# A tortoise approach for US nuclear research and development

In Aesop's fable, a swift hare races with a deliberate tortoise. In the end, the tortoise wins by taking a slow and steady approach. We argue that, given the economic constraints on US deployment of nuclear power, a 'tortoise strategy' is more prudent for US government nuclear R&D efforts.

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The role of nuclear power in a future low-carbon energy mix is uncertain. Some argue that rapid development of nuclear technology is the only way to reduce carbon emissions quickly enough to avoid a climate catastrophe[1,2]; others argue that nuclear power is inherently unsafe or that advances in renewable energy, storage and demand management will make it unnecessary[3,4]. A middle ground argues for investment in nuclear power as part of a balanced set of options for decarbonization[5–7]. Though wind and solar currently constitute the vast majority of growth in US non-fossil electricity generating capacity, aided by sharply reducing costs and market incentives, it remains unclear whether, at deeper levels of grid penetration, management of intermittent renewable sources will be possible without retaining significant backup generation, a role currently played primarily by natural gas-fired power. Simultaneously, China and Russia are moving forward in development and export of nuclear technologies, while US development efforts falter with significant cost and schedule overruns in recent attempts at new-build nuclear power plants[8]. Burdened with extensive regulation and longstanding negative externalities such as waste and perceived accident risk, current large light water reactors (LWRs) are not competitive in the US electricity market alongside cheap natural gas and renewables, a reality not projected to change for several decades[9]. Given this, what is the proper course for US government investments in nuclear research and development (R&D)?

Absent a dramatic change in nuclear economics or US energy policy (for example, a carbon tax or large development subsidies), the most likely time window in which conditions in the US electricity market might support substantial investments in the deployment of nuclear power is mid-century[9,10]. At that point, penetration of renewables may be high enough that management of intermittency will pose significant challenges as it has in nations such as Germany[5] and Ireland[11]. Additionally, aging natural gas and nuclear infrastructure will require replacement beyond 2040 — but natural gas without carbon capture and storage (CCS) may no longer be considered a 'clean' technology. Under these conditions, having nuclear options in competition with CCS, electricity storage and other low-carbon technologies would greatly enhance efforts to eliminate greenhouse gas emissions. To prepare, the US Department of Energy (DOE) should implement a new approach to nuclear technology R&D, investing in a 'nuclear tortoise': an advanced nuclear programme designed to be slow and steady, but to provide multiple technology options with high confidence so that commercial deployment is viable by mid-century. Even with this investment, there is no guarantee that nuclear power will be a major element in a non-fossil US electric grid. But without a sustained R&D effort that persists through economic and political cycles, the US will forfeit a nuclear option for the future, and that may make achieving low-carbon goals even more difficult, both for the US and the world.

## The hare approach

Large LWR plants continue to present massive challenges in terms of cost and safety perceptions. Development of smaller LWR designs has received significant R&D focus in the past 15 years and will continue, but it is unclear if these will succeed where large LWRs are failing, with limited gains in plant efficiency and still-unknown costs of construction. Many experts have thus recommended accelerating a long-envisioned transition to advanced non-LWR designs[12]. Proponents of non-LWR designs cite a manufacturing model (which would allow vendors to fabricate large portions of small modular reactors (SMRs) in factory-like settings in much the same way as other large, complex technologies, such as airliners, versus the civil engineering site construction model that is followed for large plants today), enhanced passive safety, improved efficiency, reduced waste generation and more flexible designs that can efficiently follow electricity load, making them more compatible in a future grid with deep penetration renewable[13]. Efforts have been ongoing to develop these technologies, with recent industry reviews identifying over 40 companies developing advanced concepts[14]. The more aggressive of these efforts are being developed by companies following what we refer to as the 'hare approach' — working to rapidly develop their chosen systems and become the first movers in a new age of nuclear development. Among them are companies such as TerraPower, an effort funded by Bill Gates; Terrestrial Energy, a Canadian company that recently completed the first phase of the Canadian Nuclear Safety Commission's vendor design review; and OKLO, promoters of a smaller design that may open non-electric energy markets to nuclear power.

Though companies following this hare approach are at various stages of readiness, they have common attributes. First, most have compressed — and thus riskier — R&D timelines. These timelines often posit technical maturation rates that exceed estimates of the US National Labs and many assume the ready availability of high-assay (5–20%) low-enriched uranium. Second, their business plans emphasize 'Nth-of-a-kind' cost estimation and reliability assumptions, potentially understating the scale of the hurdle facing first-of-a-kind development[15]. Third, their optimistic R&D and cost expectations suggest deployment horizons of 10–15 years. While perhaps technically feasible for the most advanced of the concepts, this is far earlier than the likely mid-century window for broad US deployment. Fourth, with few exceptions, hares have marginal capitalization and little-proven ability to manage commercialization

**Table 1 | The tortoise approach to nuclear R&D**

| Key features |
|---|
| Mid-century timeline to build multiple demonstration projects |
| Enhanced government testing and support facilities |
| US$200–250 million in dedicated, protected annual government R&D funding |
| Technology development timelines managed with outside advisory panel support |
| Extended demonstration period to ensure readiness for commercialization |
| Government surge funding support for demonstration plant construction |
| Revised regulatory guidelines for non-LWR designs |
| Option for international teaming |

or mass deployment. Finally, hares are betting on a more flexible and rapid regulatory regime — something that must still be developed[16].

It would be tremendous news if these companies can achieve a breakthrough and become commercially viable while still addressing the challenges noted above. Unfortunately, though some hares may succeed in near-term R&D efforts, most lack the readiness to support rapid, large-scale deployment, and virtually all count on significant government support. Most require support for material testing and qualification and many assume a government role in funding demonstration reactor development. But US government efforts have lacked focus and funding. Despite over US$2 billion in R&D expenditures in the past 20 years, government efforts have failed to lead to the deployment of a single advanced reactor technology[17]. National testing facilities are dated or non-existent, programme support fluctuates and research is halting in areas needed to achieve readiness for commercialization such as advanced manufacturing[17,18]. To meet aggressive hare deployment timelines, massive near-term increases in funding would likely be required to support multiple concepts, prompting calls from some experts for early technology down-select[19]. This raises significant questions regarding the viability of hare efforts.

## The tortoise approach

Considering the challenges noted above for hares, the current state of research, and the most likely timeline for future market openings, US government-funded nuclear research should follow a 'tortoise approach'. This revised R&D strategy may still boost companies following the hare approach, but de-emphasizes their near-term temporal goal. A nuclear tortoise would support a portfolio of nuclear technologies to ensure the development of options for commercial nuclear deployment in the high renewables grid mix expected by mid-century. This strategy recognizes that time is required for technology maturation and ensures a comprehensive DOE research approach that addresses all critical aspects of deployment including demonstrated reliability, safety, proliferation resistance and affordability. It also allows due diligence in addressing key factors of waste management and public perception that have plagued acceptance of the technology in the US. While hares may make rapid R&D progress when they are engaged with the task, most are unlikely to sustain their enthusiasm for the full duration of the race. Some will encounter unexpected technical obstacles, some will exhaust their funding and some will simply pause to rest. Meanwhile, a nuclear tortoise will continue to make steady progress.

A tortoise technology policy includes numerous aspects, some of which we outline here (see also Table 1). A first aspect is a mid-century R&D maturation timeline with a goal to build multiple demonstration units across multiple technologies. While development efforts may be staggered due to varying levels of technical readiness, all viable technologies should initially be considered. Another aspect is a robust demonstration plant assessment period to ensure reliability and safety. This period should include significant vendor participation to ensure readiness for transition to commercialization. Two significant assumptions in hare business cases are a high capacity factor (actual electrical energy output over a given period of time compared to the maximum possible output) and significant savings from factory-style modular manufacturing. A longer demonstration period will help reduce risk in these areas through better understanding of limiting factors in construction, maintenance and operations. Recurring technology development assessment will also be needed, using actively managed R&D roadmaps with performance gates to prevent dead ends. Guidance from an outside review group, perhaps from the National Academies, would help ensure consistency. At the same time, there needs to be an early emphasis on refocusing R&D funding toward manufacturing-centred research, in an effort to reduce the largest cost driver for nuclear deployment: site development. Finally, government funding support levels will have to be large enough and steady enough to bring multiple promising technologies to and through the demonstration phase by mid-century. This last factor brings a significant challenge: as noted in a recent review of DOE follow-through in nuclear R&D, politically driven churn has been a significant hindrance[18]. Long-term programme funding, akin to that followed for US defense programmes or long-term NASA efforts, will be required.

The R&D funding model for a nuclear tortoise would include base and variable components. Base funding costs would fall within a nominal profile of US$200–250 million per year spread across three to four projects. These base funds would be designed to help technologies reach readiness for demonstration. Additional surge funds to support demonstration plant development would be required as each technology reaches the appropriate state of readiness. This model envisions tiered funding such that one technology may take the lead for a number of years but all would retain some level of support. Projected base funding levels would be in keeping with the recent increase in the DOE Office of Nuclear Energy budget, but execution to meet development goals would require refocusing of funding lines and a commitment to substantial surge funding for demonstration efforts. As climate impacts increase or carbon-reduction goals are not achieved, funding that supports the most advanced of the new technologies can accelerate. In total, based on cost estimates from recent US National Lab studies and author-updated estimates from the International Generation IV Forum Technology Roadmap, the nuclear tortoise could cost US$5–6 billion by mid-century to complete lab system/sub-system testing for three to four concepts, and at least three to four times that amount to complete demonstration efforts for multiple designs[20,21]. These costs are not exorbitant in the context of climate mitigation insurance, and serve to reduce risk and insure against a dramatic halt in climate mitigation efforts and a collapse of the nuclear option, should it prove imperative. Financial incentive/support models can be developed to buttress initial US deployments. This could include siting support similar to the ongoing effort to host the initial NuScale light water SMR at a US National Lab facility. Ultimate commercialization of the technologies will be the responsibility of industry.

## Avoiding dead ends and mitigating risks

Some will note the enterprise risks inherent in the tortoise approach. These include widening of an industrial base gap in the

US; loss of standards development and non-proliferation leadership as China and Russia expand development; and potential for shortfalls in human capital by mid-century. Arguably, this is already occurring as other nations move forward in development and export, while US new builds stall, US vendors win fewer export contracts, and the advanced fission research enterprise lags. These and other critical issues must be addressed and managed through long-term planning but are significant considerations in the existing development paradigm. With new designs, human capital development already requires attention given the almost universal LWR focus of today's operators. Ultimately, needed capacity can be grown in time given the likely 5+ year new design build cycles. For other issues such as influence in safety, safeguards and non-proliferation regimes during the hiatus in US market deployment, US leadership in international organizations such as the International Atomic Energy Agency and World Association of Nuclear Operators will help ensure continued relevance, but will require vigilance. A consistently funded, cutting-edge research effort is also likely to forestall any significant degradation in international influence and would mitigate the potential of blindly following technology development choices of international competitors. Additionally, while the tortoise approach is not an internationally focused effort, collaborative approaches should be encouraged. Though it may be unpalatable to some in the geopolitical realm, consideration of international teaming must be an option to buttress influence until the US development effort we propose here bears fruit.

It is possible that a tortoise approach will result in China or Russia leading the way in advanced nuclear power, ceding near-term development leadership in this critical area. But as noted above, the US does have other avenues to maintain influence, and even with a significant press by private US vendors, competition with state-owned or sponsored companies will make it very challenging to retain the same level of enterprise leadership that US and western nations have previously enjoyed. Ultimately, massive, rapid government investment in advanced nuclear power cannot overcome market fundamentals. For the US to maintain relevance and achieve success in nuclear power, investments must be aligned with the most likely timescale for widespread US nuclear deployment. Until that time, US government efforts should remain focused on a historical strength — technical research.

## Smart and steady wins the race

Vendor hare development efforts have incentive to move quickly to gain first-mover advantage, but the role of government is different: it must ensure that the risk is mitigated. A steady tortoise effort is best suited to US market realities. In a best case, companies with adequate private funding may be able to reach demonstration stages earlier with some government tortoise support and deploy sooner in supportive international markets. If these technologies meet all future deployment needs, then all the better. They will provide the needed nuclear technologies with less government investment required. But by taking a measured approach, the tortoise assures that such technology is available when needed, even if many hares drop out of the race. This is true even if the technology is ultimately not required to play an outsized role in the US energy sector. It is, after all, a global mitigation effort. ❐

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### Competing interests

The authors declare no competing interests.