Producing Electricity in a Fusion Nuclear Science Facility or Similar

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1. Introduction

The ultimate goal of fusion plasma and fusion nuclear science is the construction and operation of a fusion power plant, producing electricity and possibly excess heat for cogeneration applications. Commercial electricity production started for the first time around 1870. The use of hot fluids to drive turbines, which convert the fluid's energy into (mechanical and then) electrical energy, is the primary source of electricity today. The fluid is typically water or natural gas, but can be other gases such as CO_2 or Helium. The development of direct gas turbines both for open (jet engine) and closed systems took place in the 1900's. There is a long story that could be written about the development and production of electricity, but it is for all intensive purposes, known science and technology. We do not need to discover electricity made from fusion, we do not need large fusion development resources dedicated to making electricity with fusion. If one made the list of all the technical challenges we face in the development of fusion as a commercial power source, in order of difficulty, electricity production would be at the bottom. Meanwhile, development of materials that can survive the harsh fusion environment, understanding burning plasma behavior and how to control it, understanding and creating the multiple parts that make up the tritium (breeding) fuel cycle, or describing in detail the processes in the plasma scrape-off layer and divertor that interface the walls, these are REAL technical challenges, and ones that will (and should) occupy our research program for years to come. These constitute feasibility issues for fusion, so that their resolution is absolutely needed to proceed.

Some members of our fusion community believe that producing net electricity is the critical step for fusion development, and that this must even precede understanding how materials behave in a fusion environment. This belief is based on the notion that once our program demonstrates net electricity, the government and private industry will shower the program with funding. We had a similar belief about demonstrating fusion power in TFTR and JET, which was a significant milestone for fusion research, but turned out to be less earth-shattering to those outside of fusion, and did not result in a money-shower. Producing an early electricity demonstration is clearly a political goal, and not a technical one. The US MFE program is, and should remain, focused on the technical issues that stand in the way of fusion becoming a viable power source.

2. Electricity production in a fusion facility

We can describe a simple power balance for a fusion power plant in steady state with the following definitions,

$$0 = P_{alpha} + P_{heat/CD} - P_{brem} - P_{line} - P_{cycl} - W_{th}/\tau_E \qquad \textit{(plasma)}$$

$$P_{thermal} = M_{neut}\, P_{neut} + P_{alpha} + P_{heat/CD} \qquad \textit{(thermal power recovered)}$$

$P_{elec,gross} = \eta_{th} (M_{neut} P_{neut} + P_{alpha} + P_{heat/CD})$ *(thermal power → electricity)*

$P_{elec} = P_{elec,gross} - P_{heat/CD} / \eta_{aux} - P_{sub} / \eta_{sub} - P_{pump} / \eta_{pump}$ *(net electric power)*

$P_{recir} = P_{heat/CD} / \eta_{aux} - P_{sub} / \eta_{aux} - P_{pump} / \eta_{pump}$ *(electric power needed to run plant)*

where M_{neut} is the multiplication of neutron power in the blanket, η_{th} is the thermal to electricity conversion efficiency, η_{aux} is the wall-plug efficiency of the heating and current drive system, η_{pump} is the pump efficiency, P_{sub} represents all electrical requirements of various subsystems (e.g. plasma control, cryoplant, lighting, etc.), and η_{sub} is the efficiency of the subsystems. Net electricity is produced when P_{elec} is greater than 0, or $P_{elec,gross}$ exceeds the recirculating power required to keep the plasma and plant operating, P_{recir}. The energy source is fusion nuclear reactions, in the form of neutrons, which slow down and heat the structures (breeding blanket) surrounding the plasma, and energetic charged particles, which impart their energy through radiation and collisions to the plasma facing surfaces. Both of these channels produce hot fluids (e.g. helium, Pb-Li breeder coolant, H_2O). These hot fluids ultimately enter a turbine that converts the fluids' energy into spinning machinery, making electricity. All of the fusion research that is presently done in the US and around the world is to ultimately make hot fluids that can be converted to electricity. Making electricity is the easy part, making and sustaining hot fluids is the hard part.

The Fusion Nuclear Science Facility (FNSF), recently reported in [1], is designed to accomplish multiple simultaneous missions that strongly advance the fusion plasma and nuclear science toward a power plant. The plant size was kept small since it is an intermediate facility between ITER and DEMO, with a range of experimental to demonstration activities, needed to establish the basis for fusion energy and are described elsewhere. In addition, it was not required to produce net electricity since this constraint would have made the device larger. However, producing electricity is not precluded at all, and in fact, since the FNSF is designed to produce the same operating temperatures as a fusion power plant, very hot fluids ($T_{out} \sim 450\text{-}650$ C) would be available for conversion to electricity. Using the various parameters from the FNSF study, the thermal power is 692 MW, the gross electric power from the FNSF would be 304 MW (for $\eta_{th} = 0.44$), and the recirculating power is 357 MW. Clearly the net power is negative. The FNSF would draw 357 MW from the grid to operate, but could produce and return to the grid, 228 – 304 MW (depending on the conversion cycle, water or gas with $\eta_{th} = 0.33 - 0.44$). Electricity generation would be demonstrated on a substantial scale of ~ 265 MW.

→ The FESS FNSF can generate 228-304 MW of electricity.

Using systems analysis in the FESS FNSF study [1], targeting a net electricity constraint of $Q_{engr} \sim 1$ ($Q_{engr} = P_{elec} / P_{recir}$), the device's size grew from R = 4.8 to 5.8 m. The net electricity produced is ~ 30 MW, since the target was to just reach an engineering gain of approximately 1. Of course to produce even more net electricity continues to require larger facilities. The facility size is based on several technical decisions on plasma physics, engineering, and integration, however this trend of increasing size with greater electricity output is generic.

→ An FNSF larger than the FESS FNSF is required to generate net electricity, using the same facility assumptions.

3. Proposals for How to Produce Electricity from Fusion

In the US energy source development path, the demonstration power plant (DEMO) is the facility where routine electricity production and maintenance are established in order to convince utility companies (and other associated investors) that all aspects of the power source are credible, reliable, safe, and ultimately profitable. The DEMO does not need to be as large as a 1000 MW_e power plant, however, the precise minimum size for a DEMO has not been established. The Starlite study [2] provided some high level criteria for a DEMO facility, but did not address the technical requirements of the facility to provide a confident basis on which to project to a commercial power plant. It is possible that some level of R&D could be accommodated on the DEMO facility, but this should be minimized.

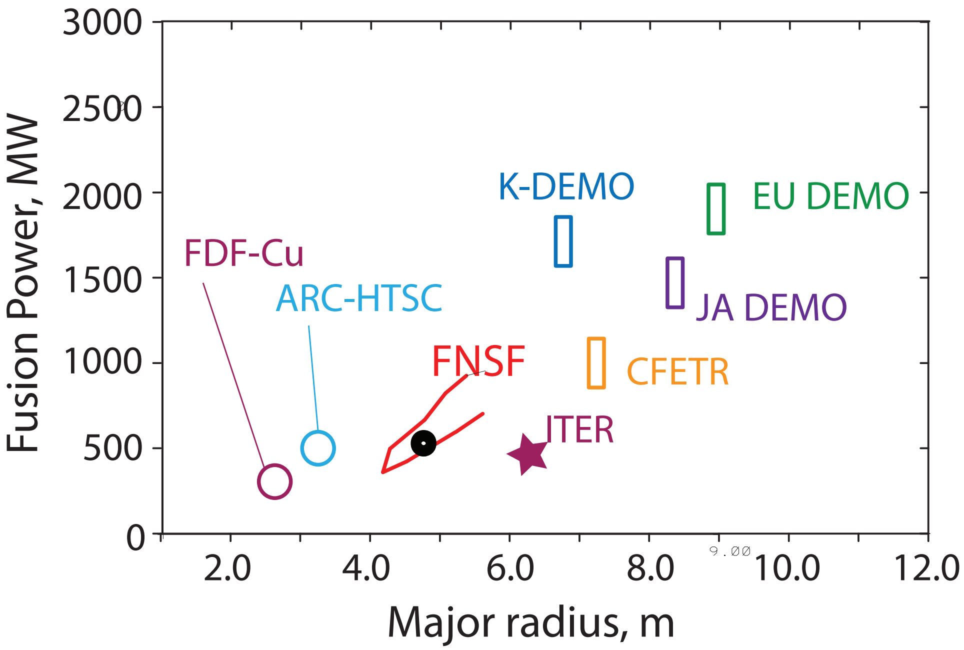

Figure 1. The fusion power versus plasma major radius for the FESS FNSF and several next step facility proposals. The operating space satisfying constraints lies inside the red contour for the FESS FNSF. These devices are designed with different target measures and constraints, and assumptions. FDF is a General Atomics design [3], ARC is an MIT PSFC design [4].

The technical extrapolation of a DEMO to full size commercial power plants requires high confidence in order to guarantee that private investment would produce a successful power source. In short, this device should produce electricity continuously for long periods in any calender year (months to a year, averaged over the plant life), attain as high availability as possible (e.g. > 50%), and show how all parts of the facility operate and are inspected and maintained. The facility should operate for at least a decade and probably even more. In addition, if an off-normal event occurs, also show how the associated maintenance and recovery is done for this situation. For the DEMO to operate in this way, significant advances in all technical areas of fusion plasma science, fusion nuclear science, materials science, and enabling technologies must have been established in advance (pre-FNSF R&D, FNSF, and pre-DEMO R&D).

The definition of DEMO outside the US can be different than the US version. In fact, the EU (500 MW_e) [5], JA (~300 MW_e) [6], KO (400 MW_e) [7], and even the CH (300 MW_e) [8] next step proposals (called DEMOs) are larger devices (see Fig. 1), with the mission to produce significant net electricity. These are also proposed to directly follow ITER, supported with a large amount of offline R&D. Each of these devices must demonstrate the slow entry into the fusion nuclear regime outlined in the FESS FNSF study [1], in addition to showing net electricity production. The large scale of these devices appears grossly inappropriate for experimentally establishing the fusion nuclear database as outlined in the FNSF study. In the FESS FNSF study, the FNSF is a facility that precedes the US DEMO, in order to provide the first full fusion in-service environment with all required integrated components in it. The technical basis developed from the FNSF would allow one to pursue the DEMO and commercial power plants, while in its absence the risk would be enormous to these electric power facilities. This is the technical philosophy on which the fusion development path of FNSF → DEMO is based.

Apart from the DEMO, three approaches to demonstrating electricity produced from fusion earlier will be briefly described and differentiated,

1) electricity first
2) FNSF + electricity (described above)
3) FNSF + net electricity (= Pilot Plant)

The ***electricity first approach*** is attempting to shortcut the many feasibility issues in materials, tritium fuel cycle, and several other areas, in order to show that it is possible to generate electricity from fusion reactions. This approach would need to

1) Avoid large neutron fluence that would lead to material degradation, and therefore must operate at some combination of low neutron flux (fusion power) and short burning durations.
2) Use conventional materials and/or first generation reduced activation martensitic steels (RAFM, fusion relevant material), that are expected to reach neutron damage levels of 10 dpa without degradation, would be used since they are available from the EU and JA.
3) Avoid tritium breeding and complex breeding blanket issues to the extent possible, requiring small tritium consumption and small facility tritium inventories.
4) The fusion core would strictly use neutron shielding to protect external components.

5) Magnets might be copper or superconducting, depending on power consumption, field requirements, shielding, or other factors.
6) Some level of electric power would need to be established, say 10 or 50 MW_e, and whether this is net electric or just electric power produced.
7) Envision operating for a day or a week intermittently in the course of a year in order to remain below the neutron fluence (dpa) limit, but show sustained electrical output power.
8) Additional topics would include non-inductive/inductive CD and source determination, PFC behavior and lifetime, coolant choice water/He/other, plasma operating mode, etc (not exhaustive).

The attractive feature of this approach is that it would be possible to design, construct and operate this facility sooner (< 10-15 years?). The activity surrounding this facility's development could be substantial (manpower and $). Although one would undoubtedly learn many things in the process of R&D, design, and operation of the device, it does not appear that significant progress is made in retiring major feasibility issues for fusion as a power plant. Therefore one must return to the technical track of materials science, fusion nuclear science, fusion plasma science, and enabling technologies in order to continue progress. Studies would be required to understand all the trade-offs in such a facility, and how the plasma and engineering constraints contribute to the operating point.

The ***FNSF + electricity option*** is described above (Section 2), showing that along with advancing the many fusion nuclear, fusion plasma, and enabling technologies, significant electricity can be produced, although here the FNSF is not designed to make electricity levels higher than it requires to operate the plasma and plant. As described in [1], the mission scope of a FNSF can take on a wide range of possibilities, and so a smaller less capable FNSF would make less electric power, and a larger more capable FNSF could produce more (we will leave this prospect to the next option). Distinct from the electricity first option, the FNSF is designed to address all the critical missions needed for a fusion power plant to some degree, and therefore pushes strongly toward resolution of fusion's feasibility issues. This approach is likely to take more time with greater R&D requirements preceding it, with operation unlikely before ~ 25 years.

Finally the ***FNSF + net electricity (= Pilot Plant) option*** (often referred to as a Pilot Plant [9]) targets an engineering gain Q_{engr} (P_{elec} / P_{recir}) ≥ 1, and as shown in the FNSF study [1], requires larger device size compared to a facility that does not require $Q_{engr} \geq 1$. This trend is true regardless of the aggressive or conservative technical assumptions made. Here one can generate a minimal amount of net electric power to convince people that more power can be produced than required to operate the plasma and plant. This version of a FNSF would take on more mission scope than that of the FESS FNSF design point, since it will pursue electricity production as a primary design goal, and therefore R&D into maximizing efficiencies of various components (e.g. H/CD sources, transmission, cryoplant, etc.) would be pursued earlier, as well as optimizing balance of plant equipment (e.g turbines, heat exchangers, etc.). These aspects were deferred to the pre-DEMO R&D and DEMO, for the FESS FNSF study reference operating point.

There are certainly approaches to demonstrating electricity production from fusion reactions before the DEMO, and some of these can be aligned with the technical needs of developing fusion at the appropriate scale and level of risk (**FNSF+electricity, FNSF+net electricity**). Others essentially provide a tangent off the technical program that is required to move toward a power plant, motivated by a hope of increased financial and political support stemming from such a demonstration (**electricity first**). Other approaches take on excessive levels of risk (IMHO) in order to compress the fusion break-in and significant net electricity missions into a single facility (**international DEMOs**) that takes on large size (and the potential of an unattractive product).

[1] C. E. Kessel et al, "The Fusion Nuclear Science Facility, a Credible Break-in Step on the Path to Fusion Energy", Fusion Eng. Des., 2017; https://doi.org/10.1016/j.fusengdes.2017.05.081.

[2] F. Najmabadi et al, "The Starlite Project – The Mission of the Fusion DEMO", http://www-ferp.ucsd.edu/LIB/REPORT/CONF/SOFE95/najmabadi.html

[3] R. Stambaugh et al, Fusion Science and Technology **59** (2011) 279.

[4] B. N. Sorbom et al, Fusion Eng. Des., **100**, (2015), 378.

[5] F. Federici et al, "European DEMO Design Strategy and Consequences for Materials", Nucl. Fusion, 57, (2017), 092002; http://iopscience.iop.org/article/10.1088/1741-4326/57/9/092002/pdf

[6] K. Tobita et al, https://www.tandfonline.com/doi/abs/10.1080/15361055.2017.1364112.

[7] K. Kim et al, 2015 Nucl. Fusion **55** 053027; http://iopscience.iop.org/article/10.1088/0029-5515/55/5/053027/pdf.

[8] Y. Wan et al, "Overview of the Present Progress and Activities on the CFETR", Nucl. Fusion, **57**, (2017), 102009; http://iopscience.iop.org/article/10.1088/1741-4326/aa686a/meta.

[9] J. E. Menard et al, "Prospects for Pilot Plants Based on the Tokamak, Sperical Tokamak, and Stellarator", Nucl. Fusion, **51** (2011) 103014.