Asian Journal of Green Chemistry 5 (2021) 294-312

Asian Journal of Green Chemistry

Journal homepage: www.ajgreenchem.com

Original Resarch Article

# Determining the direct and indirect social costs of fusion and fission nuclear power plant technologies

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**ARTICLE INFORMATION**

Received: 19 June 2021
Received in revised: 21 July 2021
Accepted: 24 July 2021
Available online: 9 August 2021

DOI: 10.22034/ajgc.2021.291239.1307

**KEYWORDS**

LCA
Levelized cost of electricity
Energy economics
Socio-environmental cost
Fusion power

**ABSTRACT**

Electricity generation has external costs that are mainly imposed on people who have no role in electricity generation. External or external costs are formed when the economic activities of one or more groups negatively affect another group or groups. For instance, construction and operation of thermal power plants emit carbon dioxide, sulfur oxides, and nitrogen, which can negatively affect buildings and human health. To determine the external costs of a unit, it is necessary to estimate the emission effects on the environment. In this study, the estimation of social costs of $SO_2$, $NO_X$, and $CO_2$ emissions from fission and nuclear fusion power plants has been done for the first time by modifying the existing and related global coefficients. The scenarios used in the study include carbon trade scenarios and statistical indicators of life. First, a study was conducted on seven technologies in Iran, and then the results were compared to the entire world energy production industry. The final results show that the fusion and fission technologies performed well in a comparative cost analysis (161 and 127$/MWh, respectively). Also, cost analysis shows that the fusion power has the least health care costs (7$/MWh), which can be interpreted that fusion power is greener than the other powers, and after that comes fission with 24$/MWh.



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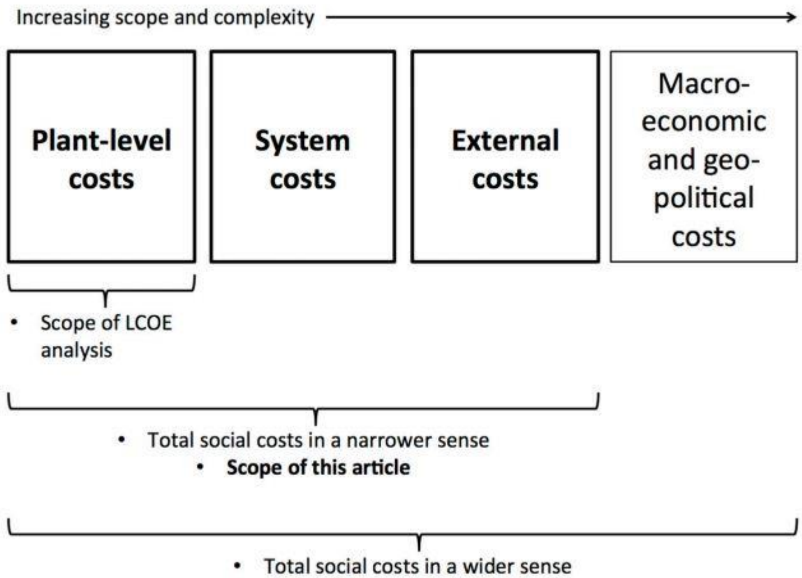
**Graphical Abstract**




## Introduction

Electricity generation has external costs, mainly imposed on people who have no role in electricity generation. External or external costs are formed when the economic activities of one or more groups negatively affect another group or groups. For instance, the construction and operation of thermal power plants emit carbon dioxide, sulfur, and nitrogen oxides, negatively affecting buildings and human health. Therefore, to accurately estimate the external costs of power plants, it is necessary to identify the effects of these pollutants on the environment [1].

The external effect is a general term that includes costs and benefits that are not reflected in normal market prices. These costs and benefits are very important for long-term energy sector planning [2].

Negative external effects or external (external) costs indicate that a person or group is causing harm without considering its consequences for others. For example, destruction and pollution of the environment due to energy production are negative external effects.

Explicit environmental costs The obvious costs of implementing an environmental policy include its management, regulatory, and enforcement costs, paid by the public sector. In addition, the costs of complying with the accepted regulations are paid by all departments. Capital costs [3] include all fixed costs for equipment, facilities, construction under construction, and process changes to reduce pollution. Operating costs [4, 5] include costs that result from operations and maintenance related to pollution reduction, such as the costs of materials, parts, fuel, research, and development. To fundamentally assess environmental costs, the concept of social costs is used [6, 7]. Social costs are the expenditures needed to compensate for the resources used by society so that the level of utility of society remains constant. In these studies, the concept of social cost has been used to express the total direct and indirect costs of electricity generation [8, 9]. In other words, the social cost is equal to the direct cost (cost of factors of production) plus indirect costs (environmental and health costs).

Social costs were first introduced in the 1930 s by the British economist (Pico). But since 1990, this issue has been seriously on the agenda of European countries [10]. Moreover, global studies show that this cost is mainly imposed on people who have no role in generating electricity. Therefore, attention to social costs has attracted the attention of some ministries and organizations in countries for several years.

The paper aims to examine the economic analysis of the European demonstration fusion power plant DEMO2 and nuclear fission PWR plant in terms of the cost of electricity and compare future fusion power plants with other types of power plants in the term of the social cost.

## Experimental

### *Materials and methods*

Seven power plants were assessed, and the results were generalized to similar power plants in the world. Then, the external costs of $CO_2$, $SO_2$, $NO_x$ gases were estimated according to economic and demographic indicators, the region's importance in terms of social and cultural capital, soil quality and natural resources, and greenhouse gases.

In this study, AIRPACT software has been used to estimate the concentration of the above gases in each power plant, and the effects of pollutants in power plants have been investigated to determine local effects up to a radius of 20 and all effects up to a radius of 50 km. After estimating the desired concentration of pollutants in the power plant area, according to demographic information and pollutant concentrations, the extent of health impact according to the case has been determined. The rate of mortality and diseases related to economic quantities has become. Considering that the dolly index has been converted into an economic unit based on the statistical value of the studied life in the country, the total damages caused by the emission of the mentioned gases have been calculated. The number of losses calculated in dollars of the base year can be updated based on the global inflation rate of the dollar. At this stage, because the statistical value of life used in the study is affected by the coefficients of the country's willingness to pay functions, in practice, the indicators are adjusted based on the level of domestic income and other variables affecting the willingness to pay internally [11].

According to the amount of electricity generated by the power plant, the number of emissions and the amount of damage combined information including the average cost of environmental damage caused by the production of one kilowatt-hour of electricity, the cost of damage per ton of pollutants in the area and the total cost of damages per emission damage costs are generalized to the whole country to extend the studied model to the whole country, according to the weight ratio of fuel consumption of the country and sample power plants, emission coefficients as well as the average weight of population density in areas affected by sample power plants and average population density.

Many studies have been conducted to estimate the cost of emission of pollutants on plants, agriculture, buildings, and physical facilities as a percentage of damage to human health. Considering the state of the country's natural resources and other sensitive parameters, the ratio of physical damage costs, Buildings, agriculture, and plants are calculated based on the percentage of health damage in several scenarios [12].

In this study, the method of transfer of benefits has been used. Transfer of benefits is a way to generalize the economic costs of conducting non-market valuation studies using cost-based studies at similar study sites and to apply them to more locations. This method can transfer reliable studies' economic benefits and values in a country from study to policymaking.

*Scenarios*

In this work, different scenarios have been used as follows. Different values can be offered if the cost of environmental damage from carbon dioxide is equal to the cost of the opportunity to participate in the carbon trade to reduce emissions.

It should be noted that the assessment of greenhouse gas impacts is a complex issue on which no global consensus has yet been reached, but the following three values are usually used under three scenarios:

Low Emissions (Scenario 1): The Carbon Sample Fund (PCF) has estimated the price at $50 per tonne, given the trade in carbon dioxide. Although these trade prices do not necessarily mean the cost of damages, they indicate how much revenue is likely to be generated through the country's emissions (in this study, Iran) in the carbon trading market. A limited carbon trading system is achieved. This scenario is considered as the basic scenario number 1 [10].

Average Emissions (Scenario 2): In this scenario, the estimate is based on a picture of prices in the future carbon trading market (over the next ten years), and this estimate is $70 per ton [13].

High Emissions (Scenario 3): According to IPCC estimates based on damage costs, the value is $100 per ton [11].

According to the existing conditions during the research period and based on the opinion of experts, the most appropriate scenario is the scenario of low greenhouse gas effects (Scenario 1),

In the present study, the main effort is to study and estimate the costs of adverse health effects. The fact is that according to most studies, health costs make up about 80% of the total cost of air pollution. In 1996, Holland and Koret estimated the share of health effects in total air pollution costs at 86 to 94% [14]. The total effects of this study were a combination of health effects, effects on plants and agriculture, and effects on buildings and physical facilities, which are the most important components of the list of negative effects of air pollution. In a 1998 study, the AEA estimated these effects between 80 and 93% of the total [15, 16]. Other studies have found similar results with approximately 80% for the share of health effects of the total effects.

Therefore, according to existing studies, the upper and lower amplitudes of 95 and 75% are considered upper and lower health effects limits. Also, the middle mode of 85% is selected as the middle scenario for the expansion of works. Doing this is the only acceptable way to achieve all the effects of pollution and change to expand the cost of health and achieve the full effect and the absence of comprehensive multimillion-dollar field research statistics. Based on the three methods based on the statistical index of life, three damages have been calculated.

*Calculation method*

In this study, the main steps were as follows:
1. After estimating the concentration of pollutants and the carbon footprint in the power plant area, according to the demographic information and the concentration of pollutants, the amount of health impact is determined according to the case and so on.
2. In the next step, it is necessary to convert the mortality rate and related diseases into

economic quantities. Based on the calculated and acceptable coefficients, the rate of all cases of illness, mortality, and lost working days are expressed in units of 'Dolly.' Because the dolly index has become an economic unit based on the statistical value of life studied in the country. Finally, the total emission damage from the pollutant can be calculated. At this stage, because the statistical value of life used in the study is affected by the coefficients of the country's willingness to pay functions, in practice, the indicators are adjusted based on the level of domestic income and other variables affecting the willingness to pay.

3. According to the amount of electricity generated by the power plant, the number of emissions, and the amount of damage, it is possible to calculate the combined information, including the average cost of environmental damage per kilowatt-hour electricity.

4. To expand the model under study, the cost of damages should be considered according to the weight ratio of fuel consumed in the country and sample power plants, emission coefficients, and also the average weight of population density in areas affected by sample power plants and the average population density of the country. Generalized to the entire technology sample.

The most important information and raw data needed to perform external cost calculations are:

- Indicators are affecting the concentration of pollutants.
- Economic and social indicators.
- Indicators that determine the relationship between the mental and practical priority of the environment in the amount of willingness to pay.
- Indicators are showing the importance of the region in terms of social and cultural capital.
- Biodiversity conservation indicators in the affected area.
- Indicators are related to soil quality and natural resources.
- Indicators are related to greenhouse gases.
- Carbon Footprint of Each Technology

In recent decades, awareness of environmental issues has increased dramatically, and the general public believes that the consumption of products and the use of a variety of services will have a significant impact on the resources and quality of the environment, and these effects can occur at all stages of the life cycle, from the extraction of raw materials to its production, distribution, consumption, and waste management. Life cycle assessment (LCA) has been developed over the past 30 years as a tool for environmental impact analysis. This tool can even be used to plan and determine the weaknesses of the life cycle of the product production process and select the appropriate and optimal option among a variety of options. LCA results can even be used to improve the compatibility of a product or service with the environment [1].

At present, there are different methods for environmental assessment in various studies, which here, regardless of the disadvantages and advantages of each method, are briefly introduced below.

Environmental Impact Assessment (EIA) is mainly done to identify the environmental impact of an activity (economic, industrial, etc.) at a specific time and place quantitatively and qualitatively.

Evaluation based on the best environmental implementation option in which cumulative indicators derived from water, soil, and air pollution estimates are used to achieve a measurement criterion in the environment.

Evaluation based on environmental impact indicators that by selecting several key parameters, related environmental effects are identified, and the basis of evaluation, scoring to these parameters is considered.

In this method, assessment based on environmental hazards, considering the hazards caused by the project in natural (air, water, soil, animal, plant) and human ecosystems, is assessed.

Evaluation based on cost-benefit analysis - in which by calculating the value of resources lost as a result of the project, an analysis is performed on the usefulness of its performance based on economic estimates [2].

Life cycle assessment, product life cycle assessment is a method to consider all aspects of production, distribution, and consumption of a product or process that extends beyond the time horizon of the manufacturer. The product life cycle is the upbringing, writing, and participatory and collective study of various aspects of the existence of a product or service.

This method is very different from other evaluation methods because it uses the whole life cycle to be evaluated.

Advantages of Life Cycle Assessment The application of this method helps the decision-maker choose the product or process with the least environmental consequences. The information gathered during the process can study other parameters such as cost and data required to select a new product or process. LCA data show how environmental artifacts are transferred from one medium to another or from one cycle to another.

The ability to track the environmental impact of a product or process enables managers and decision-makers to identify all related environmental impacts and adopt appropriate policies for each. By performing life cycle evaluation, you can:

- Provided a systematic assessment of the environmental performance of the product.
- The number of pollutants emitted into the water, air, and soil environments in each cycle or main production process was quantified.
- Assessed the ecological and human effects of consumables on the environment on a local, regional and global scale.
- Compared the health and ecological effects of two similar products or processes to select the optimal option.

According to the International Energy Agency in 2005, the country's greenhouse gas emissions from the energy, ferrous emissions, industrial processes, agriculture, and other sources are estimated at 593.91 million tons equivalent to carbon dioxide, which is a share of greenhouse gas emissions of the year was equal to 79.6% of the total release [22]. Table 1 below shows the inputs and outputs of a power generation system in general.

Estimation of carbon dioxide emissions of different power generation technologies using life cycle approach using the following assumptions (Table 1), the amount of carbon dioxide emissions from different power generation technologies (fossil, nuclear and renewable) is estimated [23].

Using the following equation, the emission coefficient equivalent to carbon dioxide per kilowatt can be calculated in all electricity generation technologies [24].

$$LCA = \frac{\sum GWP_i(\sum f_i + \sum c_i + \sum o_i + \sum d_i)}{Q} \quad (1)$$

Wherein:

f: Direct emission of greenhouse gases due to fuel

c: Indirect emission due to the process of construction of power plant and ancillary equipment

o: Indirect emission due to the operation and maintenance process of the plant and equipment

**Table 1.** Assumptions used in the study [9]

| Fuel | Lifespan | Enternal consumption | Efficiency | Access Factor | Capacity(MW) |
|---|---|---|---|---|---|
| Coal | 30 | 6.93% | 39.6% | 70% | 1000 |
| Oil | 30 | 5.67% | 38.4% | 70% | 1000 |
| Natural gas | 30 | 4.31% | 38.9% | 70% | 1000 |
| Nuclear (Fission-PWR) | 30 | 4.30% | 33.7% | 70% | 1000 |
| Nuclear (fusion-ITER) | 30 | 0.68% | 34.5% | 70% | 1000 |

**Table 2.** Inventory analysis in power generation systems

| Feed | System Boundary | Product |
|---|---|---|
| Natural sources | Mining | Biological consequences |
| Fuels | Production | Environmental impacts |
| Fossil | Usage | air pollution |
| minerals | Recycling and waste | water pollution |
| Water | Production and construction | Soil pollution |
| Land use | Operation and maintenance | Noise |
| | End of project and implementation | |
| | Machinery | |

d: Indirect emissions due to scrap and collection of power plant machinery and equipment
GWP: Global greenhouse gas heating potential
Q: The amount of electricity generation during the operation of the power plant, which is calculated based on the following:
Power Plant Capacity (KW) * 8760 (hr/a) * Access Factor * Power Plant Lifespan (Years)
i: Type of greenhouse gas (carbon dioxide, methane, nitrous oxide)

Also, the GHG payback period of a powerplant can be estimated from the following equation [25-27]:

$$PBT_{GHG} = \frac{\frac{T_{GHG}}{c}}{(E_p - E_L)\left(\frac{k}{t}\right)} \tag{2}$$

And also energy payback period of a plant:

$$PBT_{En} = \frac{E_C \times p}{(E_p - E_L)\left(\frac{k}{t}\right)} \tag{3}$$

Where $E_c$—is total energy consumption through the whole life cycle of the NP plant (Table 2); p—is adopted within the study as the efficiency of converting primary energy to electricity; $E_p$ and t-are total energy production by the plant and its lifetime (Table 2); $E_L$-is parasitic electric load (the energy consumed by the plant for its own needs); k = 3600-is coefficient for converting TWh to TJ. Also, $T_{GHG}$-is total GHG emissions through the whole life cycle of the NP plant; c-is the GHG average emissions per 1GJ of produced electricity in the region (c = 262 t of $CO_2$ eq 1TJ [28-31]).

The above formula and the assumptions listed in Table 9 carbon dioxide emission life cycle in each electricity generation technology are described in Tables 3–7.

Due to various pollution emission coefficients for different thermal power plants, emission costs in terms of tradition per kilowatt-hour have been calculated for each type of power plant in this project. According to calculations, the indirect or environmental cost (including health costs) of generating one kilowatt-hour of electricity based on different methods varies between 1.9 to 8.99 cents (based on the 2007 dollar).

**Table 3.** Life cycle of carbon dioxide emissions in coal-fired power plants

| Special production: 5707 GWh | | | |
|---|---|---|---|
| The ratio of domestic coal production to imported coal 10.6: 89.4% | | | |
| Unit | | % | gCO2/kWh |
| | Combustion | | |
| Plant | | 90.9% | 886.1 |
| | Construction | | |
| Coal mining (domestic) | | 0 | 0.04 |
| Coal Mining (Imported) | | 0 | 0.41 |
| Transportation of domestic coal | | 0 | 0.02 |
| Road transport of imported coal | | 0 | 0.03 |
| Maritime transport of imported coal | | 0 | 0.37 |
| Power Plant | | 0.2% | 2.39 |
| Coal ash | | 0 | 0.34 |
| Total | | 0.4% | 3.60 |
| | O&M | | |
| | Fuel | 0 | 0.23 |
| Coal mining (domestic) | Power | 0.1% | 1.22 |
| | Material | 0 | 0.19 |
| | Fuel | 0.3% | 3.26 |
| Coal Mining (Imported) | Power | 0.4% | 3.65 |
| | Material | 0.1% | 1.15 |
| Transportation of domestic coal | | 0.1% | 0.51 |
| Road transport of imported coal | | 0.5% | 4.41 |
| Maritime transport of imported coal | | 1.1% | 10.66 |
| Power generation | Material | 0.3% | 2.93 |
| | O&M | 0.4% | 3.74 |
| Coal ash | | 0 | 0.03 |
| Total | | 3.3% | 31.93 |
| | Methane leakage | | |
| Coal mining (domestic) | | 1.4% | 13.30 |
| Coal Mining (Imported) | | 4.1% | 39.56 |
| Total | | 5.4% | 52.86 |
| Total LCA | | 100% | 975.24 |

**Table 4.** Life cycle of carbon dioxide emissions in oil-fired power plants

| Special production: 5784 GWh | | | |
|---|---|---|---|
| Crude oil to furnace oil ratio 54.1: 45.9% | | | |
| Unit | | % | $gCO_2/kWh$ |
| | Combustion | | |
| Plant | | 94.9% | 704.34 |
| | Construction | | |
| Oil production (crude) | | 0 | 0.19 |
| Oil production (refined) | | 0 | 0.15 |
| Maritime transport (crude oil) | | 0 | 0.07 |
| Maritime transport (refined oil) | | 0 | 0.13 |
| Oil refining | | 0 | 0.37 |
| Furnace oil transportation | | 0 | 0.02 |

| | | | |
|---|---|---|---|
| Power | | 0.2% | 1.69 |
| Total | | 0.3% | 2.32 |
| | O&M | | |
| Oil production (crude) | Fuel | 0.5% | 3.75 |
| | Combusted | 0.3% | 2.26 |
| Oil production (refined) | Fuel | 0.4% | 2.97 |
| | Combusted | 0.3% | 2.10 |
| Maritime transport (crude oil) | | 0.4% | 3.15 |
| Maritime transport (refined oil) | | 0.4% | 3.30 |
| Oil refining | | 1.1% | 10.66 |
| Furnace oil transportation | | 1.7% | 12.63 |
| Power Generation | Material | 0.2% | 1.12 |
| | O&M | 0.5% | 3.69 |
| Total | | 4.7% | 35.22 |
| | Methane leakage | | |
| Oil production (crude) | | 0 | 0.14 |
| Oil production (refined) | | 0 | 0.11 |
| Total | | 0 | 0.25 |
| Total LCA | | 100% | 742.14 |

**Table 5.** Life cycle of carbon dioxide emissions in Natural gas-fired power plants

| Special production: 5868 GWh | | | |
|---|---|---|---|
| Unit | | % | $gCO_2/kWh$ |
| | Combustion | | |
| Plant | | 78.7% | 477.947 |
| | Construction | | |
| Gas production | | 0.1% | 0.80 |
| Transport | | 0.1% | 0.41 |
| Power generation | | 0.3% | 1.69 |
| Total | | 0.5% | 2.91 |
| | O&M | | |
| Gas production | Fuel | 11.1% | 67.63 |
| | CO2 | 4.3% | 26.16 |
| Transport | | 3.2% | 19.38 |
| Power Generation | Material | 0.1% | 0.90 |
| | O&M | 0.6% | 3.64 |
| Total | | 19.4% | 117.71 |
| | Methane leakage | | |
| Gas production | | 1.5% | 9.070 |
| Total | | 1.5% | 9.070 |
| Total LCA | | 100% | 607.63 |

**Table 6.** Life cycle of carbon dioxide emissions in Nuclear power plants(Fission-PWR)

| Special production: 5868 GWh | | | |
|---|---|---|---|
| Unit | | % | $gCO_2/kWh$ |
| | Construction | | |
| Mining work | | 0.7% | 0.21 |

| | | |
|---|---|---|
| Evaporation | 0.1% | 0.03 |
| Enriching | 0.4% | 0.10 |
| Fuel transfer | 0 | 0.01 |
| Power Plant | 5.6% | 1.61 |
| Fuel storage | 0.5% | 0.14 |
| Waste disposal site (final storage) | 1% | 0.29 |
| Total | 8.3% | 2.38 |
| O&M | | |
| Mining work | 4.6% | 1.33 |
| Evaporation | 1% | 0.27 |
| Enriching | 68.4% | 19.6 |
| Manufacture of fuel rods | 2.4% | 0.67 |
| Transfer of fuel to the power plant | 0.2% | 0.05 |
| Power Plant | 11% | 3.16 |
| Fuel storage | 2.4% | 0.69 |
| Fuel transfer from the power plant | 0.1% | 0.04 |
| Waste disposal site (final storage) | 0.1% | 0.04 |
| Total | 90.2% | 25.86 |
| Methane leakage | | |
| Enriching | 0 | 0.01 |
| Manufacture of fuel rods | 0 | 0 |
| Power plant (reactor) | 1.4% | 0.41 |
| Total | 1.5% | 0.42 |
| Total LCA | 100% | 28.66 |

**Table 7.** Life cycle of carbon dioxide emissions in Nuclear power plants (Fusion-ITER)

| Special production: 5868 GWh | | |
|---|---|---|
| Unit | % | $gCO_2/kWh$ |
| Construction | | |
| Hydrogen Production(Hydro) | 25.73 | 28.21 |
| Superconductor Coil | 1.07 | 1.17 |
| Blanket Shield Divertor | 10.1 | 11.07 |
| Reactor | 9.73 | 10.67 |
| Plant balance | 0.02 | 0.02 |
| Heat Transfer | 9.32 | 10.22 |
| Current Drive | 0.13 | 0.14 |
| Total | 59.39 | 65.12 |
| O&M | | |
| Hydrogen Production(Hydro) | 16.05 | 17.6 |
| Superconductor Coil | 1.21 | 1.33 |
| Blanket Shield Divertor | 0.25 | 0.27 |
| Reactor | 17.88 | 19.6 |
| Plant balance | 0.61 | 0.67 |
| Heat Transfer | 0.05 | 0.05 |
| Current Drive | 2.88 | 3.16 |
| Total | 38.93 | 42.68 |
| Methane leakage | | |
| Power plant | 0.37 | 0.41 |
| Hydrogen Production | 1.3 | 1.43 |

| | | |
|---|---|---|
| Total | 1.68 | 1.84 |
| Total LCA | 100% | 109.64 |

Then, considering the cost price obtained from the cost-benefit analysis of power plants, the total costs of different power plants were calculated. According to Table 8, considering the two scenarios of the ratio of health effects to total effects (85% and 75%), the production of one-kilowatt-hour of electricity from heating power plants between 6.87 to 11.25 cents, gas power plants between 7.37 to 12.75 cents and a combined cycle power plant has an indirect (environmental) cost between 5.03 and 7.82 cents.

**Table 8.** Environmental costs of electricity generation with different technologies (cents per kilowatt-hour)

| Type | The ratio of health effects to total effects | Scenario | | |
|---|---|---|---|---|
| | | High | Mid | Low |
| Coal | 0.75 | 11.25 | 8.42 | 7.03 |
| | 0.85 | 10.60 | 8.11 | 6.92 |
| Oil | 0.75 | 12.75 | 9.25 | 7.54 |
| | 0.85 | 11.96 | 8.88 | 7.31 |
| Natural gas | 0.75 | 7.82 | 6.04 | 5.17 |
| | 0.85 | 7.41 | 5.82 | 5.05 |
| Fusion | 0.75 | 1.41 | 1.05 | 0.48 |
| | 0.85 | 1.92 | 1.23 | 0.74 |
| Fission | 0.75 | 0.31 | 0.16 | 0.07 |
| | 0.85 | 0.34 | 0.17 | 0.08 |

The analyzed criteria of the technical-economic efficiency of each plant are the net present value of the project, profitability index, internal rate of return, discounted payback period, and levelized cost of electricity.

An annual cash flow CF was determined concerning the model data structure. Financing was simplified for the approximation to fund the project by credit:= fully

$$CF_t = (R_t - C_t - I_t - DP_t)(1 - T_t) + DP_t - IN_t \quad (4)$$

Where t denotes the current year, R is the annual revenues, C is the annual operating costs, I is the interests, DP is the depreciation, T is the income tax rate, and IN are the annual investments. A cumulative cash flow CCF means, at any time, the aggregate cash flow:

$$CCF = \sum_{t=0}^{T_p-1} CF_t \quad (5)$$

where Tp denotes the terminal year. A discounted cash flow DCF provide future cash flow projections and discounts them, using a discounted rate r:

$$DCF = \sum_{t=0}^{T_p-1} CF_t(1+r)^{-t} \quad (6)$$

The net present value NPV, a measurement of profit calculated by subtracting the present values of cash outflows from the present values of cash inflows throughout the economic lifetime, was calculated by the equation:

$$NPV = \sum_{t=0}^{T_L-1} CF_t(1+r)^{-t} \quad (7)$$

where TL denotes the economic lifetime of the plant, The profitability index PI expresses the ratio of NPV to the total investment cost IN:

$$PI = \frac{NPV}{IN} \quad (8)$$

The internal rate of return IRR, providing a zero value for NPV, was determined by the iteration process according to the equation:

$$if\ NPV = 0,\ \ 0 = \sum_{t=0}^{T_L-1} CF_t(1 + IRR)^{-t} \qquad (9)$$

The discounted payback period DPP, giving the number of years it takes to break even from undertaking the initial expenditure by recognizing the time value of the money, was found according to the Equation:

$$0 = \sum_{t=0}^{DPP-1} CF_t(1 + r)^{-t} - IN \qquad (10)$$

The levelized cost of electricity LCOE expresses the cost of electricity, including the invested capital relative to the total quantity of electricity generated during the whole lifetime of the plant:

$$LCOE = \frac{\sum_{t=0}^{T_L-1}(C_t+IN_t+I_t)(1+r)^{-t}}{\sum_{t=0}^{T_L-1} E_t(1+r)^{-t}} \qquad (11)$$

Where E stands for the net annual electricity production. The total cost of electricity TCOE accounts additionally the external costs related to the electricity production $C^{EXT}$:

$$TCOE = \frac{\sum_{t=0}^{T_L-1}(C_t+IN_t+I_t+E_tC_t^{EXT})(1+r)^{-t}}{\sum_{t=0}^{T_L-1} E_t(1+r)^{-t}} \qquad (12)$$

The analysis was carried out at constant prices of the year 2015 with a real discount rate of 7%. Concerning the analyzed model, all was calculated in US dollars. Inflation and trade exchange rates for conversion of prices to the price level of 2015 were drawn from the Iranian Central Bank. The income tax rate was chosen conservatively by the Iran corporate tax rate of 15%. The length of the plant's operation was taken from the model as 30 years. The technical preparation phase, construction phase, and decommissioning phase were all taken as ten years duration.

## Results and Discussion

### *Social cost of emission*

Considering the selection of power plants from different places as examples of all power plants, it is necessary to generalize the results to the whole country based on the fuel and emission coefficients of power plants. It is also worth noting that the selected power plants have been selected as an example of all biological sites with different population densities.

Tables 9 to 13 show how to calculate the cost of damage to five selected power plants in different scenarios, after which it is necessary to adjust the results based on the emission coefficients of the total power plants and their difference with the emission coefficients of selected power plants. Given that the type of fuel and technology of selected power plants are not necessarily equal to the average, it is necessary to consider changes in emission coefficients in generalizing the results.

Therefore, considering the value of nitrogen oxides and sulfur oxides in the study, the resulting environmental costs can be generalized to the whole.

According to the results of studies, the amount of $SO_2$ emissions from power plants was equal to 0.273 of selected power plants. This index for NOx is equal to 0.821. Regarding carbon dioxide, due to its global value, there is no need to localize it in terms of emission coefficients, and only its emission rate is adjusted in terms of kilowatt-hours.

**Table 9.** Summary of the generalized results of $SO_2$ and $NO_x$ emission evaluation in the scenario of the high statistical value of life

| Parameter | NOx | SOx |
|---|---|---|
| Emission coefficient of 7 selected power plants (gr/kWh) | 0.94 | 3.18 |
| Total emission coefficient (g/kWh) | 0.768 | 0.869 |
| Emission adjustment coefficient relative to the diffusion of the whole study population | 0.821 | 0.273 |

| | | |
|---|---|---|
| Emission cost of seven power plants ($/kg) | 35.37 | 29.52 |
| Generalized emission cost for the whole country ($/kg) | 26.435 | 7.341 |

**Table 10.** Cost of carbon dioxide emission damage according to different carbon emission scenarios (Cent, 2000)

| Scenarios | Generalized damages | Adjustment factor | Damage cost |
|---|---|---|---|
| Scenario 1($50/t) | 0.1708 | 0.940 | 0.1817 |
| Scenario 2($80/t) | 0.5694 | 0.940 | 0.5057 |
| Scenario 3($100/t) | 4.5551 | 0.940 | 4.8479 |

**Table 11.** Summary of the generalized results of $SO_2$ and NOx emission evaluation in the scenario of estimating the upper limit of the statistical value of life

| Parameter | NOx Damage Cost $ | SOx Damage Cost $ | Total |
|---|---|---|---|
| Total damage to 7 power plants (M$) | 821 | 1954 | 2775 |
| Emission cost of 7 power plants ($/kg) | 33.22 | 27.11 | - |
| Share of pollutant damage of the total | 0.31 | 0.69 | 1.00 |
| Emission adjustment coefficient relative to the total emission | 0.821 | 0.273 | - |
| Emission damage (Cents/kWh) | 3.410 | 8.577 | 11.98 |
| Total generalized emission cost (Cents/kWh) | 2.799 | 2.340 | 5.139 |

**Table 12.** Summary of the generalized results of $SO_2$ and NOx emission evaluation in the scenario of estimating the average statistical value of life

| Parameter | NOx Damage Cost $ | SOx Damage Cost $ | Total |
|---|---|---|---|
| Total damage to 7 power plants (M$) | 395 | 810 | 1205 |
| Emission cost of 7 power plants (Cents/kWh) | 1.986 | 3.891 | 5.877 |
| Emission damage ($/kg) of 7 power plants | 15.845 | 11.721 | - |
| Emission adjustment coefficient relative to the total emission | 0.821 | 0.273 | - |
| Total Emission damage (Cents/kWh) | 1.217 | 1.018 | 2.235 |
| Total generalized emission cost ($/kg) | 13.01 | 3.22 | - |

**Table 13.** Summary of the generalized results of $SO_2$ and NOx emission evaluation obtained from the per capita income method

| Parameter | NOx Damage Cost $ | SOx Damage Cost $ | Total |
|---|---|---|---|
| Total damage to 7 power plants (M$) | 198 | 409 | 607 |
| Emission Damage of 7 power plants (Cents/kWh) | 0.5 | 1.5 | 2.02 |
| Emission damage ($/kg) of 7 power plants | 5.448 | 4.847 | - |
| Emission adjustment coefficient relative to the total emission | 0.821 | 0.273 | - |
| Total Emission damage (Cents/kWh) | 0.411 | 0.419 | 0.830 |
| Total generalized emission cost ($/kg) | 4.472 | 1.241 | - |

The mentioned adjustment coefficients are multiplied by the cost of damages of the sample power plants, and the results show the generalized emission cost for the whole by dual gases and $CO_2$ (Tables 2 and 3).

Table 11 summarizes the results of the generalization of dual pollutant valuation across the country, based on high estimates of the statistical value of life. In this estimate, the environmental cost of producing each kilowatt-hour of electricity in the country for the mentioned pollutants is equal to 5.14 cents.

Table 12 shows the calculations in Table 4 based on the estimated average statistical value of life. According to these calculations, the cost of environmental damage from dual gas emissions per kilowatt-hour of electricity production in the country is equal to 2.24 cents. The minimum scenario is also calculated based on a dolly based on per capita income.

Table 13 shows the cost of environmental damage by dual gas emissions per kilowatt-hour of electricity production in the country based on this method is equal to 0.82 cents.

Table 14 categorizes the combination of three dolly methods for estimating environmental costs, considering three options for expanding the share of health effects.

According to the results of the studies, the scenario of expanding health effects to 75% of the total social and environmental effects and scenario No. 1 of carbon trade equivalent to $ 50 per ton of $CO_2$ emissions is a logical and acceptable solution. Iran was selected for the study country in this study. By selecting these scenarios and considering the real cost of electricity production in Iran, the total social costs of electricity generation from Iran's fossil and nuclear technologies in three different dolly methods, as shown in Table 15.

**Table 14.** Different modes of determining the environmental cost of gas emissions per unit of electricity generation (Cents/kWh)

| Method of calculation\|share of health effects from total effects | 95% | 85% | 75% |
|---|---|---|---|
| Dolly (statistical value of upper limit life) | 5.411 | 6.047 | 6.853 |
| Dolly (statistical value of mid limit life) | 2.350 | 2.630 | 2.980 |
| Dolly (statistical value of lower limit life) | 0.860 | 0.960 | 1.090 |

**Table 15.** The social cost of electricity generation with different technologies (Cents/kWh) in carbon trading scenario No. 1 and generalization of health effects 75%

| Type | State | Social Cost |
|---|---|---|
| Coal | Dolly (statistical value of upper limit life) | 70.3 |
| | Dolly (statistical value of average life) | 59.9 |
| | Dolly (per capita income) | 22.3 |
| Oil | Dolly (statistical value of upper limit life) | 55.2 |
| | Dolly (statistical value of average life) | 47.1 |
| | Dolly (per capita income) | 21.1 |
| Natural Gas | Dolly (statistical value of upper limit life) | 34.4 |
| | Dolly (statistical value of average life) | 22.5 |
| | Dolly (per capita income) | 18.5 |
| Fission | Dolly (statistical value of upper limit life) | 3.9 |
| | Dolly (statistical value of average life) | 3.4 |
| | Dolly (per capita income) | 25.9 |
| Fusion | Dolly (statistical value of upper limit life) | 8.2 |
| | Dolly (statistical value of average life) | 6.1 |
| | Dolly (per capita income) | 30.2 |

| | | |
|---|---|---|
| Total | Dolly (statistical value of upper limit life) | 38.3 |
| | Dolly (statistical value of average life) | 35.4 |
| | Dolly (per capita income) | 22.1 |

**Table 16.** Levelized cost of the electricity results

| Type | Technology | LCOE |
|---|---|---|
| Conventional | Natural Gas | \$152–\$206 |
| | Coal | \$60–\$143 |
| | Oil | \$102–\$175 |
| Nuclear | Fission | \$65–\$150 |
| | Fusion | \$112–\$189 |

*Levelized price of electricity*

One of the methods to calculate the cost of electricity is using the LCOE algorithm or calculating the balanced cost, which in addition to accurate calculations, provides the ability to compare the results for different technologies. According to this, five technologies of gas, coal, fission, fusion, and oil production of electricity in Iran were studied as a case study from a technical and economic perspective that the real cost of electricity with Calculating carbon emission costs per harvest. You can see the results of the calculated cost calculations in Table 16.

*Total cost of electricity*

The final results are presented in the form of comparative graphs. To compare fusion power plants, several types of existing power stations were selected: gas power, coal-fired power, nuclear power plants, and oil-fired power plants. The investment cost and results of the technologies are analyzed and are shown separately as points in the graphs.

Figure 1 illustrates the comparison of investment costs for the construction of selected types of power plants. The above-mentioned high investment cost of fusion power plants is evident in the graph.

The graph in Figure 2 reveals similar LCOE of the nuclear and fossil power plants and higher subsidized price of production of the wind and photovoltaic power plants; the average LCOE of fusion sources is higher than the average LCOE of nuclear and fossil power plants but lower than the average LCOE of the photovoltaic power plants.

Accounting for the external costs, the order of these sources in terms of LCOE change significantly. TCOE includes LCOE and external costs, and the resulting graph of TCOE is shown in Figure 3. From the perspective of the current perception of the need for sustainable energy, TCOE should be the decisive criterion for assessing the profitability of individual energy sources. When accounting for the environmental impact in internalization of external costs, fusion power plants will be economically the second most favorable source of energy (See Figure 4).

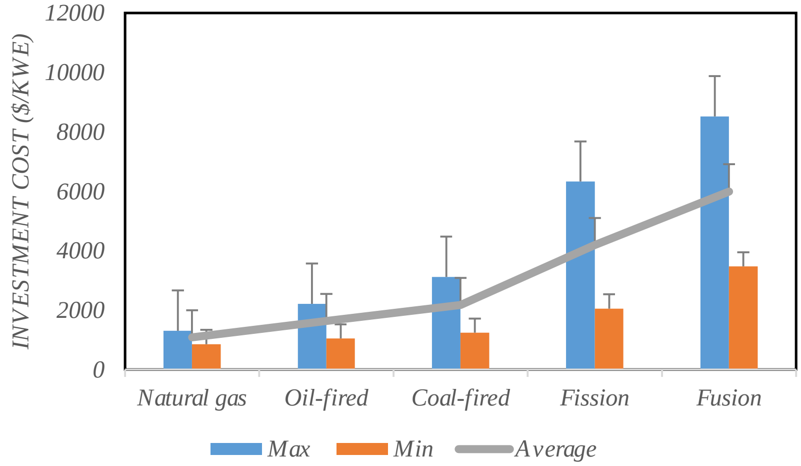



**Figure 1.** Capital investment comparison

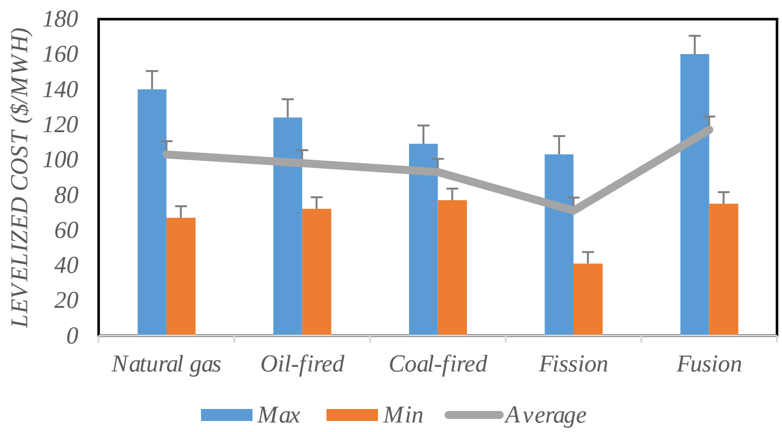



**Figure 2.** Levelized cost of electricity LCOE comparison

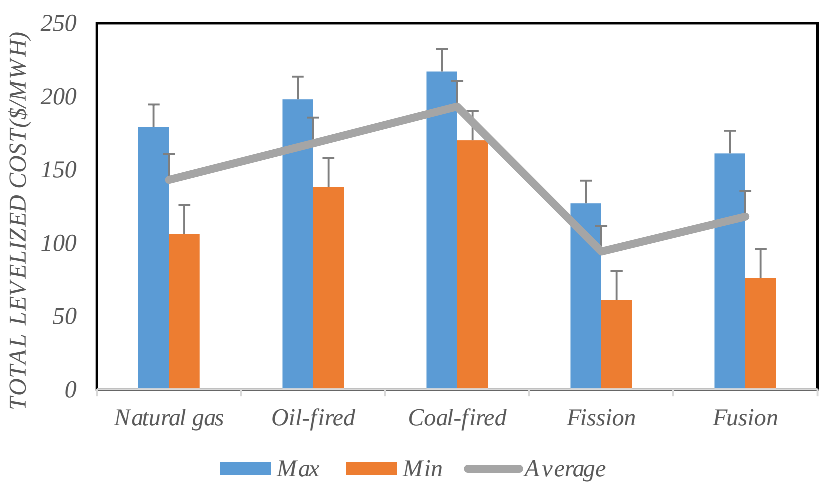



**Figure 3.** Total levelized cost of electricity, including external costs TCOE

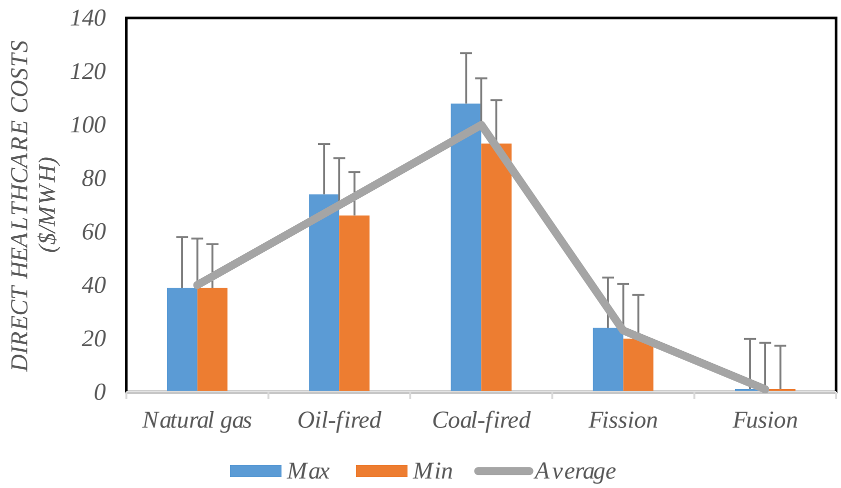



**Figure 4.** The direct healthcare cost of electricity

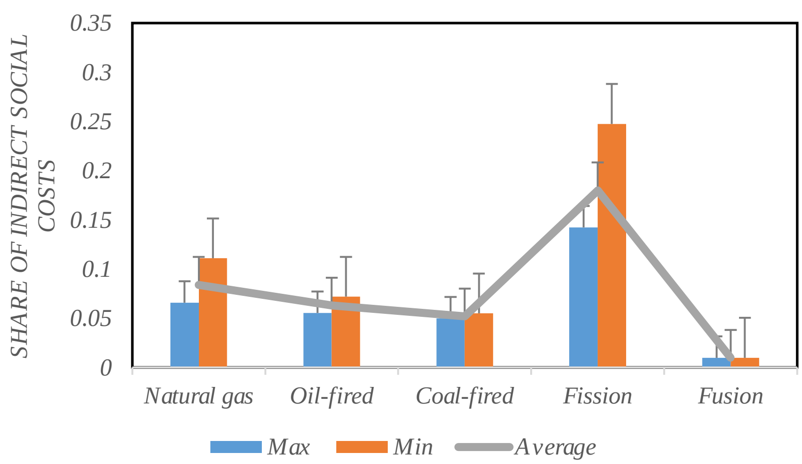



**Figure 5.** Share of direct healthcare cost of electricity

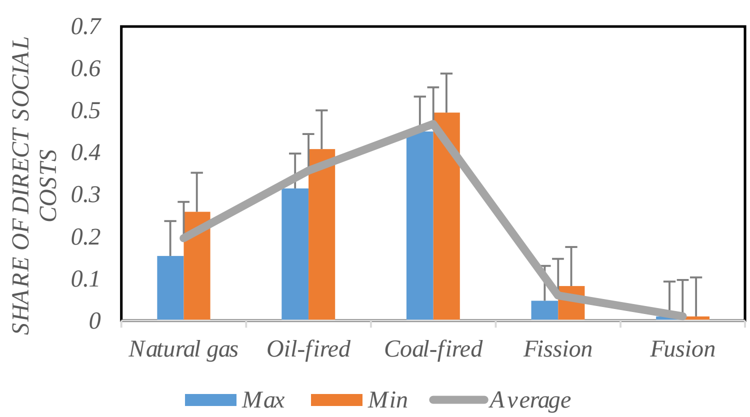



**Figure 6.** Share of direct healthcare cost of electricity

Figures 5 and 6 show why nuclear fission is losing its share in the global energy portfolio. As it can be seen in Figure 5, fission is one of the cleanest power technologies, however as it can be seen in Figure 6, indirect costs (e.g., public acceptance, etc.) is relatively high for this technology. Thus governments are forced to slow down this industry [27, 28].

The National Renewable Energy Laboratory (NREL) maintains an LCOE calculator on its website. Each year, the investment bank Lazard publishes LCOE estimates for various generation technologies. The results of this chapter are aligned with the results of that report [21]. The input data of existing power plants are statistical and, therefore, highly reliable. The fusion power plant data are based on conceptual projects, and therefore, their accuracy is consistent with the current state of knowledge of fusion technologies. Uncertainty in these data is reduced using standard turbine island and balance of plant technologies and experience from the ongoing construction of the large fusion projects like ITER or a Japan reactor JT-60SA but remains very high. It is very difficult to predict the development of the global economy and energy for several decades ahead. The real course of integration of nuclear fusion into energetics will depend on both the scientific and technological development of the entire energy sector. Full validation of the fusion data will not be possible until the first fusion power plant is in place, and ex-ante evaluations are important and needful steps in setting priorities for energy development.

## Conclusions

Various technologies can be utilized to generate electrical energy, which is one of the main energy carriers. The feasibility and evaluation of electricity industry projects have been traditionally done only from a technical and economic perspective. With the expansion of economic activities and the introduction of sustainable development, the need to consider the social and environmental aspects of activities has increased. This chapter considers three types of fossil power generation technologies (gas, coal, and oil-burning power plants) and two types of nuclear technologies (fission and fusion). First, indicators to evaluate these technologies in different aspects are introduced. Then, by quantifying the externalities of each technology, the LCOE cost of each technology is calculated separately. The results show that, given the real price of fossil fuels and the social and pollution costs, nuclear technology can compete with fossil fuel power plants. Due to the need to expand the use of new energy, policy solutions for developing these technologies have been introduced and reviewed. Studies show that in addition to providing sustainable funding for the new energy sector, policy solutions based on policy stability and a gradual reduction in the cost of new power plants should be included in medium-term government plans.

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**How to cite this manuscript:** Nima Norouzi*. Determining the direct and indirect social costs of fusion and fission nuclear power plant Technologies. *Asian Journal of Green Chemistry*, 5(3) 2021, 294-312. DOI: 10.22034/ajgc.2021.291239.1307