# STEEL-CONCRETE MODULAR CONSTRUCTION.

# ECONOMIC IMPACT ON THE LEVELIZED COST OF ELECTRICTY FOR LARGE REACTORS OR SMR

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**Abstract**

For nuclear power to remain an attractive option in the next decades, the cost of electricity must remain competitive with alternative sources, whereas investors and public acceptance have been eroded by new build projects costs overrun. Lots of reports have been published on means to stop the construction costs escalation that was observed for large reactors in the Western countries (OECD/NEA, IAEA). Regarding SMRs, the challenge to develop a viable business model is bigger, especially how to unlock cost reductions to compensate diseconomies of scale. Steel-Concrete Structures (SCS) is one of the possible economic drivers, by reduced Interests During Construction (IDC), indirect costs and owner’s costs from the shorter schedule. However, outside generalities or technical evaluations, there is a lack of information on supplementary direct costs that may lessen the savings; moreover, the expected gain compared to reinforced concrete (RC) was rarely quantified in the literary in terms of reactor economic performance, namely the cost of electricity (LCOE) all included (capitalized cost, operation & maintenance, fuel, dismantling). From the feedback of the SCHEDULE RFCS EU funded project 800732 (full-scale ultimate safety building in SCS), we have developed a simplified model to assess the economic performance sensitivity to the construction method for different confidence levels, reactor sizes, and weighted average cost of capital (WACC).

## THE CHALLENGE OF nuclear costs

The nuclear power competitiveness with alternative sources towards a free-carbon world must face not only the public acceptance, but also the investors and utilities economic evaluation in deregulated market. Besides safety and environmental impact, the history of nuclear costs, including the cost of capital and the construction duration related costs, has shown high overruns for new build large reactors in the Western countries, that finally impair confidence in the next gigawatt projects. Lots of reports have been already published on tools to mitigate the construction costs escalation (ref. [1] ; [2] ; [3] ; [4] ; [5] ; [6]). As regards Small Modular Reactors (SMR), the challenge to develop a viable business model is bigger, especially how to boost nuclear cost reductions to compensate diseconomies of scale (see Figure 1). By the time of the beginning of the first SMRs concepts, Carelli et al. (ref. [7]) had proposed some target ratios per factors affecting the cost: in particular, it was stated that the construction schedule acceleration could offer reduction factor 0.94 on the capitalized cost. Recent MIT studies on Steel-Plates macromodules calculated 0.92 (ref. [8]) and discussed the supply chain failure risk (ref. [9]). Based on French experience, our own study introduces basic insights of SMR economics compared to large reactors, to assess how Steel-Concrete Structures (SCS) can contribute to meet the capitalized price cut expectations.

 

*FIG. 1.Main paths of nuclear capitalized costs reduction in the literary*

## METHODOLOGY OF THE STUDY

### Objectives of the financial model

The Steel-Concrete Structures (SCS) are often listed in the literary as one of the possible economic drivers, by reduced Interests During Construction (IDC), reduced indirect costs and reduced owner’s costs from the shorter construction schedule. However, outside generalities or technical evaluations, there is a lack of information on supplementary direct costs that may lessen the savings. The expected gain compared to reinforced concrete (RC) was not yet quantified accurately in terms of reactor economic performance (LCOE), namely all included cost of electricity (capitalized cost, operation & maintenance, fuel, dismantling). In present paper, a simple financial model is used (Figure 3), in accordance with state-of-the-art methodology for nuclear power plants economics (ref. [11]), to assess its sensitivity to the construction method for different confidence levels, reactor sizes, and cost of money assumptions (or rate of return WACC) :

* Direct cost of civil structures is modified according to Table 1 cost ratios
* Indirect costs and Owner costs during civil works are modified according to Table 1 time factors
* Interests During Construction are recomputed considering the reduced construction time. Various WACC assumptions are tested to get the results of Fig. 7.

No change is considered for the Conventional Island nor the Balance of Plant. Regarding the Nuclear Island, the basemat is in reinforced concrete whatever the scenario and SCS impact is tested in the following areas:

* Large Reactor: all structures of Reactor Building, Auxiliary Building, and Radwaste Building
* SMR: all critical path structures and pools (extended use to the whole nuclear island was first tested and judged not enough optimized to generate additional savings)

It is reminded that the civil works duration is not the total construction duration. Preparatory works, equipment installation and commissioning represent a significant part of the schedule. Moreover, both schedule and costs breakdowns are very different depending on the reactor size. The main strategy behind any modular construction techniques, on financial perspectives, is to consider paying supplementary direct costs for civil works acceleration in order to limit the time related costs after the project funds are raised. The “time to money” exchange rate must be weighted in the equilibrium equation prior to take decision (Figure 2).

*FIG. 2. Indicative time related costs during nuclear power plant construction*





*FIG. 3. Methodology of the comparison Reinforced Concrete vs. Steel-Concrete*

### Steel-Concrete assumptions

Among expectations, SCS could be a solution to avoid budget overruns and delays from steel rebars and embedded plates congestion of the nuclear reinforced concrete buildings. Electricité de France (EDF) has been contributing actively for 10 years to the European R&D programs on SCS (also named Steel-Plates in the literary).

* SCIENCE RFCS EU funded project RFSR-CT-2013-00017 (2013-2017): tests and guidelines (ref. [12])
* SAM (2018-2019): fist mock-up (EDF Private funding)
* SCHEDULE RFCS EU funded project 800732 (2018-2023): construction of a building (ref. [13])
* The redaction of a particular design section in the Afcen RCC-CW and Eurocode is for the 2025 edition.

SCHEDULE is a full-size diesel ultimate safety building made with SCS above reinforced concrete raft, without electromechanical components nor finishings excepted anti-corrosion paintings (Figure 4). In comparison, 56 identical reinforced concrete buildings were previously installed in every EDF power plant by 4 construction companies in the frame of a Safety Upgrade Program. An aircraft crash shield zone and a pool were added to the original design specifically for the SCS prototype. Assembly provisions were made with a mix of fillet weld joins (1/3) and dowel bars connections (2/3) to check both options. It was completed in 5.6 months after basemat first concrete, which gives -25% time acceleration and confirms other countries previous performances. Many years ago, IAEA had forecasted -50% before any tests (ref. [1] ; [14] ; [15]). Further development, innovations, or a different trade-off between direct costs control (more on-site manhours) may lead to better performance closer to that forecast.

The steel plate thickness is usually oversized (compared to equivalent RC rebars quantity) to provide stiffness during lifting and stability during concrete pouring. Despite subsequently higher steel quantities, detailing connection works, and transportation costs, direct costs remain in the same order of values as reinforced concrete (Table 1) thanks to -70% on-site manhours diminution mainly due to high use of dowel bars connections. Advantages of SCS in the pools are more remarkable, offering both cost and schedule reduction compared to the usual complex steel liner, whilst direct cost remains slightly higher in ordinary walls and slabs. Our price indicators reflect a bill of quantities established in compliance with the European design practice (codification in-progress). It may be higher in a different normative context due to detailing requirements or welds control rules (e.g ref. [16] remarked that AISC/N690-18 code leads to excessive steel quantities around openings that jeopardize feasibility and competitiveness). One can also mention the MIT price calculator (NCET).

It is noteworthy that the British company Caunton Engineering Ltd, backed by Innovate-UK with grant as much as 1/4 of SCHEDULE budget, erected 1/8 of exactly the same pilot structure using the competing product SteelBricks, which seems to be at least twice more expensive per m² than SCS of the SCHEDULE design.

TABLE 1. Steel-Concrete vs. Reinforced Concrete ratios from SCHEDULE feedback

|  |  |  |  |
| --- | --- | --- | --- |
|  | PessimisticFOAK | Best EstimateNOAK | OptimisticNOAK |
| Direct costs Walls, Slabs (vs. RC) | 1.4 | 1.2 | 1.1 |
|  Pools (vs. RC +liner) | 0.78 | 0.6 | 0.4 |
| Civil works critical path planning | 0.8 | 0.7 | 0.7 |

 

*FIG. 4. Steel-Concrete modules (SCHEDULE mock-up at the site of EDF R&D in Les Renardières)*

 The use of SCS in the next years will depend on the maturity level of the program (new campaign of tests on the SCHEDULE mock-up, design codification, industrialisation, etc.) by the time of each new nuclear project construction and considering the necessary anticipation for detailed design and manufacturing. The current R&D planning is consistent to be time-to-market for SMRs. Concerning large reactors, when the FOAK projects were already at detailed design stage in reinforced concrete, SCS still gives optimization perspectives for the NOAK ; main engineering effort will be to revise the civil works detailed design of the selected areas with no impact on the buildings layout, that sounds a reasonable expense compared to the expected savings during construction.

### Reference plants size assumptions

For exercise purpose, some reinforced concrete reference cases are defined. Two reactor sizes are tested, with cost and schedule assumptions from the literature. All assumptions of these simplified models are usual orders of magnitude at Western countries economic conditions (cost breakdown, cost of electricity, construction duration, etc.) as suggested in a blend of public sources (University Chicago, MIT, OECD/NEA, etc.).

The virtual reinforced concrete large reactor (typically >1000 MWe) parameters are arbitrarily set at 100$/MWh, the medium value of the range 50-150 according to projected nuclear costs in the future by World Nuclear Association (Figure pp. 4 of [18] after OECD/NEA, and Figure ES5 pp.20 of [19] by IAEA). It approximately corresponds to 5000$/kWe with a 9% rate of return (Figure 6 of [1] by OECD/NEA, and Figure 3.2 pp.47 of [19] by IAEA). The construction is assumed 7 years (IAEA ref. [19] pp. 40). The same study could have been carried out considering another realistic set of input values, getting finally the same trends in conclusion.

 The virtual reinforced concrete SMR (typically 200-400 MWe) parameters, before taking into account any optimization tools such as SCS to raise the cost reduction challenge, are arbitrarily set at ~1.5 times the large reactors cost for the exercise in consistency with various independent forecasts (see literature review at Figure 1), for the same rate of return[[1]](#footnote-2). The construction is assumed 5 years (Table 2 of [20] by University of Cambridge). Half of civil works after first concrete is considered on the critical path including the pools construction. The reference critical path is assumed already tight thanks to an optimal reinforced concrete design respecting good practice (alignment of walls, reasonable rebars density, rational layout of openings and embedded plates, systematic 3D modeling of rebars during execution design phase to de-clash critical areas, prefabricated rebars cages, headed T-bars for shear stirrups, etc.).

Fuel cycle, operation and maintenance, dismantling and decontamination costs are taken in rough estimate from statistics or academic models as a function of the reactor size (ref. [2] ; [17] ; [18]). In particular, Rothwell highlighted SMR diseconomies of scale for O&M costs. These inputs do not significantly affect the conclusion of our study as these parameters are deemed invariable whatever the construction techniques.



*FIG. 5. Reference plants parameters and LCOE in reinforced concrete before cost & planning reduction by SCS (inspired by literature review, no relationship with any specific project)*

## RESULTS

In best estimate scenario, SCS offer to investors respectively 0.97or 0.92savings ratio on capitalized cost for SMRor Large Reactorat 9% rate of return. This performance is obtained by means of revised EPCC Vendor’s bid with factor 0.99 or 1.02, that highlights there could be real interest to pay small extra charge for schedule acceleration. Our results seem consistent with the MIT conclusions that were based on American feedback (ref. [8] without delay; ref. [9] with sensitivity to 12 months delay from supply chain failure risk).



*FIG. 6. SCS exchange rate to LCOE*

Although substantial in absolute values, the SMR relative results are less sensitive to civil works acceleration and costs for the following reasons:

* The cost breakdown is very different in comparison with large reactors. The nuclear island civil works part represents three times less in the relative total direct costs: consequently, the requested additional effort on the Vendor’s budget remains reasonable and less significant than for a large reactor (or even slightly profitable when there are many pools in the design).
* The relative civil works critical path is two or three times shorter in the delivery schedule. Although SCS enable to speed up construction, the potential gain is several months (instead of years for a large reactor) and it is moderated within the global schedule as equipment installation and commissioning still take a long time. In particular, the commissioning time cannot be scaled proportionally to the reactor power. Besides, the civil works operations are closer to the plant startup: an accelerated task at T0 minus 4 years may create less IDC savings than the same acceleration at T0 minus 7 years. Finally, on sponsors point of view, the capitalized cost savings could be perceived less attractive than for large reactors.
* All things considered, most of the SMR calculated savings come from the pools construction in which SCS enable both cost and time reductions. In other words, the SCS benefits in the pools are outstanding whereas their use in ordinary walls and slabs may be questionable on SMR economic point of view. Technical advantages, innovation risks and schedule reliability must be also considered in the trade-off decision compared to classical reinforced concrete (see technical presentation in ref. [13 ; 22])





 

*FIG. 7. Effect of steel-concrete (SC) vs. reinforced concrete (RC) on the EPCC cost, the capitalized cost, and the cost of electricity generation (application of methodology Fig. 3)*

## LIMITATIONS OF THE STUDY

The above results provide a useful picture of the relationship between SCS construction techniques and the financial mechanisms. Nonetheless, the approach remains simplified to give a general trend (to be adapted after for each project with its specific cost breakdown, schedule, target cost, local economic context, etc.). The following questions should be raised to continue deep dive analysis.

### Parameters impacted by SMR models (independently from SCS vs. RC)

The SMR mindset is to maximize prefabrication and modularity to optimize the schedule. The counterpart will be an anticipated negative cashflow, so that such expenditures timeline could penalize IDC, unless modules (or simple SCS in our study) are delivered and paid at the last minute which could represent a major risk.

After the FOAK demonstration, SMRs should benefit from lower risk perception compared to gigawatts projects according to the wealth-based model (ref. [11] ; [17]). The question of lower risk premium in the sponsors rate of return and contingencies is critical: let’s remind that 1 WACC point variation leads basically to +/-10% LCOE. Negotiating the cost of money is often an efficient economic leverage, far ahead technical improvements.

### Parameters impacted by SCS vs. RC

The study did not evaluate the SCS effect on the other technical fields than civil works. The equipment installation cost and schedule are assumed unmodified although SCS creates opportunities (macro-modules with pre-installed components; open top method ; etc.).

The direct cost ratios are based on SCHEDULE project learnings, which is more a technical pilot than a price demonstrator. Besides, the time acceleration stands for a FOAK performance. The single SCS mockup was compared to the average construction performance of dozens of identical reinforced concrete buildings by experienced civil companies. Improvements should be made by better manufacturing techniques for industrialization and learning-by-doing. The “best estimate” results could get closer to the “optimistic” ones for the NOAK.

The debate is not only the effect on capitalized cost or LCOE ; it should be also focused on how SCS can contribute to secure the construction schedule to avoid cost overruns and delays before commercial start-up, in order to control the WACC from lower risk perception. The point is that some recent new build reactors erected with Steel-Plates had to manage on the contrary years of delays, thereby canceling the acceleration objective and despite series effect (ex: Sanmen 1 & 2, Haiyang 1 & 2, Vogtle 3 & 4, Shimane). For the AP1000 Vogtle project, 46 of the 146 macro-modules (including preinstalled electromechanical components) were delivered with 6-18 months delays. Some on critical path stopped progression of the construction until delivery (ref. [1] ; [9]). Based on that observation, after computing 1000 probabilistic Monte Carlo simulations for 8 reactor architectures (AP1000, APR1400, EPR, ABWR, Holtec SMR, Nuscale SMR, BWRX300 SMR) from FOAK to 10-OAK considering the supply chain failure risk and human error, MIT demonstrated that smaller reactors were not more robust to construction risks, but on absolute vision the consequences of delays were drastically lower because of scale effect. On the other hand, the same scale effect makes the expected NOAK learning-by-doing rate is lower. Recommendations about SCS were (ref. [9]): *“technologies that reduce costs in the $10-$100/kWe range must be highly certain in the cost advantage and low in the deployment risk to be worth pursuing. For example, steel plate composites had only a marginal cost savings, but introduced significant volatility and risk into the shield building construction for the AP1000. However, the recommendation is not to shy away from innovation, but to lean into two types of innovation: (1) risk reducing innovation and (2) high-saving, high risk innovation”*. The French development program presently considers Steel Concrete Structures under the form of single civil elements of reasonable dimension instead of adventurous macro-modules, and the potential gain is in the 100-500$/kWe range.

## CONCLUSION

Claims supporting SMR economics (standardization, learning effects, cost sharing, construction acceleration and modularization) are *“difficult to quantify due to the lack of existing examples”* according to European Commission (ref. [21]). Our paper, focused on SCS construction techniques, is a first tentative to extrapolate the SCHEDULE pilot building feedback to the global scale of a reactor project. When considering in the equilibrium equation the SCS direct costs and time acceleration benefits, the target capitalized price cut ratio 0.92-0.94 that was suggested by independent authors looks achievable (see Figure 1 vs. Figure 7).

Accurate savings estimate finally depends on multiple parameters:

* the reactor size significantly changes the delivery schedule breakdown (civil works relative part), the associated expense timeline, and the costs breakdown. The relative LCOE reduction per removed construction month is quite similar in percentage for SMRs or large reactors, but the number of won months (and consequently the absolute LCOE reduction) is driven by the reactor size ;
* the selection of strategic areas where to replace reinforced concrete and steel liner by SCS (e.g pools) ;
* the rate of return (the higher is the cost of money, the higher savings are) ;
* the country design code when it exists for SCS (impact in 2nd order) ;

The calculated savings for SMRs are interesting in absolute value within the 100-500 $/kW reduction range, and SCS should contribute to secure the construction schedule compared to reinforced concrete. Meeting the SMRs competitiveness challenge will require accumulating in particular such kind of innovations in terms of design and modular construction, but always keeping special care on the risks assessment as reminded by MIT studies. The planning reliability and the economic model robustness against risks (delays, cost uncertainty, human error, etc.) have great value for a project sponsor. The past difficulties of the US nuclear industry with Steel-Plates concerned fully equipped macro-modules. On the contrary, our study considers simple civil works modules of small size in consistency with the European SCHEDULE demonstrator; that was a necessary effort to restore confidence.

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