# IMPLICATIONS OF UNCERTAINTIES ON EUROPEAN DEMO DESIGN

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**Abstract**

During the pre-conceptual design phase of fusion devices such as the European demonstration fusion power plant (DEMO), systems codes provide a fast evaluation of optimal design points and highlight high impact areas. However, determining or evaluating a design point at such an early stage comes with uncertainties in many of the design parameters. These uncertainties are both associated with the physics as well as the engineering basis of the European DEMO design. The work applies an uncertainty quantification analysis to the 2017 pulsed European DEMO design using the PROCESS systems code. It assumes that DEMO will be built as suggested by the baseline and explores what implications the currently known physics and engineering uncertainties have on the expected performance parameters (net electric output and pulse length), while optimising the fusion gain Q. A more detailed single parameter analysis is clearly identifying high impact parameters. This is confirming previous investigations as well as revealing new areas that warrant deeper investigation in particular in the technology area.

## 1. INTRODUCTION

The European DEMO concept is currently in its pre-conceptual design phase [1]. As a result, both the physics basis and the technology concepts for DEMO have relatively large uncertainties. Nevertheless, it is essential to evaluate the DEMO design and potential alternatives as rigorously as possible given the ambitious timings of the European Roadmap [1]. This allows us to focus on high impact areas as well as conduct a fair comparison of design alternatives with different technology readiness levels or different levels of confidence in its extrapolation.

Uncertainty quantification (UQ) is an ideal way to evaluate the effect of known uncertainties on the predicted results of a machine. Bustreo et al. [2] have investigated the effect of uncertainties on the cost of electricity on a DEMO-like fusion power plant using the FRESCO code. Other uncertainty quantification software like

COSSAN-X [3] is routinely used for a wide spectrum of uncertainty quantification in engineering problems. The top-level European DEMO baseline designs are determined by the system modelling code PROCESS [4,5]. It optimises a figure of merit (e.g. major radius, pulse length, fusion gain) while fulfilling a set of physics and technology constraints. In a preliminary study, Lux et al. [6] have applied an UQ tool combined with the PROCESS code to the 2015 pulsed European DEMO baseline. Their predictions were encouraging, but not comprehensive. This work applies the same tool to the 2017 European baseline design [1] and extends the scope of the work to a more complete set of uncertainties (including engineering parameters).

In this work, we present a combined approach to UQ based on a multi-parameter Monte-Carlo method together with single parameter studies investigating individual impacts. We describe our method in Section 2, the typical uncertainties in input parameters we expect in our systems modelling approach in Section 3 and the implications of our studies on the European DEMO design point evaluation in Section 4. We discuss our results and conclude in Section 5.

## 2. METHOD

In this section, we describe two complementary approaches to evaluate the effect of current physics and technology uncertainties on predicted future power plant designs. Both use the PROCESS systems code as tool to evaluate an optimal design point.

### 2.1 Monte-Carlo Approach to Uncertainty Modelling

The method described in this section, has already been documented more extensively in [7]. However, here we give a short overview of its key aspects: To efficiently determine the effects of uncertainties in the input parameters of a design point evaluation, we use Monte-Carlo sampling within user specified uncertainty distributions. The currently implemented options are

- Gaussian profile (specify mean and standard deviation);
- Lower half Gaussian profile (specify mean and standard deviation);
- Upper half Gaussian profile (specify mean and standard deviation);
- Flat top profile with relative errors (specify mean and percentage);
- Flat top profile with bounds (specify upper and lower bound).

Correlations currently cannot be modelled and are therefore not taken into account. The uncertainties cannot be specified for parameters used as iteration variables in PROCESS as these are varied within the code to determine a constrained optimal design point [4,5]. The output of the method is then the distribution of optimised design points based on the ensemble of randomly varied input points.

We have taken several steps to ensure that each of the individual design point evaluations are robustly converged and, hence, numerical noise intrinsic to the solver will not dominate the final distribution of output parameters. As the constrained optimisation solver implemented in PROCESS (VMCON [8]) is only a local solver, several measures have been implemented to automatically improve the chances of the constrained optimisation solver finding a valid solution, if one exists. This avoids neglecting valid solutions, in cases where the solver struggles to find them. To ensure reproducibility, a seed for the pseudo-random number generator can be specified by the user. One shortcoming of our current approach is that only feasible solutions are being considered in the results, as genuinely invalid input parameter sets cannot be distinguished from parameter sets where PROCESS simply searched too locally for a solution. However, additional to the measures of improving the search strategy for PROCESS, we check the actually produced output distributions. This gives us confidence that relevant cases are generally being captured.

### 2.2 Single Parameter evaluations/Sensitivity Analysis

The Monte-Carlo approach described in the previous section, is designed to evaluate the effect of a large range of uncertainties on a DEMO design point at the same time. However, parameters can be correlated, and this

approach can make it difficult to interpret individual effects or highlight high impact parameters. Therefore, it is essential to complement this method with single parameter studies to disentangle the competing influences.

For our single parameter evaluations, we again use the previously described uncertainty tool but investigate all uncertain parameters described in Section 3 individually. The result is a distribution which represents the PROCESS response function to the initial input distribution. As such it is more comprehensive than the simple sensitivity studies performed in [10] which only yield two values, but do not show the wider behaviour of the PROCESS code.

## 3. UNCERTAINTIES

In this section, we summarise a selection of known uncertainties in extrapolating the plasma conditions (Section 3.1) as well as technological parameters (Section 3.2) to fusion power plants. The lists describe the relevant quantity and the assumed uncertainty distributions[1]. Where possible this has been motivated with appropriate references.

### 3.1 Physics Parameters

Note that the majority of physics uncertainties has already been described in [6] but are included here for completeness.

**Ad hoc multiplication factor for the density limit** lower half Gaussian profile (mean 1.2 and standard deviation 0.1)
In the PROCESS runs for the European DEMO baseline the line averaged density is limited to the Greenwald limit [10] multiplied by an ad hoc factor. The ad hoc factor has been introduced as recent work suggests that the Greenwald limit really applies to the pedestal top density instead of the line averaged density and higher values than the Greenwald limit are therefore allowed for the line averaged density due to favourable density peaking. As a result, we allow the line averaged density to reach values as high as 1.2 times the Greenwald density (e.g. [11,12,13] and references therein).

**Upper bound on H-factor** lower half Gaussian (mean 1.2 and standard deviation 0.1)
Please note, that in PROCESS this is the radiation corrected H98-factor [14,15] where a certain amount of radiation from the core region of the plasma is considered as instantaneous losses and are therefore subtracted from the heating power before the loss power is calculated for the confinement scaling. Experience shows that radiation corrected H-factors between 1.0-1.2 roughly correspond to non-radiation corrected H98-factors of 0.9-1.1 for typical DEMO scenarios. This range should capture all uncertainties in the current confinement time scaling including statistical errors on the exponents and uncertainties due to operating in DEMO relevant regimes that are not covered by IPB98(y,2) [16] database (c.f. [14]).

**Core radius in radiation corrected confinement time $\tau_E$ scaling** Gaussian distribution (mean 0.6 and standard deviation 0.15)
This quantity is defined in [14,15] where also expected values for it are discussed. It is treated separately from the uncertainties on the H-factor to capture the correlations of expected corrections for high radiation scenarios. Please note, that in this work, we are only varying the radius inside of which the radiation is considered an instantaneous loss to the heating power. The fraction of the radiation that is subtracted from within the core region is fixed at 100% as the uncertainty in this value is correlated with the uncertainties in the radius and this does not need to be captured twice.

**Thermal He-4 fraction** Gaussian distribution (mean 0.1 and std 0.025)
While the production rate of helium ash in the plasma is well understood, the fraction of thermal He-4 particles with respect to the electron density in the confined plasma is relatively uncertain due to its dependence on particle transport, pumping in the main chamber, ELM behaviour etc. Ikeda [17] suggests that a lower limit for the ratio of He confinement time accounting for wall recycling and energy confinement time $\tau_{He}/\tau_E$ of 6. A reduction of the divertor neutral gas influx [18] or reduced ELM behaviour leads to an increase of this value up to an order of magnitude. The He concentration in EU DEMO1 2015 of 10% corresponds to $\tau_{He}/\tau_E$=6.5. Increasing $\tau_{He}/\tau_E$ to 12.6 would correspond to a He concentration of 16%. For numerical stability reasons $\tau_{He}/\tau_E$ is not used as an input to PROCESS: instead the He concentration is given, and the confinement time ratio is calculated as an output. Therefore, the uncertainties have been applied to this input quantity instead.

[1] We assume that the central limit theorem is applicable, and the uncertainties are typically well described by a Gaussian distribution.

**W number density fraction relative to the electron density** Gaussian distribution (mean $10^{-4}$ and std $5x10^{-5}$)
Pütterich et al. [19] have investigated the effect of varying W concentrations on the minimum value of fusion triple product for which a thermonuclear burn is possible. This places certain limits on allowed W concentrations in a DEMO reactor. However, predicting expected W concentrations in DEMO is still highly uncertain as it is unclear how much of the impurity will be screened, flushed outwards or drawn inwards (e.g. [20]).

**Maximum ratio of the divertor figure of merit $P_{sep}B_T/q_{95}AR$** Gaussian distribution (mean 8MW T/m and std 1MWT/m)
While a more detailed model predicting the power flow and the temperature on the divertor plates is currently undergoing testing [21], this has not been used in the derivation of the most recent DEMO baseline. Therefore, $P_{sep}B_T/q_{95}AR$ has been adopted as a divertor figure of merit. This differs from the divertor figure of merit for the pulsed European DEMO baseline from 2015 and therefore the work presented in [6], where $P_{sep}/R$ was used. The new divertor figure of merit is assuming the tolerable power flow to be hitting a ring of surface $2\pi R\lambda_q$ [22] and furthermore assumes the power decay length at the outer midplane $\lambda_q$ scales with the poloidal gyroradius which is proportional to $B_T/q_{95}A$ [23]. The uncertainty distribution for this figure of merit is equivalent to the one previously used assuming the DEMO 2017 baseline values of $B_T$=4.89T, $q_{95}$=3 and A=3.1.

**Lower bound on L-H-threshold limit** Gaussian distribution (mean 1.0 and std 0.25)
The European DEMO baseline design uses the well-recognised Martin-scaling [24] for the determination of the L-H threshold. While more recent results suggest that the L-H-threshold in metal wall machines is in fact lower [25], it is desirable to have a certain margin above the L-H threshold to achieve reasonable performance [26]. As a result, the distribution of the lower limit for H-mode performance has been centred on 1.0 times the L-H-threshold as given by the Martin-scaling. The standard deviation should cover both statistical errors suggested by Martin et al. [24] and uncertainties concerning how high you need to be above the LH-threshold to achieve good H-mode performance. Therefore, the standard deviation chosen in this work is larger than the one suggested by Martin et al. for typical average electron densities in DEMO. However, it does not include uncertainties due to extrapolating this scaling to high radiation reactor relevant scenarios, that have not been included in the original data set.

**Bootstrap current fraction multiplier** Gaussian distribution (mean 1.0 and std 0.1)
This parameter is a multiplication-factor for the Sauter-Angioni bootstrap current [27] implemented in PROCESS for the DEMO design. Its range should capture both the model limitations as well as uncertainties in the prediction of the achievable plasma profiles and the resulting expected bootstrap current.

**Radiation wall load peaking factor** Uniform distribution (lower bound 2.0, upper bound 3.5)
The PROCESS systems code does not calculate the distribution of the radiation on the plasma facing components. It therefore needs an estimate of how high the peak radiation wall load is in comparison to an average distribution where all the radiation is distributed evenly along the plasma facing components. Wenninger et al. [28] have estimated what the peak radiation wall load for the pulsed DEMO 2015 baseline design would be. However, the predictions have large uncertainties which are being dominated by the extrapolation of a possible X-point radiator. Assuming a dominant X-point radiator of 150 MW corresponds to a peaking factor of 3.3. However, current experiments suggest that lower value e.g. 60 MW are more realistic. This leads to lower overall peaking factors. Note that this parameter has not been included in the previously published work [6]. Furthermore, this estimate is only valid, if there is no explicit calculation of the radiation from the scrape-off-layer.

**Elongation $\kappa$** Lower half Gaussian distribution (mean 1.9 and std 0.05)
Wenninger et al. [9] have shown that the elongation has a large impact on the net electric output of a design, when optimising the fusion gain at fixed major radius. However, there are still large uncertainties attributed to the maximally allowed elongation. While the 2015 DEMO baseline assumed $\kappa$=1.781 [9] based on a passive stability study [29], the 2017 baseline assumes 1.848 [1]. The nominal value for ITER is 1.85 and the value of the 2015 European baseline for an advanced steady state DEMO (DEMO2) is 2.016 [9]. Higher elongation values are not expected to be controllable, hence, the choice for a lower half Gaussian distribution.

Further known uncertain physics parameters include the pedestal width and height of both the temperature and density profiles. However, apart from the Greenwald limit on the density pedestal height, these are not yet consistently enforced within PROCESS and therefore an analysis of the implications caused by these uncertainties is postponed for future work. Currently an approach is tested, using a more consistent model consisting of a coupled 1D transport and equilibrium solver [30]. Once this has been sufficiently tested within

PROCESS, the transport parameters will come with their own set of uncertainties whose impact will have to be evaluated. The introduction of the transport and equilibrium solver is expected to narrow down the allowed design space and will make an uncertainty evaluation even more crucial.

### 3.2 Technological Parameters

The uncertainties that can be treated in the DEMO design heavily depend on the models that are available in PROCESS. Currently the technology models in PROCESS are a bit less detailed than the physics models. Hence, a less complete treatment of uncertainties will be conducted for the technology parameters. Note that DEMO 2015 baseline used NBI as nominal heating source and 2017 baseline used ECRH.

**Wall plug efficiency of the CD system (ECRH)** Gaussian distribution (mean 0.4 and std 0.1)
Pamela et al. [31] state that the present wall plug efficiency of ECRH systems is of the order of 22%, while ECRH systems developed for ITER have an expected efficiency of 55%. More advanced technologies could in theory reach efficiencies as high as 65%. The DEMO baseline makes relatively conservative assumptions by using 0.4 as its wall plug efficiency.

**Current drive efficiency** Gaussian distribution (mean $0.3x10^{20}A/Wm^2$ and std 0.05)
The nominal value of the current drive efficiency of the ECRH heating system in in 2017 DEMO baseline design point is $0.3x10^{20}A/Wm^2$. This corresponds to the analysis by Zohm et al. [32] for flat density profiles.

**Plant thermodynamic efficiency** Gaussian distribution (mean 0.37 with std 0.05)
The value in the 2017 DEMO is 0.375 and the value previously used in [9] is 0.37.

**Fractions of the total blanket/divertor/first wall/shield thermal power required to drive the respective coolant pumps** Gaussian distribution (mean 0.08 and std 0.005)
The pumping power is the largest fraction of recirculated power in the 2017 DEMO baseline design followed by the power consumed by the HCD system. Its efficiency is therefore going to have the highest impact on the recirculated power and therefore the net electric output of DEMO. Therefore, other sources of uncertainties in the recirculated power are currently not being assessed.

Some uncertainties would lead to component failure rather than performance reduction. While the European DEMO design already takes a very conservative approach, it is not possible to estimate the probability of component failures from the uncertainty analysis of systems studies. These have to be carried out by more detailed codes.

A sufficient tritium breeding ration is one of the key performance parameters of DEMO. However, the tritium breeding ratio is currently not typically calculated within PROCESS when optimising a design. Rather the blanket thickness is kept fixed that is assumed to give a sufficient TBR for the DEMO size. Hence, the uncertainty in the tritium breeding ratio cannot be evaluated within this work.

## 4. IMPLICATIONS FOR DEMO DESIGN

In this work, we apply our uncertainty quantification tools to the design of the pulsed European DEMO baseline from 2017[2] [1]. The PROCESS reference file for the baseline has been produced with PROCESS version 1.0.10 (commit 48f7f3ee) which also has been used throughout this work.

There are various options how to evaluate the effect of uncertainties on a given design. In this work, we assume DEMO has been built as detailed in the 2017 baseline and we investigate the effect of the know uncertainties on the predicted performance of DEMO.

### 4.1 The effect of uncertainties in the physics parameters

Figure 1 shows the predicted machine performance (pulse length and net electricity) for the pulsed European DEMO baseline for scenarios that are optimised for their fusion gain Q. The distribution shows the results of the uncertainty analysis while the black diamond shows the result of the nominal baseline assumptions. As discussed in [6], the balance of plant (BoP) is likely to only tolerate variations in net electric output of +5%/-20%. While over performing scenarios can be downgraded, scenarios with a net electric output below 400MW have to be classified as not meeting the DEMO requirements. A further assumption is that the DEMO energy

[2] https://idm.euro-fusion.org/?uid=2NDSKT

storage system can cope with both 1hr as well as the nominal 2 hrs pulse length and hence scenarios with more than 1 hr pulse length are also accepted.

The left-hand side of Figure 1 shows the results analysing the uncertainties in the physics parameters. With respect to the analysis of the 2015 pulsed DEMO baseline [6], we have extended the list of our uncertain physics parameters by the elongation and the radiation wall load peaking factor and adjusted the uncertainties to the new divertor figure of merit (see Section 3.1). As a result, we find that only 75% of the scenarios have an acceptable performance, in comparison to the 90% found by the previous analysis [6]. The elongation has already previously found to have a large impact on performance of a power plant [9], while the radiation wall load peaking factor has only been included for completeness in the analysis but does not have a significant impact. Though the dominating driver for the difference with respect to the previous results is the change in the baseline design rather than the extension of the parameter list, as running the same analysis with the old parameter list gives similar numbers.

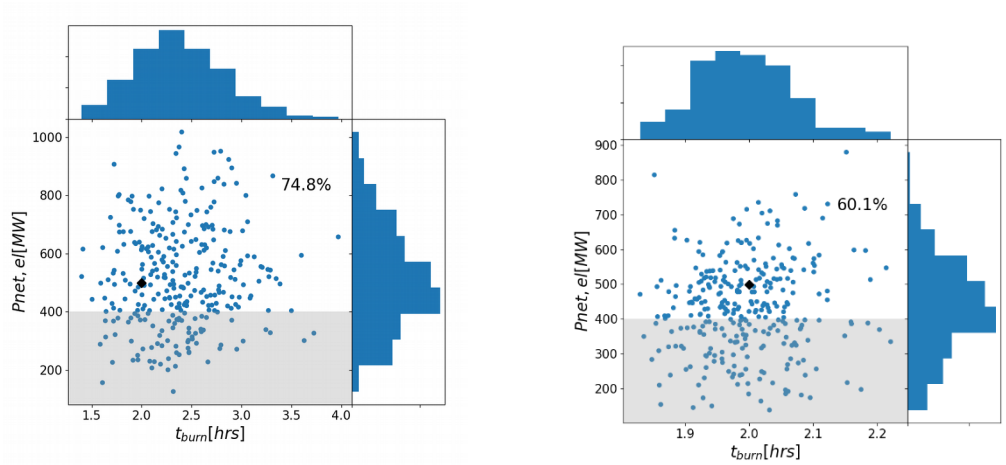


*FIG. 1. Predicted machine performance for the 2017 baseline of the pulsed European DEMO design assuming a range of uncertainties in the physics (left side) and technology (right side) parameters. The black diamond indicates the values nominal baseline design.*

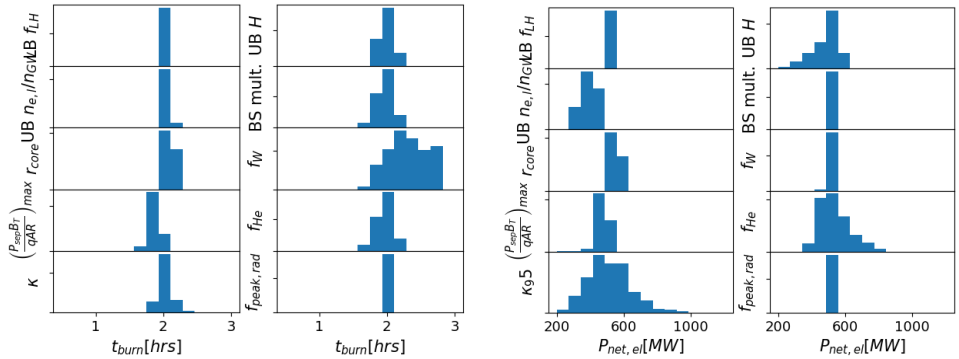


*FIG. 2. Single Parameter scans for the uncertain physics parameters left shows the impact on the burn time, while on the right the impact on the net electric output is shown.*

Figure 2 shows the individual parameter scans as discussed in Section 2.1. These very clearly illustrate which parameters have a large impact on the prediction of DEMO performance. While some parameters result in a very narrow distribution in performance parameters, others yield a rather wide spread. This shows that the uncertainty in the tungsten fraction $f_W$ has a significant impact on the predictions of the DEMO pulse length. Furthermore, the uncertainties in the helium fraction $f_{He}$ and the achievable H-factor cause uncertainties in the predictions of the net electric output as well as the pulse length. Overall the elongation remains the most significant source of uncertainty for the net electric output confirming earlier work [9]. These parameters can therefore be considered to have a high impact on machine design and preference should be given to constraining the uncertainties in their predictions.

### 4.2 The effect of uncertainties in the technology parameters

With respect to the previous analysis [6], not only has the list of physics uncertainties been extended, but also technological uncertainties have been considered. As expected, all technology uncertainties have a significant impact on the net electric output and suggest even the conservative pulsed European DEMO design only has a likelihood of ~60% in achieving its performance parameters. These results are shown on the right-hand side in Figure 1. The single parameter analysis (not shown) indicates that the plant thermal efficiency has the highest impact on the net electric output of the plant and the current drive efficiency has the highest impact on the burn time.

## 5. CONCLUSIONS AND DISCUSSION

In this work, we analysed the predicted performance of the 2017 baseline design point of the European demonstration power plant DEMO [1] in light of the currently known physics and technology uncertainties. The nominal performance criteria of the baseline DEMO design is a 2 hr pulse length and 500 MW electricity. In this analysis, we assume that DEMO will be build as described in the 2017 baseline design and evaluate the impact of the physics and technology uncertainties described in Section 3 using an uncertainty quantification tool coupled to the PROCESS systems code, which has been used to previously derive the baseline design. We assume that any net electric output of 400 MW or above is still acceptable for the balance of plant and that any pulse length longer than 1 hr is acceptable for the plant storage system. Based on this, we evaluate the likelihood of the current DEMO baseline fulfilling its performance requirements. Please note that this analysis is limited by the models implemented in PROCESS and can therefore neither assess the likelihood of component failures or evaluate the predicted tritium breeding ratio.

The parameter list of the uncertain physics parameters has been extended in this work in respect to the previous investigation of the 2015 pulsed DEMO design. However, in the evaluation of the overall impact the changes in the baseline dominate the reduction in the likelihood of achieving an acceptable performance from about 90% down to 75%. The individual parameter analysis reconfirms previous results suggesting that the uncertainties in maximum controllable elongation and impurity fractions are having a significant impact on the machine performance and future work should focus on reducing these.

For the first time, also the impact of uncertainties in the technological input parameters in PROCESS have been investigated. As these mainly cover efficiency parameters of the heating and current drive system as well as the thermal to electricity conversion parameter, they have a significant impact on the machine performance. We find that the overall likelihood of achieving an acceptable performance with respect to the studied technology uncertainties is 60%. Unsurprisingly, the individual parameter analysis suggest a high impact from determining the thermal conversion efficiency well.

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