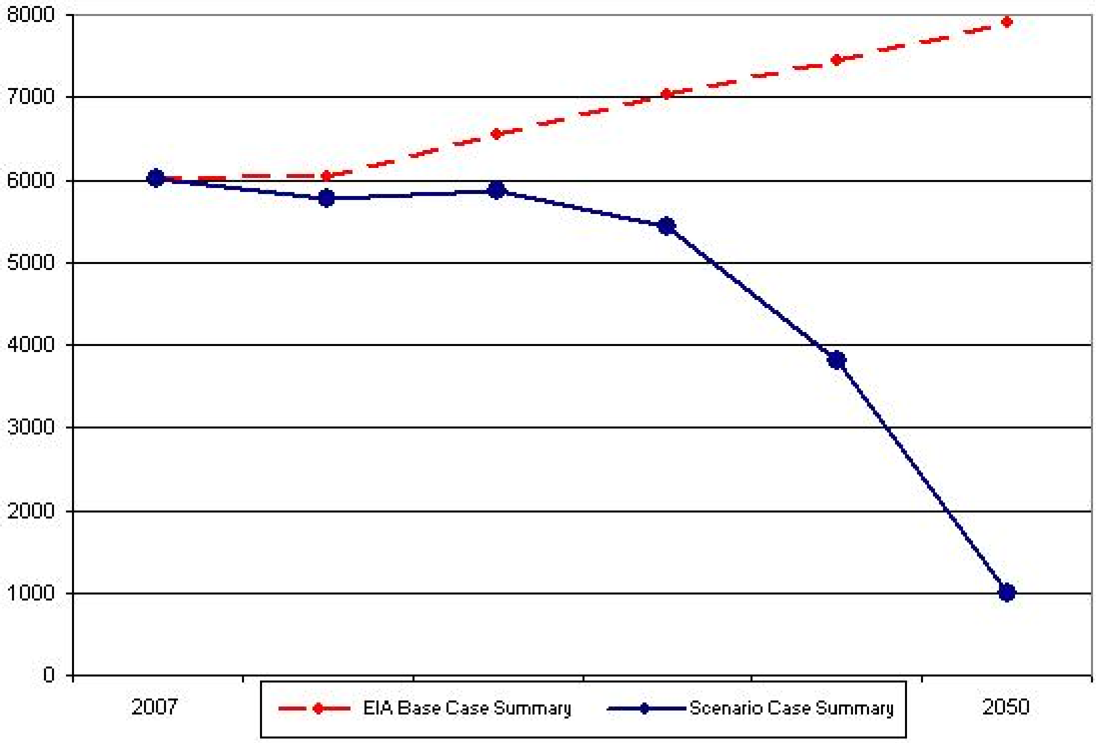
One question about this scenario is whether the built environment could change quickly enough to resemble the world painted above. A recent Bookings Institution study suggests that the answer is yes. This study estimated that approximately 50% of the built environment required to meet US needs (*i.e.*, to serve a larger population and to replace old buildings) in the year 2030 does not currently exist [84]. Extrapolated to the year 2050, the need might be in the range of 75%. So, within the planning horizon of this scenario, one could assume that the opportunity exists to virtually completely re-shape the build environment. Similarly, within this time frame the entire US transportation fleet would need to replaced and through natural attrition, a large fraction of the electric power infrastructure.

7. Sustainability Assessment

How sustainable is the scenario and resulting national energy portfolio? To begin, on the energy side, the portfolio appears to be very sustainable. Fossil fuels have been phased out. Wind, solar, and geothermal are essentially inexhaustible. Biomass and biofuels are renewable. Technical analyses suggest that, given the available nuclear materials available on earth, combined with advanced reprocessing systems, nuclear energy has a several thousand year horizon [62].

The energy portfolio is also sustainable from two other important perspectives. First, as Figure 1 suggests, greenhouse emissions could fall by 80% by 2050. Additionally, referring back to Table 4, the energy portfolio turns the US from a heavy importer of energy to an exporter. Thus, national security is enhanced through this scenario as well.

Figure 1. Total CO2 emissions: EIA base case *vs*. scenario.



7.1. Water Supply

The scenario presented above has the potential to be quite sustainable with respect to water. In the year 2000, the US used 408 billion gallons of water per day [85]. Forty-eight percent was used to cool power plants, mostly powered by fossil fuels. Although nuclear power plants require water for cooling, moving away from fossil fueled power plants and towards renewable and inexhaustible resources will substantially reduce the need for water for cooling. In turn, this will reduce risks to aquatic eco-systems from water heating, risks that may be rising in any case due to temperature increases and possibly more frequent drought situations resulting from climate change.

Thirty-four percent of the water was used for irrigation. Moving away from corn ethanol and towards cellulosic ethanol and algae-based sources of bio-fuels will greatly lessen strains on surface waters and aquifers to meet irrigation demands. Eleven percent was used by public water systems. As described above, these demands could be reduced through the implementation of closed loop systems in advanced high density settlement buildings and through extensive water conservation technologies employed in the low density settlement buildings.

7.2. Water Quality

Water quality could be greatly enhanced by the scenario described above. Elimination of fossil fuels would certainly reduce the deposition of pollutants such as mercury and other atmospheric toxics into the water supply. Increased use of pervious surfaces in the low density settlements will reduce urban run-off. Decreased dependence on corn ethanol and the use of lawns could reduce agricultural and urban run-off of fertilizers, pesticides and herbicides.

The closed systems of the high density settlements could also enhance water quality. This is because they will need to be designed to filter out almost all potential pollutants so that the water can be re-used. This means that waste waters being sent to municipal systems will be greatly reduced in quantity and that exotic pollutants such as caffeine, anti-depressants, cough medicines, and birth control substances will not be discharged into surface waters.

7.3. Bio-diversity

The settlement patterns described above could be designed to foster bio-diversity. One can imagine the low density settlements to be friendly homes for any number of terrestrial and aquatic species that are currently excluded from American suburbs. The species could find homes in the ponds, roofs, and bio-resources of these settlements. The buildings themselves could be designed to be homes for endangered bats and spiders, for example. American land development would stop fragmenting the landscape and therefore ecosystems and in fact begin to re-compose the landscape, offering species more continuous and larger ranges. The term re-environmentalization captures this process. The high density urban areas could also be re-environmentalized to a high degree. The scenario envisions restored rivers and creeks, wide-spread use of green roofs, and elegant urban forestry.

7.4. Land Use

By the year 2050, the issue that most bedevils planners in the United States, sprawl, will have disappeared. Populations will reside in dense urban settlements or spread out over the landscape in sustainable and maximally environmentally friendly eco-communities. Demands to develop undeveloped lands should decline. The scenario implies that substantial land will be devoted to solar and wind farms. Demands upon agricultural lands depend upon what mix of biomass resources develops by 2050.

There is the potential for cultivated algae to provide the raw material for production of a biofuel and to reduce the demand on these lands. Algae produce more biomass per unit land area than agricultural crops or grasses [86], can potentially be cultured on lands not suitable for agriculture using saltwater [87] , have very high growth rates relative to plants, can be used to both remove carbon dioxide from the atmosphere , and can treat waste water [88,89]. It is as yet an unanswered question as to what biofuel technologies will reduce the overall burden to the environment of producing a biofuel, but it seems clear that in terms of land use, algal cultivation has a clear advantage. In the land area required per unit energy of produced, algae cultivation uses land more than 3 times more efficiently than corn and more than 4 times more efficiently than switchgrass [86].

7.5. Metals and Other Scarce Resources

An area of growing concern with respect to the sustainability of green and clean technology initiatives is the availability of metals, rare earths and other materials needed to build the new technologies and infrastructure [90]. The United Nations has initiated a process to assess what is known and not known about critical materials. Its first report suggests that there are large information gaps [91]. Minerals that have been identified as potentially being in short supply include: lanthanum, used in electric batteries; cadmium, indium, selenium, and tellurium, used in photovoltaic cells; platinum group metals used in fuel cells [92]; rare earth elements, used in compact fluorescent lights; gallium for LEDs; and neodymium and dysprosium for wind turbine magnets. The continued growth of the electrical and telecommunications infrastructures may be threatened by shortages of copper. It should be pointed out that it will require an increase of 3–9 times in the amount of the commonly used metals aluminum, copper, iron, lead, and zinc if the use of these metals by developing countries reaches the levels of the most developed countries [93]. Recycling rates are currently very low for many of these materials mainly because usually only very small amounts are used in any one application, making recycling difficult and costly. Thus, improving recycling has the potential to significantly ameliorate this sustainability issue [94].

Thus, scarcities of rare and even common metals and minerals could be major challenges to efforts to achieve energy sustainability. The United States is not immune to these challenges. It does not have major uranium reserves. Most of the world's supplies of platinum and palladium are located in South Africa and Russia. In recent years, China has supplied 97% of the world's rare earths while the only mine in the US closed. In response, the US has embarked on research projects to find replacements for scarce materials (e.g., by replacing platinum in fuel cells with a new catalyst that is a mixture of cobalt and phosphorus [95]) and the Congress overwhelming approved H.R. 6160, the Rare Earths and Critical Materials Revitalization act of 2010 to focus efforts to achieve critical materials sustainability [96].

8. Additional Observations

8.1. Obligations to Future Generations

It is argued above that the scenario describes a world that has sustainable energy resources and improves sustainability with respect to water, bio-diversity and land. Does this scenario also meet the three obligations to future generations mentioned in the introduction? It does for several reasons. Overall risks imposed upon future generations will be less than imposed upon today's generations. Air and water pollution will be greatly reduced. Risks of economic collapse due to energy shortages will also be reduced. National security will be increased. If greenhouse gas emissions can be reduced soon enough, then maybe the most catastrophic risks associated with climate change could be avoided. Risks associated with nuclear power will increase. These risks, however, can be ameliorated with better designed reactors, plants built with standard designs (not custom-made) to improve reliability analyses, and advances in dealing with nuclear wastes (including the solution presented in the scenario).

It can be argued that the scenario above actually opens options up for future generations. A well designed and engineered energy system could be less expensive than today's system, thereby freeing up economic resources for other investments. Transportation would more rather than less flexible than today's sprawl-congested automobile dominated system. The rise of eco-communities, combined with the opportunities available in cosmopolitan areas, should lead to more lifestyle and cultural options, not less. Finally, the scenario increases the odds that humanity will be able to finish its unfinished business because catastrophic risks associated with economic collapse and climate change will allow humanity to survive to fight another day.

8.2. Affordability

The incremental cost of this scenario to society over the conventional path into the future is not easy to discern. To provide some benchmarks, Tonn *et al.* [30] estimated that the incremental cost of the Technophile and Environmentalist Perspectives to be $3.1 trillion and $2.8 trillion over a twenty-year time period. The scenario presented above can be considered as a merger of these two transformative scenarios. However, these estimated costs do not include changes in the built environment. Jacobson and Delucchi [29] estimate that the worldwide costs to transform the globe's energy system from fossil fuels, nuclear energy and ethanol to one dependent only on wind, water, and solar technologies would be $100 trillion over a 20 year period. The article does not mention the US share for this investment, but one could assume it would be in the $10 to $20 trillion range.

For the sake of argument, let's say that the incremental costs could be $20 trillion dollars over a forty year time period. To put this cost in perspective, the US Census Bureau estimated that total capital investments in the United States were $6 trillion from 2000 to 2005. If one assumes that approximately $1 trillion are invested in capital projects annually, then over a forty year period, the accumulated investment would be $40 trillion dollars. Thus, this scenario would cost about 50% more than one might expect with conventional investments, or about $500 billion per year.

To put this premium in perspective, recall that Greene [6] estimated that dependence on foreign oil also costs the United States approximately $500 billion per year. If all these estimates are within an order of magnitude of their true costs, then investing in this scenario would have a very high rate of return. These are not the only economic benefits that could accrue from this scenario. As indicated in Figure 1, greenhouse gas emissions would be drastically cut, by over 80%. A recent Tellus Institute report estimates that energy cost net savings to consumers would reach $30 billion annually just by reducing US GHG emissions to 2,000 levels by 2020 [97].

The elimination of the rush hour commutes to and from the suburbs will reduce time wasted in traffic congestion and costs and lives involved in traffic accidents. Virtual elimination of emissions of sulfur dioxides, nitrogen oxides, particular matter, and carbon monoxide and the drastic reduction in tropospheric ozone pollution will result in substantial health benefits (e.g., lowered mortality and morbidity related to respiratory diseases, fewer hospital visits, fewer missed days from work [98]), substantial agricultural and ecological benefits (e.g., less leaf damage from ozone), and less damage to the built environment and other structures (e.g., from acid deposition) [99]. Muller and Mendelsohn [100] estimate that the average marginal damages associated with the emission of one ton of fine particulate matter, nitrogen oxides, and sulfur dioxides to be $1,170, $250, and $970, respectively. In 2005, 730 thousand tons of PM2.5 [101], 6.2 million tons of nitrogen oxides [102], and 12.6 million tons of sulfur dioxide were emitted into the environment from electricity generation and fossil fuel combustion [103], respectively. Eliminating fossil fuels, then could provide an annual monetary benefit in the range of over $14 trillion. This estimate seems quite high but even if the benefits were only in the hundreds of billions of dollars, one can strongly argue that the aggregated benefits of the scenario exceed the aggregated costs.

8.3. Policy Challenges

The biggest hurdles that would prevent a scenario such as the one described above from emerging are related to resource ownership and policy levers. With respect to the former, it seems anathema to those who own fossil fuel resources directly or have rights to extract such resources that the money they could earn from those resources should be abandoned, literally left in the ground. Certainly, as long as fossil fuels are in demand those resources do have monetary value. In American society, denying someone the right to market those resources can be seen as an invasion on property rights. In land use law, this is termed 'a taking.' When government regulation takes away such rights and those rights have an expectation of monetary value, then the government needs to compensate the owners. Thus, a major challenge to policy makers is to devise policy levers deal with the owners of these resources.

To deal with both, one could imagine the imposition of a carbon tax that escalates over a period of time. Revenues from the tax would used to remake the built environment and the energy system. The revenues would also allow the government to directly acquire fossil fuel resources and buy-out leases to such resources now owned and held by the private sector. As fossil fuel consumption declines, then a national electricity systems benefit charge on electricity transmission [104] would be gradually implemented to maintain a revenue base to continue the transition. Eventually, one could imagine the national systems benefit charge being reduced as the new energy system is built out.

A carbon tax and succeeding systems benefit charges should be joined by many other policy levers. As Sovacool [104] suggests, subsidies for conventional and mature electricity technologies should be eliminated. A vigorous public-private science and technology partnership is needed to produce the advanced technologies mentioned above. Judicious use of tax credits and appliance efficiency standards are encouraged. At the state and local levels, it is apparent that changes in zoning laws, building codes, and subdivision ordinances are needed to remove barriers to the evolution of eco-communities envisioned above.

8.4. Inevitability of the Scenario

To many, the scenario and resulting US national energy portfolio presented above may appear to be unlikely, quite improbable, or even completely beyond possibility. Certainly, the probability that the scenario will occur exactly as presented is small. However, from another viewpoint, the essentials of the scenario and national energy portfolio could be seen as being inevitable. This is because not only are oil resources expected to peak and then become scarce but also within the next hundred years the natural gas [105] and another hundred years after that, coal resources will follow the same path [61]. When these non-renewable fossil fuel resources are exhausted, either nations like the US will be forced to transition to a portfolio that is essentially renewable and inexhaustible or face economic collapse. It is beneficial to move to this sustainable portfolio much sooner rather than later in order to reduce the probabilities of global environmental and economic catastrophe and harm to human and ecological health from continued emissions from the burning of fossil fuels.

9. Conclusions

Is it possible to conceive of a future version of the United States that does not use fossil fuels and corn ethanol? The answer is yes. Does this scenario seem sustainable? Again the answer is yes, from multiple perspectives. The energy system relies on energy sources that are renewable, inexhaustible, and otherwise in abundance. The system also improves sustainability with respect to water, and bio-diversity. The scenario also has extremely beneficial implications for climate change and national security. Because of its substantial reliance on biofuels and advanced technologies, sustainability of land resources and the availability of critical minerals are two areas of concern.

The scenario appears plausible. Technology currently exists or can strongly be argued will exist to support the energy system transformation. Social trends and trends in the built environment also appear favorable with respect to the scenario. It does not assume a major, voluntary de-materialization of the economy or lifestyles. This and the renewable energy aspects of the scenario would appear to be publicly acceptable and affordable. Additional analysis is needed to more accurately establish monetary costs to society and to build an efficient and equitable portfolio of policies to promote this future vision of the United States.

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