Recent developments in compact tokamak demo reactor design, including the ARC [1], compact pilot plant [2], STEP [3], and spherical torus reactor [4], show great potential for feasibility in the near future. A new computational algorithm has been developed [5] to determine the optimum demo design parameters, accounting for plasma performance, physics, and engineering constraints. By using a supercomputer, plasma performance was scanned to draw the optimum design parameters needed for a compact tokamak fusion reactor. The prospective design space was based on achieving a fusion gain of $Q > 20.0$, net electric power $> 100$ MW, neutron wall loading $< 2.0$ MW/m$^2$, $P_{\text{sol}}/R_0 < 25$ MW/m, a direct capital cost $< 4.0$ B$, and steady-state operation. Advanced engineering features were also implemented, including high-temperature superconducting magnet technology, the use of tungsten carbide shield material, and a plug-buckled toroidal field magnet support structure.

The tokamak systems analysis code coupled with the neutron transport code [4] plays a crucial role to determine the optimum build and the system parameters in a self-consistent manner. Various thermal confinement scaling laws are incorporated to address the validity of compact fusion reactor parameters. By utilising multiple scaling laws, the study aims to enhance the credibility and robustness of its findings. A number of scaling laws including the H-mode (1) IPB98y2 [6], (2) ITPA20 [7], (3) $\beta$-independent scaling laws [8], and spherical torus scaling laws [9] were employed to evaluate the energy confinement time, $\tau$, with the inclusion of a confinement enhancement factor, $H$. To explore a large parameter range for the tokamak fusion reactor design, a hybrid code was employed on the high-performance computing system KAIROS at KFE. The parameters were evenly distributed over multiple CPU cores using the message-passing interface (MPI) in C++.

A wide range of physics, technology, and system parameters was scanned using a supercomputer and resulting in a prospective design space according to the level of the physics and technology. The study investigated the dependence of the minimum $R_0$ on physics, technology, and system parameters, such as $\eta_c/\eta_{\text{in}}, \beta_N, H, q_{\text{edge}}, \kappa, P_{\text{fusion}}, A, \eta_{\text{in}},$ and $\eta_{\text{CD}},$ with different energy confinement scaling laws for both conventional and spherical tokamaks. The results showed that for small $R_0$, large $\beta_N$, large $H$, small $q_{\text{edge}}$, small $B_T$, and small $P_{\text{fusion}}$, are required, with weak dependence on $\eta_{\text{in}}$ and $\eta_{\text{CD}}.$ To access a design space with $R_0 < 4.0$ m, the conditions of $H > 1.75, f_{\text{BS}} > 0.55, B_T > 4.0$ T, $P_{\text{fusion}} > 550$ MW, $\eta_s > 0.33$, and aspect ratio, $A < 3.4$ were required for the conventional tokamak with the IPB98y2 scaling law. For a spherical tokamak, the study found that if the tritium self-sufficiency requirement is satisfied, the inboard blanket can be replaced by appropriate reflector material, and complexity associated with piping for coolant, breeder replacement, etc., can be avoided. Increased reflector/multiplier thickness but reduced inboard shield thickness made the minimum $R_0$ similar to or even smaller than the case with the inboard blanket. Compared to the conventional tokamak case, the parametric dependence of $R_0$ was weak for the spherical tokamak, except that small $R_0$ is accessible with large $A.$ To access a design space with $R_0 < 4.0$ m, the conditions of $H > 1.3, f_{\text{BS}} > 0.6, B_T < 6.0$ T, $P_{\text{fusion}} > 500$ MW, and aspect ratio, $A > 1.7$ were required for the spherical tokamak with the IPB98y2 scaling law.

An innovative approach was employed to establish a prospective design space for a compact tokamak fusion reactor, aiming to determine the minimum major radius, $R_0$, and system parameters while satisfying all physics, technology, and neutronic requirements in a self-consistent manner. The approach integrates tokamak systems analysis with neutron transport calculation, enabling the identification of the optimal system parameters and build. Through this, a comprehensive understanding of the constraints and interplay between these aspects is achieved, paving the way for the establishment of an ideal prospective design space.
Figure 1. Dependence of the minimum $R_0$ on the system parameters according to level of physics and technology parameters for the case of (a) CT (b) ST with IPB98y2 scaling. IPB98y2 cases are representatively shown.

REFERENCES