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ECONOMIC ANALYSIS OF THE UK NUCLEAR ENERGY SYSTEM FROM 1956 TO 2035

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RESUMO

One of the most important topics about nuclear programs is the economic development of their nuclear energy system. One of the most remarkable programs was the UK's nuclear energy systems. Their first commercial nuclear power reactor connected to the grid was the Calder Hall -1 at Seascale in 1956. After that, 45 reactors built until 1995 for electricity production. Currently, 30 of them are permanently shutdown and 15, which comprises around 19% of the UK energy matrix are still operational. Despite the last reactor built in 1995 was a PWR - SIZEWELL-B connected to the grid 23 years ago, the UK government plans to build new generation plants to supply 19 GWe until 2025 and aims to have additional 16 GWe until 2023. This work shows the economic needs of the UK's nuclear program to continue with their nuclear program. The software MESSAGE was used in the analysis taking into consideration the uranium spot price during the time. The results indicate the government investment needed to replace most of their current fleet with a new reactor fleet by 2025. This work also evaluates the economy of the nuclear fuel cycle comprising: mining price, fuel fabrication, the amount of nuclear waste produced by the nuclear reactor activity, the uranium ore needed to supply the reactor transition from old AGR to new generation of nuclear reactors, and spent fuel produced due to the nuclear activity until 2035.

1. INTRODUCTION

The world's first commercial nuclear reactor was built at Calder Hall 1 in the United Kingdom by 1956. The original nuclear policy in the UK promised a nuclear power program between 5-6 GW of net capacity until 1965. This originated the Gas Cooled Reactor (GCR) generation, the model called Magnox. Around 1963 begun the era of the Advanced Gas cooled Reactor (AGR) design, where the Windscale AGR was the first of its kind [1, 2]. In addition, two Fast Breeder Reactor (FBR) were built, Dounreay DFR and PFR, without succeeding from 1962 to 1994. In the early 1990s, a new policy of nuclear energy promoting a new fleet of PWRs encouraged the government, but the plans were abandoned due to the lack of support. One of the major concerns aboute nuclear energy was the nuclear waste problem, the UK had a serious energy crisis that, in 2006, with Tony Blair on the command, let them think again in the nuclear program to avoid

CO_2 emissions and the nuclear energy could make a great contribution to decrease the emissions [3].

The aim of this work is to study the economic aspects of the nuclear energy system from the beginning of the UK's nuclear era, in 1956, to the near future 2035. Therefore, this work simulates the energy contribution of 43 out of the 45 nuclear reactors connected to the grid and their nuclear waste produced during the time. The two aforementioned FBR reactors were due to their very short contribution to the electricity production share [2]. The economic aspects are based on the investment cost, operation and maintenance of each reactor technology and the uranium spot price in the market for each year from 1956 to 2018. The fuel fabrication cost to supply the reactor's fuel considers the spot price of the conversion process from U_3O_8 and for the UF_6 without enrichment (SGHWR, GCR), with enrichment (AGR, PWR) and finally, the cost for fuel fabrication.

Besides, the nuclear energy system simlated at MESSAGE [4] takes into consideration the shutdown from most of their nuclear reactor fleet (AGR) in the near future. Therefore, it is simulated the transition from the shutdown of 15 reactors around 2025 to the new generation of reactors and the investment cost needed to fulfill the forecasted future demand of energy by building the new fleet of reactors [5], which are divided into two groups of Advanced Light Water Reactor (ALWR). The ALWR-1 represents the European Pressurized Reactor (EPR) [6] and the ALWR-2 represents the Advanced Boiling Water Reactor (ABWR) [7].

2. METHODOLOGY

The UK nuclear energy system was simulated from the beginning of the nuclear program to 2035. Nevertheless, the most important consideration was not include the two FBR and for the increase of electricity share, two light types of LWR reactors were considered an EPR and ABWR [4]. Thus, 43 nuclear reactors were simulated until 1995 due to the exclusion of the two FBR. This group were sorted in eight different types of reactors according to the power and reactor features. The planned reactors were classified in two different groups according to their features. The categories were:

1. GCR- MAGNOX-I: Hunterston (A-1, A-2); Berkeley (1, 2); Bradwell (1,2)
2. GCR- MAGNOX-II: Dungeness (A-1, A-2); Hinkley Point (A-1, A-2); Oldbury (A-1, A-2); Sizewell (A-1, A-2); Trawsfynydd (1, 2)
3. GCR- MAGNOX-III: Calder Hall (1,2,3,4); Chapelcross (1, 2, 3, 4)
4. GCR- MAGNOX-IV: Wylfa (1, 2)
5. SGHWR: Winfrith SGHWR
6. AGR – I: Windscale AGR
7. AGR –II: Dungemess (B-1, B-2); Hartlepool (A-1, A-2), Heysham (A-1, A-2, B-1, B-2); Hinkley Point (B-1, B-2); Hunterston (B-1, B-2), Torness (1, 2)

8. PWR: Sizewell B
9. ALWR1 (EPR & AP1000): Hinkley Point (C1, C2); Sizewell (C1, C2); Moorside (1, 2, 3)
10. ALWR2 (ABWR): Wylfa Newydd (1, 2); Oldbury (C1, C2)

Tab.1 shows the average parameters for each category presented above. The operation factor and load factor were an average along the lifetime of the corresponding reactors. The table also shows the sum of electricity production (TWh) for all the reactors in each category during their respectively lifetime as well as the type of fuel considered for each reactor. For the ALWR1 and ALWR2 the considerations were: UOX nuclear fuel and a load factor of 80% for both and a nuclear capacity of 1650 MW and 1000 MW, respectively.

Tab. 1. Main features of the 43 UK reactors modelled in Message [2]

Reactor	Electricity sum of each one (TW.h)	Average Gross Capacity (MWe)	Average Net Capacity (MWe)	Operation Factor (%)	Load Factor (%)	Fuel Type
Magnox-I	154.24	161.67	146.00	87.02	68.40	UOX-NatU
Magnox-II	521.26	241.40	273.00	87.50	75.64	UOX-NatU
Magnox-III	112.96	60.00	35.00	60.00	81.20	UOX-NatU
Magnox-IV	235.75	535.00	550.00	82.40	70.05	UOX-NatU
SGHWR	10.96	318.00	100.00	60.90	60.70	UOX-NatU
AGR-I	3.26	36.00	32.00	56.80	59.80	UOX
AGR-II	1553.44	650.86	619.93	74.70	68.54	UOX
PWR	164.56	1250.00	1188.00	86.20	83.70	UOX

The burnup of each reactor type, the prices, costs, fuel costs, uranium price, the thermal efficiency, and other data were obtained from different sources [8-16]

3. RESULTS

The nuclear electricity production is shown in Fig.1. The timeline was chosen until the end of life of the PWR-Sizewell B. Therefore, it represents the transition of all the old reactors to the new generation fleet plan of 16 GW that will be built until 2030. The figure also shows how the peaks of energy decrease after the different reactors shutdown during the nuclear history and the transition to new generations.

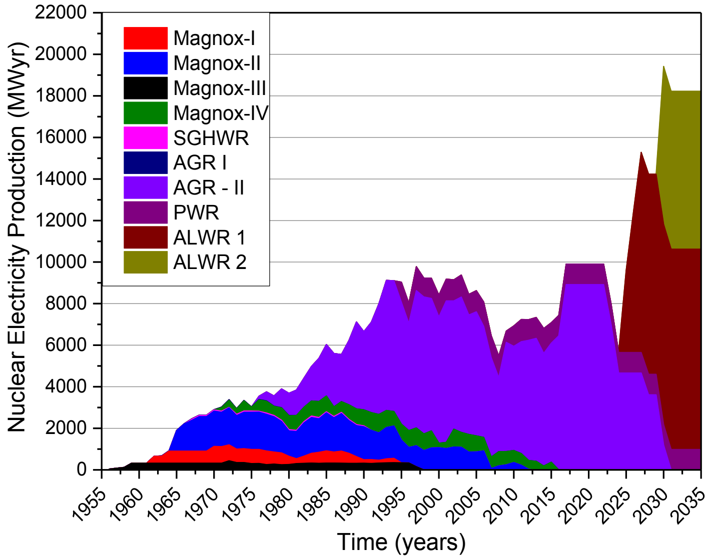

Fig. 1. Nuclear electricity production by reactor feature

The uranium supplied all the nuclear power reactors since the beginning of the UK nuclear program. The uranium price has been varied along the period since 1956. The highest price registered was in 2007 and the lowest was in the beginning of the time span. After 2018, the uranium price (US$/kg) was set constant due to the fact that unpredictability price changes (Fig. 2a). On the other hand, Fig.2b shows the price paid by the uranium use since 1956 to 2035 in "once-through nuclear fuel cycle".

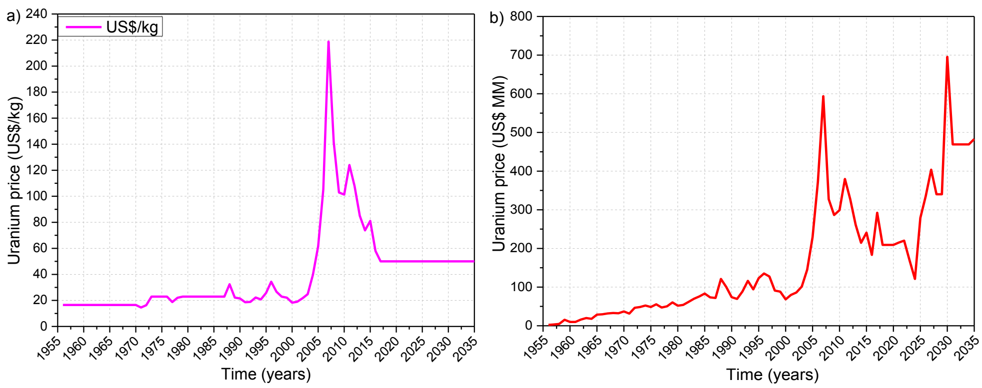

Fig. 2. (a) Uranium price and (b) uranium price paid by the nuclear reactor used

Fig. 3a shows the conversion price and the enrichment price, the conversion was separated in two different conversions, one for the GCR and the SGHWR, and the other one for the AGR, the LWR, and ALWR. On the other hand, the fuel production price for each reactor type used is presented in Fig. 3b. The UK is remarkable due to their two great eras, the first one of the GCR and the second one of AGR. The third era is the reactors planned to be built until 2030.

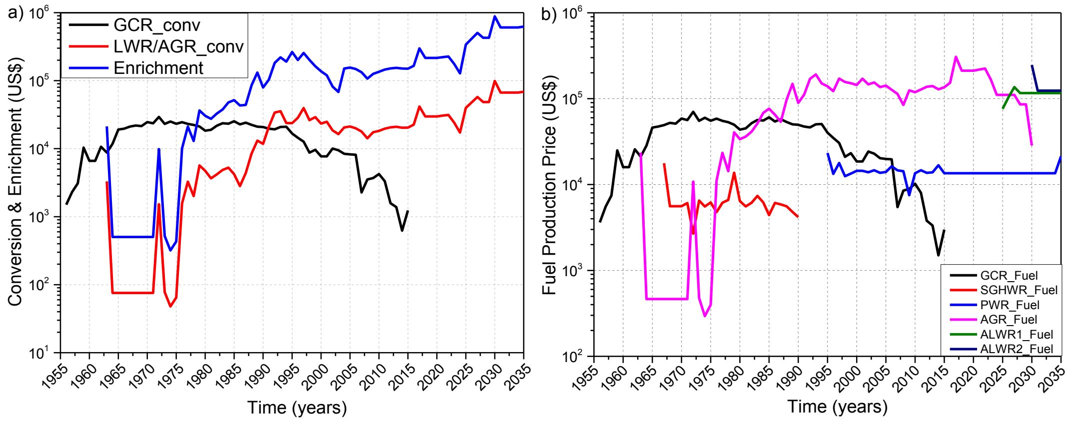

Fig.3. (a) Conversion and enrichment cost and (b) Fuel production price by nuclear reactor type

Fig.4 presents the spent fuel production after the nuclear activity of each type of reactor. It shows that the GCR was the highest producer of spent fuel due to their several numbers of reactors operation and their fuel cycle needs. Finally, Fig.5a shows the levelized price per type of reactor build. The most expensive reactors are the Magnox-III and the AGR-I, both of them were the first of their kind. Fig.5b shows the nuclear investment cost, the major investment would be for the ALWR reactors planned to be built until 2030. On the other hand, the second highest investment was for the AGR reactors due to them decommission and construction.

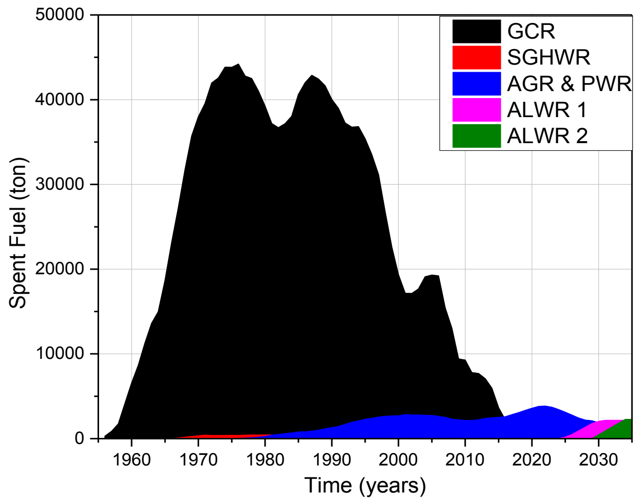

Fig.4 Nuclear Spent fuel produced by nuclear reactor activity

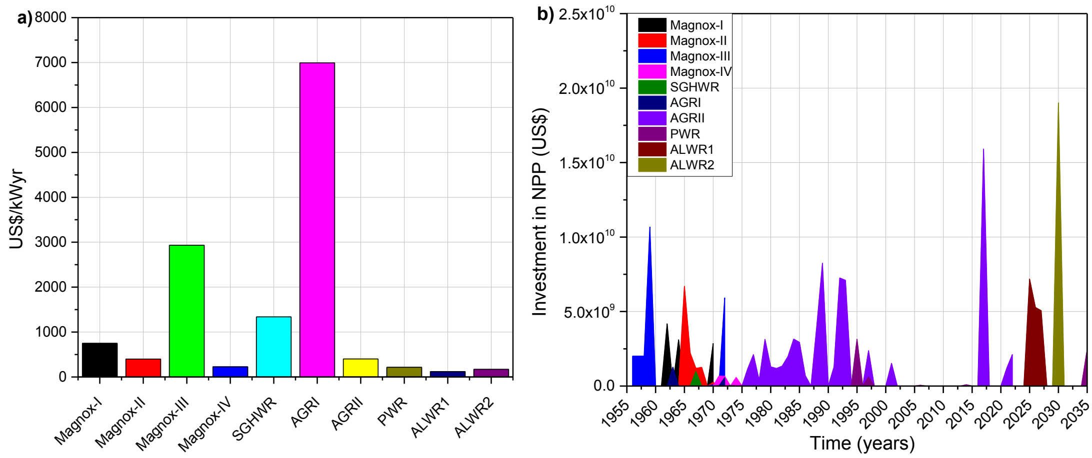

Fig.5. a) Levelized cost and b) Investment in NPP

4. CONCLUSION

To simulate the UK's nuclear energy program has been simulated 10 different kinds of reactors from the eldest ones to the future ones. The highest amount of spent fuel is for the GCR reactors due to their fuel cycle and natural uranium needs. The more expensive reactors are their first of their kinds such as the Magnox-I, SGHWR and the AGR-I. The highest investment is for the construction of nuclear power plants. The highest amount of spent nuclear fuel is highest for the GCR due to their nuclear fuel cycle consumption. The nuclear fuel cycle was analyzed separately due to the differences in uranium price since the beginning of the nuclear era, then due to the differences in conversion between the GCR uses of natural uranium and the AGR and PWR enrichment one and the fuel production by type of reactor. Thereby, this work contributes to show the expenses of the UK's nuclear program during their lifetime. This is an initial work to have a vision of the evolution in investment and nuclear fuel cost of one of the eldest nuclear programs in the world.

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