Air Quality in a Cleaner Energy World

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Abstract Two major environmental issues, air quality and climate change, are interlinked because of their large dependence on atmospheric emissions from human activities, especially from the burning of fossil fuels. Emission of air pollutants and heat trapping gases have greatly increased over the last five decades from our dependence throughout the world on conventional fossil fuel sources in production of electricity and in transportation systems, resulting in significant environmental issues with air quality and climate change throughout our planet. Future emissions of pollutants will depend on the choices made about our use of energy and transportation. The purpose of this study is to examine for now and into the future the relationship between energy production, the associated use of fossil fuels, and resulting effects on air pollution. In the process, we examine a clean energy future, imagined in this case for 2050, and then consider the resulting potential effects on air quality.

Keywords Energy · Air quality · Ozone · Particles

Introduction

One of the biggest challenges that the world faces today is providing clean and sustainable energy to future generations.

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With a growing population and increasing economic development throughout the world, there is an ever-increasing need and stress on energy production. Every sector of human life is now energy dependent, be it for transportation, or electricity demands or heating and cooling system. From 1971 to 2012, the world's total energy supply increased from 6106 Mtoes (megatons of oil equivalent energy) to 13,371 Mtoes [1•], while the total consumption of energy almost doubled, from 4672 to 8979 Mtoes. Meanwhile, the world's consumption of electricity almost quadrupled during this same period, from 6129 TWh (terawatt hours) to 22,668 TWh. In 2012, 81.7 % of the global total primary energy supply, 67.9 % of global electricity generation, and 78.3 % of global total final consumption were met by fossil fuels. With the world population expected to continue to rise from about 7 billion today (2015) to about 9.6 billion in 2050, the demand for energy will continue to increase. The corresponding increase in energy and transportation needs and their major dependence on fossil fuels create several major problems that need to be dealt with over the coming decades, for example, the effects of fossil fuel emissions on climate and on air quality, and an uneven distribution of fossil fuels and other energy sources leading to a growing dependence in some countries on others for energy availability [1•].

Many of the pertinent environmental issues today, such as local and regional air pollution, acid precipitation (also called acid rain), and global climate change (or global warming as it gets called by the media), can be traced primarily to emissions from the use of fossil fuels for different energy and transportation sectors. Air quality is most strongly affected by some of the short-lived species like carbon monoxide (CO), different oxides of nitrogen ($\text{NO} + \text{NO}_2 = \text{NO}_x$), sulfur dioxide (SO_2), ozone (O_3), volatile organic compounds (VOCs), and various atmospheric particles (also called aerosols). The particles of most concern are those that can lodge deeply into the lungs; these are primarily the particles of less than $2.5 \mu\text{m}$ in diameter

(called PM_{2.5}) that are primarily produced from gases like SO₂, but also includes black carbon (soot) and other very fine particles. Some of the pollutants like NO_x and VOCs are especially important for forming ozone, a key component of urban smog, whereas SO₂, NO_x and other gases can produce particles that also lead to environmental concerns from acid rain. A variety of gases and particles, especially the long-lived gases like carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and various chlorofluorocarbons (CFCs) and other halocarbons, are of special concern to the changes occurring in the Earth's climate system. The CFCs and other halocarbons have also been the primary sources of observed decreases in stratospheric ozone that are now in the process of being controlled through the international Montreal Protocol to Protect the Stratospheric Ozone Layer.

Some of the atmospheric pollutants are directly emitted into the atmosphere from various anthropogenic and natural activities, and can have direct effects on the environment, while others are formed from secondary reactions (and from other processes, e.g., the nucleation of aerosols) in the atmosphere. Emissions from vehicles are the primary source of CO₂, CO, NO_x, and human-related VOCs, while electric utilities and industry are important sources for CO₂, CH₄, NO_x, VOCs, and SO₂. VOCs are not only emitted from the sources mentioned above, they are also emitted from natural sources. O₃ is a secondary pollutant formed in the atmosphere from photochemical reactions, especially between NO_x and VOCs. The local and regional air pollutants like ozone and the particles (PM_{2.5}) can significantly affect human health through the cardio-vascular and pulmonary system, causing shortness of breath, asthma, other issues—these effects are particularly harmful for children and the elderly.

The major sources of PM_{2.5} are biomass burning and fossil fuel combustion. Almost all of the aerosols in the atmosphere have heterogeneous composition and are composed of inorganic and organic components. Ammonium nitrate, sulfate, and chloride mostly make up the inorganic fraction. The particles are formed due to the reaction between NH⁺₄ (mostly resulting from anthropogenic activities like use of fertilizer or from animal husbandry [2, 3]) and SO[−]₄ (from oxidation of SO₂ mostly emitted from coal-burning power plants [4]), NO[−]₃ (formed from oxidation of NO_x emitted from fossil fuel combustion and biomass burning [5]), or with Cl[−] (from sea spray or from hydrochloric acid emitted from incinerators or power plants [6]). The second major component making up the aerosols is the carbonaceous fraction that includes black carbon aerosols (BC) and organic aerosols (OA) that contain carbon along with hydrogen and oxygen. Organic aerosols have both natural biogenic sources and human-related emissions like biomass burning and meat cooking [7–9]). OA can also form in the atmosphere due to complex chemical reaction involving VOCs and subsequent gas to particle conversion [10], thus forming secondary organic aerosol (SOA). Organic

carbon (OC) is the fraction of carbon in organic aerosol excluding the associated hydrogen and oxygen [11, 12]. Black carbon or soot is the other carbonaceous fraction of aerosol and is formed during combustion processes.

According to estimates made by the World Health Association (WHO), about 7 million people die each year as a result of their exposure to air pollution (<http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/>). This estimate is more than twice larger than prior estimates because of stronger links to heart disease and strokes. This corresponds to roughly one in 8 of total global deaths per year. Over half of these, about 3.7 million (in 2012) are related to outdoor air pollution. WHO also states that this confirms that air pollution is now the world's largest single environmental health risk. Countries with the highest risks include China, with over 1.2 million deaths per year from outdoor air pollution, mostly related to exposure to particulate matter and India, with over 600,000 deaths per year [1••].

Ambient particulate matter pollution remains in the top 10 risk factors associated with Disability Associated Life Years in the USA but declined by 35 % since 1990 (US Burden of Disease Collaborators, 2013) and is one of the major air pollutants [13], causing negative effects on human health [14, 15], impairing visibility [16], and affecting climate [17]. Recent studies still suggest that there are about 200,000 outdoor air pollution related premature deaths in the USA each year related to PM_{2.5} and another 10,000 due to changes in ambient levels of ozone, with the primary source of emissions coming from combustion of fossil fuels [18].

The purpose of this study is to examine the relationship between energy production, and the associated use of fossil fuels, and resulting effects on air pollution. In the process, we examine a clean energy future imagined in this case for 2050 and then to consider the resulting effects on air quality. The next section looks into the current energy use portfolio and its impact on air quality in the USA and worldwide. This is followed with a discussion of projections of future energy needs and scenarios for the corresponding emissions of air pollutants. Finally, we examine scenarios for a clean energy future and the resulting implications on future emissions of air pollutants.

Current Energy and Resulting Pollutant Emissions and Concentrations

Figure 1 shows a conceptual diagram of key components in the global energy system. Shown in Fig. 1 are conventional sources of energy from fossil fuels, e.g., from coal, natural gas, and oil, and alternate sources of energy such as biomass burning, nuclear power, and renewable sources (which includes a number of different possibilities including wind,

Fig. 1 Key components of the global energy system. The *red arrows* indicate the pathways for use of different energy sources in the different sectors. The *blue arrows* indicate the pathway for generation of air pollutant emissions

solar, hydroelectricity, and geothermal). The resulting energy produced is used in a variety of different sectors including industry, homes, office buildings, and transportation (which includes road vehicles, trains, ships, and others). A major factor in this system is the generation of pollutants, especially emissions that affect air quality and climate change, plus other environmental concerns listed in Table 1. The use of fossil fuels is by far the largest source of air pollutants but biomass burning also contributes to the production of CO, NO_x, VOCs, and some other pollutants. Direct use of fossil fuels and biomass by end users, e.g., in transportation systems or in heating homes, also contribute significantly to pollutant production. The pathway of air pollutant emissions is shown using blue arrows.

Electricity generation accounted for 38 % of global primary energy use in 2010 making it the single largest element of primary demand [19••]. The global electricity supply sector accounts for about 80 % of the total human-related CO₂ emissions in 2010 [20]. Energy production, industry, transportation, and buildings account for 47, 30, 11, and 3 % rise, respectively, in GHG emission from 2000 to 2010 [21••]. Coal-fired power plants have been the primary source of pollutant emissions from the power production sector [22••].

About 40 % of US energy is used in the private, commercial, and institutional activities associated with residential and commercial buildings while roughly 30 % is used in industries and another 30 % in transport of goods and passengers [23]. Transportation accounts for 29 % of total global energy consumption [1••]. At present the transportation sector depends primarily on fossil fuel burning, especially oil consumption through gasoline and diesel fuel. According to the U.S. Environmental Protection Agency (EPA), mobile sources, including both on-road sources and non-road sources are major emitters of

pollutants in the U.S. Mobile sources are also one the major contributor to air toxics. Gasoline is one of the major contributors of benzene emission. EPA identified that emissions from vehicles contributed to about 21 of the 188 identified hazardous air pollutants.

Figure 2 shows the emissions of different air pollutants for the USA and the world from different energy sectors, including stationary sources (like fuel combustion in electrical utilities and industries), industries, and transportation (including both highway and non-highway vehicles). In the USA, fossil fuels account for 90 % of all energy production and use [24] and contributed to about 87, 3, and 14 % of SO₂, VOC, and PM_{2.5} emissions, respectively (adapted from the National Emission Inventory of air pollutants in 2010 by EPA, <http://www.epa.gov/ttnchie1/trends/>). States with larger areas, larger populations, and more intensive energy industries typically use more energy (EAP, 2012). The transportation sector also contributes greatly to pollutant emissions, about 53, 23, 57, and 6 % respectively to total CO, VOC, NO_x, and PM_{2.5} emissions in the USA. The US damages from the transportation sector are about \$56 million in health and from coal and natural gas are \$62 billion and \$740 million, respectively, due to emissions of criteria pollutants, not including the effects on climate [25]. The emission data for the world was obtained from the IPCC RCP4.5 scenario, which is described in a later section (<http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=compare>) [26–31]. Fossil fuel contributed about 50 and 13 %, respectively, to SO₂ and VOC emissions, and stationary combustion sources in total contributed about 78 and 16 %, respectively, of SO₂ and VOC emissions, while transportation (including surface transportation, international shipping, and aviation) contributed about 21, 19, and 45 % to CO, VOC, and NO_x emissions, respectively.

Table 1 Different air pollutants resulting from human activities that affect important environmental issues

Pollutants	Impact on air quality	Acid rain	Stratospheric O ₃ depletion	Climate change
CO	✓			
O ₃	✓			✓
NO _x	✓	✓	✓	
VOCs	✓			
CO ₂				✓
N ₂ O			✓	✓
CH ₄			✓	✓
CFCs			✓	✓
Other halocarbons			✓	✓
BC	✓			✓
OC	✓			✓
SO ₂ /SO ₄ ⁻²	✓	✓		✓
NO ₃ ⁻	✓	✓		✓
NH ₄ ⁺	✓	✓		✓

Check marks show the different cases where the pollutants contribute to various environmental issues. VOCs and CFCs include emissions of a number of different gases. Ozone is produced in the atmosphere, and is a very important component of local air pollution, but it is not directly emitted by human activities. Some pollutants, like those of mercury (Hg) from coal burning, are not included in this list because they primarily affect the environment by other means

Fig. 2 Emissions from stationary fuel combustion, industrial processes and transportation sector in 2010 in the USA (adapted from data in the National Emission Inventory for 2010 by EPA) and the World (adapted from emission data from RCP4.5 scenario) in panels **a** and panel **b**, respectively

According to EPA, large reductions in pollution emissions in the USA occurred from 2001 to 2010, including a NO₂ decrease by 33 %, CO decrease by 52 %, SO₂ decrease by 50 %, ground level O₃ decrease by 13 %, and PM_{2.5} decrease by 24 %. This resulted primarily from a shift to cleaner technologies (control measures applied on vehicular emissions and on industries like chemical plants, dry cleaners, coke ovens, and incinerators). Despite this reduction, millions of people in the USA still live in counties that exceed one or more of the National Ambient Air Quality Standards (NAAQS) [32]. A similar trend is seen overall in the world, with emissions of pollutants in the Asian countries actually increasing as they continue to build their economies. Without major control measures, the world's energy demand will likely continue to increase, with estimates of about 22 % [33] from 2010 to 2035. Existing control measures are definitely not sufficient to reduce air pollution enough to greatly reduce health concerns. Worldwide, as population continues to increase and economies develop, so does the demand on the energy sector, increasing emissions from fuel combustion, industry, and transportation, leading to further concerns about pollutant emissions and degrading air quality.

Future Projection of Air Quality

Climate change is one of the most important issues of our time [21•, 34]. The science is clear that climate change is not just a problem for the future, it is happening now across the world, and we are already being affected by changing trends in

certain types of severe weather and by the rising sea level. Analyses of past changes in climate show that the recent changes are occurring over 10 times faster than past natural changes. The scientific evidence also clearly points to the emissions from the burning of fossil fuels used for transportation and energy as being the primary cause of the changes in climate observed over at least the last five decades.

The changing climate is already affecting humanity and our economies in many ways. These effects will increase as the climate continues to change, and the effects are expected to increase dramatically over the coming decades [24, 34]. Large reductions in global emissions of the heat-trapping gases could avoid some of the damaging impacts of climate change. Just as importantly, countries and their local communities that adapt and prepare for the range of climate change impacts can prevent needless harm.

Air quality and climate change are interlinked in a variety of ways. Emissions of both long-lived pollutants like CO₂ and methane, and short-lived climate forcing pollutants like black carbon and SO₂ need to be addressed if we want to really mitigate or slow down the amount of future climate change. At the same time, reducing emissions that affect climate would also reduce the concerns about air quality. Coordinated action on both climate change and air quality is necessary [35–41, 42••].

Climate change will continue—global emissions and concentrations of CO₂ and other heat-trapping gases continue to rise. Choices made now and in the next few decades about emissions from fossil fuel use and land use change will determine the amount of additional future warming over this century and beyond. How much climate will change depends on (1) human activities and resulting emissions and (2) how sensitive the climate is to those changes (that is, the response of global temperature to a change in radiative forcing caused by human emissions). Uncertainties in how the economy will evolve, what types of energy will be used, and how our cities, buildings, and vehicles will evolve all limit the ability to make accurate projections of future changes in climate. As a result, scenarios—plausible projections of what might happen—have been developed for a range of different assumptions. These scenarios describe possible futures in terms of population, economic development, energy sources, technology, lifestyle choices, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

On the global scale, climate model simulations show consistent projections of future conditions under a range of emission scenarios [24, 34]. The most commonly used sets of scenarios used in these studies are those from the 2000 IPCC Special Report on Emission Scenarios (SRES) [43] and the 2010 Representative Concentration Pathways (RCPs) [44]. The latter were used in the latest international climate assessment [24]. Comparing carbon dioxide concentrations and global temperature change between the SRES and RCP

scenarios, the high SRES A1FI scenario is similar to RCP8.5, the middle scenario SRES A1B to RCP6.0, and the low scenario SRES B1 to RCP4.5. The RCP2.6 scenario is much lower than any SRES scenario because it includes the option of using policies to significantly reduce emissions and also requires net negative carbon dioxide emissions in the later decades of this century where CO₂ would need to be removed from the atmosphere, while the SRES scenarios do not attempt such a policy requirement [34]. The high scenarios assume continued heavy use of fossil fuels while the lower scenarios assume different rates of movement towards alternative energy sources.

As has been shown in a number of studies [39, 45–52], the warmer summer climates throughout much of the world will lead to more concerns about ozone production. Major air pollutants like O₃ and PM_{2.5} are dependent on many meteorological parameters making it imperative to understand the relationship between air quality and meteorology [53]. Various studies [45, 46, 54] have also shown that the effects of climate change itself (e.g., changes in temperature) on air quality are small relative to the effects of future emissions of NO_x and VOCs on air quality. Recent studies conclude that O₃ and PM_{2.5} concentrations would decrease in the continental USA in the future under lower climate change scenarios like B1 or RCP4.5 [45, 46, 49, 53, 55, 56]. But for high emission scenarios like RCP8.5, ozone concentrations would increase due to the continuing dependence on fossil fuels and also high methane emissions assumed [52]. In the middling A1B scenario, which has rapid economic growth and balanced energy growth from both fossil fuel and alternative sources of energy, NO_x emissions from fossil fuels are projected to decrease by 40 % in the USA but are likely to increase by 90 % globally [49]. In all cases, projected mean surface ozone and aerosol concentrations were more sensitive to the projected anthropogenic emissions than they were to the changes in climate.

These and other studies have shown that policies to limit future climate changes by encouraging alternative energy sources and a reduction in emissions from burning fossil fuels would also result in a reduction in emissions affecting ozone and PM_{2.5}. Also, policies to protect air quality tend to lead to more efficient energy production and transportation systems that reduce the emissions of carbon dioxide, the gas of most concern to climate change.

The general conclusions from existing studies is that the high scenarios like A1FI and RCP8.5 result in much larger pollutant emissions and near surface ozone and PM_{2.5} concentrations than the middle emission scenarios like A1B and RCP6.0 and the low emission scenarios like B1 and RCP4.5 [38, 45, 46, 57–60].

Figure 3 shows the worldwide anthropogenic emission various gases and aerosols for the different RCP scenarios (adapted from IPCC 2014 [21••]). For the RCP2.6 scenario, all pollutant emissions decrease remarkably except for NO_x

Fig. 3 Global human-related emissions for CO₂ (a) and short-lived gases (b to d) and aerosols (e and f) under the Representative Concentration Pathway scenarios from IPCC, 2013, for 2010 and projections to 2030 and 2050. Finally, we show estimated emissions Clean Energy Scenario I

that still depends heavily on use of biofuels and Clean Energy Scenario II in which dependence on biofuel is much lower for 2050 only. The numbers on the green bars indicate emission in 2050 for the different scenarios

emissions. CO₂ emissions increase from 2010 to 2050 for all the other three scenarios. CO, VOCs, SO_x (which is mostly SO₂ but also includes some other minor sulfur gases), and BC have lower emission in 2050 compared to 2010, but in some cases, they show a slight increase in 2030. It is well recognized that the RCP scenarios are not likely representative of future BC and OC particle emissions [61]. SO_x emissions consistently decrease because all the scenarios look for an alternate to coal as an energy source. NO_x emissions are always higher than 2010 for all of the RCP scenarios. OC emission goes down by 2050 for RCP4.5 and RCP8.5, but increases a little for RCP6.0. OC emission can be tied to that particular scenario's stress on using biomass burning as a source of fuel.

A Clean Energy Future

The most likely means that can be implemented to improve air quality while also reducing effects on future climate are increased use of renewable energy technologies, more efficient energy utilization, alternative energies for transportation, and increased energy storage technologies. In this section, we consider a clean energy future.

Although transitioning our energy system to cleaner fuels and/or changing to complete renewable sources of energy may seem daunting, the potential benefits to human health and lives are large. A number of studies have begun to examine alternative energy futures. A 100 % renewable energy system is technically possible and may even be economically

beneficial compared to the present situation [62]. A change to cleaner sources of energy would greatly reduce the emissions of short-lived species affecting ozone and PM_{2.5}, and thus reduce concerns about air pollution, while also reducing emissions of the long-lived species having the largest effects on climate. We start the discussion by examining alternative renewable energy technologies for the transportation and electricity production sectors.

Transportation Systems

The majority of today's vehicles operate on gasoline or diesel, although some use liquefied petroleum or compressed natural gas. A number of studies have shown transportation to be a major source of ozone and PM_{2.5} precursor emissions. For example, a study in the San Francisco area showed that trucks account for 56 and 26 % of BC and OA emissions, respectively [63]. Vehicular exhaust contributed about 17.1, 40, and about 17–24 % of primary PM_{2.5} pollution in Beijing [64], in six cities in Brazil [65], and in Milan [66], respectively.

To control emissions from vehicles, one of the control measures that can be applied is use of alternative fuels like biodiesel, hydrogen, natural gas, ethanol, propane, and electricity. Addition of biofuel additives to gasoline and diesel vehicles is a common practice to reduce tailpipe emissions. The addition of biofuels to gasoline and diesel engines reduces CO₂, CO, and VOC emissions (because of the presence of more oxygenated fuels), but does not show any appreciable change in NO_x emissions [67–70].

Natural gas vehicles have been shown to improve air quality by reducing particulate emissions and photochemical smog. Introducing compressed natural gas (CNG) vehicles to the fleet reduces emissions of air pollutants overall, but increases hydrocarbons (specially methane due to leakage) [71–77]. Although biofuels additives and CNG engines may reduce tailpipe emission to a certain extent, the overall energy production is still fossil fuel based, and their use does not eliminate emissions of all key pollutants.

Another method is to shift to hybrid and/or electric and/or hydrogen fueled vehicles. Electric vehicles use electrical energy stored in rechargeable batteries and other energy storage devices, hybrid vehicles combine internal combustion engines with electric motors, and hydrogen-fueled vehicles use either hydrogen fuel cells or hydrogen in internal combustion engines as an energy source. Electrification of the vehicles will address three important environmental issues: (a) reduction of GHG emissions; (b) reduction of tail pipe emissions affecting air quality; and (c) reduction of gasoline consumption, which will reduce air pollutant emissions [78].

Plug in hybrid vehicles uses electricity from the grid to power a portion of the vehicle use, but there is still use of petroleum-based fuels. If charged with other than fossil fuel intense electricity sources, hybrid vehicles can reduce gasoline

consumption, resulting in reduced tail pipe emissions [78–80]. The use of plug in hybrid vehicles also reduces NO_x emissions and resulting O₃ production [81].

Electric vehicles have the potential to transform the effects of vehicles on the environment, especially if the electricity comes from non-fossil fuel sources [82]. Since electric vehicles do not depend on petroleum-based fuels at all, there are no tail pipe emissions. The global-warming potential (GWP) of electric vehicles is much lower than gasoline or diesel vehicles, even if the electricity does come from fossil fuel sources [82–87]. At present a conventional vehicle emits 100–150 g of CO₂/km whereas a hybrid vehicle achieves about 90 g of CO₂/km. Electric vehicles have the potential to reduce this to about 50 g CO₂/km vehicle travelled [88•], when using fossil fuels as their power source, and it goes to zero when using power from alternate energy.

Another potential alternate fuel is based on the use of hydrogen (H₂). Hydrogen itself is not a primary energy source but it can be produced in fuel cells through catalysis or burned in internal combustion engines to supply electricity to the cars. Hydrogen gas can be extracted in various ways, from many conventional sources like coal and biomass, or from clean sources like water, wind, or solar power. Since it can be extracted from both renewable and non-renewable sources, it would be easy to incorporate it into an existing energy structure [89]. H₂ fuel cells emit only water vapor, thus eliminating CO, NO_x, and VOC emissions from the tailpipe. Both H₂ fuel cells and H₂ combustion engines could greatly decrease the O₃, CO, NO_x, and soot atmospheric burdens [90]. Vehicles powered by hydrogen extracted using wind energy for the chemical conversion could save 2300 to 4000 lives/year and \$32 billion to \$180 billion relative to even hybrid vehicles and could reduce asthma by 1 to 3 million cases/year relative to conventional vehicles in the USA due to improvement in air quality. [91].

All alternate technologies discussed above for vehicles significantly reduce the tail pipe emissions compared to the conventional vehicles. A key factor though is that these vehicles need a “electric supply” to charge the batteries or to provide hydrogen in the combustion engines; if the electricity production still depends on conventional fossil fuel sources of energy then the net pollution will still be high.

Electricity Production and Other Energy Use

As mentioned earlier, electricity production and other energy use (e.g., use of fossil fuels by industry) currently account for very high pollutant emissions in the USA and throughout the world. Alternate sources of energy like nuclear power, and renewable power sources like hydroelectricity, wind, solar, and geothermal, and even to some extent biomass burning, have the potential to provide energy with greatly reduced pollutant emissions, thus improving air quality and also

mitigating GHG production. It has been estimated that to keep further changes in climate below 2 °C throughout the twenty-first century, the cumulative carbon emission between 2011 and 2050 have to be limited to around 1100 Gt CO₂ [92]. But to meet this level globally, a third of oil reserves, half of gas reserves and over 80 % of current coal reserves would need to remain unused for energy production from 2010 to 2050 [93]. All conventional sources of energy like coal, oil, and natural gas are all non-renewable and unevenly distributed in the earth with the Middle East holding the maximum oil reserves, Russia holding the maximum natural gas reserves, and the USA holding the maximum coal reserves. How long these reserves last will depend on the demand we put on them. In absence of any mitigation policy, the world's energy use of fossil fuels would rise by over one third by 2035 with demand of coal rising by 21 % and natural gas by 51 %. The power sector would increase from ~20 % today to 31 % in 2035. These analyses suggest energy demand in China would likely account for the largest share of the projected growth in global energy use demand, rising by 60 % in 2035, followed by India and the Middle East [33].

Table 2 gives the data for the changing demand of different energy sources in the whole world, in the OECD90 countries, and Asia till 2050 for three different SRES emission scenarios, B1, A1B, and A1FI (adapted from Nakicenovic et al. [94]). Before going into the description of the trend in the data some of the terms used in association with the table are clarified first. The Organisation for Economic Co-operation and Development

(OECD) is comprised of the higher developed countries; OECD90 consists of 90 countries from Western Europe, Northern America, and higher developed Pacific nations such as Australia, New Zealand, and Japan. Asian countries like China and India are going through extensive economic growth and an unprecedented growth of energy and population is seen in this region. Regarding the IPCC SRES scenarios, we would expect the highest transition to alternate energy technologies in the B1 scenario, and the least in the A1FI scenario. Until at least mid century, total energy demand in Asia should increase at a higher rate than that in the OECD countries. Even in the most conservative scenario B1, energy from fossil fuels (coal and oil) keeps on increasing to 2050 for Asia. The OECD countries reduce dependence on fossil fuel by 2050 in the B1 and A1B scenarios, but in the fossil fuel intensive scenario A1FI, the consumption increases even for OECD countries. The B1 scenario does not consider nuclear power as a viable alternate energy. But use of biomass burning increases in both Asia and the OECD countries for all the scenarios, but we do not see a similar trend in renewable energy, and actually we see a reduction in use of renewable energy in Asia in case of B1 scenario. Even in the A1FI scenario, the use of alternative energy sources increase, but this is mostly because of the high-energy demand projected by this scenario. From Fig. 3, while pollutant emissions are reduced in the lower emission scenarios, air quality would still remain a serious issue over the coming decades. Only by a dramatic switch to alternatives can we greatly reduce air quality concerns.

Table 2 Changing energy usage in the world, OECD countries and Asia from 2010 to 2050 under three of the SRES emission scenarios, B1, A1B, and A1FI

		B1			A1B			A1FI		
		World	OECD	Asia	World	OECD	Asia	World	OECD	Asia
Coal (EJ)	2010	120	46	51	134	41	64	150	48	73
	2030	163	36	67	179	30	108	299	51	165
	2050	167	24	64	186	28	104	475	82	251
Oil (EJ)	2010	176	74	39	209	92	45	150	79	30
	2030	230	64	63	239	78	68	165	71	48
	2050	228	39	56	214	54	51	283	70	97
Nuclear (EJ)	2010	—	—	—	16	10	2	35	14	9
	2030	—	—	—	53	23	15	79	17	33
	2050	—	—	—	123	24	45	137	18	67
Biomass (EJ)	2010	11	5	3	38	0	19	12	4	5
	2030	54	14	23	85	9	19	28	5	15
	2050	95	21	40	193	29	46	52	9	26
Renewable (EJ)	2010	71	10	32	15	8	2	27	10	5
	2030	61	10	23	40	16	10	42	10	11
	2050	46	10	13	167	35	58	86	14	33

The energy usage is given in terms of EJ (1EJ (exajoule)=10¹⁸ J) (adapted from Nakicenovic et al. [94])

A Clean Energy Scenario

Very few complete scenarios have been developed for an extensive switch to clean energy by 2050. This is not because it could not be done, but there needs to be a strong willpower to do so. Also, new technology development, like battery storage systems, will likely be key to that transition. Most of the studies that we found on use of clean energy from around the world were restricted to relatively small European countries [62, 95–97]. The common feature of all these transformations was looking at high share of biomass, wind power, and solar power. Also, emphasis was given to new energy storage technologies, and the use of electric vehicles and heat pumps (to increase efficient heating and cooling in buildings). The studies showed that with these assumptions, electricity generation by renewable sources would increase in those countries, while operational cost decrease and CO₂ emissions are eliminated.

Towards examining a clean energy future, we have considered three existing idealized scenarios for shifting to clean energy, two of which are based on an energy shift throughout the world and one based on the USA. [33, 98, 99]. The study for the USA [98] assumed 80 % penetration of renewable energy by 2050 using technologies that are only currently available commercially. A strongly growing energy demand but much more energy efficient future in the world by 2035 is considered in scenarios developed by the World Energy Outlook 2012 [33]. A study by World Wildlife Fund for Nature (WWF) [99] looked into a 100 % renewable energy world by 2050 (see Fig. 4). The working principles of all these scenarios were to primarily supply electricity through renewable energy sources while also increasing energy efficiency. Simple measures like insulating building, recycling materials, use of energy efficient materials in industries, and shifting to more efficient forms of transportation can reduce total energy demand by 2050. Bioenergy (liquid biofuels and solid biomass) are likely to be important where other renewable energy sources are not viable,

Fig. 4 Global energy provided by different sources from 2000 to 2050 for a renewable energy future (adapted from the WWF study [99])

especially in providing fuels for airplanes and ships, and in industrial processes that require high temperatures. Compared to current fuels, the use of biofuels could still result in significant emissions of NO_x and VOCs, but there would likely be a significant reduction in PM_{2.5} precursor emissions.

Figure 4 shows the change in global energy usage by sources from 2000 to 2050 for a clean energy future based on the WWF study [99]. Energy requirement for transportation and residential uses is completely provided by alternate sources of energy. Fossil fuels are assumed to be needed for some industrial processes, particularly for their mechanical properties and not to provide energy. This scenario reduces fossil fuel usage by 95 % and clean renewable sources like wind, solar, hydropower, and geothermal energy sources increase by 12, 31, 6, and 6 %, respectively, by 2050. Bioenergy is assumed to provide 40 % of the total energy by 2050. Implementation of these large-scale uses of alternatives will, of course, require careful planning and international cooperation. This is just one of many possible scenarios for achieving a clean energy future.

The last two sets of columns for the pollutants considered in Fig. 3 show a range of emissions for two scenarios of an idealized clean energy world. In clean energy scenario 1, we follow the WWF scenario and assume fossil fuel use has been brought down to 5 % and current fossil fuel use has been replaced by other cleaner energy sources. Therefore, emission of CO₂ can also be brought down to 95 % and SO₂ emission can also be reduced by 95 % (since its major source is fossil fuel combustion). The WWF scenario assumes that biofuels will become about 40 % of the total energy production by 2050. Given this, NO_x and VOC emissions should decrease relative to today in roughly proportion to the amount of use of biofuels, while BC and OC emissions are likely to be much lower, perhaps 50 % of that proportion. Clean energy scenario 2 considers a world with even smaller emissions. The development of battery storage technologies, leading to electric vehicles along with much more extensive use of solar and wind power could make such an idealized clean energy world possible. If all energy production sources were entirely renewables without biofuels, and transportation systems, except for aviation (most emissions occur in the upper troposphere) and ships, were assumed to be run on electrical battery systems, then human-related emissions of NO_x and VOCs can be assumed to drop by at least 90 % of current emissions even when the growth in energy demand is included for 2050. BC and OC emissions are also assumed to be reduced by 90 % in this scenario. Although these scenarios are hypothetical, Fig. 3 shows that a cleaner energy world would greatly reduce emissions of air pollutants, resulting in greatly reduced concerns about air quality and the resulting effects on human health.

Conclusions

Increasing population and economic development throughout the world could continue to exert a high demand on the conventional sources of energy, leading to higher pollutant emission which will directly affect both air quality and climate change in adverse ways. Europe, North America, Japan, and the other OECD countries already have widespread development of renewable energy technologies. Developing countries like China, India, Kenya, Argentina, Costa Rica, Brazil, and others also have large resource capability and market for renewable energy.

In March 2015, Costa Rica ran for more than 75 days with 100 % renewable energy using mostly hydro and wind power [100]. In rural areas in most developing countries, there is no electricity grid. In these situations, off-grid renewable technologies like solar photovoltaic cells or micro-hydroelectric system can provide cost-effective and sustainable alternative to diesel generators, kerosene lamp, or biomass burning as source of energy. This can provide electricity in homes and can also provide electricity to run schools, small businesses, and health clinics, thus increasing literacy, improving living conditions, and reducing poverty [101]. End users should also be made aware of the environmental benefits of using cleaner and newer technologies, for example using electric vehicles instead of gasoline/diesel run vehicles or constructing green buildings. This will ensure that the change from conventional energy to alternate energy sources does not meet with a high resistance from the end users. Incentives may be needed. Renewable energy gives a country energy security by providing access to clean and natural sources of energy at cheap price. To enhance the market reach of these technologies, there might also be a need to subsidize the cost of alternate energy services to make them affordable to major part of the population.

A country's physical border does not restrict impact of degrading air quality or climate change issues. International collaboration can help in controlling impact of long-range transport or intercontinental transport of air pollutants. Sharing research and newer technologies pertaining to renewable sources can help countries without the immediate means to do so in implementing these without taking a very high setback in their industrial or economic developments. IPCC which is aimed at understanding climate change and its impact and not directly related to policy developments, also include analyses of the effects of climate change on air quality (IPCC Working group II: Impacts, Adaptation, and Vulnerability) and their assessment is extremely relevant to the discussion in this paper. Such assessments provide useful guidelines for policymakers as to the importance of the issues associated with climate change. They also provide useful summaries of state of the science to help guide further research.

Greater emphasis should be given to research on clean energy like wind, solar, geothermal, and hydroelectricity. Research on new technologies like development of battery storage and incorporating electricity developed from the alternate sources in the current electricity grid system is also very important. If the renewable energy technologies take over conventional energy sources, a life cycle assessment of the newer technologies will also be very pertinent. For example, if vehicles shift from using gasoline/diesel to electric batteries from electricity generated from renewable sources, the tail pipe emission becomes almost zero but there can be newer emissions from the battery manufacturing facilities [80]. Also, as the vehicles shift to the newer technologies, older vehicles have to be scraped and similar situation will arise for all the sectors changing from conventional sources to renewable sources. Extensive research should also go into handling the waste produced so that more pollutant and GHGs are not emitted from handling the waste. Air quality research is also needed. The processes affecting local and regional ozone production are reasonably well understood, but there remain some questions about the complete chemistry of some of the hydrocarbons. Much more uncertain are the processes affecting the microphysics and chemistry in the life cycle of many of the particles. More emphasis on research in this direction is needed.

A shift from conventional energy sources that rely heavily on fossil fuel combustion, and from gasoline and diesel in vehicles, to renewable sources would greatly improve air quality and save a lot of lives. At the same time, such a shift would greatly reduce the concerns about future climate change. The study shows that such a world is possible—it is really our choice. Do we emphasize the push for the technology development required to get there or do we continue to heavily depend on fossil fuels and face the resulting effects on climate and air quality?

Conflict of Interest Dr. Wuebbles and Ms. Sanyal have no conflicts of interest.

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