Minimizing World Electrical Cost

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1 Introduction

The world generates electricity from a variety of different sources. Fossil fuels were crucial in the emergence of the industrial revolution and have since been the staple fuel source for the planet. Renewable fuel sources on the other hand are the new kid on the block. They are an appetizing option for the future as producing electricity from renewable resources costs less and has less negative impact. However, installation costs of renewable power plants have prevented widespread use on a mass scale, and as such electricity from renewable resources is still limited.

The cost of establishing and furthering the advancement of renewable energy discourages governments and businesses from producing more electricty from renewable sources. The electricity generated from fossil fuels in 2018 came in at 17,087 TWh (Terawatt-hours = 1x10^{12} Watt-hours) while the combination of electricity from nuclear and renewable sources totalled to 7,048 TWh, with the majority of that coming from hydropower and nuclear[1].

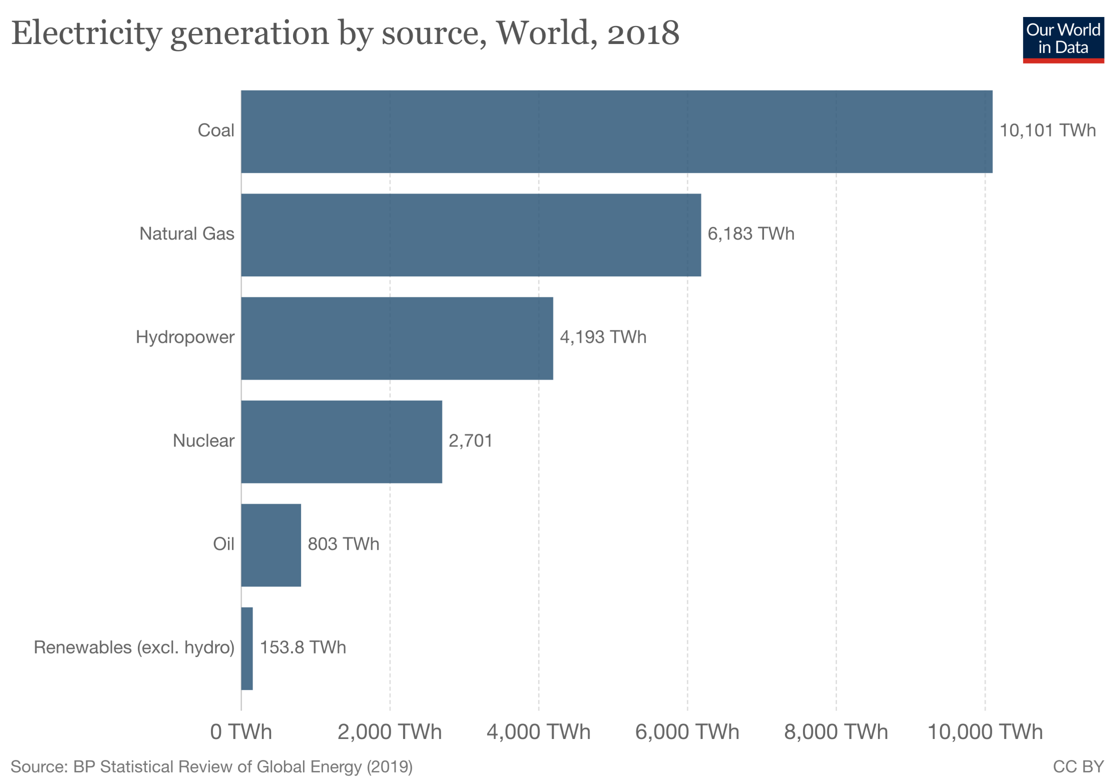

Figure 1: Source: "Energy". Published online at OurWorldInData.org (2020)

The main question this projects seeks to answer, is how expensive the generation of electricity from fossil fuels needs to be in order for the installation of renewable power plants to be a more viable, and more importantly, more cost effective option. To answer this question, a linear optimization model was built in Python to minimize the global cost of electricity production and usage.

2 Constructing the Minimization Problem

2.1 Objective Function

To answer the question of how to minimize world electrical cost, the problem is formatted as a linear optimization problem. The estimation variables are arrays of 28 elements, which represent 4 electricity factors in each of the 7 major fuel sources. There are 44 estimation variables, each representing one of the 44 nations considered in the model.

The cost coefficient is a 28x1 array that represents the monetary value corresponding to each element in the estimation variables. For the sake of the model, the cost coefficient is uniform for each nation.

The objective function is the sum of the inner products of each estimation variable with the cost array. The problem therefore takes the form

$$\text{Minimize } \sum_{i=1}^{44} \langle c, x_i \rangle$$

where $x_1, x_2, x_3, ..., x_{44} \in \mathbb{R}^{28}$ are the estimation variables, and $c \in \mathbb{R}^{28}$ is the cost coefficient.

2.2 Estimation Variables

Each optimization variable represents the electricity generated and used by a single nation. The variables are each broken down into seven major fuel sources: coal, natural gas, oil, nuclear, hydropower, windpower, and solarpower. Each fuel source is then further broken down into four categories: production, imports, exports, and consumption.

2.2.1 Sources of Electricity Generation

Below each fuel source is outlined in detail. Due to their widespread power plants and ease of access, fossil fuels (coal, natural gas, and oil) currently dominate the market and world electrical supply. Renewable electricity alternatives (hydro, wind, and solarpower) have shown increasing promise, but the lack of established power plants holds them back from taking center stage in world electricity production.

1. *Coal* is defined in the model as the combination of the four main types of coal used for electricity production (anthracite, lignite, bituminuos, and sub-butiminous)[2]. Coal is the fossil fuel most heavily relied upon for electricity production. Burning coal to generate electricity elicits the highest amount of CO_2 emissions amongst fossil fuels in the electricity sector[3] and has the highest associated death rate in terms of electricity production[1].

2. *Natural Gas* is the second major source of fossil fuels used to generate electricity. Electricity production using natural gas emits less CO_2 than coal in the electricity sector (about 33% compared to coal's 65%)[3]. However, natural gas emits higher doses of other greenhouse gases including methane, which is 20 times more potent than CO_2[4].

3. *Crude Oil* is utilized the least for electricity generation[1] among fossil fuels, instead being more heavily relied upon in the transportation sector. Oil production on the whole has an extremely high contribution to greenhouse gas emissions[4] and the second highest associated death rate[1].

4. *Nuclear* is the electricity generated from nuclear power plants. Nuclear electricity is an extremely attractive alternative to fossil fuels with an estimated generation capacity of 7.5TWh/Year-Reactor in the model[5].

   However, there are several drawbacks hindering nuclear power. Installation costs are the highest for none fossil fuel energy sources[6], and also require the adequate technology (which less developed nations and those without dedicated nuclear programs may not have access to).

   Furthermore, while nuclear is a safe source of electricity[1] (especially when compared to fossil fuels) nuclear energy can be extremely controversial. Though rare, nuclear meltdowns cause panic and an aversion to continued nuclear production when they occur. In 2014, Japan had the 2nd most nuclear reactors installed in the world (50)[5], but in the aftermath of the meltdown at Fukushima in 2011, the nation halted its nuclear production to the degree where it only output 0.017 TWh total in 2014[5].

5. *Hyrdopower* is the most accessible source renewable electricity and requires the least amount of technological advancement compared to wind and solar power. It has been in use for electricity generation the longest and is more accessible to developing nations as a source of electricity (as long as they have the requisite bodies of water). Zambia for instance utilizies hydropower for over 95% of its energy demand[7].

   Developed nations with extended waterways are also able to utilize hydropower to an extreme effect. Norway is the prime example, generating 97% of its electricity from hydropower[8].

   Hydropower does however demand the most capital among the three renewable sources to install new power plants[6]. The major negative drawback of hydropowered electricity is the water (often fresh water) it consumes in electricity generation.

6. *Windpower* offers two avenues for electricity production, on-shore and off-shore. Off-shore windpower is an attractive option in the future, but is problematic due to the logistics of large scale installation in the ocean. Therefore, in this model only on-shore wind is being considered.

   Electricity generation from windpower requires the smallest operational cost once installed[9], and offers the lowest installation cost as well[6]. There are little to no known negative impacts from wind powered electricity.

7. *Solarpower* comes in two primary types of electricity generation: photovoltaic and concentrated solar thermal. Photovoltaic solar panels generate electricity directly from the

sunlight. Concentrated solar thermal systems use heat from sunlight to power steam engines that generate electricity. In this model only photovolataic was considered.

Along with windpower, it is the most attractive electricity source for the future. Generation costs are the lowest among all fuel sources in the model (tied with wind)[9], and installation costs are virtually equal to that of windpower while beating those of nuclear and hydropower by a large margin[6]. An additional benefit to solar power is the versatility of solar panels, allowing installation in urban and residential areas. There are little to no known negative consequences from solar powered electricity.

The "Country" class was created in the model to represent the specific details of electricity generation within each nation. In the class definition is a countries name, energy demand, and relative production percentage of the world supply for each fuel source. Furthermore it contains the self._variables, which becomes the estimation variable for each nation.

The list "countries" is the list containing each of the 44 nations considered. This list will be constantly referenced when activating the constraints defined within the "Country" class.

2.2.2 Fuel Categories

Each fuel source is broken down into four categories to reflect how each nation utilizes that fuel source.

- *Production* is the amount of electricity generated from a fuel source. In the model it is defined as production_variables(self) and represents the 4th element from the _variables list starting from index 0.
- The second category differs between fossil fuels and nuclear / renewable sources.
  - *Imports* is the quantity of electricity from imported fossil fuels.
  - *Installation* is the amount electricity generated from newly installed renewable and nuclear power plants.

  In the model these variables are defined as import_install_variables(self) and represent the 4th element from the _variables list starting from index 1. The model makes the assumption that no renewable energy resources are established enough for widespread trade. Conversely, the cost of installing new fossil fuel power plants are not taken under consideration.
- *Exports* is quantity of fossil fuels produced in a nation and sold for consumption outside the nation. This is the only category with a negative cost, as exporting fossil fuels bring in profit. Nuclear and renewable exports were given a zero cost as to not factor into the model. In the model exports are defined as export_variables(self) and represents the 4th element from the _variables list starting from index 2.
- *Consumption* is the amount of electricity a nation utilizes to meet its energy demand. In the model it is defined as consumption_variables(self) and represents the 4th element from the _variables list starting from index 3.

2.3 Cost Coefficient

The major cost for each fuel source is the production cost. This includes the capital necessary to operate, fuel, and maintain power plants. This is also where additional costs reflecting indirect impacts, such as environmental and health considerations, will be added.

The import cost is the capital needed to import fossil fossil fuels or install new sources of renewable and nuclear electricity plus the production cost to actually produce the electricity from the sources attained.

The export cost is the negative cost that reflects the profit to be made from exporting fossil fuels.

The consumption cost is the cost to use the electricity a nation attains to meet its energy demand. The consumption variable is the lynch pin that reflects how the other categories interact with one another to meet demand. All costs associated with each fuel source are represented by the other three categories. The consumption cost is therefore 0 for each fuel source.

The baseline cost for each fuel source in each category are outlined in the following table[6,9,10].

Fuel Source	Production Cost	Importation Cost	Exportation Cost	Consumption Cost
Coal	0.03586	0.04444 + (0.03586)	-0.04444	0
Natural Gas	0.03243	0.01194 + (0.03243)	-0.01194	0
Oil	0.03586	0.03871 + (0.03586)	-0.03871	0
Nuclear	0.02386	0.7211 + (0.02386)	0	0
Hydropower	0.01065	0.3142 + (0.01065)	0	0
Windpower	0.00508	0.1506 + (0.00508)	0	0
Solarpower	0.00508	0.1519 + (0.00508)	0	0

Table 1: All costs measured in $/KWh (Kilowatt-hour)

2.4 Constraints

In order for the model to run and reflect the reality of today's electricity usage, a multitude of constraints were implemented.

1. **nonnegativity**: every element in each estimation variable must be greater than or equal to zero
$$0 \leq \text{all.\_variables}$$

2. **demand_countries**: sets the total electricity a nation must consume equal to the nation's energy demand. The self.demand is the specific energy demand defined within each nation. It is based on the total electricity consumption of each nation in 2018[8].
$$\sum_{0}^{6} \text{consumption\_variables()} = \text{self.demand}$$

3. **production_world**: limits the total amount of electricity generated from each fuel source by all nations to be less than the total world supply. This limits electricity from fossil fuels to not exceed the supply of the raw materials available, and limits nuclear and renewable electricity sources to their currently installed capacity.

   Total world supply is defined as supply_world_source within the model and is based on the total primary energy supply of each fuel source[11].
$$\sum \text{production\_variables()} \leq \text{supply\_world\_source}$$

4. **cr_countries**: for each individual nation, this represents the primary relationship between all four categories for each fuel source. The total amount of a electricity consumed from a given source must equal the amount of that source produced, plus any imports, minus any exports.
$$\text{consumption\_variables()} = \text{production\_variables()} + \text{import\_variables()} - \text{export\_variables()}$$

5. **ilse_countries**: limits the total amount of a fossil fuel source available to be imported by a single nation to the world supply of that fuel source minus the amount produced within the nation itself.
$$\text{import\_variables()} \leq \text{supply\_world\_source} - \text{production\_variables()}$$

6. **imports_ff_world**: limits the total electricity generated from fossil fuel imports among all nations to be less than the total world supply.
$$\sum_{n=1}^{44} \text{import\_variables()} \leq \text{supply\_world\_source}$$

7. **supply_demand_world**: sets the total imports for each fossil fuel among all nations equal to the total exports. Imports cannot be bought if no one is exporting, and exports cannot be sold if no one is buying.
$$\sum_{n=1}^{44} \text{import\_variables()} = \sum_{n=1}^{44} \text{export\_variables}$$

8. **elp_countries**: in each nation, the total amount exported of a fuel source cannot be greater than that produced.

$$\text{export\_variables()} \ \leq \ \text{production\_variables()}$$

9. **ff_countries**: details how much of each fossil fuel source each nation is able to produce, for its own consumption or for exportation. Three percentages were defined within each nation to reflect the the relative percentage of total electrical supply each nation is able to generate from each of the three fossil fuels.

   These percentages are based on the observed production proportion of the total world supply each nation contributed for each fossil fuel in 2018[8].

$$\text{production\_variables()[0]} \ (\textit{coal}) \leq \ \text{coal\_ability*supply\_world\_source[0]}$$

$$\text{production\_variables()[1]} \ (\textit{natural gas}) \leq \ \text{naturalgas\_ability*supply\_world\_source[1]}$$

$$\text{production\_variables()[2]} \ (\textit{oil}) \leq \ \text{oil\_ability*supply\_world\_source[2]}$$

10. **nu_countries**: limits the amount of nuclear powered electricity a nation can generate based on the number of operational nuclear reactors it has[12]. The amount of nuclear generated electricity from each nation must be less than or equal to 7.5 TWh times the number of reactors it has in operation.

$$\text{production\_variables()[3]} \ (\textit{nuclear}) \leq 7.5 * \ \# \text{ nuclear reactors}$$

11. **rc_countries**: puts a cap on how much electricity from renewable sources a nation is able to generate, based on its observed percentage of electricity from renewables in 2018[8].

    The constraint caps the sum of the electricity generated from hydropower, windpower, and solarpower to the observed percentage of renewable capability times the total consumption demand.

$$\sum_{4}^{6} \text{production\_variables()} \ (\textit{renewables}) \leq \ \text{renewable\_ability} * \sum_{0}^{6} \text{consumption\_variables()}$$

12. **ws_countries**: takes the renewable constraint one step further and limits the amount of electricity that can be generated by windpower and solarpower. These are much less developed than hydropower, and as such hold a much smaller percentage of current electricity production. The windsolar_ability factor is based on the observed percentage of each nations electricity that came from these sources in 2018[8].

$$\sum_{5}^{6} \text{production\_variables()} \ (\textit{wind + solar}) \leq \ \text{windsolar\_ability} * \sum_{0}^{6} \text{consumption\_variables()}$$

13. **ws_install**: mandates that windpower and solarpower, when installed, must be installed at a 1:1 rate. Windpower and solarpower are both extremely viable energy options for the future, and this constraints prevents one of them from dominating renewable electricity installation, as the installation costs are only slightly different.

$$\text{import\_install\_variables[5]} \ (\textit{windpower}) \ = \ \text{import\_install\_variables[6]} \ (\textit{solarpower})$$

3 Results

3.1 Base Model

Initially the model was run with only the baseline costs required to physically run the power plants and generate the electricity produced. These costs are the easiest to quantify and have the most available data as they are the costs that must be paid to generate electricity.

The results were as follows:

Global Expenditure on Electricity	$598,700,000,000

Coal	Natural Gas	Oil	Nuclear	Hydropower	Windpower	Solarpower
2.35e3	9.22e3	1.55e3	2.70e3	3.52e3	1.08e3	5.46e2

Table 2: Total Electricity Produced (TWh)

Coal	Natural Gas	Oil	Nuclear	Hydropower	Windpower	Solarpower
2.35e3	9.22e3	1.55e3	2.70e3	3.52e3	1.08e3	5.46e2

Table 3: Total Electricity Consumed (TWh)

Nuclear	Hydropower	Windpower	Solarpower
0	0	0	0

Table 4: Electricity from Newly Installed Nuclear and Renewable Power Plants (TWh)

The lack of installed capacity for alternative electricity sources led to fossil fuels dominating electricity production and consumption. Natural gas was the least expensive fossil fuel to produce electricity from and has the lowest trade value among fossil fuels. As such, it is the primary resource to meet electrical energy demands. After natural gas, electricity from coal and oil were relied upon to meet any left over demand that renewable and nuclear sources were not able to address.

Nuclear and renewable fuel sources were produced to their maximum output. The lack of currently installed renewable and nuclear power plants and the high cost of installing new power plants, relative to the cost of generating electricity from fossil fuels, holds electricity generation from alternative sources back. This severely restricts how much they can contribute to world electrical generation.

3.2 Model with Indirect Costs

After the numbers from the base model were calculated, the next step was to factor in probable indirect costs of electricity production. The aim in doing so was to determine how high the supposed cost of electricity generated from each fossil fuel source needs to be in order for renewable fuel sources to be a more cost effective, and therefore more viable, option.

Some indirect costs were able to be roughly estimated, but some (such as environmental impact from greenhouse gases) were unable to be quantified as the scope is too broad and there is little concrete data available. Therefore estimates were made were able, and where not able the determined cost was set at how expensive it needed to be in order to antiquate fossil fuel electricity production.

3.2.1 Indirect Costs

1. **death_cost**: the \$/KWh cost of human life based on the estimated number of deaths/TWh according to the chart below. This calculation estimates the value of a human life at 3.4 million dollars[13].

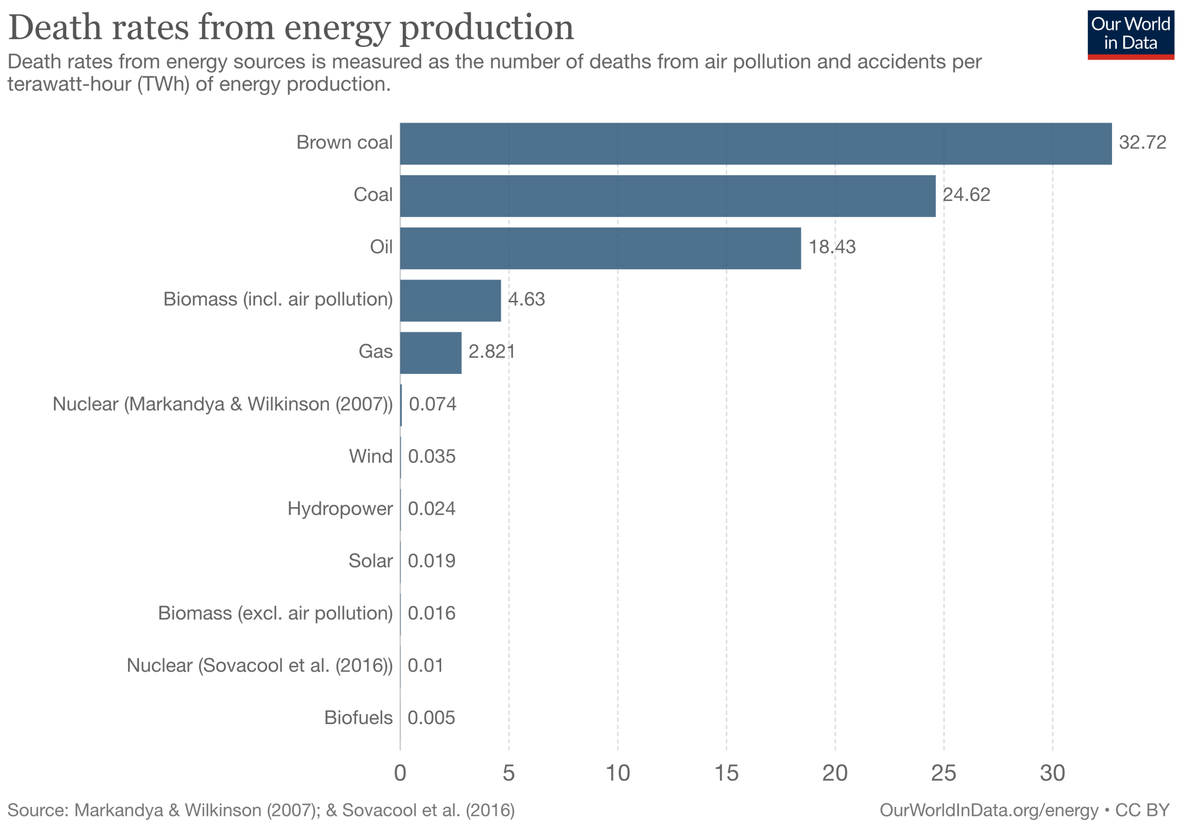

Figure 2: Source: "Energy". Published online at OurWorldInData.org (2020)

Coal	Natural Gas	Oil	Nuclear	Hydropower	Windpower	Solarpower
0.085	0.010	0.061	0	0	0	0

Table 5: Cost of Human Life ($/KWh)

2. **water_cost**: the cost of the water that is consumed from electricity generation. This comes primarily in the form of evaporation as water is a major factor in the operation of various types of steam and hydro power plants.

Coal	Natural Gas	Oil	Nuclear	Hydropower	Windpower	Solarpower
5.00e-3	2.06e-3	4.12e-3	7.94e-3	1.32e-3	0	0

Table 6: Cost of Water Consumption ($/KWh)

3. **greenhouse_gas_cost**: how expensive the environmental impact cost from greenhouse gases needs to be to outdate fossil fuels. To reflect the relative output of greenhouse gases from each fossil fuel source, each was multiplied by a factor according to their relative contribution to emissions in the United States (coal makes up 32%, natural gas 29%, and oil 45%[4]).

Coal	Natural Gas	Oil	Nuclear	Hydropower	Windpower	Solarpower
0.124	0.112	0.173	0	0	0	0

Table 7: Environmental Cost of Greenhouse Gas Emissions ($/KWh)

In total, the minimum indirect costs for each fossil fuel source to make renewable installation a more cost effective option were:

Coal	Natural Gas	Oil
5.24e-2	0.124	5.44e-2

Table 8: Minimum Cost to Overprice Electricity from Fossil Fuels ($/KWh)

The cost necessary for coal and oil to be outdated is less than their estimated costs of human life lost in their production. Environmental costs for coal and oil are therefore only additional supplemental evidence.

Natural gas is the only fossil fuel where the estimated environmental impact costs needs to hit a certain level in order to be outdated as an electricity source.

3.2.2 Factoring in the Indirect Costs

When the "extra costs" of electricity generation were included in the model, the results were as follows.

Global Expenditure on Electricity	$2,232,000,000,000

Coal	Natural Gas	Oil	Nuclear	Hydropower	Windpower	Solarpower
0	0	0	2.70e3	3.52e3	1.08e3	5.46e2

Table 9: Total Electricity Produced (TWh)

Coal	Natural Gas	Oil	Nuclear	Hydropower	Windpower	Solarpower
0	0	0	2.70e3	3.52e3	7.61e3	7.15e3

Table 10: Total Electricity Consumed (TWh)

Nuclear	Hydropower	Windpower	Solarpower
0	0	6.56e3	6.56e3

Table 11: Electricity from Newly Installed Nuclear and Renewable Power Plants (TWh)

After factoring in the indirect costs, the price of electricity in a year from installing renewable power plants to replace fossil fuels is 3.73 times greater than the base model that does not consider the indirect costs. However, once the new power plants are installed, with the increased capacity of windpower and solarpower, the cost of electricity the following year is:

Global Expenditure on Electricity	$259,970,000,00

Assuming this new global expenditure on electricity remains constant, it would take 5.82 years for the indirect cost and renewable installation model to break even with the base fossil fuel production model. After 5.82 years the renewable installation model becomes continually more cost effective than the continued production of electricity from fossil fuel sources.

4 Conclusion

Renewable fuel sources are more cost effective, have virtually no negative impact, and are the next step to a healthier planet and society in terms of energy usage. However, fossil fuels are a staple of the modern world and eliminating the dependency on them is an expensive and challenging undertaking. The results from the model show that it is in the best interest of the world to invest in wind and solar powered power plants, but doing so will require heavy overhead costs.

To gradually build momentum towards this goal, the world should initially concentrate on limiting its use of the most damaging and expensive fossil fuels: coal and oil. They are the heaviest contributors to greenhouse gas emissions (especially CO_2 emissions) and bring about the greatest loss in human life[1,4]. Phasing these fuel sources out is the first step to 100% renewable and clean electricity. Natural gas is not as harmful, but still emits its fair share of greenhouse gases. Once coal and oil are on their way out, the next step would be to gradually decrease the reliance on natural gas as well.

If the world can come together and pool resources to fund the overhead cost of mass renewable power plant installation, not only will environmental impacts be drastically reduced and lives saved, but in well under ten years it will be more cost effective than the continued generation of electricity from fossil fuels. The major flaw of the model however is that it looks to minimize the cost of electricity from a global point of view. This assumes nations work together to do so. The model does not factor in individual nations trading fossil fuel commodities for their personal gain.

To make the results of this model a reality, the nations of the world must work together by putting aside their differences and self-interests. Only then will the world will be on its way to a healthier, cleaner, and much less expensive version of electrical energy.

5 References

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