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Economic aspects of the deployment of fusion energy: the valley of death and the innovation cycle

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The speed at which fusion energy can be deployed is considered. Several economical factors are identified that impede this speed. Most importantly, the combination of an unprecedentedly high investment level needed for the proof of principle and the relatively long construction time of fusion plants precludes an effective innovation cycle. The valley of death is discussed, i.e. the period when a large investment is needed for the construction of early generations of fusion reactors, when there is no return yet. It is concluded that, within the mainstream scenario—a few DEMO reactors towards 2060 followed by generations of relatively large reactors—there is no realistic path to an appreciable contribution to the energy mix in the twenty-first century if economic constraints are applied. In other words, fusion will not contribute to the energy transition in the time frame of the Paris climate agreement. Within the frame of this analysis, the development of smaller, cheaper and most importantly, fast-to-build fusion plants could possibly represent an option to accelerate the introduction of fusion power. Whether this is possible is a technical question that is outside the scope of this paper, but this question is addressed in other contributions to the Royal Society workshop.

This article is part of a discussion meeting issue 'Fusion energy using tokamaks: can development be accelerated?'.

1. Introduction

This paper addresses the question if the introduction of fusion power can be accelerated, taking economical aspects into consideration. To that end, we must consider

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the energy market at the time fusion could make its entry, analyse the competition and the unique contribution fusion could make.

Before all else a disclaimer: due to the nature of the question, this paper attempts an economic analysis of the energy system in the second half of the twenty-first century. Doubtless, social, economical, scientific and technological developments will occur in that time span. Since a future this far away is impossible to predict—certainly this paper does not claim to be able to—we have tried to select questions that can be reasonably analysed today.

We can, today, analyse what the fastest rate of deployment of fusion power (or any other new energy technology) would be if (a) all technological problems were solved and (b) there is no competition and infinite market pull.

And we can, today, analyse how the time needed to build a power plant and take it into operation affects the maximum rate of exponential growth, how it relates to financial risk for the investor and how it interacts with the innovation cycle.

These are the types of questions we will address in this paper, while fully acknowledging that we cannot, today, foresee in what kind of society and economy the deployment of fusion would have to take place.

As a starting point, we need to consider the time frame in which we should place the development and deployment of fusion power. Spurred by the man-induced changes of the climate and the devastating effects these threaten to have on the long run, the world is embarking on a complete transition of the energy system. The 2015 Paris agreement[1] has set internationally agreed targets for the limitation of the global temperature rise that translate into a near-complete decarbonization of energy generation by 2050 [1]. This is an unprecedented economical, technical and societal challenge and it is by no means certain the goals will be realized in time. But there is no doubt that in the coming decades massive investments will be directed towards the technologies that can contribute to the required energy transition. This concerns in particular existing, proven technologies that mainly need upscaling, including renewable energy technologies (RET)—especially wind and solar photovoltaic (PV), and possibly carbon capture and storage (CCS) or carbon capture and use (CCU) and nuclear fission. To give an indication of the scale of the effort, we note that in the past few years, the investment in solar PV and wind power has been around 300 billion USD/year, approximately 3% of the world energy market. In parallel with the large-scale deployment of RET, conversion of electricity to molecules—hydrogen or other—allowing storage and transportation, will have to be scaled up by a large factor. For these technologies, the physical and technological principles are proven and industrial scale installations are already available, although major progress in efficiency and cost reduction is needed.

Comparing fusion to these technologies, we must first of all note that fusion has not—yet—reached the status of a ‘proven’ technology, and that—as will be substantiated later in this paper—fusion will not, not even in the fastest of scenarios, contribute to the energy transition on the time scale set by the Paris agreement. This implies that when fusion does become available as a viable energy source, it enters a largely decarbonized energy market that has organized itself in one way or another. This is not to say that that the energy system will be ‘finished’ in the sense that further innovation would not be welcome. On the contrary, the rapid pace that is imposed on the energy transition is likely to result in installed technology that does not keep up with technological developments and continued innovation will be needed.

But it does mean that this market is not waiting for just *any* new energy source; a newcomer in the market will have to offer something that is not already available, or offer it more cheaply, or be competitive in any other way. In particular, fusion energy is commonly positioned as being ‘CO_2-free, safe, clean, unlimited’. Which is true enough in itself, but these are qualities that already today are required from every new energy source, and they will be the default in the new energy system. So these are not the distinguishing features that will shoehorn fusion power

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[1] The Paris agreement, http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf, is undersigned by 159 of the 197 parties to the convention. While in May 2017 the US government has announced to withdraw, there is reconfirmed commitment from US cities, states and companies.

into the market. Fusion will need to clearly identify which of its characteristics fills a specific need in the system. This consideration may impact the design choices for the early phase fusion development.

The question of market introduction is most pregnant at the early stage, when from a technology perspective fusion is ready to offer a first generation of, say 10, power plants. These will be the first full-fledged power plants to be constructed after the proof of principle has been given by the DEMO generation. So, building 10 constitutes a significant technological risk, and we may not expect this first generation to be very good performers; they will not have a high availability, are likely to be prone to unplanned outages, have low plant efficiency and couple that to a relatively high capital investment cost. Yet, if these 10 Gen1 fusion plants will be offered to the market, which according to the present roadmap could be in 2070 or so, together they will be good for an average electric power comparable to that of wind in 2000.

In other words, Gen1 fusion requires an upfront investment of hundreds of billions of Euros, which is coupled to a large technological risk, in order to bring a product to the market that is not competitive in performance or price, at a scale that is meaningless in terms of energy generation.

This begs the question 'who is going to pay for the Gen1 fusion power plants, and why'? This phase corresponds to what is commonly called the 'valley of death' in product development, which can only be crossed with solid financial backing, often with government support of one form or another. What is unique in the case of fusion, however, is that crossing the valley of death will require high-risk investment at the level of hundreds or even thousands of billion Euros. In comparison, other energy technologies provided proof of technical viability at investment levels orders of magnitude lower than that. We mark out the valley of death and the unprecedentedly high level of investment needed to cross it as one of the big economic issues facing the deployment of fusion power.

2. An illustration of what it means to introduce fusion by 2100

In the paper 'Analysing the role of fusion power in the future global energy system' by H. Cabal *et al.* [2], the EFDA Times model is used to project the introduction of fusion power under the constraint of a globally optimized energy system in a scenario that limits the global CO_2 concentration to 450 ppm. This results in an almost *linear* build up of fusion power from a negligible contribution in 2080 to 4–5 TWe[2] electric power in 2100.

Assuming for the sake of the argument that fusion power plants have a unit size of 1 GWe, this build-up calls for the construction of 5000 plants in 20 years, or 250 per year. To put this into perspective: the world is presently pooling resources to realize 1 ITER in 20 years; and the present global nuclear *fission* industry has the capacity to build about ten[3], not hundreds, reactors per year.

With an estimated time of 10 years between the launch of construction and the actual full power operation, i.e. after construction, commissioning, licensing and start-up of the nuclear operation, this leads to a further three major economic issues:

(1) Building at a rate of 250 plants per year with a lead-time of 10 years requires investors to put up the cash for 2500 plants before they have seen the first one work. That would typically amount to an upfront investment of tens of trillion USD (today's money), with an economic payback that only starts well after the 10-year construction time.
(2) This would mean that at the end of the linear growth phase an industrial capacity exists capable of producing 250 plants per year, while the replacement rate of 5000 plants with a lifetime of 50 years is only 100 per year. So here is the next economic problem: this speed assumes that investors will build an industrial complex more than twice the size

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[2] The paper gives the power in PJ per year: 120–150 10^3 PJ yr^{-1}.

[3] There are presently about 50 power plants under construction worldwide (world nuclear association). The nominal construction time is about 5 years, from the start of concrete pouring to loading the fuel, excluding the preparation of the site (typically 1 year) and the start-up procedure.

needed in the end. It is this argument that is used in [3] to estimate that the linear growth phase will last as long as the life time of the plants, which then puts a limit on the rate of production. This would result in a much more gradual introduction of fusion power, stretching out well into the twenty-second century.

(3) Thirdly, there is a fundamental techno-economical argument: With a 10-year construction time, there can effectively not be a learning effect. The construction of 2500 plants will need to have been started before information about the performance of the preceding generation becomes available. To allow an effective learning curve, an innovation cycle much shorter than 10 years, and a unit size and unit cost much lower than is presently foreseen, will be crucial.

We have been considering the linear growth phase here. This presumes that, at day 1, there is an industrial capacity capable of taking on the construction of 250 full-scale power plants per year. Such capacity needs to be built up first, and this in itself requires a massive investment. As is argued above, the phase leading up to the linear growth typically has an exponential nature. If we take the starting point for fusion—independent of when that point is reached—to be the DEMOnstrator plant, which if successful could be followed by a first generation of 10 Gen1 plants with a construction time of 10 years, the industrial capacity has to grow from 1 plant/year to 250 plants/year in the above example. This corresponds to eight doublings, i.e. 20 years if a doubling every 2.5 years can be achieved. While these numbers are consistent with the projection in [2], they shift the focus of the attention from the linear growth to the start of the exponential growth phase: how will that Gen1 fusion reactor enter the market? This brings us back to the first economic challenge, the 'valley of death'. To discuss this, we shall first introduce a model that describes the basic stages of the market introduction of fusion power (or any other energy technology).

3. A model for the stages of the development of a new power source

In [3], we have analysed the question when fusion could become a meaningful contributor to the energy mix under the assumption that all technical problems are solved today and that there is an unlimited market pull (i.e. there is no competition, and cost does not play a role). To this end, we developed a model that describes the fastest feasible market introduction of a new technology with the sole constraint that the production capacity be a smooth and monotonical function of time. Since production capacity is associated with entities like a number of factories, it may grow but cannot jump overnight, and prudency on the part of the investor would make the market refrain from installing industrial capacity that is superfluous before it has reached its economic life time.

The model distinguishes four phases in the development:

(1) Before all else: basic research and development.
   - No production
   - Ends with DEMOnstrator

(2) From about 100 MW to typically 100 GW: exponential growth.
   - No significant production
   - Niche market, helped by subsidies or tax breaks
   - Valley of death: large investment needed decades before any return
   - Doubling time typically greater than 2.5 years
   - 10 doublings needed: greater than 25 years

(3) Linear growth.
   - Linear growth of production, i.e. contribution to energy supply
   - Commercial, competition with existing technologies (replacement market)

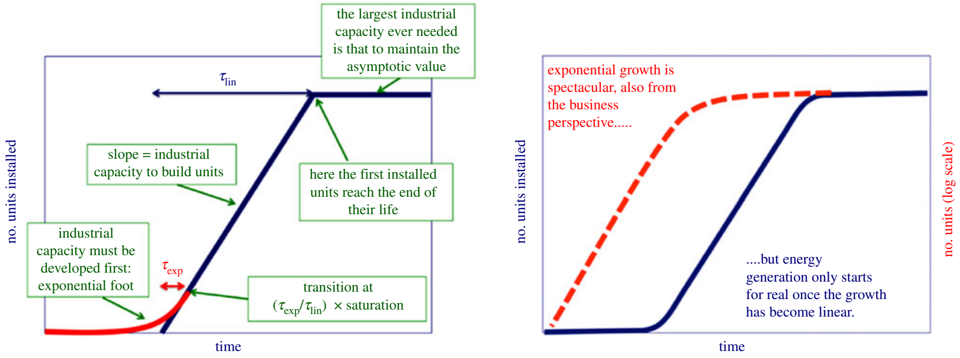

Figure 1. Illustration of the growth model introduced in [3]. A comparison of the same model in linear or logarithmic representation (graph on the right) makes clear that the exponential growth is an essential phase to prepare the industry for the linear growth, but the contribution to power generation is negligible. In view of the stage of development of fusion energy, this paper concentrates on the exponential growth phase. (Online version in colour.)

- Additional 30–50 years. Determined by life time/replacement time of installations or industrial capacity

(4) Saturation at final market share.

The model is summarized in figure 1.

Fusion energy is in phase 1: basic research and development. The EUROfusion roadmap foresees as major milestones the scientific proof of principle with the deuterium–tritium (d–t) operation of ITER (planned for 2037) and a DEMO (end of construction towards the end of the 2050[4]). It seems therefore premature to discuss the linear growth phase in any detail, and, instead, we shall concentrate on the exponential growth phase in this paper.

4. The exponential growth phase

Summarizing the findings in [3], a few important aspects of the exponential growth phase are the following:

(1) The energy production in the exponential phase is irrelevant. (Obvious, if counter-intuitive: because the exponential growth stops at typically 10% of the final capacity, i.e. typically 1% of world energy demand, the total energy production up to then is negligible)
(2) If the *doubling time* is shorter than the *energy payback time*, the net energy production is *negative* during the entire exponential growth phase.
(3) If the *doubling time* is shorter than the *economic payback time*, the net financial gain is *negative* during the entire exponential growth phase.
(4) During the entire exponential phase, all costs are associated with the investment, and there is not yet any payback. This means that in the foreseeable future, the overnight investment cost will be the factor that dominates the economy of fusion deployment. The Cost of Electricity only becomes important once the linear growth phase has been reached.

These are mathematical properties of this phase. They say that any system has to go through a growth phase before it starts to produce. This phase builds the industrial capacity needed to

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[4] The European *Fusion Roadmap*: EFDA-rapport ‘Fusion Electricity; a roadmap to the realisation of fusion energy’ 2012. See https://www.euro-fusion.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf and updates thereof.

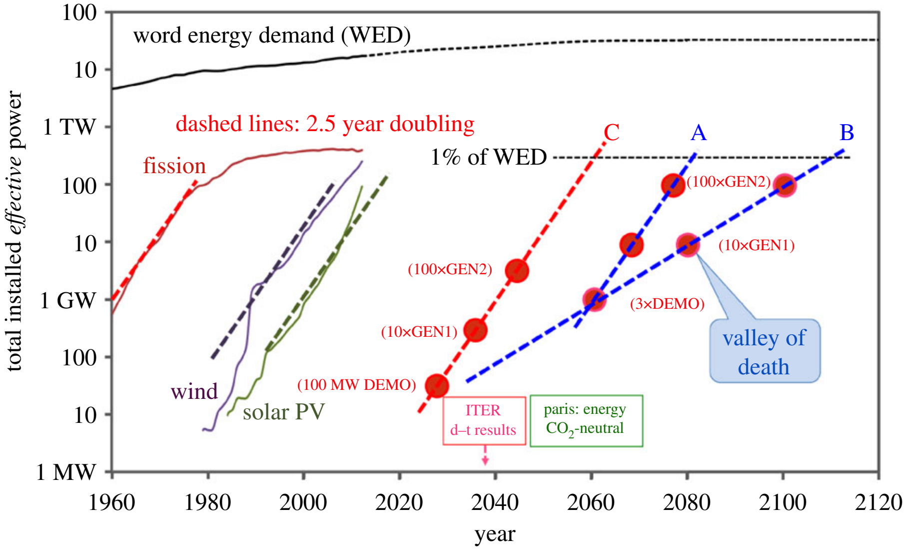

Figure 2. Total *effective*—year averaged—power as a function of time. Historical data (source [4]) are given for the total World Energy Demand, fission, wind and solar PV. The dashed lines represent the exponential growth phases of the different technologies. The graph illustrates firstly the approximately 60-year time lag of fusion compared to other technologies; and secondly what could realistically be expected from fusion in terms of contribution to WED. The graph also shows that a 'smarter, smaller, sooner' fusion concept could significantly speed up the introduction of fusion power, not so much because of the earlier 'DEMO' point, but because it has a more realistic chance of realizing the fast, 2.5-year doubling growth that has been typical of previous technologies. (Online version in colour.)

build and maintain the future park. The exponential growth phase is the necessary investment in a future energy source.

5. *When* will fusion become available?

With these preliminary considerations, let us analyse when fusion power can become available. Of course, there is the stale joke that this will always be 50 years from now. More than just stale, that statement is very imprecise. Which milestone is 50 years from now? The first fusion demonstration reactor (DEMO), the first generation of 'commercial' fusion plants (Gen1), the moment fusion could—if needed—supply e.g. 1% of the world energy demand (WED1%)?

Figure 2 visualizes the prospect of new energy technologies [4].[5] It is a graphical tool that quantifies the question 'when will fusion become available?' Thereto, only two parameters need to be estimated: the starting point of the deployment, e.g. a DEMOnstration reactor; and the subsequent deployment rate. It is then a simple matter to read off the time when e.g. WED1% can be reached. As to the deployment rate: as is shown in [1], the track records of existing energy technologies demonstrate that a sustained exponential growth with a doubling time of 2.5–3 years is about the fastest achievable. In this paper, we confine the discussion to the exponential growth phase, as that is what matters for fusion in the foreseeable future, while noting that exponential growth will necessarily be followed by a linear growth phase that also lasts decades, as discussed in the introduction. We shall return to this topic in the discussion section.

The arrow marking 'ITER' represents the present fusion flagship project, which is scheduled to reach its full potential [5] in 2037. ITER is primarily a scientific experiment, which aims at reaching the reactor regime relevant for a power plant, i.e. d–t plasma with such parameters that the energy released in fusion reactions leads to significant self-heating. ITER is not expected to

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[5] The concept of this graph and the historic data for fission, wind and solar PV, are derived from [3,4].

reach fully self-sustained burn and will not convert fusion power to electricity.[6] However, in the roadmap of the EU and others, the results of ITER are considered to be an essential input for the decision on further steps.

Three projections for fusion are plotted. Scenario A and B follow the EU roadmap by assuming that worldwide a few DEMOs will be realized by 2060 (i.e. the time DEMO could reach full power operation, rather than 'completion of construction'). Scenario A continues from there with the 2.5-year doubling time that has been realized by solar PV and wind in the recent past. For the assignment of an effective electric power output to the Gen1 and Gen2[7] plant efficiency, availability and capacity factor were factored in, as was done for wind and PV.

6. The valley of death, the generation divide and the innovation cycle

The big question is: is it realistic to expect that fusion can grow as fast as PV and wind have? Doubling every 2.5 years corresponds to a growth by a factor of 10 in 8 years. The time for construction, nuclear licensing and commissioning of a fusion plant is typically longer than that.[8] This has severe implications for the exponential upscaling. For clarity of the argument, we will assume that the development of fusion proceeds in generations, whereby the construction of each new generation is only started after the previous generation started operation. In a system driven by economical considerations, the long time for construction hurts this process in two distinct ways:

(1) Because the time between generations is relatively long compared to the exponential doubling time, the growth factor from one generation to the next has to be large. This constitutes a major financial risk: Would investors order 100 Gen2 plants if they have not seen Gen1 in operation? And this financial risk should be offset against the technological risk, which for a first generation of machines as complex and technologically advanced as fusion reactors, will be relatively high.

(2) If the next generation must be ordered by the time the preceding generation comes into operation, no major design evolution may be implemented. In short: if the innovation cycle is much longer than the intended doubling time of the scale-up, this will result in technology lock-in. For instance:

   — If DEMO employs classical superconductors, then Gen1 will not use High T_c superconductors

   — If Gen1 is a tokamak, then Gen2 will not be a stellarator, at least not while scaling up at the same time

The technology lock-in, which is due to the long innovation cycle, is aggravated by the high level of investment costs. These factors together make it unlikely that the 2.5-year doubling can be realized in the exponential growth phase of fusion. Therefore, we also plotted scenario B, in which a 6-year doubling time has been assumed. This shows that, starting with the DEMO generation in 2060 as per the EU roadmap and assuming a realistic exponential growth, fusion power will not contribute significantly to the world energy mix until well into the twenty-second century.

We note again that this graph only considers the exponential growth. According to the observations and modelling in [4], this will lead up to a linear growth starting when the total

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[6] To avoid any misunderstanding: ITER will not produce electricity, it is a physics experiment and no heat-to-electricity conversion is planned. It aims at achieving $Q = 10$ (i.e. 500 MW of fusion power generated for 50 MW of power injected into the plasma). It will operate in pulses of 10 min.

[7] For this graph—scenario A and B—it is assumed that 3 DEMOs will be realized in parallel (Europa, China, India, S-Korea all have road maps featuring a DEMO plant in the 2050s, each producing a nominal ~1 GWe output) and have 30% effective availability. After that, the Gen1 could consist of 10 plants of 1.5 GWe unit power and availability of 50–70%, etc. In scenario C, a single hypothetical 'small' DEMO is projected with an effective output power of 50 MWe.

[8] Note that a fusion reactor is intrinsically a much more complex apparatus than a fission reactor, due to the combination of a.o. a vacuum vessel, high-field superconducting magnetic field coils and power production inside a cryostat.

production has reached approximately 1% of the world energy demand. The ensuing linear growth typically takes several decades.

In summary, we have identified several major hindrances for the rapid deployment of fusion power that are of economical nature. They all pivot around the point that fusion power plants are large, complex installations, with a long construction time and large overnight investment compared to any other source. This precludes an effective innovation cycle. This is exacerbated by the fact that the proof of principle is of such a size that the innovation path starts at a level of investment that is not found in any other technology.

7. How about the options to make fusion available earlier?

The workshop addresses the question if fusion can be realized earlier. In the above analysis, we have shown that a realistic expectation is of the development path that starts where the EUROfusion roadmap ends, i.e. with a DEMO reactor in 2060, implies that fusion will only make a significant contribution to energy generation well past 2100, and we have indicated which economic factors constrain that development.

The third scenario (C) in figure 2 explores the most optimistic case of 'acceleration of fusion power' by bringing forward the DEMO point to 2030 (which assumes that a much smaller DEMO can be built, with the consequence that its fusion power is smaller, too), and following this up with the fast exponential growth with a 2.5-year doubling time.

The smaller DEMO has two advantages over the mainstream scenarios:

- The valley of death can be crossed at a level of risk-carrying investment that is 1–2 orders lower
- The shorter construction time allows a more effective innovation cycle, which makes it more realistic to aim for a fast exponential growth

The big question here is, of course, whether it is actually possible—from a physics and technology perspective—to realize a smaller, faster-to-build and cheaper DEMO. Within the frame of the established fusion science, the ITER design was the answer to the question what the smallest and cheapest $Q = 10$ machine would be. Any claim for a significantly smaller DEMO solution will have to be based on new developments or insights, be they in physics, technology or in design concept. It is interesting that there are a number of developments in fields not directly related to fusion that are seeing great progress. Examples are high temperature superconductors, allowing higher magnetic fields; developments in materials science, including additive manufacturing; robotics, and of course the power of computational science.

We stress that also in the optimistic assumption that a smaller DEMO can indeed be developed, figure 2 shows that fusion will not become a big factor in the energy mix overnight. But it is clear that the smaller, modular approach to introducing fusion power in the system would in principle allow for a significant acceleration. More importantly, it could bring fusion back in the time horizon of energy policy makers.

We do not, in this paper, intend to say anything about the scientific and technical feasibility of smaller tokamak reactors. Also, smaller machines may not be the best solution in terms of efficiency. But if feasible, they do offer the possibility of crossing the valley of death at a lower financial risk level. And they do offer, crucially, the possibility of an innovation cycle which is compatible with fast exponential growth.

8. Concluding remark

There are economical constraints to the speed at which fusion power can be deployed. These derive from the large unit size, large overnight investment cost and long construction time, which preclude an effective innovation cycle, and the fact that the valley of death must be crossed at an unprecedented level of investment. All of these constraints could be significantly softened if—through technological advances or new design concept—the DEMO reactor can be smaller simpler and cheaper. This could potentially bring the introduction of fusion power forward by decades.

Realizing that the primary economic challenge of fusion—after DEMO has given the proof of concept—will be the market introduction, i.e. crossing the valley of death, we find that it is much more sensible to direct the design efforts at producing a Gen1 fusion plant that is cheap and fast to build, than design for the optimized economics of the 1000th reactor.

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