

ENERGY SUPPLY OPTIONS FOR CLIMATE CHANGE MITIGATION AND SUSTAINABLE DEVELOPMENT

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Abstract

Modern society is dependent on fossil fuels for its energy needs, but their combustion produces emissions of greenhouse gases that contribute to global warming. If these emissions remain unconstrained they risk producing significant impacts on humanity and ecosystems. Replacement of fossil fuels with alternative energy sources can stabilize anthropogenic global warming and thus reduce the climate change impacts. The deployment of alternative energy supply technologies should be based on objectives that are consistent with sustainability indicators and incorporate quantitative risk assessment multiattribute utility decision methodologies capable of ascertaining effective future energy supply options.

Keywords: energy, climate change, sustainable development

1. Energy Consumption Effects on Climate Change

The Industrial Revolution began in the mid eighteenth century and brought unprecedented prosperity to the masses and the world population increased from half a billion people to 6.3 billion people today. This Revolution was possible because of cheap fossil energy fuels (coal, oil, gas) which substituted low power labor with high power machines. Over 400 Gtoe of energy has been used since and over 1000 GtCO₂e of greenhouse gases (GHGs) has been produced and emitted into the atmosphere where they have increased the average surface temperature of the Earth by about 1°C (1-3). About 40 GtCO₂e of GHGs are currently being emitted every year (2) and this number is steadily increasing as some developing countries (China and India) are rapidly industrializing. It takes centuries for carbon dioxide in the air to be absorbed by the ocean and land masses and even if emissions of all GHGs are stopped today the Earth's climate system will continue to respond to the emissions already present in the atmosphere. This is because the Earth's climate system is nonlinear and responds with both positive and negative feedbacks which may produce abrupt system responses and climates that are considerably different from those known to the humans (4). Global warming causes melting of glaciers and polar ice. This in turn reduces the amount of solar energy being reflected from the Earth's surface into the space and produces further warming of the atmosphere. Discharges of melted ice into the oceans can weaken the ocean circulatory patterns and thus affect the weather patterns worldwide. These and other consequences of global warming can produce large-scale impacts on societies and ecosystems and cost large portions of gross domestic products to mitigate these impacts (5,6).

With the business as usual fossil fuel consumption, it is projected that the concentration of GHGs in the atmosphere will reach 800 ppm or more by the end of this century and that the mean global surface temperature will rise more than 5°C (7). This temperature rise will melt portions of world glaciers and rise sea level by several meters. Millions of people living near the coastal regions will

be impacted and it is estimated that it may cost over 20% of the world gross domestic product (currently at \$44 trillion/y) to mitigate the effects of such climate change impacts (6,8). By implementing aggressive climate change mitigation policies today, the same economic analysis projects that this cost will be about an order of magnitude lower – about 2% of the world domestic product.

Most well-informed individuals agree that we should switch from fossil fuels to non-fossil fuels dependence, but they do not agree how and how rapidly this switch should take place. This is because the economics or the interest conducive for this switch is not perceived to be favorable in the short-term, and long-term investments into new technologies appear to be too risky because a variety of renewable energy technologies appear to be necessary to displace the fossil fuels. Renewable energy systems lack the energy density of fossil fuels, which makes them less favorable. For the skeptics, global warming is not sufficiently threatening and therefore does not warrant immediate actions on fuel switching, whereas for the global warming enthusiasts who agree with the scientific consensus that “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level” (9) not enough is being done on the diplomatic levels, by energy service providers, and by educating the public to begin mitigating this warming without delay.

In recent years, a significant increase of renewable energy systems (wind, small hydropower, solar photovoltaic) took place (10), but we are far from substituting the current 85% use of fossil fuels with renewables. For the time being, we are hooked on coal, oil, and gas, and perhaps only their scarcities will force us to seek seriously alternative solutions. For oil and gas this scarcity will be felt during his century, but the world has plenty of coal to supply humans with the necessary energy well into the next century. We could argue in favor of carbon storage and sequestration (CCS) as a means to justify the continual combustion of fossil fuels, but this technology has so far not demonstrated that it could work economically and with little or no risk on a large scale (11). We could build large solar power plants in sunny locations such as Sahara and Southwest United States where the land is cheap, plant millions of wind turbines along the ocean shores, install billions of roof-mounted PV modules, and design whole new energy efficient distribution networks to integrate many different renewable energy mixes (12-14), but the economic restraints, security issues, fear of losing immediate returns from investments, and refusing to change our habits of generating energy with fossil fuels are severely impeding our ability to act for our own benefits. Since the hazard of climate change is of no significant immediate threat and little or no incentives are available to mitigate this change, we tend to remain indifferent and take no serious actions to reduce the risk posed by the hazard.

In Section 2, some of the key energy supply options are reviewed for the purpose of discussing energy supply objectives in Section 3. These objectives should be consistent with the values and priorities that are associated with the anthropogenic climate change and sustainable development indicators, and as such should help us choose the most effective options. These objectives can be incorporated into a multiattribute utility theory which is discussed in Section 4.

2. Energy Supply Options

Most of our current energy supply comes from burning fossil fuels (34% from oil, 26% from coal and peat, 20% from gas, and 10% from combustible renewable and waste). Nuclear energy accounts for 6%, hydro for 3%, and only 1% or less is being captured directly from the Sun (1). The United States consumption figures are 39% petroleum, 22% coal, 23% natural gas, 8% nuclear, and 7% renewable generated from hydro, wood, biofuels, waste, geothermal, wind, solar thermal, and

photovoltaics, and the US Energy Information Administration projects that these numbers will not change substantially for several decades (15). Some of the characteristics of different energy supply options are as follows.

Energy From Fossil Fuels

Fossil fuels account for over 85% of all energy produced today and currently some 500 quads of energy is being consumed annually (16). Known reserves are estimated from exploratory drilling and the current global reserves to production ratio are 42 years for oil, 60 years for natural gas, and 122 years for coal. The United States reserves are 12 years for oil and natural gas, and 225 years for coal (17). The uncertainty of these projections is not well-publicized, but there is likely considerably more fossil fuel reserves tied in continental shelves and deep waters, either in the form of conventional fuels (oil, gas, coal) or more exotic fuels such methane hydrates, oil shales, and alike. Their exploitation may not, however, fair well economically and environmentally and most of these reserves may remain untapped.

Developing the important fossil fuels utilization scenarios and their likelihoods and consequences should be a high priority, because the risk associated with utilizing this energy source is great, as far as the climate change and pollution of the environment are concerned. It is possible that the use of fossil fuels will begin decreasing, because of the gradual depletion of these fuels and possibly because of their phase outs as new renewable energy sources come online, but their consequences will remain for decades, and perhaps for centuries, into the future. Greenhouse gases emitted into the atmosphere will continue to produce global impacts and risk decreasing the quality of life for millions of individuals. Capturing CO₂ from the atmosphere (18) should become one of the last resorts, because this technology deals with the treatment of the disease instead of its prevention.

Solar Thermal Energy

Depending on solar energy concentration ratio and tracking, solar thermal systems can produce temperatures from 30–1500°C and thus supply the necessary energy to run our industries, commerce, transportation, and building services (19). Efficiencies of these systems can be optimized through the thermoeconomic analysis, but, fundamentally, these efficiencies are Carnot-limited and such systems should be designed from the application point of view instead from the energy supply end. This is because these systems have very low second law efficiencies when a high quality energy such as electricity is employed to produce a low temperature heat as in cooling and heating of buildings. The capital cost of installing solar thermal systems depends on plant capacity, site preparation, solar collectors, construction work, power conversion units and controls, infrastructure, and services, and these costs per kW are currently 2-5 times higher than the power generated from conventional combustion systems.

The cost of electricity delivered to consumers is also about 2–5 times higher, which is still non-competitive. Building large solar power installations in Sahara with concentrating solar collectors as proposed through the DESERTECH initiative (13) has the advantages of cheap land and plenty of sunshine, but this requires building extensive energy distribution networks and may cause energy security problems for Europeans. A similar initiative has been proposed for the Southwest US (12) where the available solar radiation can reach as high as 8000 kWh/m²d.

Solar Photovoltaics

Solar photovoltaics (PV) technology produces high quality electric energy and its likelihood of competing with conventional fossil fuels generating electricity systems depends on future breakthroughs in mass productions of inexpensive multi-junction and concentrating solar cells

which extract solar power from a wide range of solar spectrum (20-24). The current grid-connected cost of electricity of PV systems is several times higher than the cost of conventionally produced electricity, and until the third generation solar cells are developed the likelihood of PV implementation on large scales does not appear to be very high. US, Germany, Spain, China, and India, are, however, rapidly developing and implementing this technology (10).

Wind Energy

Wind turbines are very effective for producing power for small and large communities if effectively integrated into power distribution grids or energy storage systems, but large area requirements, intermittent energy generation, and expensive maintenance pose some of their most noted drawbacks. Today's wind turbines are built with capacities of up to 5 MW per unit and integrated into wind farms with several hundred MW (14, 25). Wind resources in US are enormous and concentrated in Great Plain states, the Great Lakes, the mountain ridges of the Rockies and the Appalachians, and along the Eastern and Southern seashores of the nation. Northwest Africa, Northwest Europe, Western South America, and Eastern Asian seashore also have large wind power resources. Wind energy is planned to provide 20% of US electricity needs by 2030 and expected to grow to 300 GW. This requires constructing a new 645 kV electricity distribution network and could potentially mitigate some 15 Gt of greenhouse gas emissions (15). Application of wind energy systems is growing rapidly (10), but their large-scale implementation requires an effective electricity distribution grid or energy storage systems.

Biomass Energy

Energy from the Sun can be converted into living plant matter or biomass via the natural photosynthesis in green plants or artificial photosynthesis in human-engineered systems. All living plant matter as well as organic waste derived from plants, humans, marine life, and animals are biomass (26, 27). About 100 TW of solar energy is used in natural photosynthesis which has an efficiency limit of less than 2%, and it is estimated that the world's harvestable biomass energy is about 100 times the world's energy consumption. Biomass can be harvested for feed, food, and materials for construction, combusted to produce heat, converted into synthetic fuels (biofuels), and grown to produce high energy hydrocarbons by employing genetic engineering. China and India are the largest biomass energy consumers, but in terms of electricity generation from biomass the United States, Japan, and Germany are the largest producers.

Considerable energy, land resources, and enormous quantities of water (28) are required to produce the biomass energy on large scale. Growth of biomass can also decrease the surface albedo and contribute to global warming. There are thus positive and negative consequences of biomass utilization for energy generation and careful studies of the scenarios and their likelihoods and consequences need to be carried out before this renewable energy source may become justifiable on large scale.

Nuclear energy

All forms of energy used on Earth have been ultimately produced by nuclear reactions in the Sun. These are fusion reactions which fuse light nuclei (currently hydrogen and some helium) into helium and heavier nuclei and in the process produce a mass deficit, Δm , that is converted into energy through Einstein equation, $E=c^2\Delta m$, where c is the speed of light. In fission reactions, heavier-than-iron nuclei such as uranium, thorium, and plutonium, are split into lighter nuclei and the mass deficit is again converted into energy. Most fission power reactors on the market today employ uranium extracted from the uranium ore contained in the Earth's crust through energy intensive processes, but this fuel is not renewable, even if the most abundant isotope ^{238}U is

fissioned in breeder reactors. According to an authoritative study, the worldwide nuclear power should triple by 2050 and save the planet some 2 Gt of carbon emissions per year with new Generation IV reactors which employ safer passive cooling (29). Because of limited availability of fissionable materials, the current 400 GW reactors can supply this energy need for some 10,000 years. By supplying all energy needs with nuclear power from fission reactions cannot produce the required long-term energy supply stability.

Nuclear fusion power is at the present speculative, but if developed during this century as projected through the International Thermonuclear Experimental Reactor (ITER) project (30), this energy source is sustainable for at least one million years or more, depending on the implemented type of fusion reaction. The low temperature ignition (100 million Kelvin) deuterium-tritium reaction requires lithium and thus it is limited by the availability of lithium in seawater, which currently stands at 17 ppm and could be extracted at some 100 Mkg/y to deliver some 100 kWh/d per person for over a million years (31). The deuterium-deuterium reaction requires no lithium, but much higher ignition temperatures (300 million Kelvin) and could power the planet for many millions of years. It is projected that the first commercial fusion reactor employing D-T reactions and based on magnetic field plasma confinement will come on line around 2050 (30). At Lawrence Livermore National Laboratory, US is developing the inertial fusion capability by employing high power lasers to achieve high plasma temperatures, but no large-scale demonstration power producing reactor is being planned. Energy from fusion reactions can be considered effectively unlimited, but the likelihood of its practical exploitation during this century is poorly constrained. Achieving the necessary plasma confinement, high ignition temperatures, and developing the necessary reactor materials technology, are some of the principal obstacles for developing this technology. The low-level radioactive waste from fusion reactors is an advantage over fission reactors which also produce high-level waste that remains radioactive for thousands of years.

Harvesting 13 TW of power currently required to run human enterprises on the Earth from 10^5 TW of power delivered by the Sun to our planet with solar thermal, wind, photovoltaic, and biomass energy conversion systems is not beyond our technical capability. Neither is the nuclear energy option from fission reactors, but the fusion energy option is more speculative and well worth developing, because this energy source can produce all the energy required to power humanity for several million years. We have, however, a long way to go before completely retiring fossil fuels and the energy utilization future will remain uncertain until we assess much more precisely what our future energy utilization options are and what will be their consequences on the environment and future generations. The utilities of these options can be developed from some fundamental energy supply objectives and multiattribute risk analysis methodologies.

3. Energy Supply Objectives

Which future energy supply options will be developed depends on the decisions we take, and even if we do not make such decisions this constitutes a decision nevertheless and we will have to live with the consequences. The development of an effective energy supply decision methodology constitutes a proactive risk management approach and is better than facing consequences that could be very severe. It is better to be safe than sorry is one of the basic principles of risk management. But making decisions, and especially the right decisions for the future of humanity, is very difficult and controversial.

A decision is framed by the alternatives and the values considered in making the decision (32). Values are made explicit with objectives and these objectives provide guidelines for action which can be quantified by modeling or qualified by articulation. Since the values are expressed through the objectives, they can be no better than the objectives themselves. An objective is something that

one desires to achieve and in our situation may be a reduction of GHG emissions from fossil fuels, but a broader objective may be more effective. This is because there are alternative ways of achieving reduction of GHG emissions by using different energy supply strategies and therefore producing different consequences on the environment and humanity. Specifying values through objectives should, however, precede the specification of alternatives since this can broaden the range of alternatives and thus make the decision process more effective. Values and ethics are related concepts. Ethics represent the absolute values that are unalterable and the ethical principles eliminate some possible alternatives that may be associated with the decision process.

A broader objective than reducing GHG emissions is safeguarding certain values whose objectives, and the resulting energy supply alternatives, do not only mitigate anthropogenic climate change, but also account for broader social and environmental issues. This broader objective is sustainability, but this depends on context, and if we intend to use this concept we must know what this implies. *Sustainability* could be a capacity to maintain energy supply according to the demand of humans, maximizing the benefits of economic development, a dynamic equilibrium between the energy supplied by nature and energy utilized for human enterprises, improving the quality of human life while living within the carrying capacity of supporting ecosystems, or the “development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations”. This oft-quoted definition of sustainability from the World Commission on Environment and Development (33) appears to be reasonable, but what exactly is the development, needs, and aspirations that we should be aiming at and over what space and time frames do they need to be achieved. The spatial scale can be the entire planet, a country, or something else, whereas the time scale is relative because our values are often inconsistent and can change considerably from culture to culture, generation to generation, etc. An improvement of the *quality of life* of an individual is an important factor, but this quality means different things to different people. Sustainability is therefore influenced by value judgments and ethics. Given that a sustainable development is a practical goal to be reached by some sort of intervention, we could be guided by the Agenda 21 document of Rio de Janeiro’s United Nations Framework Convention on Climate Change (UNFCCC) and by a more recent elaboration of such principles as summarized in Table 1.

Table 1. A summary of principles for gauging progress towards sustainable development (34, 35).

1	What is meant by sustainable development should be clearly defined.
2	Sustainability should be viewed in a holistic sense, including economic, social and ecological components.
3	Notions of equity should be included in any perspective of sustainable development. This includes access to resources as well as human rights and other ‘non-market’ activities that contribute to human and social well being.
4	Time horizon should span ‘both human and ecosystem time scales’, and the spatial scale should include ‘not only local but also long-distance impacts on people and ecosystems’.
5	Progress towards sustainable development should be based on the measurement of ‘a limited number of indicators’ based on ‘standardized measurement’.
6	Methods and data employed for assessment of progress should be open and accessible to all.
7	Progress should be effectively communicated to all.
8	Broad participation is required.
9	Allowance should be made for repeated measurement in order to determine trends and incorporate the results of experience.
10	Institutional capacity in order to monitor progress towards sustainable development needs to be assured.

The need for a clear definition, the focus on holism for sustainability, and the importance of time and spatial scales, are the principles 1, 2, and 4, respectively, in the table. Principles 5-10 emphasize the use of a limited number of indicators and how they should be developed and employed. The

sustainability indicators (SIs) can be grouped into state SIs which determine the physical state such as the amount of GHGs in the atmosphere, control or process SIs such as the rate at which GHGs are being emitted, response SIs which monitor the response of governments to state and control indicators. Although the decision of what SIs to use is crucial to the final outcome, there is much disagreement over which SIs to use for the decision process (36). Sustainability is difficult to quantify because it is veiled in both objective and subjective clothes. Included in the subjective category are the issues associated with the value of human health, availability of open spaces, species diversity, preservation of pristine environments, etc.

Both the United Nations and the World Bank agree on three broad indicators that measure a sustainable progress in the environment, the economy, and the society (37). The *environmental group* includes government and institutional commitment (countries with a national strategy for sustainable development), water resources (population with access to safe water, intensity of freshwater use, percentage of annual available resources used), biodiversity (nationally protected area as a percentage of total land), and energy use (gross domestic product (GDP) per unit of energy use, total and per-capita carbon dioxide emissions). The *economic group* deals with total and per-capita GDP, national debt, employment rates, investment rates, housing market, Dow Jones and other stock market averages, balance of trade, etc. The *social group* indicators include poverty, education, and health.

Energy is a major enabling force in many of the above indicators. The availability of electricity facilitates education, improves health-care services, and provides the infrastructure for commercial and industrial development. Affordable and accessible energy from fossil fuels has been historically a major force driving the world economies and the nations have been placing a priority on these energy sources. This suggests that the sustainability of a technologically intensive activity should reflect how many people use the technology, the role of the technology in the economy, and some measure of the resource consumption or environmental degradation caused by the technology. Kaya (38) employed these parameters in the form of world population, P , GDP per-capita, GDP/P , total primary energy supply per GDP, E/GDP , net amount of CO₂ emitted per year into the atmosphere per world primary energy supply, GHG/E , and the yearly amount of CO₂ sequestration, CO_2seq , i.e.

$$S = P \frac{GDP}{P} \frac{E}{GDP} \frac{GHG}{E} - CO_2seq$$

CO_2seq represents the amount of emitted CO₂ prevented from entering into the atmosphere owing to its capture and sequestration in a suitably stable manner. GDP/P represents the *standard of living*, E/GDP represents the *energy intensity* of the economy, and GHG/E represents the *carbon intensity* of the energy source. Kaya equation factors for the world over a time period from 1980 to 1999 are (37): Population 1.6%, standard of living 1.28%, energy intensity -1.12%, carbon intensity -0.45%, and carbon emissions 1.30%. Similar factors for US are 0.96%, 2.15%, -1.64%, -0.21%, and 1.23%, respectively. In comparison, China's numbers are 1.37%, 8.54%, -5.22%, -0.26%, and 4.00%. Under the initial agreement of UNFCCC strong reductions of greenhouse gases supposed to have been taken, but this has not been accomplished and the near future indicators project an increase in these emissions.

Sustainable development supports a consensus that a successful program of action on climate change must include stabilization of atmospheric greenhouse gases and maintenance of economic growth. The ratio between GDP produced per unit of carbon equivalent (CO₂e) is defined as the *carbon productivity* and MGI (39) estimates that it must increase from \$740/tCO₂e today to \$7300/tCO₂e by 2050 – an amount that is consistent with the labor productivity increase of the Industrial Revolution – in order to maintain the current GDP growth of about 3% per year and to

reduce emissions to 20 GtCO₂e per year by 2050 (Figure 1). This would keep the emissions of greenhouse gases at 500 ppm and cost about 1% of global GDP. Such a tenfold productivity growth calls upon for the development and deployment of new technologies, making new investments, placing into operation new infrastructure, and changing the ways the decisions are made by businesses and behavior practiced by the consumers. Technology alone is not sufficient to achieve this carbon productivity growth and must be complemented by wider political, institutional, and cultural environment that enable these technologies to be exploited and deployed. MGI also estimates that this Carbon Revolution will have to be three times faster than the Industrial Revolution rise in labor productivity.

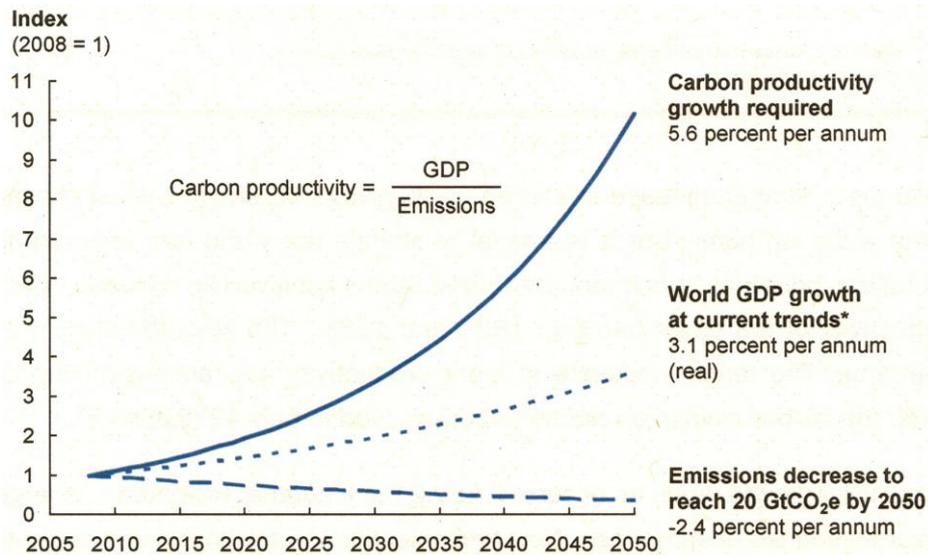


Figure 1. The *cost curve* showing carbon productivity growth of 5.6%/y with world GDP growth of 3.1%/y and emissions of GHGs decreasing to 20 GtCO₂e/y by 2050 (39).

The first 7 Gt of annual emissions could be produced at a negative cost to society, or with the economic return derived from savings in energy costs through more efficient energy conversion systems. The 27 Gt per year of mitigation required by 2030 to stay below 500 ppm would be produced at a marginal cost of under \$US60 per ton. Industry and power generation represent less than half of the total 2030 abatement potential and only about 40% of the negative cost is taken by the developed countries. The developing world excluding China represents more than 40% of the total 2030 mitigation potential and only about 30% of this total is dependent on new technology. The mitigation cost of these actions is about 1% of GDP or three times less than the global spending on insurance (excluding life insurance) (40). In 2005 world GDP amounted to about US\$44 trillion. US's GDP was \$12 trillion and that of OECD countries was about \$34 trillion (8), implying that the developed countries would have little difficulty in financing technologies with low greenhouse gas emissions.

Carbon productivity can increase by increasing the energy efficiency in residential, commercial, industrial, and transportation sectors; accelerating and deploying new technologies through substantial research and development (R&D) efforts and expanding markets for direct solar, wind, and biomass energy systems; decarbonizing energy sources through the CCS technology and increasing the share of renewable (and nuclear) energy sources; preserving and expanding carbon sinks by avoiding deforestation and promoting afforestation; and changing the attitudes and behaviors of managers and consumers (39). An increased energy productivity has the potential to reduce energy demand by about 130 quad or about 25% of projected end-use energy demand in 2020. About 0.8 GtCO₂e can be mitigated by improving energy efficiency in buildings and appliances, 0.6 GtCO₂e by improving fuel efficiency in vehicles and reducing carbon intensity in

transportation fuels. China and US are the largest markets in terms of their potential to abate energy (about 40% of global potential). The electric power production has the potential to mitigate about 6 GtCO_{2e} by shifting toward renewable energy sources (primarily wind and solar), additional nuclear capacity, improved power plant efficiency, and eventual deployment of CCS technologies on coal-fired plants. Demand on oil can be kept at current levels or decreased by reducing end-user demand, fuel substitution with biofuels, and reducing industry's emissions. More fuel-efficient vehicles can reduce emissions by about 1 GtCO_{2e} by 2020. The current global R&D investment aimed at increasing energy efficiency and decarbonizing energy sources is about \$10 billion/y and would have to be doubled by 2020 and reach \$80 billion/y in 2050 in order to prevent the concentrations of greenhouse gases in the atmosphere to exceed 450 ppm. New R&D technologies include "next-generation" (much safer) nuclear power plants; scaling up, commercialization, and deployment of carbon capture technologies; and driving down the capital costs of solar thermal, solar photovoltaics, wind, and ethanol energy producing systems through large capacity installations. But changing the attitudes and behaviors of managers and consumers is a very difficult task, since the habits of mind prevent overcoming mental barriers, unless a trigger mechanism arises that is able to overcome this barrier. Neither the climate change problem nor the world running out of fossil fuels appear to be, at the present time, sufficient triggers to begin changing seriously our attitudes toward a different energy supply future.

The first step in the direction of producing a sustainable energy future is to produce a preliminary list of *future energy supply values or objectives*. These objectives indicate the *direction* in which we should strive to do better. They differ from the goals which are either achievable or not. We can start with the following list:

1. Energy should be produced from sustainable natural resources.
2. Emissions from sources producing energy should limit the anthropogenic change of the environment.
3. Emissions from sources producing energy should not cause health problems.
4. The energy produced should be affordable.
5. The costs of producing energy from sustainable natural resources should not decrease the standard of living.
6. Energy produced from non-fossil fuels should be rewarded.

These objectives can be viewed as *fundamental*, because they state all that should be of interest in providing guidance for action and the foundation of a quantitative modeling or analysis dealing with future energy supply alternatives. They are values abstracted from sustainability indicators or broader principles dealing with the sustainable future. Certain sustainable energy sources, such as the biomass produce emissions of GHGs and other pollutants, may cause health problems, but their use is limited by objectives 2 and 3. Both the ocean and land masses can absorb GHGs from the atmosphere over extended periods of time, but the rate of their removal are limited and therefore are safeguarded by objective 2. Replacement of fossil fuels with alternative energies may be costly, but these costs should not decrease the standard of living of present and future generations (objective 5) and the deployments of these energies should be rewarded (objective 6). Some emissions of GHGs should be tolerated and are therefore permitted by objectives 2 and 3. Costly energy is inconsistent with human development and is therefore protected by objective 4. It should be noted that a more extensive list of energy supply objectives can be produced by accounting for the interests of different stakeholders and by developing hierarchies of objectives and then subdividing these objectives into lower-level objectives. Keeping the initial list of future energy supply objectives as simple as possible has, however, the advantage of producing a preliminary energy options analysis more tractable. More numerous objectives may not necessarily produce better models because of the difficulties in providing measures for some intangible objectives.

Having defined a guiding set of energy supply objectives, it is important to transform these objectives into measurable quantities. Objective 2 can be measured by expressing atmospheric concentrations of GHGs and other industrial pollutants in ppm (parts per million) and objective 3 by the annual number of deaths attributed to climate change and air pollution and by the annual number of man-days of morbidity attributed to air pollution. The costs of objective 5 can be expressed in terms of the standard of living (%GDP/P). Objective 4 can be measured with the cost of energy (\$/kWh), whereas objective 6 can be measured in terms of fees or tax breaks. These are the *natural attributes* of objectives, because they have a common interpretation. Measures of performance, measures of effectiveness, or attributes of objectives that do not have clear direct measures can be developed with the so-called *proxy attributes* which substitute natural measures when these are not available or unreachable. This is the situation with objective 1. This objective can be further subdivided into lower-level objectives for the purpose of extracting some natural measures or we may measure it with a suitable proxy, such as by a carbon tax on emissions of GHGs, by implementing emissions trading schemes, or by other suitable indicators that discourage carbon emissions. It is important, however, that the measure of an objective defines the objective in more detail than that provided by the objective alone. An attribute is measurable if it describes a probability distribution for each alternative over the possible levels of the attribute and if it is possible to assess the decision maker's preferences for possible levels of the attribute. The attribute's preferences can be expressed in terms of a suitable *utility or value function*.

4. Quantification of Energy Supply Options

The energy supply objectives and their attributes can be combined into an *energy value model*. This model should account for all possible uncertainties associated with different energy supply options and ascertain the utilities of different energy supply scenarios. Utilities reflect risk attitudes and the decision analysis provides a formal process for dealing with alternatives, uncertainties, outcomes, and objectives associated with our values. The optimal alternative is the alternative with the highest expected utility, computed by forming the sum of the decision-maker's values for possible outcomes times their probabilities. This analysis ensures a logical incorporation of uncertainties and assessment of risk associated with the deployment of future energy supplies, and it provides the results and insights for communicating to those involved in making the final decisions. Less tangible objectives can be incorporated into the analysis by employing acceptable proxies for attributes of these objectives, but this analysis suffers of being rather complicated when the decision problem involves multiple attributes which may be correlated. This situation can be addressed by the *multiattribute utility theory* (MAUT) (41, 42).

MAUT builds on the principles and methods of decision analysis and it sets to determine the overall value of an alternative with respect to other alternatives by determining the trade-offs between the competing objectives. MAUT is especially suited to the energy supply problem because it involves complex uncertainties, difficult value trade-offs, and the need to justify the resulting decisions. Its complexity arises in the construction of multiattribute utility function that captures the trade-offs among different attributes. The consequences of decisions may also not all occur simultaneously, such as when the income from long-term investments is distributed in time (43). Once this utility function is identified through MAUT, the suitability of each energy supply alternative can be determined and the preferred alternative established by finding the highest expected utility. Figure 2 depicts a summary of this decision process – a process starting from values and progressing to objectives, attributes of objectives, alternatives represented by different energy supply options or scenarios, likelihoods and consequences of different options, decisions based on multiattribute utility analysis, communication of optimal decisions to decision makers, and implementation of decisions through the appropriate entities. This overall decision analysis strategy leading to a sustainable energy supply future has the principal goal of accounting for our values and aspirations.

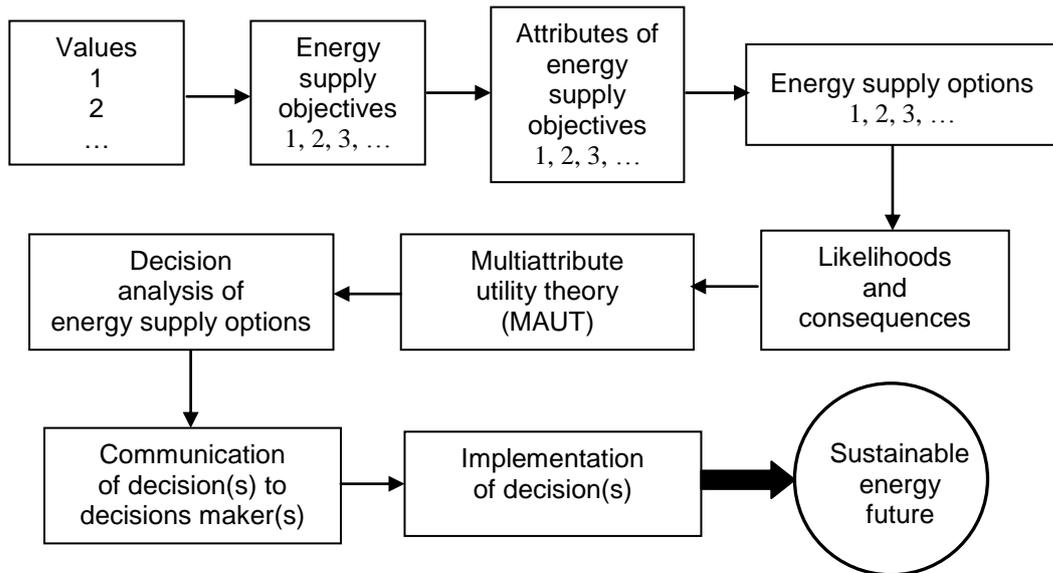


Figure 2. Schematic representation of a multiattribute risk analysis model leading to decisions, communication, and implementation of energy supply option(s). The end result is a sustainable energy future.

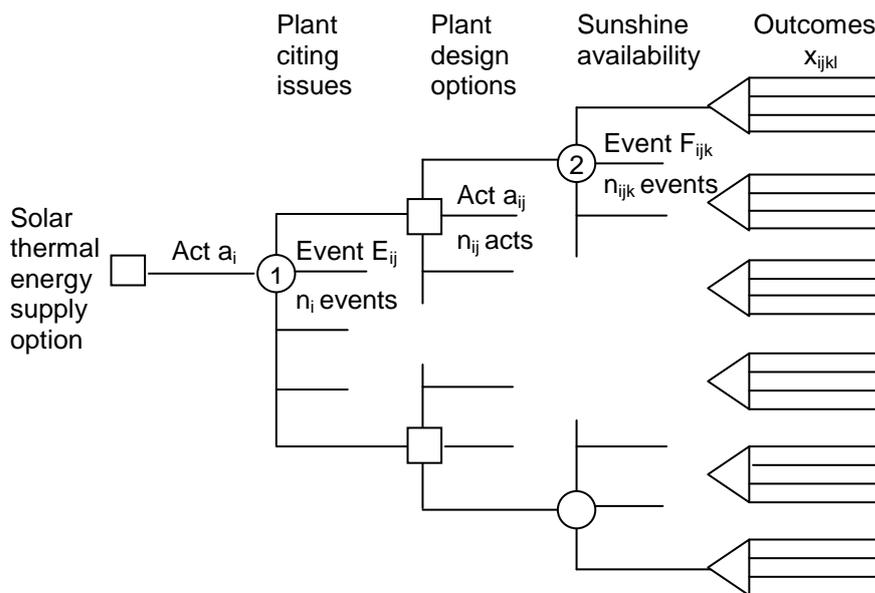


Figure 3. Decision tree for solar thermal energy supply option. Squares denote decision nodes from which fan out acts or decisions, and circles the uncertainty nodes from which fan out events. Any particular path through the tree defines a scenario. Each scenario produces one or more outcomes or consequences with certain probabilities. Outcomes terminate at value nodes which are denoted by triangles.

With the future energy supply problem being identified it is now necessary to develop an overall analytic structure that addresses this problem. For each energy supply option a *decision tree* can be constructed that assesses the probabilities of realizing this option through different values of attributes of energy supply objectives. The trunk of the tree is defined by the energy supply option (initiating event) and at the top of the tree are the *outcomes* that describe where a specific act-event sequence leads. Any specific path through the tree defines a scenario. Figure 3 illustrates such a tree for the situation of solar thermal energy supply option.

The decision to produce energy with solar thermal systems may lead first of all to plant citing issues. These issues are geographic, logistic, and socio-politic in nature, and it is uncertain whether or not they will be able to meet energy demand and satisfy the community and other interests. The first uncertainty node 1 can therefore have several possible outcomes, each with its own probability. With plant location being decided, a decision must be made on plant design options, such as a plant with heliostats, parabolic trough, or parabolic dish receivers; arrangements of plant components with and without energy storage systems; local energy supply or grid-connected system; etc. The availability of sunshine will be intermittent and this intermittency is weather or chance-dependent, and is represented by the second uncertainty node 2 for any particular scenario through the tree. Each scenario can produce several outcomes, such as the emissions of pollutants and GHGs from secondary equipment in the plant (fossil fuel-powered emergency electrical generators), different levels of energy availability (no energy supply because of system malfunction, base load energy supply, peak shaving energy supply), energy cost depending on market conditions and capital investments, economic benefits to nearby residents, psychological effects on residents, etc. The outcomes of some of the scenarios may or may not be acceptable from the multiattribute utility analysis point of view and thus some solar thermal energy supply system designs may not be acceptable.

The decision tree in Figure 3 is just one branch of a more complete *energy supply options tree* where there are n energy supply acts or options. We have in Figure 3 the act a_i specified by the choice “solar thermal energy supply option”. The act a_i is followed by n_i events E_{ij} , and there are n_{ij} acts following these events. n_{ijk} final events F_{ijk} follow n_{ij} acts and produce x_{ijk} outcomes. The expected value of the act a_i is therefore

$$EV(a_i) = \sum_{j=1}^{n_i} P(E_{ij}) \max_k \left\langle \sum_{l=1}^{n_{ijk}} P(F_{ijk}) x_{ijkl} \right\rangle$$

Reading the equation from right to left, we find first the expected value of outcomes, take then the act that maximizes the expected value and calculate the expected value of maxima. $P(E_{ij})$ and $P(F_{ijk})$ are the probabilities of events E_{ij} and F_{ijk} , respectively. For n energy supply acts or options the above formula provides a way to calculate the expected value of each option. A MAUT applied to the complete energy supply options tree would have the objective of producing the most acceptable energy supply system or systems for a variety of different locations under the considerations. It includes the following steps:

1. Definition of energy supply options and specification of value-relevant attributes.
2. Evaluation of each option separately on each attribute.
3. Assignment of relative weights to attributes.
4. Aggregation of the weights of attributes and the single-attribute evaluations of options to obtain an overall evaluation of energy supply options.
5. Sensitivity analysis and recommendations.

It should be clear that only a sketch of an energy supply decision process has been presented here and that the precise quantification of valued future energy supply options requires much more thought on structuring objectives, assigning attributes, determining event probabilities, deciding on different systems designs, assigning utility functions to consequences, assessing trade-offs between different attributes, etc. This analysis has both merits and demerits. To some, it encourages the introduction of subjective judgments and preferences into the formal analysis, whereas to others it is a disadvantage because the managers may legitimize prejudices and misconceptions. It is important, however, to keep in mind the following important merits of this analysis:

- The decision process methodology encourages the decision maker to quantify various aspects of the problem. A complex problem such as energy supply can be broken down into its basic parts and one can focus on the issues of disagreements. These may be the assignments of probabilities, consequences, or other data associated with any particular energy option.
- The systematic approach of decision analysis fosters communication and evaluation and structuring of information. Opposing points of view can be better evaluated and irrelevant factors can be more easily eliminated.
- The analysis allows for contingency planning and for incorporating new information as it becomes available. The decisions can be continuously reevaluated, suggesting thus not only the present actions but pointing also what could happen in the future.

The formal analysis of decision process can present barriers to those who lack formalization of their thought processes. For some, certain qualities cannot be quantified with numbers, and the breakdown of a complex problem into its parts and providing answers to basic questions where some of them may be hypothetical is not very appealing. But if the assessment of future energy supply options by formal analyses of these options is not the correct way to proceed, what path should we follow, and where do we expect to arrive? And what will the future generations have to pay for our lack of foresight?

5. Conclusions

In this paper some techniques used for developing optimum decision strategies aimed at mitigating climate change and global warming produced from the emissions of greenhouse gases into the atmosphere from combustion of fossil fuels are presented. Whether to continue with these fuels until they become depleted or start phasing them out and replacing them with renewable energy technologies as soon as these become viable, or rush toward a speedy deployment of such technologies, depends on many interrelated issues, not all of which are technical. Both the technical, economic, social, and ethical issues must be involved in the decision process. This process should account for our values and be based on an effective set of fundamental objectives which describe these values. The objectives should be defined by attributes which are measurable and operational. A multiattribute utility analysis should then be employed to capture the tradeoffs among different objectives, determine the suitability of each energy supply alternative, and propose an energy supply option or options with the highest expected utility. The end result of this analysis should be properly communicated to decision makers.

It is generally agreed that the fossil fuels should be substituted with renewable energy as soon as possible, but no detailed risk analysis and assessment methodology appears to have been developed to produce acceptable sustainable energy supply strategies. Perhaps the market itself will determine these strategies, but this is risky and the precautionary principle is not consistent with reactive measures. This principle calls for actions *before* some sustainability indicators reach tipping points, beyond which we may have to deal with a future not previously faced by humans and forced to spend many trillions of dollars to mitigate the impacts produced from carbon emissions. The benefits of prevention are in the future, and unless this principle is respected in the present, there may not be a better future for our children.

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