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Approximation of the economy of fusion energy

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ABSTRACT

Conceptual design activities of the first fusion power plants were launched in recent years with a view to putting them into operation by 2050. Nuclear fusion offers significant benefits in comparison with exploited energy sources, especially limitless fuel reserves, inherent nuclear safety, and negligible impact on the environment. The challenge is a high heat and neutron loading of the fusion reactors nuclear zone. The paper brings the ex-ante economic analysis of the fusion power plant model DEMO2 in terms of the cost of electricity. The model investment and operating costs are presented. The limit sales price of electricity was found using the net present value method. The levelized cost of electricity LCOE method with the inclusion of external costs is used for a comparison of selected power plant types based on the OECD statistical data and the EU ExternE project results. The comparison shows the levelized cost of electricity of fusion power plants competitive to the actual renewable resources. After internalisation of external costs, the fusion power plants should become even the second cheapest power source.

1. Introduction

The capability of releasing energy under controlled nuclear fusion was demonstrated already in the 1990s when the US TFTR reactor reached the 10.7 MW fusion power and the European JET reactor the 16 MW fusion power (5 MW in a quasi-steady-state scenario). The demonstration of the technical feasibility of the energy use of nuclear fusion is the objective of the ITER International Thermonuclear Experimental Reactor project. The ITER 500 MW fusion reactor, built in Provence, France, will test equipment and technology for the first fusion power plants (Fig. 1). ITER will be commissioned in 2025 and will achieve 500 MW burning fusion plasma since 2036 [1].

The ITER project is directly linked to Demonstration Fusion Power Plant (DEMO) projects. The DEMO projects aim to develop and build a demonstration power plant with a fusion reactor. At present, a selection of technologies suitable for fusion power takes place. A conceptual design activity of the European DEMO project was launched in 2014 with the intention to start production of electricity from fusion by 2050 [2].

In fusion reactors of the first generation, the thermonuclear reaction of nuclei of hydrogen isotopes deuterium and tritium will be exploited. The optimum reaction temperature is approximately 160 million °C. The reactants will be in the state of fully ionized plasma. Deuterium will be separated from water, tritium will be obtained by the nuclear reaction of the lithium isotope ^{6}Li with the neutrons generated by the fusion reaction in a fusion reactor blanket.

The most advanced fusion reactors are the so-called tokamaks based on a magnetic confinement of plasma. Their main components are a toroidal vacuum vessel and a robust magnetic system generating a strong magnetic field to prevent hot plasma contact with the reactor structure. The plasma is surrounded by a nuclear zone (Fig. 2). Nuclear zone components, the first wall, blanket, and divertor, will be loaded by high neutron and heat flux from plasma causing intensive component wear. To achieve the temperatures required for the thermonuclear reaction, the plasma will be heated by a physically and technically sophisticated heating system - high electric current, neutral beams injection and electromagnetic waves. The neutral beams and electromagnetic waves will also be used as non-inductive drivers of the plasma electric current, which is necessary for plasma confinement [3].

In nuclear fusion, the same nuclear energy is released as in nuclear fission power plants. However, the fusion reactors bring an important feature in nuclear power - inherent nuclear safety. It is based on the fact that maintaining high temperatures and running fusion reactions in the reactor require the active synergy of a number of reactor technologies. In the event of failure of any of

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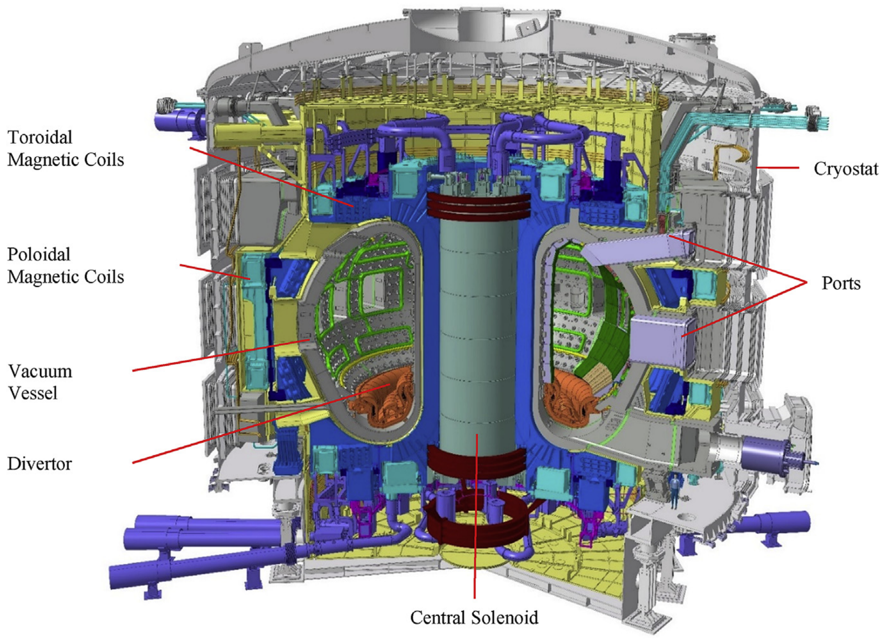


Fig. 1. Fusion reactor ITER [1].

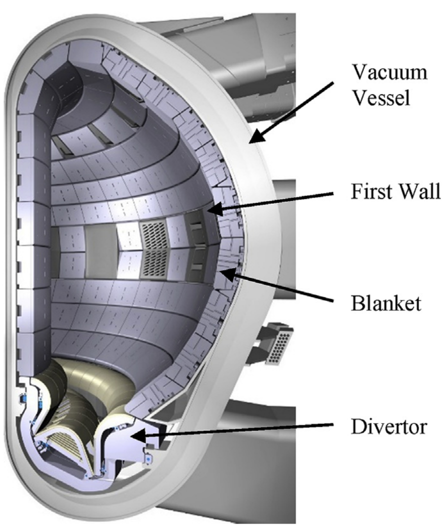


Fig. 2. Nuclear zone of ITER [1].

these technologies, the reaction will immediately naturally end.

The key features of future fusion energy will be the light chemical elements fuelling and high fuel temperature. These features imply inexhaustible and globally available fuel reserves, high ecological and emission-free electricity generation and inherent nuclear safety. The electricity production yields no long-term radioactive waste, just a small amount of inert gas helium.

Future 1 GWe fusion power plant needs less than 2 kg of the fusion fuel per day, and the fusion reaction will generate less than 1.5 kg of helium, which will be used for internal power plant technologies [4]. The environmental impact of fusion power plants will be comparable to the impact of renewable resources, and consequently, the external costs will be very low.

However, a characteristic feature will also be a high heat and neutron loading of the fusion reactors nuclear zone requiring high-performance durable components. The nuclear zone will be exposed to intense heat radiation at MW/m^2 level, 14 MeV neutron radiation, ionized particles, and hard X-ray radiation. At the current technological level, low lifetime of nuclear components is expected. The high energy flux, composed of intense neutron and heat radiation, is currently the major technological challenge in the development of fusion power reactors.

Cooling nuclear zone components transfers the released energy off the reactor. Fusion power plants will be of the two-circuit type with multiple primary cooling circuits of individual nuclear components (Fig. 3). For the production of electricity, utilization of conventional turbine island technologies is expected.

The aim of the paper is the ex-ante economic analysis of the European demonstration fusion power plant DEMO2 in terms of the cost of electricity and to compare future fusion power plants with other types of power plants.

2. Methods

The net present value (NPV) method based on the discounted cash flow (DCF) technique is used in project DEMO2 valuation. The European reference model of the demonstration fusion power plant DEMO2 [5] proposed by the EUROfusion consortium of fusion

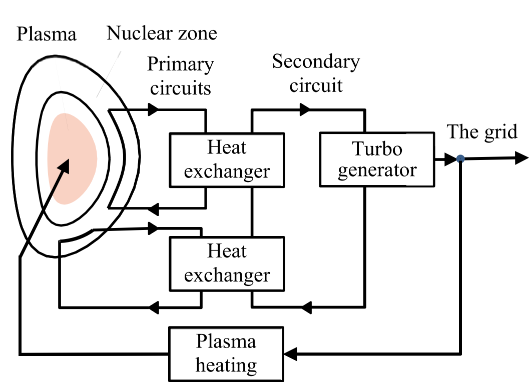


Fig. 3. Fusion power plant scheme.

laboratories in 2015 was chosen for the analysis. The model was built at the CCFE Fusion Energy Centre in Culham, UK using a specialized system code PROCESS designed for the physical, technical and economic modelling of the fusion power plants [6].

The levelized cost of electricity (LCOE) method with the inclusion of external costs (i.e. internalizing the externalities) is used for the final comparison of different types of power plants. The LCOE calculations are based on a levelized average lifetime cost approach, using the DCF method. The calculations use a combination of generic, country-specific and technology-specific assumptions for the various technical and economic parameters, as agreed by the Expert Group on Projected Costs of Generating Electricity (EGC Expert Group) [7]. The analysis was performed using 7% discount rate.

External costs are estimated based on the ExternE EU-funded research project including the impact pathway approach and life cycle assessment (LCA) of energy. A detailed description of the methodology provides [8].

3. Power plant model

Two different demonstration fusion power plant reference designs are currently investigated in EU. A near-term conservative baseline design DEMO1 and more advanced DEMO2 design based on more optimistic physics assumptions, e.g. a current drive steady-state plasma scenario [9].

The DEMO2 model, representing the most relevant prototype of future fusion power plants, was used in the analysis because it currently represents one of the most accurate estimates of the cost of construction and operation of fusion power plants. According to the model, the DEMO2 fusion power plant with net electric output ~1 GW should provide yearly about 6.3 TWh of electricity to the grid. Energy parameters of the model are summarized in Table 1 demonstrating two specific features of fusion power plants. At first, the reactor thermal output will be higher than the nuclear fusion power, as it also includes the heat released during the tritium production from lithium in the blanket and the recirculated power of the fuel heating. At second, the self-consumption of the first fusion power plants will be comparable to net output power due to the high consumption of the heating and current drive system [10].

4. Investment costs

Investment costs of the model DEMO2 in 2015 prices are summarized in Table 2 [5]. The presented costs do not include the cost of money (overnight costs type).

The model includes the cost of implementing the power plant technologies in continuously updated prices. The costs are split into the standard accounting categories generally used in the reporting of power plant costs. The unit costs of the components of the fusion power core are relevant to “first-of-a-kind” items. That is to say, the items are assumed to be relatively expensive to build as they are

Table 1
Energy-related parameters of the DEMO2 fusion power plant reference model.

Fusion power	3255	MW
Thermal power[a]	4149	MW
Gross electric power	1660	MW
Net electric power	953	MW
Plant self-consumption[b]	707	MW
Plant availability fraction	75	%

[a] The reactor thermal power includes the fusion power, the power released during a tritium breeding, and the reradiated heating power.
[b] The self-consumption includes among others the plasma heating and current drive system.

Table 2
Investment costs of the DEMO2 reference model (overnight costs).

Reactor systems	862	M$
Magnets	2216	M$
Vacuum system	39	M$
Cryogenic system	99	M$
Fuel handling system	298	M$
Heating & current drive system	439	M$
Cooling systems	221	M$
Control & Diagnostics	150	M$
Maintenance equipment	300	M$
Turbine plant	321	M$
Buildings	1027	M$
Direct cost	6043	M$
Indirect cost	1473	M$
Contingency	1009	M$
Total capital investment	8525	M$

effectively prototypes and specialized tools and machines have perhaps been made specially to create them. The cost of the fusion-specific technologies accounts for approximately 75% of the total direct costs of constructing the plant, reflecting the lack of know-how and the risks involved in their production and commissioning [11]. The structure of the direct investment costs is shown in Fig. 4.

Unlike the ongoing project ITER, the DEMO2 model includes neither the cost of developing individual fusion technologies nor the cost of complicated international participation in the implementation of the project through in-kind contributions, and therefore the total investment cost is roughly half that of the ITER project, even though ITER dimensions are smaller by factor of 1.5 (with fusion power only 500 MW instead of 3255 MW in DEMO2), and that ITER does not include both the electricity generation and tritium breeding technologies.

5. Cost of electricity

According to the purpose of this analysis, the cost of electricity (COE) was determined by the simplified equation without the cost of money:

$$COE = \frac{C + DP}{E}, \tag{1}$$

where C denotes the annual operating costs, DP is the annual depreciation, and E is the net annual electricity production.

The composition of COE will be significantly different from that of existing plants. The main reasons include the high ongoing costs

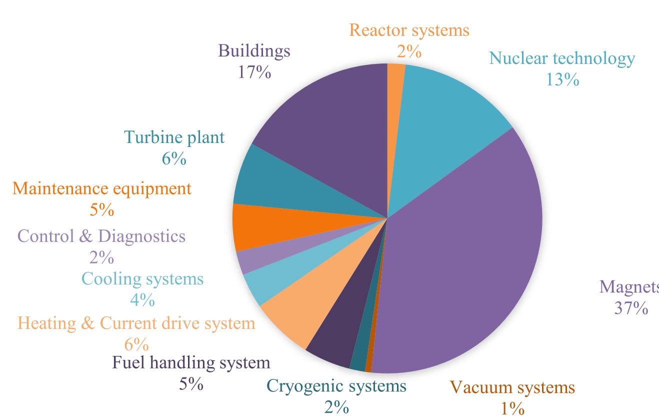


Fig. 4. Structure of the direct costs of the DEMO2 reference model.

Table 3
DEMO2 reference model cost of electricity without the cost of money.

Operation & Maintenance	9.81	\$/MWh
Replaceable components cost	13.61	\$/MWh
Fuel costs	0.44	\$/MWh
Waste disposal	0.56	\$/MWh
Decommissioning fund	0.78	\$/MWh
Depreciation	34.11	\$/MWh
Cost of electricity w/o the cost of money	59.31	\$/MWh

for the replacement of damaged nuclear components and negligible fuel costs, as shown in Table 3 [5] and Fig. 5.

Heat and neutron loading of the nuclear components will be so high that the expected lifetime of specific nuclear components (from 4.5 to 10.5 years [5]) will be much shorter than the plant lifetime (40 years). The components replacement cost will be spread throughout the plant operation, yielding an average annual replacement cost of 85 M\$. In contrast, the average annual fuel costs will not exceed 2.75 M\$ [5].

COE is affected by high depreciation as shown in Fig. 5. Since a substantial part of the investment cost and COE is related to the production of the fusion technologies such as the nuclear technology or magnets, the costs will significantly decrease depending on the progress in research and development of the fusion technologies.

For example, according to Table 2, the major part of the investment cost sustains uniquely from the tokamak magnets made of industrially well-established low-temperature superconductors. The recent boom in the second generation of high-temperature superconductor cables industrial production could allow for a construction of a powerful tokamak reactor with the higher magnetic field, thus much smaller in physical dimensions, thus possibly reduced the investment cost [12].

6. Analysis of technical-economic efficiency

The analysed criteria of the technical-economic efficiency of the plant DEMO2 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 with respect to the model data structure. Financing was simplified for the purpose of the approximation to fully fund the project by credit:

$$CF_t = (R_t - C_t - I_t - DP_t)\cdot(1 - T_t) + DP_t - IN_t\ , \tag{2}$$

where t denotes the current year, R are the annual revenues, C are the annual operating costs, I are the interests, DP is the depreciation, T is the rate of income tax, and IN are the annual investments.

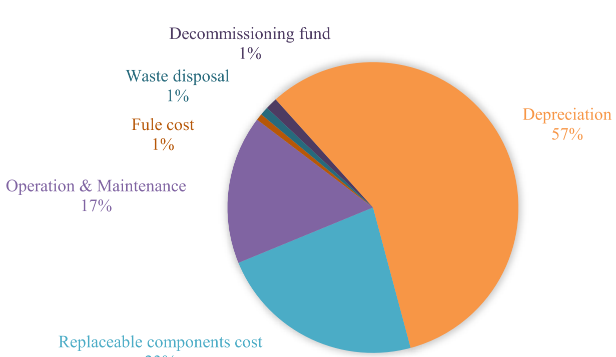


Fig. 5. Structure of the cost of electricity of the DEMO2 reference model.

A cumulative cash flow *CCF* means, at any time, the aggregate cash flow:

$$CCF = \sum_{t=0}^{Tp-1} CF_t, \tag{3}$$

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

$$DCF = \sum_{t=0}^{T_p-1} CF_t\cdot(1+r)^{-t}, \tag{4}$$

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 over a period of the economic lifetime, was calculated by the equation:

$$NPV = \sum_{t=0}^{T_L-1} CF_t\cdot(1+r)^{-t}, \tag{5}$$

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

$$PI = \frac{NPV}{IN}\ , \tag{6}$$

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

$$\sum_{t=0}^{T_L-1} CF_t\cdot(1+IRR)^{-t} = 0\ , \tag{7}$$

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:

$$\sum_{t=0}^{DPP-1} CF_t\cdot(1+r)^{-t} - IN = 0, \tag{8}$$

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:

$$LCOE = \frac{\sum_{t=0}^{T_L-1}(IN_t + C_t + I_t)\cdot(1+r)^{-t}}{\sum_{t=0}^{T_L-1}E_t\cdot(1+r)^{-t}}\ , \tag{9}$$

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

$$TCOE = \frac{\sum_{t=0}^{T_L-1}\left(IN_t + C_t + I_t + E_t\cdot C_t^{EXT}\right)\cdot(1+r)^{-t}}{\sum_{t=0}^{T_L-1}E_t\cdot(1+r)^{-t}}\ , \tag{10}$$

The analysis was carried out at constant prices of the year 2015 with the real discount rate of 7%. With regard to the analysed 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 European Central Bank. Income tax rate was chosen

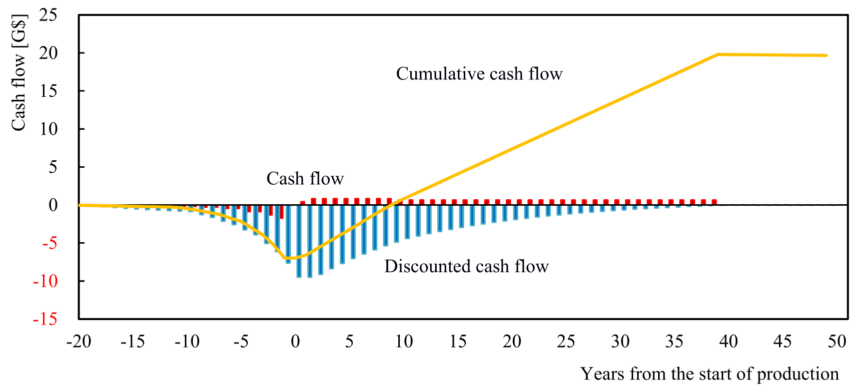


Fig. 6. Cash flow in the limiting case of the zero profitability at the sales price of electricity of 175 $/MWh.

conservatively by the Germany corporate tax rate of 30%. The length of the plant's operation was taken from the model as 40 years. The technical preparation phase, construction phase, and the decommissioning phase were all taken as ten years duration.

7. Results of the DEMO2 model analysis

Development of the projected cash-flow in the limiting case of zero profitability is shown in Fig. 6. The model levelized cost of electricity was found in the amount of ~160 $/MWh and the limit sales price of electricity in the amount of ~175 $/MWh. The net present value of the project would reach initial investment at the sales price of electricity ~312 $/MWh. The dependency of the criteria of the technical and economic efficiency on the sales price of electricity is shown in Figs. 7 and 8. The results of the analysis are summarized in Table 4.

8. Sensitivity analysis

The analysis showed the high sensitivity of the fusion plant economy on both the investment cost and the net efficiency of the electricity production.

Low level of fusion technology industry know-how and the associated risks significantly affect the investment cost of the project. On the basis of gradually acquired know-how, however, this cost will decrease (i.e. Learning factor). Generally, this decrease may be achieved in the construction of the tenth power plant up to 40% [13] in an average high-tech novel industrial project. One can expect, however, that the investment cost of fusion plants with a high proportion of advanced technologies which are strongly fusion-specific (not used elsewhere) provides even further scope for reducing if compared to the wind and photovoltaic systems which are already on the market for dozens of years.

In the case of fusion, the inherent safety of fusion reactors yields no reason to increase the cost of ensuring nuclear safety, which is currently the trend in the fission nuclear industry. Similarly, there is hardly increasing the cost of protecting the environment. Therefore, the investment cost of fusion power plants will certainly decrease from the first plant onwards in relation to the improvement, optimization, and standardization of the fusion technology.

Higher net production efficiency increases the amount of produced electricity without the rise of the reactor's thermal power, thus without shortening the lifetime of nuclear components. Increasing the net efficiency from 23% to 30% would reduce the limit sales price of electricity by 21% (Table 5). Increase in efficiency, as well as the investment cost reduction, depends on the progress in the development of the fusion technology, mainly in the reduction of the plasma heating system consumption.

9. Discussion of DEMO2 model analysis

The identified limit sales price of electricity in the amount of 175 $/MWh is several times higher than the current market price of electricity: ~34 $/MWh in 2015 on the EU stock market. Unprofitableness without the public aid of an environmentally-friendly energy project is nowadays nothing unusual. Excess of electricity from subsidized renewable sources and competition in fossil fuels strongly compress the market price of electricity. Subsidies and feed-in tariffs are usually related to renewable energy sources but are also emerging in the context of new nuclear fission power plants as in the case of the construction of nuclear power plants in the UK or in the Czech Republic.

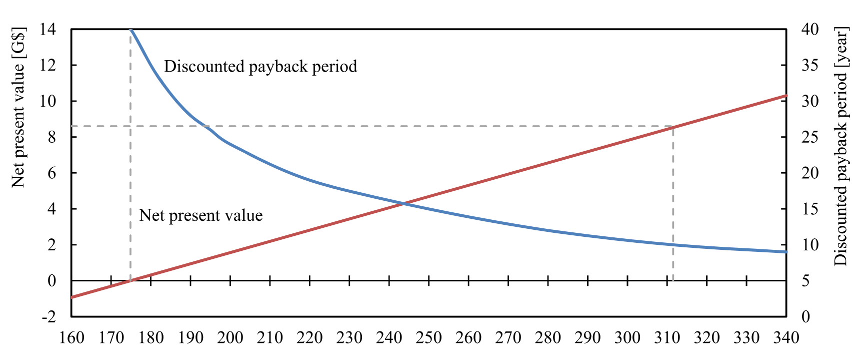


Fig. 7. Development of the net present value and discounted payback period depending on the sales price of electricity.

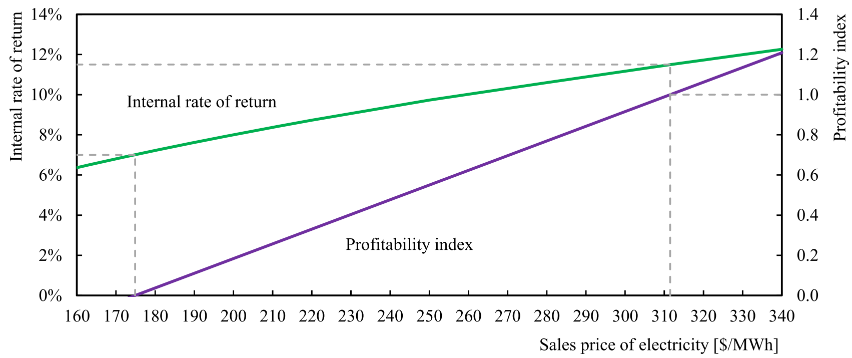


Fig. 8. Development of the internal rate of return and profitability index depending on the sales price of electricity.

Table 4
Results of the analysis of the DEMO2 technical-economic efficiency.

Profitability index	0.00	1.00	
Net present value	0.00	8.53	G$
Internal rate of return	7,0	11,5	%
Discounted payback period	40	10	Year
Cost of electricity w/o the cost of money	59,3	59,3	$/MWh
Levelized cost of electricity LCOE	160,3	160,3	$/MWh
Limit sales price of electricity	174,9	311,5	$/MWh

Table 5
Technical-economic efficiency parameters depending on the net efficiency.

Power plant net efficiency	23%	30%	33%	
Levelized cost of electricity LCOE	160.3	125.5	115.1	$/MWh
Limit sales price of electricity	174.9	136.7	125.3	$/MWh

The required funding about 141 $/MWh is comparable to the subsidies paid to offshore wind which totalled 136 $/MWh in the EU in 2012 in the price level of 2015, and is much lower than the subsidies provided in the same year for photovoltaic plants in the amount of 249 $/MWh in 2015 price level [8]. These subsidies to renewable resources do not include the costs of maintaining large standby power plants ran on coal, gas or pumping hydroelectric power stations, which in the case of fusion plants will not be necessary. In conclusion, compared to these renewable resources, the fusion power plants will produce electrical energy as well safely, more environmentally friendly, and cheaper as evaluated just below.

The validity of the presented results is closely related to the validity of the DEMO2 input model data. Conceptual design activities are currently taking place and the model costs, therefore, represent only a rough estimate of costs. The uncertainty is partially reduced by the use of standardized proven non-fusion technologies. Using the technology of operated nuclear power plants reduces the technical and economic risks on the basis of technical and economic experience. However, since the construction of DEMO2 will begin not earlier than in the second half of the century, the data can only be seen as a rough estimate and the results as an approximation of economy of the first fusion power plants.

10. External costs

Since different energy sources variously affect the environment, it is necessary to count the external costs incurred in connection with the activities of these sources. External costs are defined as the impact of the production or consuming behaviour of the economic entities on the welfare of a third party, whilst it is not reflected in the market transactions.

The European methodology ExternE for the evaluation of external costs of energy in its present form assesses three main categories of the energetics impact: damage to human health (increased risk of mortality and morbidity), effects on ecosystems and biodiversity (changes in the environment, biodiversity loss) and the impact on resources and depletion (mainly of water, metals and fuels, but also crops, buildings, etc.). The impacts include climate change, ozone depletion, soil acidification, eutrophication of freshwater and marine environments, increasing the toxicity of the environment, increasing background radiation, land appropriation, annexation of areas in cities, transforming the natural soil, depletion of water resources, depletion of mineral deposits, exploitation of energy resources and disasters and accidents [8]. The graph in Fig. 9 summarizes the total external costs of various types of power plants quantified by the methodology ExternE [8] and [14], recalculated for the price level of 2015. Nuclear fusion will create the lowest external costs of all the benchmarked sources.

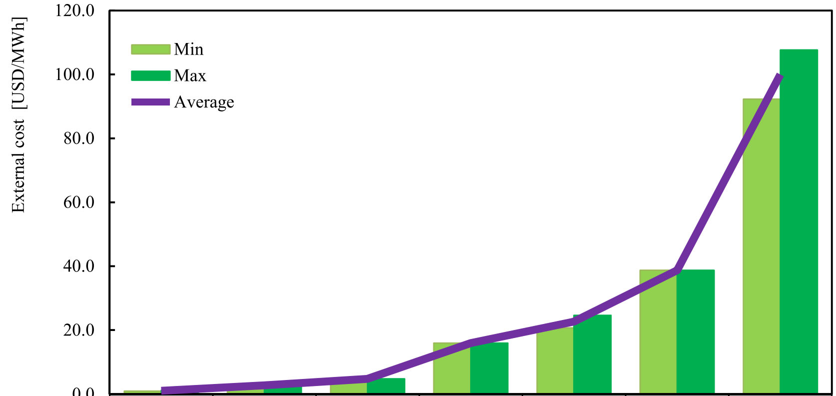
11. Compared data

To compare the economic effectiveness of different types of operating plants, we used the statistical data on the investment cost and LCOE at 7% discount rate published by the OECD in 2015 [7].

For fusion, the data published by the European Fusion Development Agreement in 2005 [14] recalculated on the price level of 2015 and the data of the analysed DEMO2 fusion power plant model were used.

Costs are calculated at the plant level (busbar), and therefore do not include transmission and distribution costs. Similarly, the LCOE calculation does not capture other systemic costs or externalities beyond CO2 emissions.

The analysis within the used report is based on data for 181 operated plants in 22 countries (including 3 non-OECD countries) [7]. This includes 17 natural gas-fired generators (13 combined-cycle gas turbines CCGT and 4 open-cycle gas turbines OCGT), 14



	Fusion	Wind offshore	Wind onshore	Solar large PV	Nuclear	Natural gas	Coal
Min	0.9	2.7	4.7	16	21	39	92
Max	1.1	2.7	4.7	16	25	39	108
Average	1.0	2.7	4.7	16	23	39	100

Fig. 9. External costs of selected energy sources according to the ExternE methodology [8,14].

coal plants, 11 nuclear power plants, 12 solar large photovoltaic plants, and 21 onshore and 12 offshore wind plants.

The European Power Plant Conceptual Study [14] is a report summarizing European conceptual designs for commercial fusion power plants based on the tokamak concept, proceeding through JET (Joint European Torus, UK) and ITER. The study focuses on four power plant models which are illustrative of a wider spectrum of possibilities. These span a range from relatively near-term concepts, based on limited technology and plasma physics extrapolations, to a more advanced conception. All four plant models differ from one another in their size, plasma physics, electrical output, reactor technology, and these differences lead to differences in economic performance and in the details of safety and environmental impacts.

12. Final results

The final results are presented in the form of comparative graphs. For the comparison of fusion power plants, several types of existing power stations were selected: gas power stations, coal-fired power stations, nuclear power plants, large photovoltaic power plants, and large wind power plants. The investment cost and results of the DEMO2 analysis from Section 4., resp. 7. are shown separately as points in the graphs.

Fig. 10 shows the results of 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 Fig. 11 shows 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 LCOE change significantly. TCOE includes LCOE and external costs, and the resulting graph of TCOE is shown in Fig. 12. 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 the environmental impact in the case of internalisation of external costs, fusion power plants will be economically the second most favourable source of energy.

13. Discussion

The input data of existing power plants are of a statistical nature and therefore highly reliable. The fusion power plants 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.

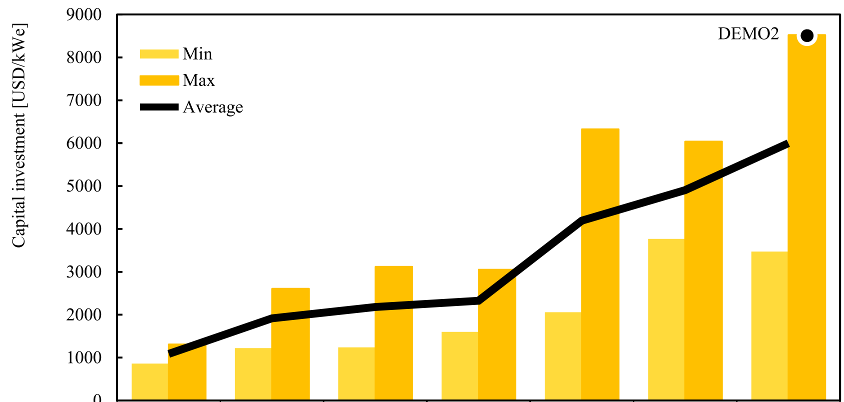
It is very difficult to predict the development of the global economy and energy for several decades ahead. The real course of integration of nuclear fusion into energetics will depend on both the scientific and technological development of the entire energy sector.

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 the energy development.

14. Conclusions

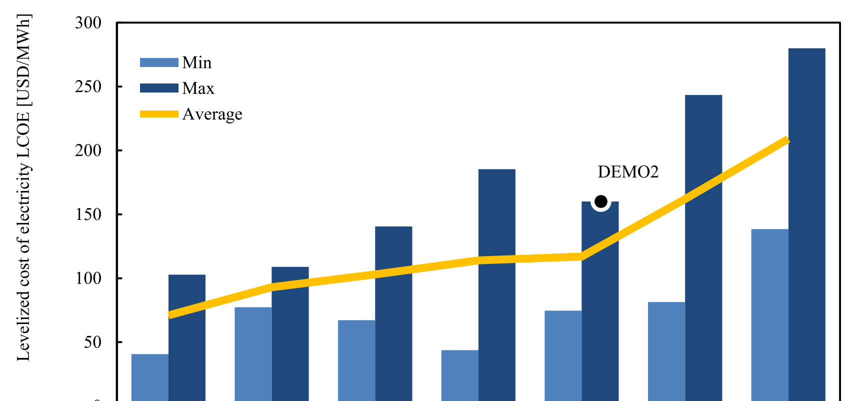
The economy of fusion power plants will be an important factor in the development of fusion energy. The technical-economic ex-ante analysis of the European DEMO2 fusion power plant described the main economic features of future fusion energy. The composition of the investment cost and cost of electricity of the fusion power plants will be significantly different from existing power plants.

Especially, the COE is given in majority by the assumed plant investment cost and cost of the replaceable nuclear components. Therefore, COE and subsequently LCOE and TCOE strongly depend on the industrial fusion technology assumptions evaluated. In the initial period, this will cause the electricity price from fusion power plants comparable to the electricity price from photovoltaics and wind power. At the same time, high-power production of electricity would take place without any fluctuations caused by daylight, seasons or weather, and without the need to maintain fossil backup resources. Given the inexhaustible fuel with insignificant price, inherent nuclear safety as well as its negligible environmental impact, there will be great scope for reducing investment cost on the basis of technological research and development with high



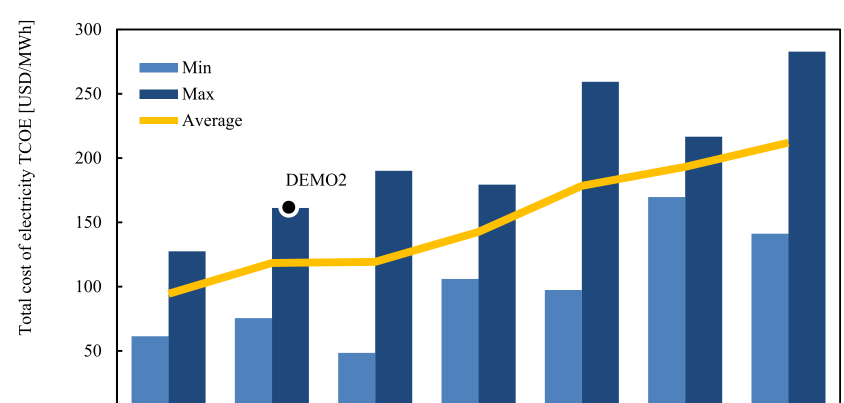
	Natural gas	Solar large PV	Coal	Wind onshore	Nuclear	Wind offshore	Fusion
Min	860	1222	1240	1599	2058	3770	3472
Max	1312	2609	3123	3053	6328	6040	8525
Average	1086	1916	2181	2326	4193	4905	5999

Fig. 10. Capital investment comparison.



	Nuclear	Coal	Natural gas	Wind onshore	Fusion	Solar large PV	Wind offshore
Min	41	77	67	44	75	81	138
Max	103	109	140	185	160	243	280
Average	71	93	103	114	117	162	209

Fig. 11. Levelized cost of electricity LCOE comparison.



	Nuclear	Fusion	Wind onshore	Natural gas	Solar large PV	Coal	Wind offshore
Min	61	76	49	106	97	170	141
Max	127	161	190	179	259	217	283
Average	94	118	119	143	178	193	212

Fig. 12. Total levelized cost of electricity including external costs TCOE.

probability to become the cheapest and cleanest energy source since the end of this century for an unlimited time onwards.

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