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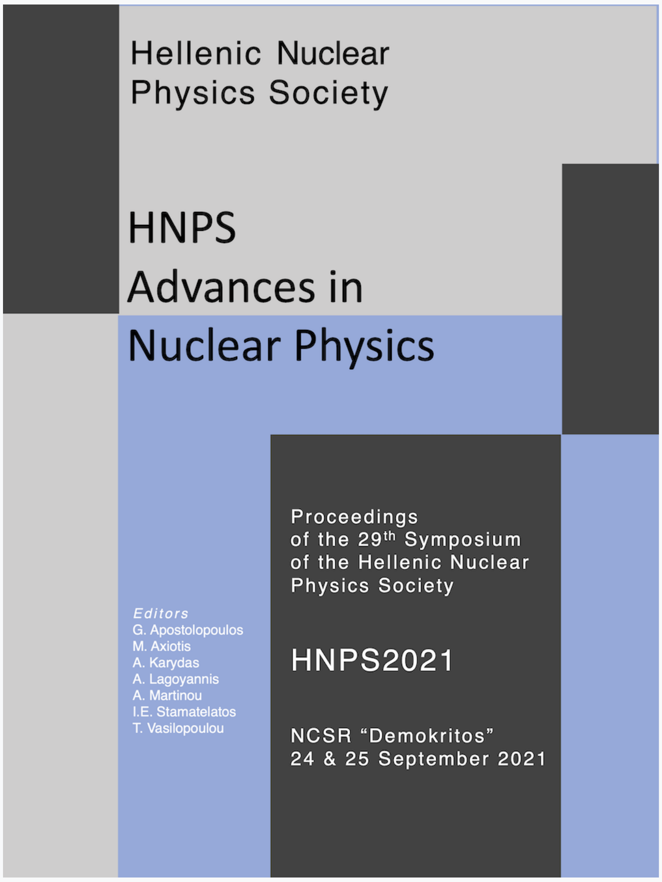

Review of technical-economic trends for currently operating nuclear power reactors

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Review of technical-economic trends for currently operating nuclear power reactors

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Abstract This work attempts a compilation on the performance and evolution indicators for today's (2020) operating nuclear power reactors. Data were obtained from IAEA's Power Reactor Information System (PRIS) Database, transferred to spreadsheets, post-processed, plotted in cognitive graphs and interpreted appropriately. The aim was to identify past, present and possibly future trends related to the usage of nuclear power for electricity production. The examined time span covers mainly currently operating power reactors, which have been grid connected since the '70s. Several operational periods could be identified, each one with its own properties and characteristics: (a) pre Three-Mile-Island, (b) post Three-Mile-Island, (c) post Chernobyl, (d) post Fukushima and, (e) New Build. These periods are loosely connected to the reactor generations as released and installed, i.e. Gen-II, Gen-III and Gen-III+. Although discussed as early as in the late '90s, Gen-IV reactors have not yet been developed. The New Build period involves mainly Gen-III+ types, the proposed Small Modular Reactors (SMR) and, recently, Mini Modular Reactors (MMR). Overall, these indicators point out that: (i) there is no negative trend on the number of active power reactors, (ii) the annual electricity produced by nuclear sources is steadily increasing, (iii) the reactors performance is getting better, (iv) despite their negligible number, the reactor accidents have been the main factors, which prohibited the expansion of nuclear reactors for electricity production, (v) all such accidents were followed by a period of conservative usage of most reactors, and, (vi) there is long-term improvement of the average reactor operational characteristics.

Keywords nuclear power reactors, technical-economic trends

INTRODUCTION

Data available at IAEA's PRIS Database were compiled in terms of performance and evolution indicators for today's (2020) operating nuclear power reactors (see [1] - [5]). The aim was to identify past, present and future trends related to the usage of nuclear power for electricity production. The examined time span extends as far back as the 70's, when some of today's reactors have been grid connected. Several operational periods could be identified: (a) pre 1979 Three-Mile-Island (TMI), (b) post 1979 TMI (or pre Chernobyl), (c) post 1986 Chernobyl (or pre 2011 Fukushima), (d) post 2011 Fukushima and, finally, (e) New Build. These periods are loosely connected to the reactor generations as licensed and constructed, i.e. Gen-I, Gen-II, Gen-III, Gen-III+. Gen-I reactors are now extinct. The typical reactor capacity for Gen-II to Gen-III+ reactors is 1000 MWe. The periods mentioned do not include the long-debated Gen-IV reactors, which, yet, have not been through the demonstration phase. Instead, the New Build period involves Gen-III+ types and a controversial heavy discussion on the market possibilities of Small Modular Reactors (SMR) and Mini Modular Reactors (MMR). It seems that both SMRs and MMRs will incorporate most of the technological advances prescribed for the Gen-IV reactors. It is worthy to mention that the typical capacity of an SMR reactor is expected to be in the range between 50 and 250 MWe, while that of an MMR reactor between 5 and 50 MWe.

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REACTORS IN OPERATION (1970 - 2020)

Figure 1 depicts in black square symbols the net number of reactors in operation between the years 1970 and 2020 (left *y* axis). In blue circle symbols (right *y* axis), one can find the operating reactors total nominal power in GWe.

The following could be observed:

(a) The grid connections between 1970 and 1986 were more than 20 per year. This, combined with the fact that there was no significant number of permanent shutdowns during that period, explains the rapid increase of the operating reactors up to 1986.

(b) The Chernobyl accident, obviously disrupted the development rate of nuclear reactors. However, despite otherwise anticipated, the Fukushima accident does not seem to have influenced the current (2020) number of reactors in operation.

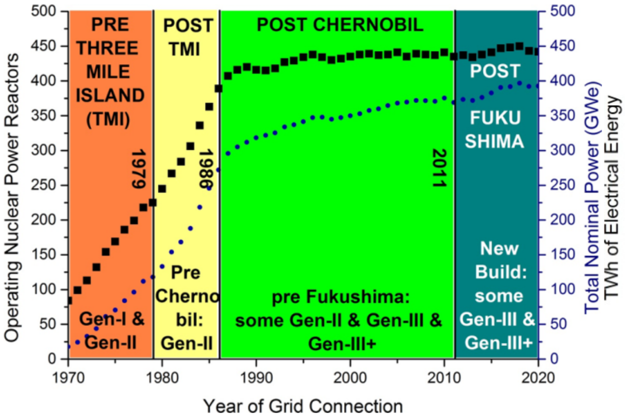

Fig. 1. *Net number of reactors in operation and their corresponding nominal electric power output for the period between 1970 and 2020*

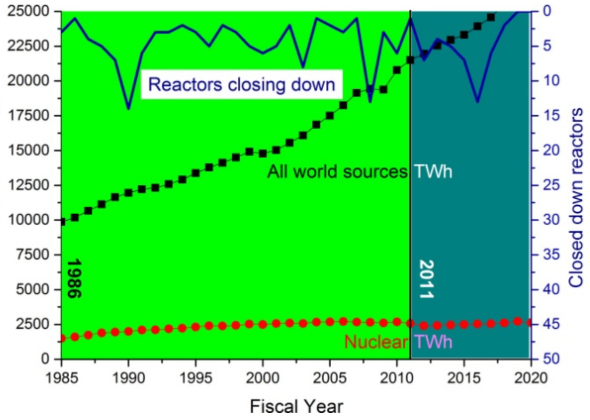

Fig. 2. *Annual world (in black) and nuclear (in red) TWh of electricity between 1986 and 2000. The zigzagged line connects the reactors retiring annually.*

(c) The nominal power of the operating reactors presents slightly sharper trends than that of the reactor number. This is due to the fact that, in most cases, retiring reactors are of nominal power less than 1000 MWe, while newly connected reactors are of nominal power equal to or greater than 1000 MWe. Today's large reactors can have nominal power up to 1600 MWe.

Overall, there is no negative trend on the number of active power reactors. The currently operating power reactors are ~440. Their increase rate (net, i.e. those grid connected minus those retired) after 1986 is about 1 - 2, 1000 MWe reactors per year.

ANNUAL WORLD AND NUCLEAR TWh OF ELECTRICITY (1986-2020)

Since 1986, the rate of increase for nuclear electricity TWh is stable at 0.1 – 0.2% annually. In the same period world electricity TWh have increased at a rate of about 2% annually following the respective increase of actual needs and living standards in terms of worldwide averages. There are indications that this rate of increase accelerates, since, for a significant part of engineers, technologists, decision makers and other stakeholders, nuclear electricity production does not promote greenhouse gases emissions and seems suitable as a transition power technology up to the goal of net zero carbon, set, for the vast majority of developed nations, for 2050. Figure 2 culminates the respective data. Overall, there is no negative trend on the electricity TWh from nuclear reactors. In addition, the rate of reactors closing down is about 4 annually. This, in conjunction with what has been mentioned in the previous section, means that the new reactors grid connection rate is between four and six yearly for the period between 1986 and 2020.

UCF (%) AND EAF (%) FOR PWR TYPE REACTORS (1986-2020)

For any power producing unit, and especially for those producing electricity, several quality indicators have been established to comprehensively present their performance. Most common quality indicators are the *unit capacity factor* (or *UCF*, %) and the *energy availability factor* (or *EAF*, %). These two factors are defined as it follows:

$$UCF(\%) = 100\frac{REG - PEL - UEL}{REG} \tag{1}$$

and

$$EAF(\%) = 100\frac{REG - PEL - UEL - XEL}{REG} \tag{2}$$

where, for each year

REG = reference energy generation, PEL = planned losses, UEL = unplanned losses and XEL = external losses beyond operational management control

In order to investigate comprehensively the reactors operational quality indicators *UCF* and *EAF*, the reactor type considered was the Pressurized Water Reactor, as it covers about 60% of today's (2020) operating reactors. It was found that these reactors present very high *UCF*: mean 83%, range from 61 to 94%, and, also, very high *EAF*: mean 84%, range from 62 to 95%. Such *UCF*s and *EAF*s could not be met or even approximated by any other type of conventional thermal plant or renewable energy source plant. Further to this fact, both *UCF*s and *EAF*s for those reactors have been increasing yearly at a rate greater than 0.2%. Figure 3 summarizes the respective data.

ENGINEERING INDICATORS FOR PWR TYPE REACTORS (1986-2020)

Since 1986, engineering indicators, such as *the thermal efficiency*, *the power density* (MW-thermal/m^3 core) and *the fuel burnup at discharge* (MW/day/ton fuel) remain fairly stable indicating the nuclear energy sector strong maturity. A slight drop of these indicators post Chernobyl shows a conservative reactors operation mode from 1986 to about 2002. On the other hand, significant improvement of indicators after the Fukushima accident shows a somewhat aggressive trust in this technology. Figure 4 presents, what the relevant collected data demonstrate in terms of efficiency, power density and burnup. Due to noisy data per year, all input has been smoothed by the adjacent average method.

Today's intensive use of currently operating reactors is further demonstrated by additional engineering indicators, such as the *forced loss rate* (*FLR*, %), the *unplanned capability loss factor* (*UCL*, %) and the New Build *energy output per unit. FLR* (%) and *UCL* (%) are defined as it follows:

$$UCL(\%) = 100\frac{UEL}{REG} \tag{3}$$

and

$$FLR(\%) = 100\frac{FEL}{REG - PEL - EPL} \tag{4}$$

where, for each year

UEL = total unplanned losses, FEL = unplanned forced losses and EPL = unplanned extensions of planned losses

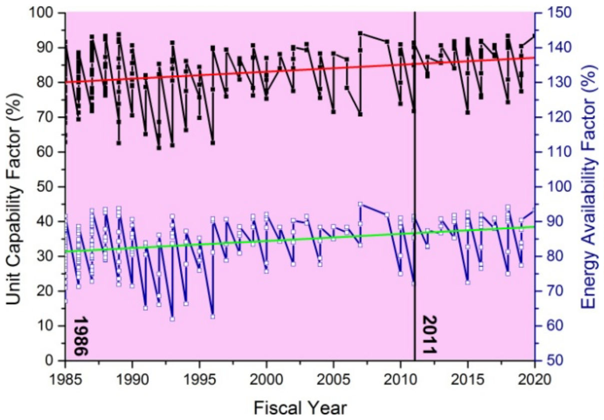

Fig. 3. *UCF (%, red line, left y axis) and EAF (%, green line, right y axis) for PWR type reactors for the period between 1986 and 2000.*

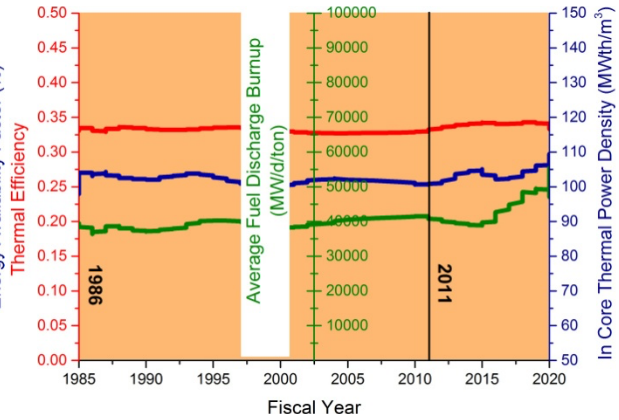

Fig. 4. *Indicators for PWR type reactors between 1986 and 2000: thermal efficiency in red; in core thermal power density in blue; average fuel discharge burnup in green.*

UCL (%) and *FLR* (%) were found low or very low. These indicators show a tendency for increase lately, which might be attributed to the increased age of a significant part of the nuclear reactors fleet, or to the introduction of RES, mostly in the developed countries. As anticipated the energy output per unit is steadily increasing; compare with the discussion for Fig. 1. SMRs and MMRs as part of the New Build era, up to 2050, are anticipated to present at least the engineering qualities of the so far operating 1 GWe units.

Figure 5 presents, what the relevant collected data demonstrate in terms of *UCL* (%), *FLR* (%) and electric power per unit. Once more, and due to noisy data per year, all input has been smoothed using the adjacent average method.

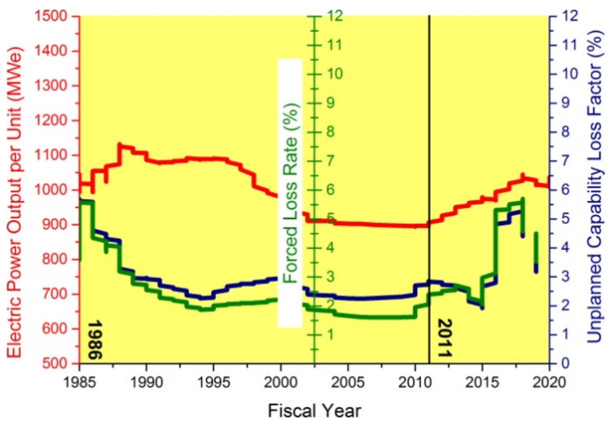

Fig. 5. *Additional engineering indicators for PWR type reactors between 1986 and 2000: electric power output in red; UCL (%) in blue; FLR (%) in green.*

REMARKS AND CONCLUSIONS

The annual consumption increase of electricity produced in nuclear reactors is at about 2% (almost equal to the world's annual TWh increase rate), reasons being lower costs and environmental friendliness. Further, electricity produced in nuclear reactors is around 30% of all electricity complying to low carbon requirements. More engineering advances are anticipated for reactors in the course of SMRs and MMRs development, which will be part of the New Build era.

Overall, there are indications that: (i) there is no negative trend on the number of active power reactors, (ii) the yearly electrical power by nuclear sources is steadily increasing, (iii) the reactor performance indicators are steadily getting better, (iv) despite their negligible number, the limited serious reactor accidents have been the main factors, which prohibited the expansion of nuclear generated electricity, (v) all such accidents were followed by a period of conservative usage of most operating reactors, and, (vi) there is observed a long-term improvement of the average reactor operational characteristics. Further, as it now seems, it could be supported that the increase of the share of renewable energy sources (RES) has not significantly affected the nuclear reactors operational mode, since their role as base units is further enhanced by the extensive retirement of fossil fuel - fired conventional plants.

References

[1] IAEA, International Atomic Energy Agency, Computer Manual Series, Power Reactor Information System (PRIS) Statistics Users Manual, Vienna (2012)
[2] IAEA, International Atomic Energy Agency, Operating Experience with Nuclear Power Stations in Member States (2020)
[3] IAEA, International Atomic Energy Agency, Reference Data Series No. 2, Nuclear Power Reactors in the World (2021)
[4] Ritchie H., Roser M., "Energy", Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/energy' (2021)
[5] "Electricity generation", Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/energy' (2021)