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NEWLY DEVELOPING CONCEPTIONS OF DEMOS: PULSING AND HYDROGEN

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Conceptions of the aims and characteristics of DEMOs are evolving in response to world issues. Many areas are important in these considerations: two particularly important, and technically related, ones are examined here.

Firstly, in the recent Strategic Energy Technology plan (SET plan) in the EU, approaches to technological development that could substantially change the future energy supply system were investigated. For fusion, this included considering how fusion development could be accelerated, particularly whether construction of a DEMO plant could start earlier than is normally assumed, perhaps before full exploitation of ITER. This is described in the technology map of the EU SET plan as an Early DEMO, or EDEMO. In this context, reconsidering the balance of the arguments between a steady-state and a pulsed design for EDEMO is motivated by the possibility that a sufficiently reliable and efficient current drive system may not be available on the necessary timescale.

Secondly, the context for a fusion power plant, and consequently for DEMO, is set by the assumed applications, amongst which hydrogen production is an important possibility. Although this is a very different issue from pulsed operation of a fusion plant, it may be crucial in setting the framework in which a fusion plant operates. Both issues have the potential to radically change the view of what a DEMO plant should do.

I. INTRODUCTION

With the ITER era of fusion development now beginning, attention is turning to the outline design of the fusion demonstrator, DEMO, which is to follow. The first considerations are of a strategic nature: for instance, where in the range between ITER and a fusion power station, should DEMO lie? Too close to ITER and there may need to be further prototyping before a power station could be built; too close to a power station and the construction may be delayed whilst outstanding issues are resolved.

DEMO is the bridge between ITER and a power station and is often divided into two phases, one initial phase to demonstrate the integration of fusion technology, materials and physics developments, with a second phase to refine the technology and build up availability to the levels needed for a power station.

Recently, there has been a review of energy strategy in Europe resulting in the Strategic Energy Technology (SET) plan¹. In discussing fusion, the natural question of how to accelerate fusion development was raised, to which one obvious answer is early construction of DEMO. This was actually described in the resulting documentation as “EDEMO” or Early DEMO, and this has motivated a re-analysis of DEMO in Europe. The technology documentation of the SET plan states “the proposal of a new paradigm in which electricity production would be demonstrated much sooner by a relatively modest performance “Early DEMO”.

This discussion has naturally raised questions about what DEMO should try to achieve if it is to be built early, for instance, would sufficient information be available from ITER and IFMIF, and could this be a distraction that would force another DEMO stage, thus slowing down the fusion development programme?

In this paper, two options for DEMO have been studied, the first looks at the possibility that a reliable, efficient current drive system may not be available in time so a pulsed device might be preferable to true steady-state device; the second considers whether the potential future application of hydrogen production should substantially change the view of the main design parameters of a power plant, and therefore of DEMO. In what follows, a systems code, PROCESS, is modified to study pulsed power plant concepts and to include a hydrogen module, and then used to explore power plant concepts with a range of assumptions. In each case the question posed is “what is the cheapest way of generating power given the imposed constraints?”

II. PULSED VERSUS STEADY-STATE

One potential difficulty of a pulsed version of DEMO is that it naturally leads to a pulsed version of a power plant so we must take seriously the pulsed issues in a power plant. It does not appear wise to design a DEMO just to demonstrate electricity production without seeing how that could be incorporated into a power station.

The requirements of a pulsed device are very different from those of a steady-state device. The need for a long-lived power plant means that fatigue-life must be extended by having a reasonably long pulse length. A restriction of 30,000 pulses, broadly as anticipated for ITER for instance², would suggest a pulse length of around 8 hours if a 30-40 years lifetime is to be attained. This implies the need for a large flux swing, large machine bore, large major radius device. In addition the need for an energy storage system and larger power supplies, to minimize the recharge time between pulses, can partially or wholly offset the reduced need for a current drive system.

The trade-off between the different challenges of a steady-state device and a pulsed device is quite complex and some of the most important aspects of this are discussed below. In this analysis, the effect of cyclic stresses is included by restricting the magnet stresses to a value 12% lower than would be allowed in a steady-state plant³.

II.A. Flux swing for a long pulse device

A completely pulsed device of the sort described above, in which there is no non-inductive current except for the bootstrap current, tends to be a large device with a major radius approaching 10 m. An example of a pulsed plant is given in Table 1. Here we already see a characteristic of a pulsed device; because of the large size and restricted use of additional heating in the burn phase, the overall power density is relatively low and consequently both the divertor heat load and the first wall neutron power load is low.

It will, of course, be necessary to include some heating scheme to start up such a device so it is interesting to investigate an extension of such a device in which small, but increasing, amounts of current drive are used. Figure 1 shows the required flux swing for such plants and how it is possible to reduce the amount of flux swing needed by gradually increasing the amount of current drive power, reducing the amount of inductive current drive.

TABLE I. Example of parameters for a pulsed fusion power plant concept

R(m)	9.55
Aspect ratio	4
I (MA)	15.5
B(T)	7.4
q	3.4
$\langle T \rangle$	15.6
$\langle n \rangle$	0.95
Z_{eff}	1.77
P_{fus} (GW)	2.03
P_e (GW)	1.0
Av neutron wall load (MW/m ²)	1.2
Peak div heat load (MW/m ²)	5.1
Bootstrap fraction	0.43
β_N thermal, total	2.4, 2.6
β_N limit (thermal)	3.0
H factor	1.3
H factor limit	1.3
Pulse time (hours)	8.5
n peaking	0.1
T peaking	1.5

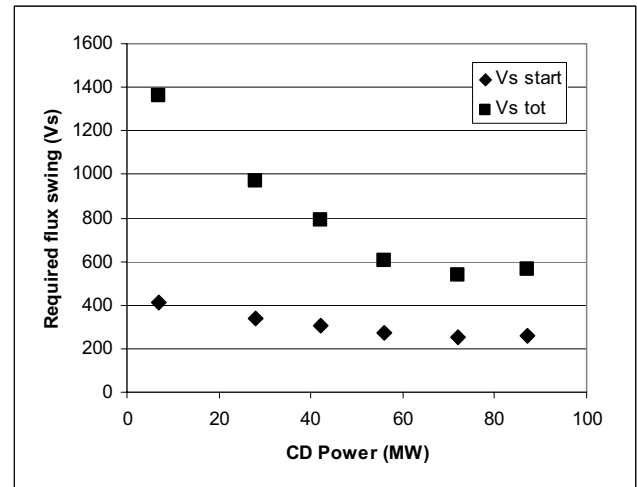


Fig. 1. Adding increasing amounts of current drive power can considerably reduce the flux swing needed to sustain an 8 hour pulse length.

As is apparent from Figure 1, the fact that not only the total flux swing, but also the start-up flux swing, is decreasing with current drive power, suggests that the machine size is decreasing as the current drive is increased. This is shown in Figure 2 which shows the major radius for the same range of power plant concepts.

Although all these are pulsed plants, the non-inductive current drive approaches 100% as the current drive power increases. These plants are a hybrid design of plant characterized by the support of the pulse length with a current drive system, but still remain pulsed plants.

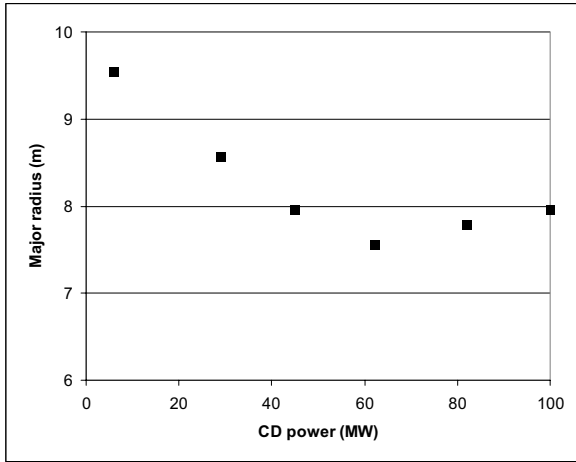


Fig. 2. Supporting the pulse length with increasing amounts of current drive power reduces the major radius of the plant.

A comment on the current drive assumptions is necessary here, partly to explain the relatively low amounts of current drive used. The calculation assumes 2 MeV negative ion neutral beams which, in a high temperature plasma, are predicted to have a high efficiency of current drive. Reduced efficiency current drive systems could still play a role, as illustrated by Figure 3 which shows the effect of multiplying the current drive efficiency by an arbitrary multiplier, less than one,

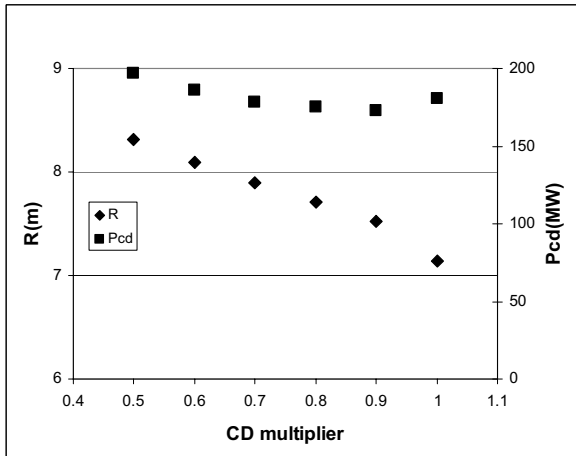


Fig. 3. In steady-state devices, reducing the current drive efficiency leads to larger plant designs, without much increase in current drive power.

in examples of fully steady-state devices. The results of such a study also indicate the complexity of systems studies, in which many parameters can vary to reach an optimum design, hence the current drive power does not necessarily scale with the efficiency multiplier, rather the whole plant design changes to accommodate the reduced efficiency; in this case the size increases, preventing an escalation of the current drive power. Of course, other families of design are possible, but this is the optimum found here.

As a comparison of the different options, Table 2 shows examples of a pulsed plant, a steady-state plant and a steady-state plant with low current drive efficiency.

TABLE 2. Comparison of the main parameters of a pulsed device, a steady-state device and a steady-state device with low current drive efficiency

	Pulsed	Steady-state	Steady-state low CD efficiency
R(m)	9.55	7.25	8.6
Aspect ratio	4	3	3
I (MA)	15.5	19.1	17.2
B(T)	7.4	5.8	6.5
q	3.4	4.1	5.6
<T> (keV)	15.6	14.9	16.7
<n> (10^{20}m^{-3})	0.95	1.2	0.91
Z_{eff}	1.77	2.4	2.1
P_{fus} (GW)	2.03	2.71	2.80
P_e (GW)	1.0	1.0	1.0
Av neutron wall load (MW/m^2)	1.2	1.9	1.4
Peak div heat load (MW/m^2)	5.1	10	10
Bootstrap fraction	0.43	0.46	0.66
β_N thermal, total	2.4, 2.6	3.0, 3.6	3.0, 3.6
β_N limit (thermal)	3.0	3.0	3.0
H factor	1.3	1.15	1.3
Pulse time (hours)	8.5	∞	∞
n peaking	0.1	0.1	0.1
T peaking	1.5	1.5	1.5
γ_{NB} ($10^{20}\text{A}/\text{Wm}^2$)	-	0.49	0.23
P_{CD} (MW)	-	189	200
Eff_{NB} (A/W)	-	0.055	0.029

Although the power plant concepts of Figure 2 are all pulsed designs, they begin to approach the corresponding steady-state design. This can be used to look at the variation of key parameters such as the divertor heat load. In the large pulsed designs it was not necessary to invoke impurity seeding to enhance radiation and protect the divertor; the heat flux was already sufficiently low. However adding current drive and reducing the machine size would be expected to increase power density and divertor heat loads, closer to those characteristic of steady-state plants. This is illustrated in Figure 4 which shows the divertor heat load (without any impurity seeding) for the range of supported pulse designs. Clearly the higher current drive examples would require efforts to reduce the heat load by, for instance, impurity seeding.

Having looked at some of the possible options for a pulsed device we can say more about the viability of different options. The option of a pulsed design of power plant is motivated by the possibility of removing a whole system, an efficient and reliable current drive system.

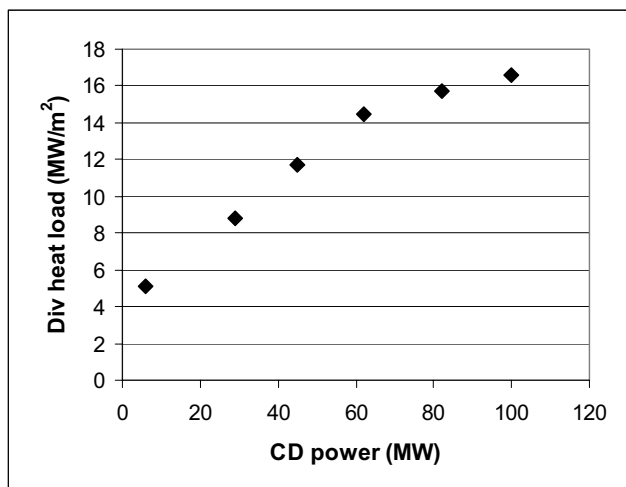


Fig. 4. The divertor heat load in the supported pulse concepts increases beyond the point expected to be tolerable. Impurity seeding would probably be needed to reduce the highest levels.

However, for steady-state electricity production, this introduces the need for a new system – an energy storage system, as well as increased power supply needs and increased plant size. The fatigue and thermal cycling issues are also not to be ignored but are given little attention here. Whilst the balance of these is more than just an economic one, we look here at the relative costs of the steady-state and pulsed plants.

Figure 5 shows the cost comparison of a typical steady-state power plant concept compared to a pulsed version. The costs are normalized to the total capital cost

of the steady-state plant. It is clear that, whilst the heating (including current drive) costs are lower in the pulsed case, the magnet power supplies and energy storage system costs are correspondingly larger. However the main cost difference lies in the capital costs of the magnets and vessel, which are substantially larger in the pulsed case. Overall, the pulsed plant is approximately 25% more expensive than the steady-state plant.

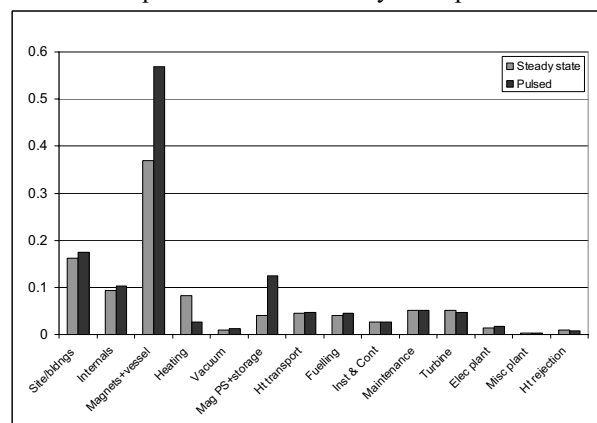


Fig. 5. Although the costs of the heating (including current drive) system are lower in the pulsed power plant concept, this is far outweighed by the increased capital costs of the larger machine and its power supply and energy storage systems.

II.B. Summary of pulsed options

Although a pulsed device may remove the need for an efficient, reliable current drive system, which could allow a simpler demonstration of electricity production from fusion, this may not extend smoothly to an economically attractive power station design.

To allow a long lifetime of the plant, the number of pulses needs to be restricted by having relatively long pulse length. This drives the machine to large size, to achieve the necessary flux swing, or to the addition of a smaller current drive system to support the pulse length non-inductively, again driving a need for a current drive system, albeit a smaller one. This causes a substantial increase in cost over the steady-state plant.

Conversely, there are other, natural advantages in the larger pulsed plant. The divertor heat flux is naturally lower – because of lower overall power density and the reduced heating power, as is the neutron wall load. These will have inevitable benefits in materials and technology lifetimes, and consequently in plant availability.

This suggests that a more detailed study of a pulsed power station (that a pulsed DEMO could point towards),

in particular addressing the thermal cycling, fatigue life and component lifetimes, should be carried out.

The idea of a supported pulse device has the other potential advantage that, during the pulse, if there are restricted trips in the current drive system, these may be compensated by increased flux swing from the inductive system. Although clearly a complex option, since the current profile would change and the mode of operation would need to tolerate that change, it does introduce an element of redundancy that could allow increase reliability. This concept could also be considered in a steady-state device.

III. HYDROGEN PRODUCTION

The possibility of producing hydrogen (for instance as a transport fuel) in addition to, or instead of, producing electricity, is now much discussed. For DEMO it is important to know if this provides a strong motivation to introduce new design constraints. A possible example is very high temperature operation, sufficient to allow the use of thermochemical cycles, obviating the need for electricity generation and producing hydrogen more efficiently.

To investigate this further, a hydrogen module has been included in the PROCESS code, allowing different technologies for hydrogen production. Four options are included, with the characteristics described in Table 3 (Ref. 4). These options differ in the mix of power (thermal or electrical), hydrogen production efficiency, and cost. The processes included are:

1. low temperature electrolysis;
2. high temperature electrolysis (endothermic);
3. high temperature electrolysis (exothermic), and
4. thermo-chemical production (for instance based on a sulphur-iodine cycle).

The power balance parts of PROCESS were modified so that power diverted to hydrogen production is not double counted in electrical generation or as net electricity for export.

In exploring the production of hydrogen, there are a range of options that can be considered, but here we look at a plant that produces both electricity (on the 1GW scale) and hydrogen. This is partly because the majority of the hydrogen generation options need electricity production anyway, and partly because the fusion plant needs electricity to drive its main systems, primarily the current drive system. Figure 6 shows a range of power plant concepts with steadily increasing hydrogen production (expressed in terms of MWth of hydrogen product). The hydrogen generation chosen in this case is based on the thermochemical cycle. Both the device major radius and the fusion power are shown.

TABLE 3. The default assumptions for the main parameters of the 4 technologies allowed in the PROCESS Hydrogen module⁴

OPTION	1	2	3	4
Efficiency ¹	0.75	1.35	1.12	0.5
Electrical power used for H production?	Yes	Yes	Yes	No
Thermal power used for H production?	No	Yes	Yes	Yes
Ratio of thermal to electrical power		0.48	0.19	
Capital cost ²	400 \$/kW	1,350 \$/kW	900 \$/kW	700 \$/kW

¹ For options 1, 2 and 3, the efficiency refers to the electrical power so can be greater than 1 because there is also thermal power added to the system. For option 4 the efficiency refers to the thermal power as there is no electrical power.

² The capital cost is normalised to the output of hydrogen expressed in kW, where 1kW corresponds to 0.28 Nm³ (normal meter cubed) per hour.

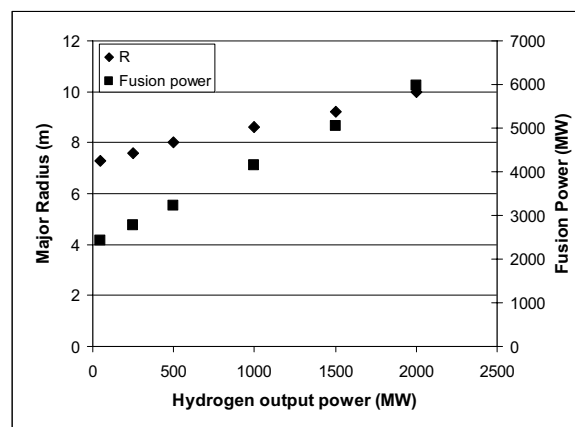


Fig. 6. As the hydrogen output power is raised, always producing 1GW net electric power as well, the machine size and fusion power inevitably increase.

Figure 6 shows hydrogen production rising to 2GW. It is important, in the context of existing fuel production systems, to determine whether this is a large or small production level. In fact, compared to an oil refinery, this is a small output. As an example, the Fawley oil refinery in the UK has an output equivalent to around 25 GW. It is

clear that considering hydrogen as a transport fuel moves the potential power output onto a new scale when compared to electricity generation. This is likely to be advantageous for fusion, which has strong economies of scale.

Figure 7 shows the how the estimated cost of power varies as increasing amounts of hydrogen are produced. In each case 1 GW of the power is in the form of electricity, and in this plot it is assumed that the value of product is the same for electricity as for hydrogen. There is clearly a significant gain in moving to the larger unit size. This is usually a disadvantage for an electrical grid system, but here the plant is only exporting 1 GW_e to the grid, so the increased economies of scale are being accessed without undue pressure on the grid.

III.A. Comparison of different options for hydrogen generation

The data in Figures 6 and 7 was derived using the most advanced cycle for the hydrogen production, the thermochemical cycle. This presents enormous challenges, both for operating the fusion plant at very high temperature and operating a complex chemical plant. It is therefore very important to determine whether this degree of complexity is justified by delivering a substantial economic advantage. There is a complexity in such an analysis, that a higher temperature plant can also achieve higher thermodynamic efficiency, so cost of power will be lower regardless of hydrogen technology. For that reason, we will look at the theoretical calculation where only the hydrogen generation technology is varied; the thermodynamic efficiency of electricity production is kept constant across the plant designs.

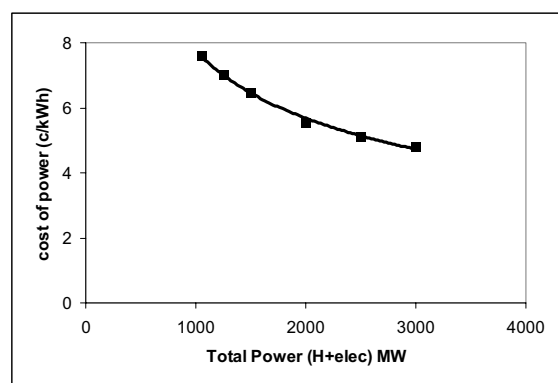


Fig. 7. Producing larger amounts of hydrogen allows access to greater economies of scale and the overall cost of power (the sum of electrical and hydrogen power) decreases substantially.

Figure 8 shows the results of a calculation where the different hydrogen options are used, in fusion plants producing 1 GW of electricity and 2 GW of hydrogen. The surprising result is that there is little gain in moving to the more advanced hydrogen options; the savings in efficiency are largely cancelled out by the increase in cost of the hydrogen generating technology.

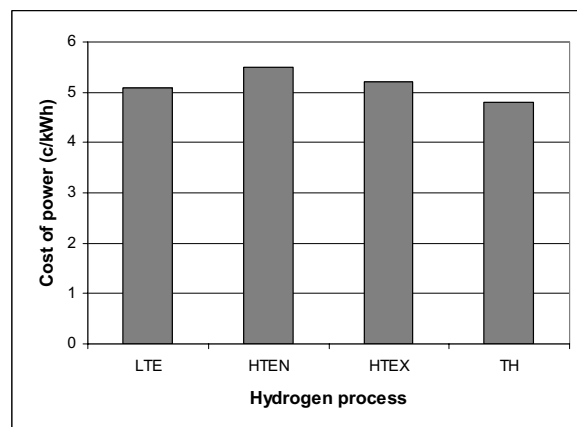


Fig. 8. Exploring the different options for hydrogen production shows little difference in the cost of hydrogen. In each case the plants produce 1 GW of electricity and 2 GW of hydrogen.

Whilst it remains the case that high thermodynamic efficiency of a fusion power plant, from high temperature coolant operation, would be beneficial, there does not appear to be an additional substantial benefit from high efficiency hydrogen production at very high temperatures. This is an important result since it suggests that even if DEMO does not target very high temperature operation, that will not preclude an eventual power station playing an important role in a future hydrogen economy.

III.B. Centralised hydrogen generation

If a hydrogen economy were to play an important role in the future energy market, it may bring about substantial changes, not least in energy distribution. With very low volumetric energy density, it is relatively inefficient to transport hydrogen and it may be more efficient to generate it locally near the point of consumption, rather than centrally, for instance at a fusion power station.

There has been significant work in this area⁵ which we can draw on and incorporate in these studies. We look here at 4 options for hydrogen production and distribution:

1. Centralised production by electrolysis with distribution by pipeline as gas
2. Centralised production by electrolysis with distribution by road as a gas
3. Centralised production by electrolysis with distribution by road as liquid
4. Distributed production by electrolysis.

Because of our interest in fusion applications, option 4 is only concerned with centralised generation of electricity which is then distributed to local hydrogen production stations, not with distributed generation of the electricity itself.

The most important aspect of what follows is that the dominant cost is the cost of electricity needed to generate the hydrogen. This is always lower at the point of generation than after transmission and distribution costs and inefficiencies are included so there is a strong bias in favour of production in centralised facilities where the price of electricity is lowest. The countervailing effect of costly transport of hydrogen, including liquefaction where necessary, biases the analysis in favour of distributed production. It is the balance of these effects that is key in the economic analysis. As is often the case, the economic optimum is not necessarily the most energy efficient option (in simple terms) because of the wider consideration of the use of other resources such as transmission and distribution networks for the electricity. These resources also involve energy inputs so a full energy efficiency analysis would be quite complex.

TABLE 4. Data underlying the comparison of different options for location of hydrogen production and its distribution.

Option	Production cost (\$/GJ)	Transmission Cost (100 miles) (\$/GJ)	Storage Costs (3 days) (\$/GJ)
1 pipeline	12-25	0.5-3	1.5-5
2 road, gas	12-25	10	1.5-5
3 road, liquid	12-25	0.5-2	5-15
4 distributed	33-66	0	2-3.5

The ranges of costs are taken from⁵ (converted to \$ at 1.5\$ to 1£) and represent reasonable ranges from the literature reviewed in Ref.5. The largest cost, and the main cause of the wide range, is in the electricity prices. These data are reproduced graphically in Figure 9. All these costs are significantly higher than present costs of

hydrogen by steam reforming of methane which is around 10\$/GJ.

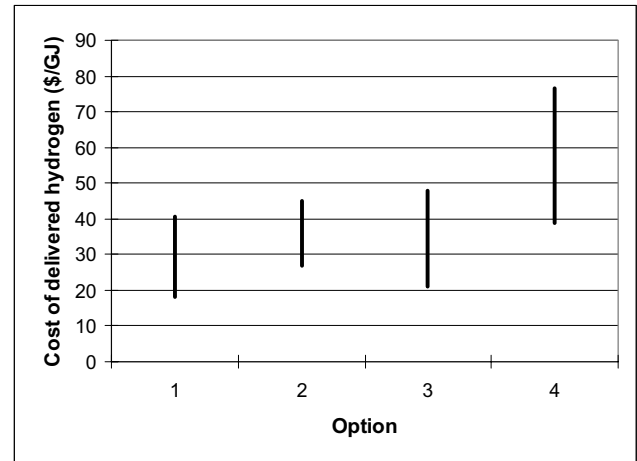


Fig. 9. The cost ranges for hydrogen, as delivered to the customer, for the different production and delivery methods.

It is clear from Table 4 and Figure 9 that the distribution of centrally generated hydrogen is preferable to the local production of hydrogen following distribution of the electricity. This largely reflects the additional costs of distributing the electricity over a balanced grid network, which appears more expensive than transporting hydrogen. This confirms that the economies of scale for a centralized fusion electricity and hydrogen plant can be realized. If the electricity had to be distributed over the grid first, the tolerable unit size would be more restricted.

III.B. Other benefits of hydrogen generation

The principal benefit of hydrogen production in these studies is to allow access to the economies of scale intrinsic to large fusion power plants. However there are other natural benefits of hydrogen production. It would allow a fusion plant to produce its own deuterium whilst generating the hydrogen, although a plant would be capable of producing far more deuterium than it needed as fuel. It is also possible that the hydrogen system could be used as an energy storage system for a pulsed fusion plant, to smooth the electrical output by consuming some of the hydrogen during the down time. This would probably require the electrolyzers in the hydrogen generation system to be run as fuel cells, rather than investment in additional capital intensive systems, and is something that merits detailed consideration.

There are other possible benefits which refer back to the different options for hydrogen production. If the hydrogen were produced at high pressure, that option would ease the difficulties of transporting hydrogen since

a lot of energy can be used in compressing hydrogen for transport⁵. It could also produce a side product of high pressure oxygen, which could be very important in carbon capture technologies which rely on oxy-fuel combustion of fossil fuels. Although these additional benefits do not appear to compete strongly with the electricity and hydrogen production, they could be important in a future energy economy which is radically different from the present one.

IV. CONCLUSIONS

Renewed interest in future energy systems at the political level in Europe is driving a re-examination of the goals for DEMO, particularly for an earlier construction than commonly considered.

As part of this a re-examination of pulsed options for DEMO has been carried out. In a pulsed machine the issues are entirely different from a steady-state device: flux swing, pulse length, fatigue life and increased cost become most important; divertor heat load is less important.

If the early construction of DEMO were required and an efficient, reliable current drive system were a limiting factor, a pulsed version of DEMO could remain an option. However, a pulsed machine appears to be around 2 m larger in major radius than a steady-state device although this can be reduced by adding some current drive. Although this reduces size (and cost) it re-introduces the need for a reliable, efficient current drive system. The development of current drive systems remains important.

The possible importance of hydrogen production in a future energy market has driven a study of hydrogen production from fusion, and the possible impact on a design for DEMO.

There are options for high temperature, high efficiency, production of hydrogen from a fusion plant, however in this study there is not a decisive economic advantage of such very high temperature operation. At this stage it is not strong enough to motivate a very high temperature version of DEMO (beyond what is important for high thermodynamic efficiency).

The most important role for hydrogen appears to be in giving access to economies of scale by favouring large plants producing both electricity and hydrogen (probably mostly hydrogen).

This study suggests that DEMO should continue to focus on its mission of large-scale electricity production in a timely and efficient manner.

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