

1 Evaluating Labor Needs for Fleet-Scale Deployments of Large vs.
2 Small Modular Light Water Reactors

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5 **Abstract**

6 The United States aims to achieve net-zero greenhouse gas emissions by 2050, which will require
7 the construction of over 500 GWe of new, firm, zero-emission electrical power, with at least 200
8 GWe met by new nuclear generating capacity. This study compares the labor requirements for
9 deploying 200 GWe of small modular light water reactors (SM-LWRs) and large modular light water
10 reactors (LM-LWRs) using the Nuclear Cost Estimation Tool (NCET). Results show that deploying
11 SM-LWRs, such as the 300 MWe SM-BWR (based on the BWRX-300) and 924 MWe MMNC (NuScale
12 Voygr) designs, would require a significantly larger total labor force compared to LM-LWRs like the
13 1,117 MWe LPSR (AP1000) and 1,350 MWe LM-BWR (ABWR) designs. Deploying 200 GWe of SM-
14 BWRs would necessitate a perpetual direct construction workforce of 116,904, nearly twice that of
15 LPSR (62,372) or LM-BWR (60,648). The analysis also found that the large modular LWR surrogate
16 designs exhibited a slightly higher ratio of offsite to onsite work compared to the SMR surrogate
17 designs, contrary to the purported advantage of increased offsite manufacturing for SMRs. Given
18 the immense scale of deployment required, the potential early learning advantages of SMRs are
19 largely offset in fleet deployment scenarios. The study concludes that LM-LWRs offer significant
20 advantages over SM-LWRs in terms of total labor requirements for large-scale nuclear
21 deployments.

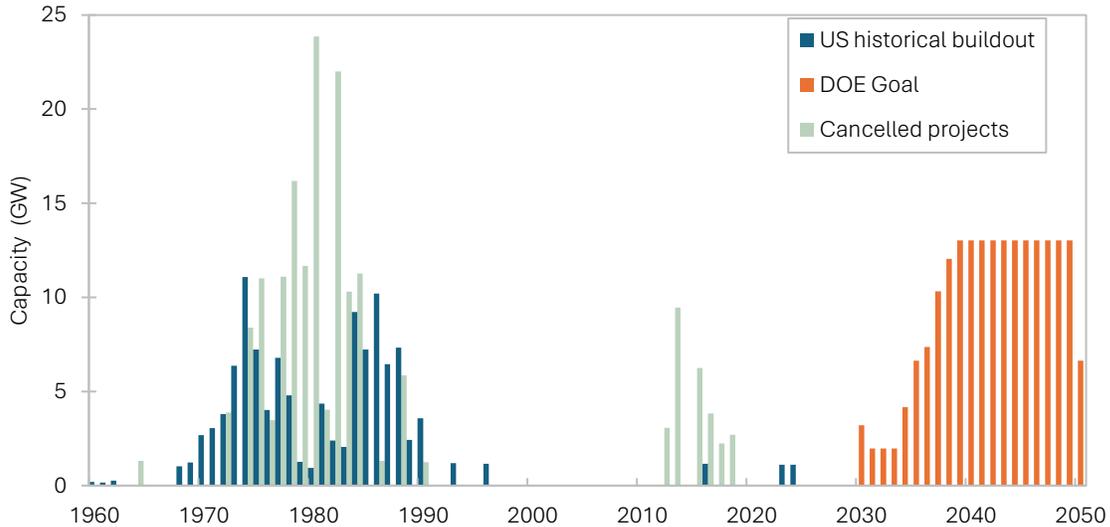
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26 **Introduction**

27 To achieve the United States' ambitious goal of reaching net-zero greenhouse gas emissions by 2050,
28 the U.S. Department of Energy (U.S. DOE) estimates that over 500 gigawatts-electric (GWe) capacity
29 of new, "firm" (i.e., non-intermittent and dispatchable) zero-emission electrical power will need to be
30 built. In its 2023 report, *Pathways to Commercial Liftoff: Advanced Nuclear*, the U.S. DOE estimates
31 that at least 200 GWe of this firm capacity must be met by the construction of new nuclear power
32 plants, with small contributions from potential uprates of currently operating plants [1].

33 To meet the DOE's 2050 target, the U.S. will need to achieve an annual deployment rate that
34 significantly exceeds the peak of its previous nuclear buildout that occurred during the 1970s and
35 1980s, shown in *Figure 1* [2]. For such a large and fast deployment to be successful, strategic tradeoffs
36 of the various reactor designs under consideration must be carefully evaluated.

37



38

39 *Figure 1. Annual capacity additions from commercial nuclear power in the U.S. by year of*
40 *commercial operation. Cancelled projects are by year of cancellation.*

41 Utilities, governments, and reactor developers are working earnestly to unleash this fleet scale
42 deployment. Ontario Power Generation made the final investment decision to proceed with
43 construction of the first BWRX-300 at the Darlington site in May 2025 [3]. The Tennessee Valley
44 Authority submitted a construction permit application for a BWRX-300 at the Clinch River site in
45 April 2025 [4]. Long Mott Energy, LLC submitted a construction permit application in March 2025
46 for 4 Xe-100 reactors from X-Energy [5], and Terrapower submitted a construction permit application
47 in March 2024 for Kemmerer Unit 1 [6].

48 A consistent challenge in the deployment of nuclear power plants is the large quantity of craft and
49 non-craft labor necessary to construct the plant [7]. Here we defined craft as trade labor, such as
50 ironworkers, welders, carpenters, etc., and non-craft as management, field engineering, quality

51 assurance and control, etc. The current short supply of workers in the U.S. construction industry and
52 associated trades makes labor recruitment particularly challenging [8]. In 1987, the U.S. DOE and
53 United Engineering and Constructors' Economic Energy Database (EEDB) estimated that 21.9 million
54 direct labor-hours are necessary to construct a large (1,144 MWe), generation II pressurized water
55 reactor (PWR) [9], and a more recent analysis estimated 17.7 million for a simplified advanced LWR
56 such as the AP1000 [10]. This figure excludes significant numbers of indirect labor hours, such as for
57 site supervision, quality assurance and quality control, and home office engineering services, as well
58 as hours of support provided by owner operator for oversight, site security, and project execution,
59 which cumulatively are of a similar magnitude. The EEDB estimated that FOAK projects have
60 approximately equal direct and indirect costs, suggesting that FOAK generation II PWR and
61 simplified advanced PWR projects are near 45 and 35 million total labor hours, respectively.

62 In Vogtle Construction Monitoring combined report 20 and 21, Georgia Power reported that the
63 construction of the two Westinghouse AP1000 reactors at Vogtle 3 and 4 performed 60 million labor
64 hours from 2015 through 2018 [11]. Extrapolating this figure through the entirety of the project,
65 including lost time during COVID, plant Vogtle consumed more than 150 million total labor hours,
66 of which we can assume approximately half, 75 million, were direct labor hours.

67 Multiple small modular light water reactor (SM-LWRs) designs have been proposed for the U.S.
68 market. NuScale's US600 50 MWe-based small modular reactor (SMR) is so far the only SMR to
69 receive a design certification from the US Nuclear Regulatory Commission (US NRC) [12]. A
70 purported advantage of SMRs is that their smaller size, coupled with their ostensibly highly modular
71 design, may allow for individual reactor builds that are faster than builds for large modular
72 Generation III and Generation III+ reactor designs such as Westinghouse's AP1000 PWR and GE-
73 Hitachi's ABWR [13].

74 Previous peer-reviewed analyses have compared the capital costs of SM-LWRs and large modular
75 light water reactors (LM-LWRs). Some studies have qualitatively suggested that SM-LWRs could
76 achieve equal or lower specific capital costs (i.e., capital costs per unit of nameplate electrical
77 generating capacity) compared to LM-LWRs [14,15]. However, quantitative meta-analyses and other
78 quantitative studies have not supported these findings [10,16]. These quantitative studies concluded
79 that while individual SM-LWRs are expected to have lower total capital costs per reactor or plant,
80 their specific capital costs are likely to be significantly higher than those of LM-LWRs [10,17]. To
81 date, no analyses have specifically estimated the differences in labor requirements between these two
82 classes of reactor designs for large-scale nuclear deployments, such as the deployment of 200 GWe of
83 nuclear power as called for by the U.S. Department of Energy.

84 **Materials and Methods**

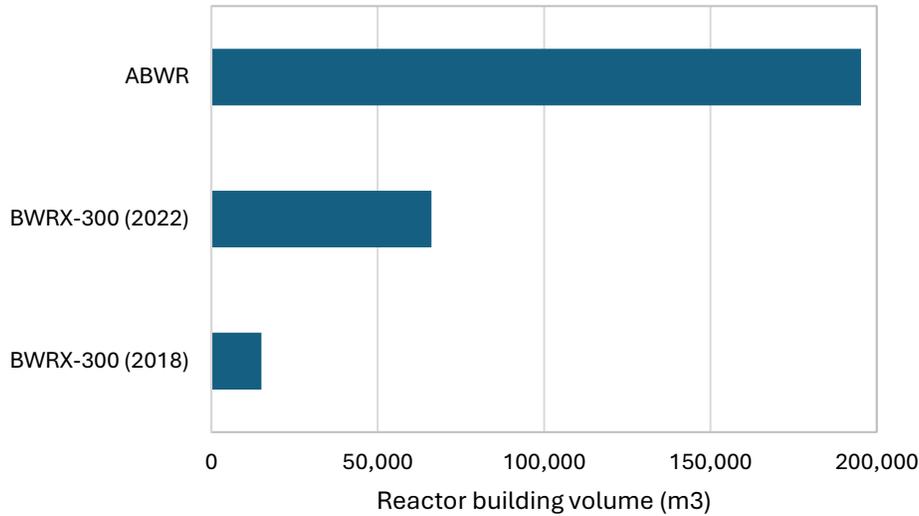
85 To conduct this analysis, we used the Nuclear Cost Estimation Tool (NCET), an open-source software
86 tool developed at the Massachusetts Institute of Technology (MIT). NCET estimates the direct capital
87 costs and direct labor requirements for the manufacturing and construction of 226 distinct structures,
88 systems, and components (SSCs) across various nuclear power plant designs, considering factors such
89 as SSC size and design, on-site versus off-site fabrication, and the use of modular construction. The

90 tool can also simulate learning effects as more reactor plants of a specific design are built, which may
91 lead to increased labor efficiency, schedule compression, and cost reductions over time. NCET
92 employs reference costs for each SSC based on previous work from the U.S. Department of Energy
93 and United Engineering, Inc.'s EEDB. A comprehensive description of the NCET tool, its
94 methodology, and its applications can be found in previously published works [10].

95 NCET cost and labor estimates are intended to serve as a useful point of comparison between
96 different reactor plant embodiments. They are not intended to be accurate estimates of future
97 realizations. As such, the labor requirement estimates in this work should be considered relative to
98 each other, not relative to estimates conducted outside of this work.

99 In lieu of proprietary design details, we used the surrogate conceptual reactor plant designs—based
100 on designs that are commercially available or under development—previously described in [10].
101 Apart from the SM-BWR, input parameters for NCET for all surrogate plants are identical to
102 previously published works. Table 1 serves as a reminder of the surrogate reactors, their commercial
103 basis, and the source material.

104 Since the first release of NCET, the BWRX-300 design has continued to evolve, with major changes
105 to the dimensions of the combined reactor-auxiliary building. GE-Hitachi released renderings of the
106 BWRX-300 in 2019 and 2024. The SM-BWR surrogate design as created in 2021 was a hybrid from
107 two sources on the BWRX-300: (1) the 2019 public version published in an IAEA status report [18]
108 and (2) a 2021 topical report submitted to the US NRC [19]. The 2021 version of the SM-BWR had
109 reactor building dimensions 29 meters in diameter and 47 meters tall. A more recent BWRX-300
110 topical report indicates the reactor building is 64.8 meters from the top of the basemat to the roof
111 [20]. When the outer diameter of the reactor building was 31.2 meters, the outer diameter of the
112 slurry wall for the embedded reactor was 36.7 meters, and the updated building diameter is 35.5
113 meters, so we estimate that the outer diameter of the slurry wall is approximately 40 meters [19,20].
114 These changes were likely the result of a combination of underestimation by Stewart and Shirvan and
115 design evolution. The other design parameters of the SM-BWR were unchanged. *Figure 2* shows the
116 increase in the estimated BWRX-300 reactor building volume from 2018 to 2022.



117

118 *Figure 2. Estimated reactor building volume of the 2018 and 2022 BWRX-300 designs compared to*
 119 *the reactor building volume of the ABWR. ABWR from the DCD, BWRX-300 (2022) from [20],*
 120 *BWRX-300 (2018) from [21].*

121 *Table 1. Surrogate reactors, corresponding commercial basis, net capacities, and source material.*

Surrogate Design	Base Design	Net Nameplate Capacity (MWe)	Reference
SM-BWR	GE-Hitachi BWRX-300	290	[20]
MMNC-77	NuScale 6x77 or 12x77	462 or 888	NuScale FDAA [22]
LPSR	Westinghouse AP1000	1,117	AP1000 DCD Rev. 19 [23]
LM-BWR	GE-Hitachi ABWR	1,350	ABWR DCD Rev. 4 [24]

122

123 *Modeling labor hours required for 200 GWe nuclear deployment*

124 To estimate the differences in labor requirements between SM-LWRs and LM-LWRs for large scale
 125 deployment, we modeled 200 GWe of deployment of each of the four selected surrogate reactor
 126 designs. Two of the selected designs were SM-LWRs (SM-BWR and MMNC-77); two designs were
 127 LM-LWRs (LPSR and LM-BWR). While it is unlikely that future nuclear deployment in the U.S.
 128 would consist of a single reactor or plant design, this analytical approach was selected to facilitate a
 129 direct comparison of the labor requirements of deploying each reactor design at scale.

130

Table 2. Strategies evaluated for deploying 200 GWe of new capacity.

	Net Power capacity (MWe)	Power Plants required for 200 GWe	Annual reactors deployed at 13 GW/year
SM-BWR	290	690	45
MMNC	888	226	15

LPSR	1117	180	12
LM-BWR	1350	149	10

131

132 We assumed that before each surrogate reactor design was deployed on a large scale, at least 10 plants
 133 of each design had been built, allowing for significant learning and optimization prior to widespread
 134 deployment. In other words, we used the 10th-of-a-kind (10-OAK) cost and labor estimates from
 135 NCET. In NCET, the first-OAK (FOAK) to 10-OAK cost and labor reductions are based on the
 136 between better- and median-experience nuclear plant construction projects in the 1980s [9]. This
 137 translated to a 37% reduction in labor hours from the FOAK estimate for all plants. The labor cost
 138 reduction can increase to 66% if the FOAK plant experienced typical modern nuclear cost overruns
 139 and delays due to supply chain issues, change orders, and human error [17]. Stewart and Shirvan
 140 define supply chain as timely delivery of factory equipment and modules, changes orders as changes
 141 to the design either already constructed or in-construction, and human error as mistakes that require
 142 rework. These elements are also described in detail in a report from the Nuclear Energy Agency [25].

143 The factory costs and associated labor hours for module production facilities were distributed over
 144 these first 10 reactors. While historical deployments of nuclear have not achieved their NOAK cost
 145 reduction targets, we hypothesize that any reactor plant deployed at the 200 GWe scale is likely to
 146 achieve 10-OAK cost reductions. The historical maximum build volume of any one reactor design is
 147 25 (the VVER-1000/320), and the build volumes proposed here are an order of magnitude larger,
 148 suggesting NOAK learning effects are possible [26].

149 The NCET tool is based on a set of cost scaling relations, and the parameters in these models are
 150 uncertain. Therefore, Stewart and Shirvan created a Monte Carlo version of NCET that samples from
 151 known possible values of these scaling parameters [17]. This methodology shows increasing
 152 uncertainty in cost and labor estimates the more a given reactor architecture deviates from the based
 153 architecture, a four loop PWR. In this analysis, we include both the deterministic and probabilistic
 154 estimates of labor hours in the results. The probabilistic bounds are the 95% interval of the Monte
 155 Carlo samples, and they do not include bias uncertainties or the risk of overruns or delays, so they are
 156 not confidence intervals. They are included to illustrate the precision of NCET.

157 It is important to note that neither SM-LWR reactor design modeled in this analysis has been built
 158 before. The LPSR surrogate design is based on the AP1000, of which 6 reactors have entered
 159 commercial operation. Similarly, the LM-BWR surrogate design is based on the ABWR, with 4
 160 reactors having entered commercial operation. The lack of real-world construction and operational
 161 experience for the SMR surrogate designs highlights the theoretical nature of the assumptions made
 162 in this analysis.

163 Results and Discussion

164 *Impact of BWRX-300 (SM-BWR) changes on labor hours and capital cost*

165 The updated SM-BWR reactor building dimensions increased the building volume by more than
 166 150%. The consequence of this change was an 11% increase in the total cost and a 19% increase in

167 the site labor hours. Table 3 summarizes these results. These numbers do not include the risk factors
 168 such as supply chain delays, design changes, and human error, which can drive FOAK costs even
 169 higher than is estimated in these initial FOAK calculations.

170 *Table 3. Updated SM-BWR cost and labor estimate results with the current reactor building design.*

Plant	Site Labor Hours (Ms)	Site Labor Cost (\$Ms)	Site Material Cost (\$Ms)	Factory Cost (\$Ms)	Direct Cost (\$Ms)
FOAK, 2021 NCET SM-BWR	7.3	375	150	622	997
10-OAK, 2021	4.6	235	118	431	666
FOAK, 2024 NCET SM-BWR	8.6	445	172	658	1102
10-OAK, 2024	5.4	279	135	462	741

171

172 *Labor hours required for 200 GWe deployment*

173 Our analysis found that large-scale deployment of SMR surrogate designs entails a substantially larger
 174 total labor-hour and construction headcount compared to a similar capacity deployment of large
 175 modular LWRs (*Table 4*). While NCET is intended only for relative comparisons between reactor
 176 plants analyzed within NCET, some benchmarking is possible. Black and Peterson estimated that a
 177 12-pack NuScale plant would bring 2000 construction jobs to Idaho [27], and the present estimate
 178 was 1676 direct workers per reactor which approximately translates to 2600 total staff when
 179 including indirect engineering, quality control, and management. A report from Jenson et al. cited a
 180 NuScale claim that 1600 jobs are created during construction [28].

181 The direct, onsite construction workforce required for a 200 GWe deployment of the SM-BWR
 182 design is nearly twice that of the LPSR or LM-BWR (*Figure 4*). The data in *Figure 4* does not include
 183 factory labor, which was also higher per unit capacity for SMRs. The significantly lower labor
 184 requirements of large modular reactors, in addition to their lower specific overnight capital costs (i.e.
 185 cost per unit of nameplate electricity generation capacity), favor large modular LWR designs over
 186 SM-LWRs for large-scale nuclear buildouts. Large scale nuclear deployment in a context of
 187 constrained labor supply would likely further exacerbate the cost differentials between these reactor
 188 types.

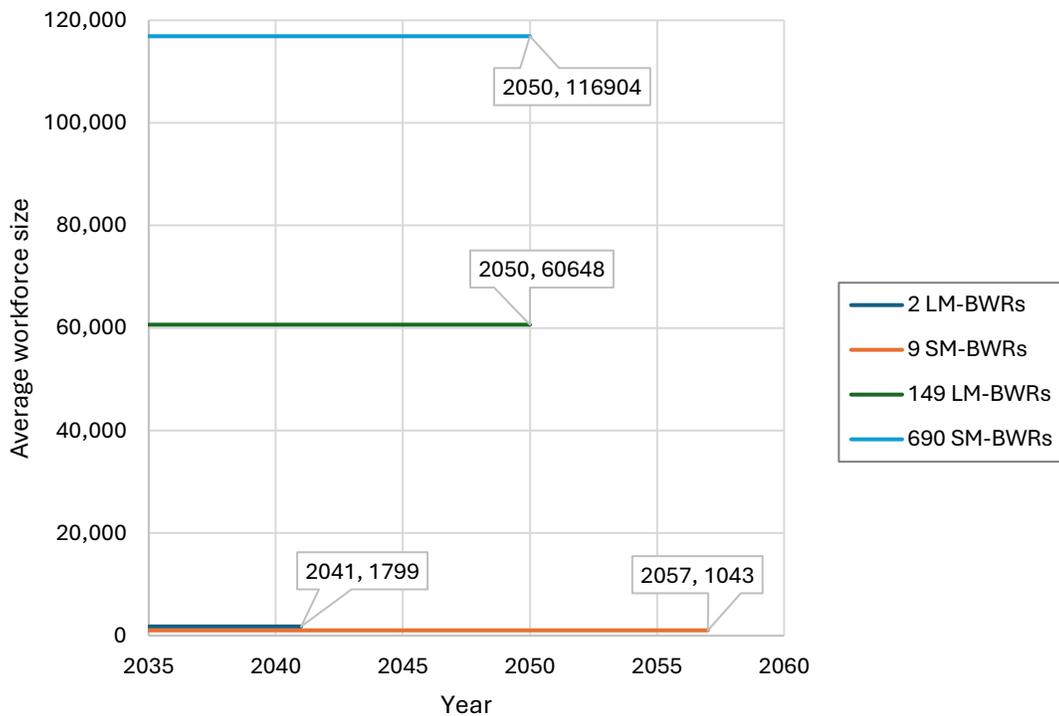
189 Note that this contrasts slightly with previous results comparing one large reactor to one small
 190 reactor under constrained labor markets where the single small reactor was more robust to labor
 191 constraints [29]. The previous work also compared equal capacity plants such as two large reactors to
 192 nine small reactors, but the nine-reactor case distributed the labor over a much longer construction
 193 period reducing the labor sensitivity for any one year. Figure 3 shows the difference between the
 194 previous analysis which was for sequential deployments to get to a 2.7 GWe capacity deployment,
 195 and the present analysis which is for 13 GWe per year of deployments over 15 years. In the present
 196 analysis, we are comparing the construction of a *fleet* of small reactors to a *fleet* of large reactors
 197 installed over a fixed time period. In this situation, the LM-LWR put less strain on the craft labor
 198 market. Our analysis suggests the incentives of a fleet advocate, such as the U.S. DOE, may differ
 199 from independent agents, such as utilities.

200 Our analysis suggests that the incentives of a fleet advocate, such as the U.S. Department of Energy,
 201 may differ from those of independent agents, like utilities. A fleet advocate is concerned with the
 202 overall deployment of nuclear power and may prioritize the option that minimizes the strain on the
 203 labor market across the entire fleet. In contrast, individual utilities may focus on the labor
 204 requirements and costs associated with their specific projects, which could lead to different
 205 preferences between SM-LWRs and LM-LWRs.

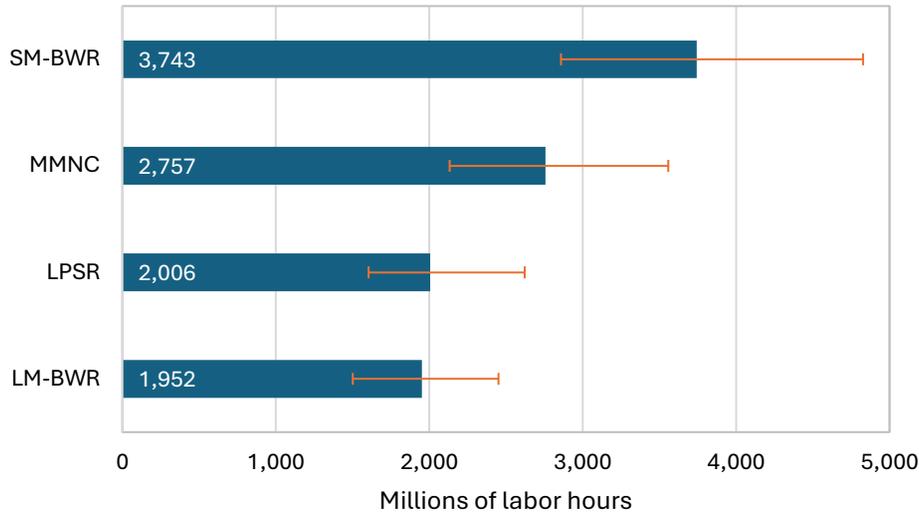
206 *Table 4. Labor hour and workforce requirements for the surrogate reactor designs.*

	10-OAK construction duration (high/low labor availability, in months)	10-OAK direct labor (millions of hours per plant)	Annual plants built at 13 GW/year	Perpetual direct construction workforce
SM-BWR	29/31	5.4	45	116,904
MMNC	34/54	12.2	15	85,867
LPSR	34/47	11.1	12	62,372
LM-BWR	37/58	13.1	10	60,648

207



208 *Figure 3. Average workforce size for a sequential deployment of 2 LM-BWRs and 9 SM-BWRs*
 209 *compared to parallel builds of ~34 LM-BWRs (149 total) and ~112 SM-BWRs (690 total) over 15*
 210 *years.*
 211



212
 213 *Figure 4. Total site labor requirements (with Monte Carlo sample bars) for a 200 GWe deployment of*
 214 *each reactor design*

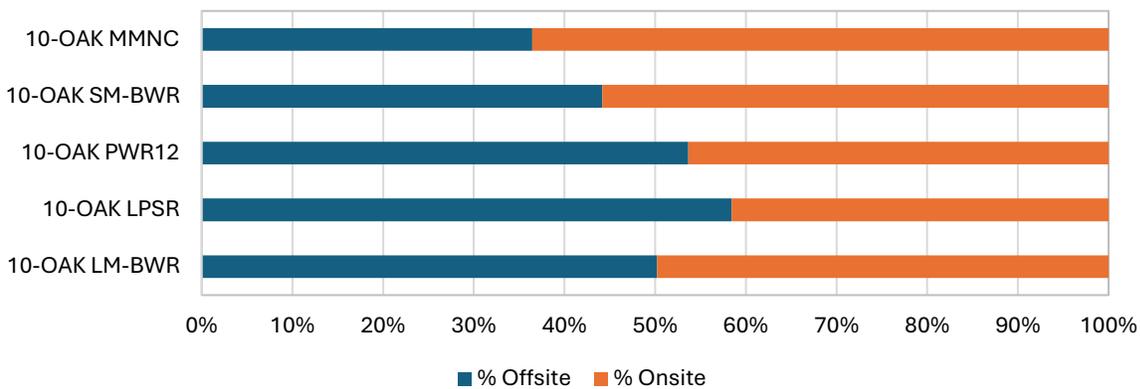
215 SMRs have a potential advantage over larger reactors because their smaller size allows for learning
 216 effects to be captured sooner, meaning the benefits of experience and optimization can be realized
 217 after building a smaller total capacity. However, for a large-scale deployment of 200 GWe, this
 218 advantage becomes less significant. The total capacity to be built is so large that it requires
 219 constructing a substantial number of reactor units, and fleet-wide learning effects will still be
 220 captured due to the sheer number of units being built, regardless of the individual reactor's size.

221 It is important to note, however, that SMR' smaller size may enable a higher number of individual
 222 units per plant site to be built. This, by enabling more on-site learning, may help facilitate more
 223 efficient deployment at individual sites. However, some sites are space constrained and large reactors
 224 may be a more efficient and cost-effective use of their land. Additionally, larger numbers of smaller
 225 power capacity units may stress the supply chain further. As noted by an MPR Associates report, an
 226 annual deployment of 3 NuScale 12-module plants would require nearly 600 control rod drive
 227 mechanisms which is almost 3.5X the number for the equivalent power capacity from AP1000s [30].
 228 Nevertheless, this phenomenon was not explored in this analysis, and further research is needed to
 229 quantify the potential benefits of increased on-site learning for SMRs compared to larger reactors in
 230 the context of large-scale deployment.

231 A purported deployment advantage of SMRs versus large LWRs is their ostensible ability to shift a
 232 larger portion of capital costs offsite to centralized manufacturing facilities (as opposed to onsite
 233 construction and fabrication). However, this potential advantage is not realized among the surrogate
 234 reactor designs we analyzed. Among the designs we studied, the larger surrogate designs exhibited a
 235 slightly *higher* ratio of offsite to onsite work compared to the SMR surrogate designs (*Figure 5*).

236 This result is counterintuitive, but it likely stems from the inherent difficulties in *proportionally*
 237 scaling down site civil works and site improvements with SMRs' scaled down nuclear islands. For

238 example, the 12x50 MWe NuScale Voygr reactor plant boasts a significantly *larger* seismic category 1
 239 building footprint than the AP1000 reactor plant, despite generating substantially less electrical
 240 power. As another example, the AP1000 was a design evolution of the AP600 which Westinghouse
 241 indicated was un-economic at the smaller size. Davis et al. stated the AP1000 was only an 11%
 242 increase in the cost of the AP600 but an almost 80% increase in power [31]. Similarly, the BWRX-300
 243 reactor building is ~1/3 the size of the ABWR reactor building but only outputs ~1/5 the power. This
 244 is because civil works and site improvements are predominantly onsite activities, the inability to
 245 proportionally scale them down likely offsets any potential benefits gained from increased offsite
 246 manufacturing of other structures, systems, and components (SSCs)—such as nuclear steam supply
 247 system SSCs—achieved through size reduction.



248
 249 *Figure 5. 10-OAK direct cost breakdown by onsite or offsite costs. Onsite costs include labor and*
 250 *materials. Offsite costs include factory equipment as well as large bore piping.*

251
 252 *Conclusion*

253 For the large-scale deployment of new nuclear power plants needed to achieve net-zero emissions in
 254 the United States by 2050, our analysis finds that large modular LWR designs offer significant
 255 advantages over small modular LWR designs in terms of total labor requirements. Due to the
 256 immense scale of deployment required—an estimated 200 GWe of new nuclear capacity—the
 257 potential early learning advantages of SMRs are largely offset, as substantial learning effects will be
 258 captured for both large and small designs simply due to the sheer number of units that must be built.
 259 The <40 month construction timelines for the first ABWRs confirm that rapid construction of large
 260 LWRs is possible with sufficiently ready and de-risked supply chains, designs, and workforces.
 261 Regardless of the reactor designs ultimately chosen, the labor requirements for such a rapid and
 262 extensive nuclear buildout will be immense, likely exceeding the current capacity of the domestic
 263 nuclear construction workforce and necessitating extensive planning and investment.

264 Given the preliminary nature of the SMR designs analyzed and the uncertainties around their
 265 ultimate labor requirements at scale, further analysis is needed to rigorously evaluate the various
 266 tradeoffs between SMR and large LWR designs. While our model relied on assumed learning effects,
 267 real-world experience with early SMR construction may reveal more potential for labor-saving

268 innovations. However, the substantial gap in total labor requirements between SMRs and large LWRs
269 suggests it is unlikely that learning effects would be sufficient to make SMR labor needs competitive
270 with those of large LWRs for a 200 GWe deployment. Ultimately, the choice of reactor design must
271 weigh multiple factors, and our findings highlight the importance of considering total labor
272 requirements in this decision-making framework.

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