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Plug and Play Hydrogen Microgrid

prepared by Jingbo Wang and Jie Zhang
University of Texas at Dallas
800 W Campbell Rd, Richardson, TX

Funded by the National Security Innovation Network (NSIN) under Army Contracting Command (ACC) Contract Number W911NF-20-F-0050 with GXM Consulting LLC

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Disclaimers

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14. ABSTRACT

Hydrogen storage technology and small modular reactors (SMRs) are gaining popularity due to environmental concerns. Furthermore, both forms of clean energy offer exceptional mobility and stealth capability in a combat environment. In this report, we describe various hydrogen storage options, with a focus on transportation applications, and their current state of development and associated products. Compressed hydrogen is a widely used technology today. Chemical and adsorption storage have great potential for storing hydrogen as well. However, many challenges remain, and research must be conducted to improve their characteristics, such as storage capacity, slow release kinetics, storage temperature, and pressure conditions. In the advanced reactor technology review, we discuss options for microreactors and SMRs that have the potential to meet military requirements, as well as typical development timelines. Finally, we utilize existing open-source libraries such as "Hybrid" and "VirtualFCS" in the Modelica language and use the Dymola 2022x to simulate SMR power and hydrogen generation in normal mode and fuel cell supply power in stealth mode. From this review, it appears that hydrogen and SMRs have great potential for military use, and a series of preliminary simulations indicate that they can be used to generate electricity to meet microgrid demand.

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1. Hydrogen Storage Introduction and Literature Review

Hydrogen has recently gained significant attention as a next-generation fuel due to the fact that it has the highest energy per mass of all fuels. Hydrogen produced from renewable energy sources is highly renewable and sustainable because only water is produced in the process of electricity and heat generation. However, hydrogen has a very low energy per unit volume, a drawback from using it pervasively. Therefore, advanced storage methods are required to increase its energy density in order to make it usable.[1] With further research, it may be developed as a future fuel.

In this literature review, we present a variety of hydrogen storage options with a focus on transportation applications, as well as their current state of development and related products. Section 1.1 introduces the US Department of Energy's (DOE's) Hydrogen Storage target. Section 1.2 provides an overview of hydrogen storage technologies, including their advantages and disadvantages; technologies currently under investigation, such as hydride and liquid organic hydrogen storage; projects and products for transportation; and potential military transportation.

1.1 DOE Hydrogen Storage Target

The DOE's hydrogen storage targets for 2020, 2025, and ultimately are shown in Table 1.[1] Figure 1 provides a more intuitive way to illustrate the DOE's hydrogen storage target together with the capacity of various storage methods. Cryo-compressed and liquid hydrogen are approaching the stipulated target. At present, only the chemical carriers of liquid organic hydrogen carrier (LOHC), methanol, and liquid ammonia meets the DOE's capacity requirements for a hydrogen storage system.

Table 1 DOE hydrogen storage target (reproduced from DOE[1])

Storage parameter	Unit	2020	2025	Ultimately
System gravimetric capacity				
Usable, specific-energy from H_2	kWh/kg	1.5	1.8	2.2
(net useful energy/max system mass)	(kg H_2/kg system * 100%)	4.5%	5.5%	6.5%
System volumetric capacity				
Usable energy density from H_2	kWh/L	1	1.3	1.7
(net useful energy/max system volume)	(kg H_2/m^3 system)	30	40	50

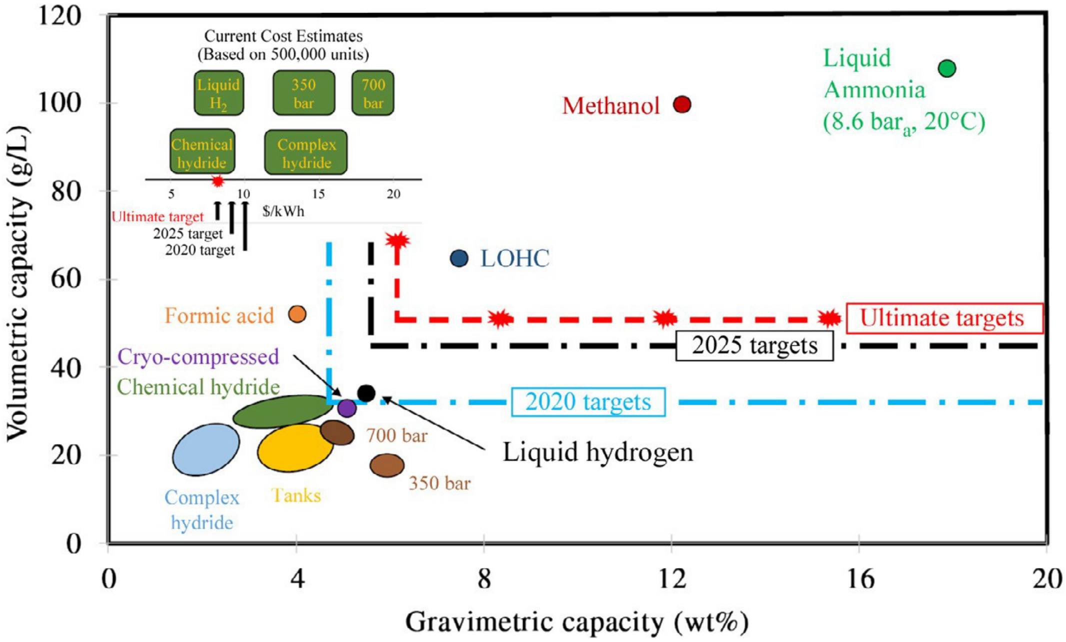


Fig. 1 **Hydrogen storage methods: volumetric vs. gravimetric capacity**[2]

1.2 Hydrogen Storage Methods Overview

This section focuses on viable storage options for mobile applications; options that have been ruled out are not discussed in this evaluation. Hydrogen storage technologies can be broadly classified into three main categories: 1) physical methods (in the form of compressed gases, cryogenic liquids, or cryogenic compressed gases), 2) chemical methods (also known as material-based hydrogen storage, in metal hydrides or liquid carriers), and 3) hybrid methods. Figure 2 depicts an overview of hydrogen storage technologies.

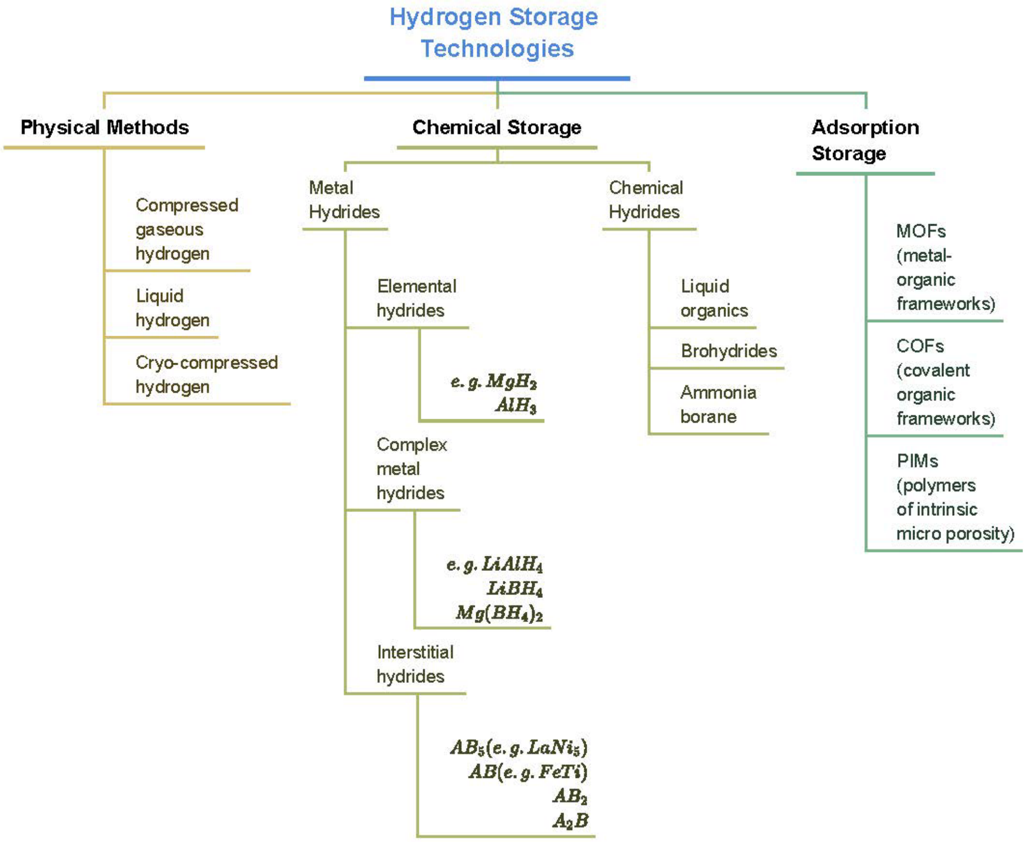


Fig. 2 **Hydrogen storage methods**

Onboard regenerative materials are considered to be a critical factor in fuel cell vehicle market penetration.[3] The current state of hydrogen storage technologies is summarized in Table 2. The hydrogen storage capacities of the various methods range from 1.9 to 6.8 wt% (gravimetric capacity) and 13 to 39 g/L (volumetric capacity). Overall, chemical hydrogen storage technologies are outperformed by physical hydrogen storage methods.[4]

Solid-state storage materials have the lowest storage capacity. Complex hydrides can only store 1.9%–2.5% of hydrogen. C-sorbent (activated carbon sorbent) is a physisorption substance capable of holding approximately 3% hydrogen by weight. Chemical storage materials (e.g., chemical hydrides in Table 2) perform marginally better than solid-state storage materials. Chemical hydrides have a hydrogen content of 2.6%–3.5% by weight. A compressed hydrogen storage tank at 70 MPa can hold up to 4.5 wt% hydrogen. In terms of gravimetric storage capacity, liquid hydrogen and cryo-compressed hydrogen are two of the best methods.[4]

Table 2 Current status of the hydrogen storage technologies (reproduced from Chen et al.[8])

Hydrogen storage method		Gravimetric capacity (wt%)	Volumetric capacity (g/L)
Physical storage	Compressed (350 bar)	2.8–3.8	16–18
	Compressed (700 bar)	2.6–4.4	19–25
	Liquid	4.8–6.8	31–39
	Cryo-compressed	5.0–5.8	28–38
Chemical storage	Complex hydride	1.9–2.5	16–28
	Carbon (porous)	2.9–3.1	13–15
	Chemical hydride	2.6–3.5	22–29
Adsorption storage	Carbon (porous)	2.9–3.1	13–15

1.2.1 Physical Storage

1.2.1.1 Compressed Hydrogen Storage

For automotive applications, hydrogen is compressed to 700 bar for sufficient range (>450 km) and fast refueling (3 min); the cost of compressing H_2 to this level consumes approximately 10% of the energy content.[5] Type IV pressure vessels, for example, are the lightest of the pressure vessels, making them ideal for vehicle applications where they can withstand high pressures of up to 1000 bar. However, they are prohibitively expensive due to the significant cost contribution of carbon fiber, which is estimated to be approximately 75% of the cost of storage vessels.[6]

The technical evaluation of storage tanks with pressures of 350 and 700 bar revealed that both types of tanks did not meet the final DOE requirements. The cost of compression is one of the disadvantages of compressed gaseous hydrogen storage. The compression effort required to reach a hydrogen pressure of 350 and 700 bar is 12% and 15% of the hydrogen, respectively. The cost of compression is predicted to be even greater when the energy penalty of compression and cooling is taken into account.[7]

Despite the drawbacks of compressed hydrogen storage, gaseous storage is currently the most commercially viable solution. It is the only technology that has been commercially implemented. Among the automotive applications, vehicles models include Toyota Mirai, Hyundai Tucson, and Honda Clarity all use Type IV hydrogen compression containers at 350 and 700 bar. The proton-exchange membrane fuel cells (PEMFC) system in Toyota's commercial fuel cell passenger car Mirai has an energy density of over 350 Wh/kg, while the power density and volumetric density have reached 2.0 kW/kg and 3.1 kW/L, respectively, and the vehicle uses a 70-MPa hydrogen storage vessel with a storage tank that has a hydrogen storage density of 5.7% by weight and a volumetric hydrogen storage density of 29 g/L. A single hydrogen fuel replacement takes roughly 3 min to complete.[8]

1.2.1.2 Cryogenic Hydrogen Storage (Liquid Hydrogen)

Storing hydrogen as a liquid increases its volumetric density. The basic requirement for storing liquid hydrogen (LH2) is to reduce its temperature to –253 °C, which is the boiling point of equilibrium hydrogen at ambient pressure.[9] At the boiling point of hydrogen and at atmospheric pressure, the theoretical volumetric density of liquid hydrogen is 70 g/L, whereas at room temperature, the volumetric density of compressed hydrogen at 350 and 700 bar is 24 and 40 g/L, respectively.[2,10] To maintain hydrogen below its boiling point, it is essential to design a storage system with effective thermal insulation that minimizes the heat transfer between storage tank and environment. Additionally, liquid hydrogen tanks are usually not designed to withstand internal pressure, but to contain cryogenic liquids. Since the heat transfer from the ambient to the liquid increases the pressure inside the tank, hydrogen is allowed to leak through the pressure relief valve.[11,12]

Notwithstanding the increased volumetric density of liquid hydrogen storage, the liquefaction energy penalty and boil-off losses are the drawbacks of this storage method.[4] To preserve hydrogen at the cryogenic temperature, cooling must be used. It is an energy-intensive process that consumes 25%–40% of the energy content of hydrogen, compared to 10%–15% energy loss during hydrogen compression.[2] Once the hydrogen pressure in the tank reaches about 1 MPa, any excess hydrogen must be removed, and this excess hydrogen, which is not used by the vehicle, is referred to as boil-off loss. The "dormancy period" is the time between when the vehicle is parked and when the venting process begins. A longer period of dormancy is preferable.[4] The boiling rate, which can reach 0.4% every day, depends on the thermal insulation as well as the container's size and shape.[13] The state-of-the-art tank designs have a dormancy period of 3 days; in addition, dormancy can be further improved by applying innovative cooling methods.[14] When considered in combination with boil-off losses, the overall cost of liquid hydrogen storage can easily surpass the cost of gaseous hydrogen storage. Currently, liquid hydrogen storage is only attractive for short-term storage (e.g., space applications) due to the aforementioned limitations.[13]

With regard to the storage tank materials for liquid hydrogen, several materials are currently used or in the perspective directions, such as stainless steel, aluminum alloy, titanium alloy, and cryogenic composites.

While composite materials have a significant advantage in being lightweight, hydrogen permeation is the key bottleneck of composites. At present, there still exist many technical problems that have not been solved. Potential future research and development of liquid hydrogen storage and transportation container materials mainly include the following directions: 1) the establishment of a database of mechanical properties in conventional low-temperature materials (e.g., stainless steel, titanium alloy, and aluminum alloy) in the liquid hydrogen temperature range; 2) the development of new low-temperature materials with high performance and low cost; and 3) research on the basic theory and technology of fiber-reinforced composites.[15]

BMW AG hydrogen vehicles (e.g., BMW Model: Hydrogen 7, H2R, 750hL, 745i[16]) have been a well-known deployment of liquid hydrogen storage in automotive applications. Aluminum was primarily used in the storage vessel to reduce weight. However, because of dormancy and insulation design, storage efficiency varies greatly depending on automotive applications (i.e., driving habit). Furthermore, charging the liquid hydrogen necessitates a "cold finger" connection point with helium purge to cool the transfer line to 20 K, resulting in significant thermal and hydrogen loss. The success of liquid hydrogen storage is ultimately determined by insulation, the vessel, and liquefaction infrastructure efficiency and design.[17]

1.2.1.3 Cryo-Compressed Hydrogen Storage

Research in physical hydrogen storage has now shifted to cryogenic compressed hydrogen, which is a combination of compressed hydrogen storage and cryogenic hydrogen storage. A notable disadvantage of compressed hydrogen storage is the large volumes and high pressures required. In addition, one of the challenges of cryogenic hydrogen storage is the inevitable boil-off losses. The target of the cryogenic compressed hydrogen is to address the challenges of both storage methods.[2]

Unlike hydrogen liquefaction, cooling hydrogen to low temperatures at high pressures reduces the high energy penalty associated with liquefaction. With a cryogenic tank, the dormancy period can be greatly increased. Since evaporated hydrogen can be stored in the high-pressure tank for a longer period of time, the heat transfer into the tank becomes less important.[4]

According to a technology assessment,[18] cryogenic compression hydrogen storage systems have the potential to meet the DOE ultimate target for system gravimetric capacity, the mid-term target for system volumetric capacity, and the target for hydrogen loss during dormancy periods under certain minimum daily driving conditions. The cryogenic compression hydrogen storage system is expected to enhance the gravimetric and volumetric capacity by 91% and 175%, respectively, while reducing the mass of the carbon-fiber composite material by 46% and the system cost by 21%. Furthermore, with the tank initially filled to 85%, the dormancy period could be extended to 7 days without losses.[2] The disadvantage is that the technology has not achieved the required manufacturing cost and well-to-wheel efficiency.[18]

In 2012, the automotive manufacturer BMW reported a prototype cryo-compressed hydrogen technology. However, the availability and cost of infrastructure are still major hurdles for this storage method, hence limiting its viability.[2] With more infrastructure and cost reductions, cryo-compression hydrogen storage technology is promising.

1.2.2 Chemical Storage

1.2.2.1 Metal Hydrides Hydrogen Storage

Metal hydride hydrogen storage, compared to conventional methods of compressed and liquid hydrogen storage, has the potential to provide lower containment pressures and higher volumetric densities, which offers the possibility of obtaining better well-to-power efficiencies through the use of material-based systems.[19]

Metal hydrides can be classified into three groups: intermetallic hydrides, binary hydrides, and complex metal hydrides. Intermetallic (or interstitial) hydrides, in which hydrogen occupies interstitial spaces within metal alloys, are considered low-temperature hydrides. The hydrogen storage capacities of AB5 (e.g., lanthanum-nickel alloy [$LaNi_5$]), AB2, A2B, and AB type intermetallic alloys are limited to less than 2 wt% due to the limitations arising from the crystal structure and unit cell volume, but indicate a relatively fast hydrogen absorption/desorption kinetics.[2] Among the binary hydrogen storage, magnesium hydride (MgH_2) and aluminum hydride (AlH_3) are studied the most. The drawbacks of MgH_2 are the slow hydrogen uptake/release kinetics and the high temperature required for hydrogen desorption, and AlH_3 synthesis requires high temperatures and extreme pressure (>1000 bar), reducing their suitability and efficiency for practical hydrogen storage.[2] Complex hydrides, in which hydrogen covalently bonds to a metal to form a multi-element anion that combines with another metal(s) through ionic interactions (e.g., lithium aluminum hydride [$LiAlH_4$], sodium aluminum hydride [$NaAlH_4$], calcium aluminum hydride [$Ca(AlH_4)_2$], lithium borohydride [$LiBH_4$], magnesium borohydride [$Mg(BH_4)_2$], and zinc borohydride [$Zn(BH_4)_2$]). They have attracted much attention because of their theoretical gravimetric hydrogen contents. The main barriers to using these materials for hydrogen storage are their high stability, the requirement for high decomposition temperatures, and the lack of reversibility. To overcome the problems, a variety of strategies have been investigated, including alloying with other elements, catalyst addition, nanostructuring, nanoconfinement, and formation of composites. These properties would likely result in faster kinetics and/or reduce the enthalpy or activation energy required for hydrogen desorption.[2]

Hydrogen storage in solid metal hydrides is both safe and small, and various studies on the subject are now underway. Metal hydride research has made considerable strides. However, various challenges remain unresolved, one of which is the necessity to increase the gravimetric capabilities of inter metallic hydrides. The existing metal hydrides storage system with hydrogen release at moderate temperatures produces just a modest amount of useable hydrogen: generally 1–2 wt%.

Chemical hydrogen storage, which combines atomic hydrogen and another material, can increase the hydrogen storage capability. The kinetics of absorption and release, however, can be slow. Second, due to the large activation energy required for the release of hydrogen, high temperatures are typically required, which can result in irreversible hydrogen uptake. Therefore, the present focus is on enhancing the chemical hydrogen storage materials' thermodynamics, kinetics, and hydrogen absorption/release cycle capabilities.[2]

There are a few projects that are working to make metal hydrogen storage on automobiles a reality. One example is in the mining business, where fuel cell vehicles are used. The Hydrogen South Africa (HySA) Systems Competence Center has developed a metal hydride hydrogen prototype for a heavy-duty fuel cell utility vehicle (including forklifts). The tank is assembled from several metal hydride cassettes made of stainless steel tubing embedded with perforated copper fins and filled with AB_{2}– and AB_{5}–type hydride forming alloys and expanded natural graphite. The tank can supply more than 2 h of hydrogen to a fuel cell stack operating at 11 kWe (H_2 flow rate of 120 NL/min). The tank refueling time ($T = 15–20$ °C, $P(H_2) = 100–50$ bar) is approximately 15–20 min.[20] Commercial 3-ton forklift with metal hydride hydrogen storage takes approximately 6–15 min to refuel.[21]

As mentioned in a review paper,[22] metal hydride-based storage has the greatest potential for storing hydrogen due to it is highly safe and practical, and has beneficial features. The challenges are still associated with the storage capacity, low-temperature absorption, and release kinetics. Research is still needed in storage safety while refitting the hydrogen energy storage systems, as rapid refitting leads to a rise in container temperature, which may lead to tank failure.

1.2.2.2 Liquid Organics

Liquid organics hydrogen storage can be defined as organic molecules capable of storing and releasing hydrogen through reversible catalytic hydrogenation reactions to store and release hydrogen. Due to their straightforward approach to handle hydrogen, LOHCs have lately piqued attention in onboard hydrogen storage applications. By using a catalyst at high temperatures, it has been proved that LOHCs can reversibly store hydrogen.[2] A typical LOHC has a theoretical hydrogen storage capacity of 6–8 wt%, which is relatively low when compared to other chemical hydrogen storage materials (e.g., AB of 19.6 wt%). More research work is required on LOHC methods, particularly on toxicity, thermal stability, safety, and mass production/regeneration methods.[23]

1.2.3 Adsorption Storage

In the adsorption storage of hydrogen, hydrogen molecules are bound to the surface of the pores of the materials through physical interaction (physisorption), which involves weak van der Waals forces. Researchers have recently considered relatively new classes of adsorbent materials for hydrogen storage, such as metal organic frameworks (MOFs), covalent organic frameworks (COFs), and intrinsically microporous polymers (PIMs). Physisorption-based storage has several advantages over chemisorption-based storage, including fast hydrogen adsorption/desorption kinetics, complete reversibility, and long-term stability. In general, the hydrogen storage capacity of porous materials is strongly dependent on the surface area and pore volume of the material accessible to hydrogen molecules. High hydrogen storage capacity can only be achieved at low temperatures (typically 77 K) and high pressures due to the weak interaction between hydrogen molecules and the surfaces of these materials. At room temperature and pressure, hydrogen adsorption capacity is very low (<1 wt%).[2]

2. Small Modular Reactor (SMR) Literature Review

The modularization concept is a key feature of SMRs. Typically, it refers to methods adapted from more established sectors like the automobile, shipbuilding, and aerospace. These methods combine quality and productivity gains from serial factory production, component standardization to the extent practical, and easier onsite assembly of preassembled modules.[24]

The SMRs are well suited for remote and off-grid locations, and can enhance military security and capabilities with resilient energy supply and less dependency on constant and costly diesel fuel. Over the approximately 70 ongoing advanced reactor projects in the United States, both SMRs and microreactors offer an innovative technology, which holds a special promise for the US military.[25] The SMRs usually range from 20 to 300 MWe, and the microreactors are typically less than 20 MWe in size. The road map of deploying the microreactors at a domestic DOD facility is planned to be ready by December 31, 2027. Several microreactors products produced by companies such as General Atomics, NuScale Power LLC, Oklo Inc, Ultra Safe Nuclear Corp (USNC), and X-Energy LLC are aligned with the DOD's needs for energy security and resilience, and on the pipeline for demonstration phase between 2025 to 2027. Some of them will be demonstrated at chosen DOD locations such as Alaska and Idaho.[25,26]

The DOD has initiated Project Pele to develop 1–5 MW (MWe) power range of mobile and safe microreactors, with the DOE's support at its Idaho National Laboratory.[27] The DOD has assigned three teams (BWX Technologies, Inc., Westinghouse Government Services, and X-energy, LLC) to design the microreactors for military use, which are possibly later to be selected to develop prototypes for the DOD.[28] The nominal deployment time of a microreactor is 7 years, including license application, Nuclear Regulatory Commission (NRC) licensing, construction, and startup upon entering the contract. An exemplary deployment timeline is illustrated in Fig. 3 based on entering the contract with the DOD in the third quarter of 2019.

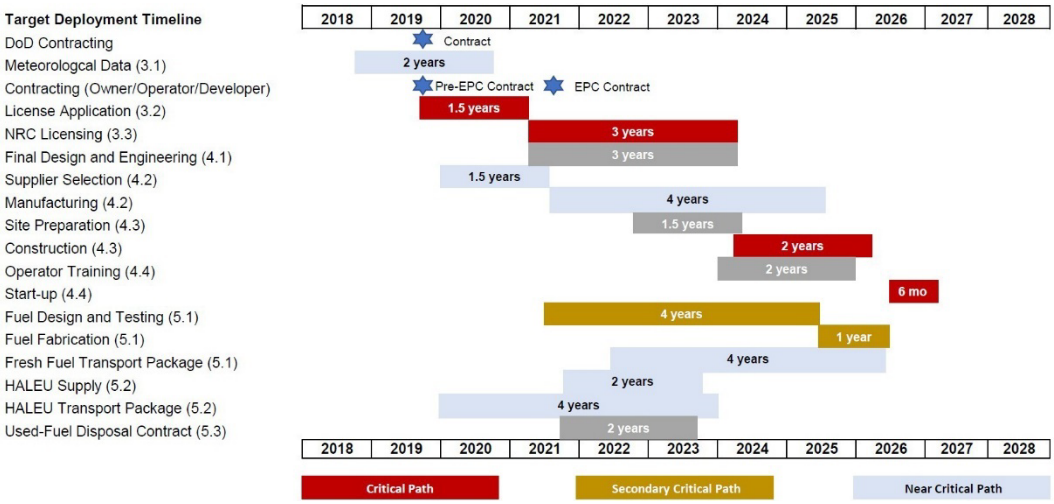


Fig. 3 **DOD target of SMR/microreactor deployment timeline (reproduced from Nichol[29])**

Another program that run through The Under Secretary of Defense for Acquisition and Sustainment aims to develop 2–10 MWe range SMRs/microreactors, which is planned to be tested in the 2023 timeframe at a DOE site.[27] If testing out of the pilot projects goes smoothly, NRC licensed reactors will be demonstrated on a "permanent domestic military installation by 2027."[27]

According to the listed planned/existing microreactors products in Table 3 and the SMR Book,[30] the Westinghouse eVinci microreactor does not require refueling for years and easy to transport.[31] They are possible to provide both electricity and heat at the same time,[25] which are benefit characteristics for military use.

Table 3 Microreactor characteristics of existing products

Developer	Product name	Microreactor scale	Technology	Refueling period (years)	Fuel type
Westinghouse	eVinci	2–3.5 MWe	Heat → pipe cooled	>10	TRISO or another encapsulation
Nuscale	NuScale Power Module (NPM), → reduced NPM	1–10 MWe	Heat pipe reactor	>10	Single-unit NPM: <5% U- 235; Reduced size NPM: HALEU fuel
Oklo → Power LLC	AURORA	1.5 MWe	Fast → spectrum reactor	≤20	Metal fuel
Ultra-Safe Nuclear Corporation	Micro Modular Reactor (MMR)	5 MWe	High → temperature gas-cooled reactor → / microreactor / → nuclear battery	≤20	FCMTM → or → TRISO graphite / Hexagonal
X-Energy	Xe-Mobile	1 MWe	N/A	>3	TRISO fuel
BWX Technologies	BWXT Advanced Nuclear Reactor (BANR)	50 MWt	High-temperature gas → reactor (HTGR)	5	TRISO fuel
Radiant Nuclear	N/A	1 MWe/Unit	N/A	8	Helium coolant
Toshiba Energy Systems Solutions Corporation	MoveluX	3–4 MWe	Heat-pipe cooled → and calcium- hydride moderated reactor	≤15	Silicide (U_3Si_2) / Hexagonal
Centrum vy´zkumu Rˇeˇz	Energy Well	8 MWe	Fluoride high temperature reactor, → pool type	7	TRISO
Urenco	U-Battery	4 MWe	High-temperature gas-cooled micro nuclear reactor		TRISO / Hexagonal

The SMR technology can be categorized as 1) integral/compact pressurized water reactor (iPWR), 2) high-temperature gas cooled reactors, 3) molten salt reactors, and 4) liquid-metal cooled fast reactors.

- The iPWR is trending in recent SMR technology development, which integrate the main components of the primary coolant system within the reactor’s pressure vessel. The benefit of such a design is that it compacts the reactor and its containment, and eliminates large-size piping. The iPWR provides enhanced safety margin, and offers potential to expand the use of safe, clean, and reliable nuclear energy in a broader applications. There are currently 11 types of iPWR under different development phase.[32]
- High-temperature gas cooled reactors improve plant thermal efficiency while operating at a low pressure. In these reactors, Triple coated isotropic (TRISO) ceramic particle fuel is typically used to withstand high temperatures and provide a large heat transfer surface.

- In the molten salt reactors, the fuel is either incorporated into the coolant as a molten salt (e.g., actinide fluorides) or used as a solid fuel coolant. Either concept allows for high-temperature operation at near-atmospheric pressure.
- Liquid-metal cooled fast reactors cool a reactor with a molten liquid, and it offers high heat removal capacity and relatively high temperature at a low pressure. In this design, monitoring the coolant flow is required to detect any flow blockage.
- The organics-cooled reactor is currently absent in the SMR designs.[33]

In addition to the microreactors listed in Table 3, we have selected the following SMR products from the SMR Book[32] and indicated their characteristics in Table 4, which could also be suitable for military use. Further assessment is necessary for evaluation with detailed military use requirement.

Table 4 SMR potentially suitable for military use

Developer	Product name	Rating (MWe)	Development → Status
Hydromine → Nuclear → Energy, Luxembourg	LFR-TL-X	5 / 10 / 20	Conceptual design in progress
OKBM → Afrikantov, → Russian Federation	RITM-200M	50	6 prototypes available
JAEA Consortium, Japan	GTHTR300	100-300	Pre-licensing basic design completed
UNIST, Republic of Korea	MicroURANUS	20	Pre-conceptual design
SINAP, CAS, China	smTMSR-400	168	Pre-conceptual design
Kairos Power, USA	KP-FHR	140	Conceptual design in progress
Elysium Industries, USA	Molten chloride salt fast reactor (MCSFR)	50 / 200 / 400 / 1200	Conceptual design

The LFR-TL-X product developed by the Hydromine Nuclear Energy is an innovative concept encompassing a family of very small modular reactors (vSMRs) cooled by molten lead; its compactness benefit for transportation makes it suitable for microgrid and Naval propulsion applications. Both KP-FHR and MCSFR are designed to have cost competitive and low-emission electricity, and be transportable via road. Energy Well is mainly intended for remote areas as a long-term source of electrical energy and heat source, and is designed with a focus on being transportable; its components can fit in ISO containers and reactor containers. For security reasons, there are also products for underground installation in the SMR portfolio such as MoveluX and MMR. The underground installation needs to be susceptible to underground hazards such as flooding, ground shifts, and so on.

As a base-load source of power with load-following capabilities, nuclear energy sourced from SMRs or microreactors could meet needs of remote operations and provide flexible integration with variable renewable energy sources. Deploying SMRs/microreactors offers opportunities to fulfill both electricity and heat demand.[32] Concerns about climate change and the intermittent nature of renewable resources have also motivated the integration of SMRs with renewable energy sources to consolidate the benefits of renewables with the dependability of nuclear energy. SMRs as a flexible baseload supply and in hybrid configurations with renewable energy sources could provide a beneficial synergy between these clean energy options.[24]

3. SMR and Hydrogen-Based Microgrid Simulation

3.1 Simulation Overview

SMR and hydrogen-based microgrid energy generation is gaining popularity for localized energy production due to its clean form, safe standalone, and off-grid operation. Concurrently, as discussed in the previous section, the energy industry is developing various types of SMRs and shifting toward green resources. On the research front, efforts have been underway to analyze the ability of SMRs to meet microgrid power needs and test the SMR integration with other energy resources in order to optimize the deployment of integrated energy systems (IESs) based on usage requirements.

Physics-based modeling can greatly improve simulation accuracy when evaluating microgrid performance. Given the multi-domain interactions in IESs, the Modelica language[34] is an appropriate tool for model development and control infrastructure design. A supervisory controller oversees the physical system, which is driven by appropriate control mechanisms on valves and pumps. In these models, conventional proportional-integral-derivative (PID) controllers are used, which are known to be reliable and have simple control strategies.

During the project timeframe, we have performed preliminary studies based on existing models. In our simulation work, we have leveraged component models in the Modelica framework from the Hybrid Library[35] developed by the Idaho National Laboratory (INL) and Virtual Fuel Cell System (VirtualFCS) Modelica Library[36] developed by SINTEF, and both are open-source libraries.

The models we used in this study are briefly described here. The SMR, Steam Manifold, Balance of Plant, Hydrogen Production, Switch Yard, Electrical Grid, and Supervisory Control Block are from the Hybrid Library. The fuel cell system model is used from the VirtualFCS library.

SMR: The SMR model developed using the Modelica language is based on a NuScale natural circulation SMR power module, which is an integral pressurized water reactor (IPWR) with a nominal thermal power of 160 MWt and a capacity of 50 MWe to the electric grid. The primary system consists of a feed water inlet at the bottom of the helical coil steam generator and a steam exit at the top of the steam generator.[35]

Steam Manifold: The energy manifold is designed as a fluid diversion module, which is extended to multiple sub-modules via a series of pipes. In our study, we used the Steam-Manifold L1 boundary module for our integrated energy system, which allows the entry and exit of "n" sub-modules with no control valve because the control strategy resides in the sub-module.[35]

Simple Balance of Plant: The Balance of Plant model consists of an ideal steam turbine model, a condenser, feed-water heater, and several valves which direct the steam either to turbine or to the condenser.[35]

Switch Yard: The purpose of the switch yard is to distribute electricity among subsystems, including the grid. In our case study, we have only connected the switch yard to the grid.[35]

Electrical Grid: Currently, the electrical grid assumes an ideal grid as an infinite sink. In another word, it is assumed that the grid consumes all generated electricity. Equivalently to proper scaled electrical grid, the grid demand is passed via the supervisory control module in our simulation setup, which serves as the control demand to the Balance of Plant for electricity generation.[35]

Industrial Process—Hydrogen Production: The hybrid repository consists of hydrogen production through high-temperature steam electrolysis (HTSE). In solid oxide electrolytic cells (SOECs), HTSE uses a combination of thermal and electrical energy to split water into hydrogen (H_2) and oxygen (O_2). This is simply the reverse operation of SOFCs. Under this assumption, the HTSE unit within the Modelica framework is specifically designed for integration with a light water reactor system and has the necessary components sized to allow for steam-side preheating.[35]

Fuel Cell System: The FuelCellSystem package consists of a FuelCellStack module and a FuelCellSubSystems module for controlling hydrogen, air, and coolant feeds into and out of the fuel cell.[36]

The following three scenarios have been studied: 1) Scenario I (normal mode): SMR with Balance of Plant to fulfill microgrid electricity demand; 2) Scenario II (normal mode): SMR with surplus energy for hydrogen production; and 3) Scenario

III (stealth mode): hydrogen and fuel cell storage to fulfill microgrid electricity demand.

3.2 Scenario I (Normal Mode): SMR with Balance of Plant to Fulfill Microgrid Electricity Demand

Scenario I depicts a typical operating scenario in which the SMR supplies power to the microgrid. The SMR generates heat energy that flows through the energy manifold; all steam entering the manifold is diverted to the balance of plant (in this case). The first 24 h of the power curve from the HYBRID library (timeSeriesData.txt, scaling down 10 times to match the SMR capacity) were used as a daily profile to direct the simulation process, during which the average demand for electricity was 22.4 MW, ranging from 0.6 to 41 MW. The supervisory control model uses this profile to simulate the microgrid demand in order to control the turbine control valve and turbine bypass valve from the BOP to meet the power demand. The simulation layout in this scenario is depicted in Fig. 4.

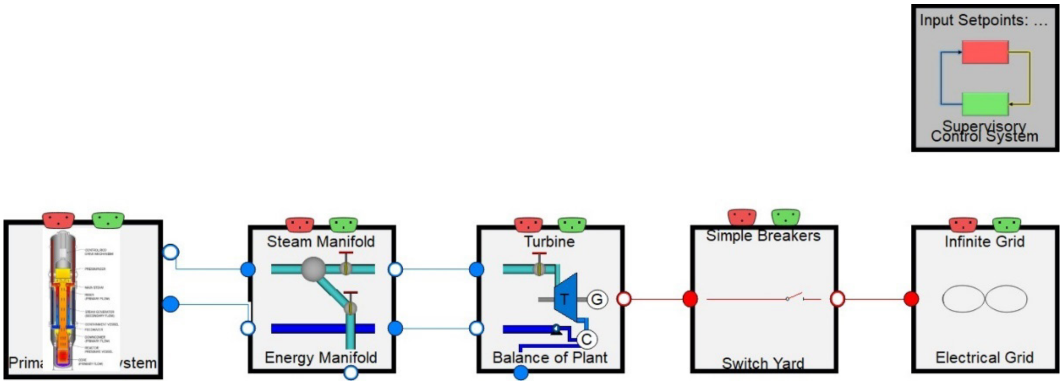
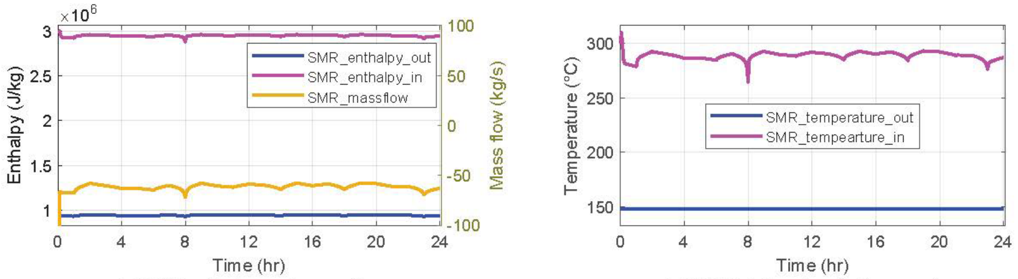
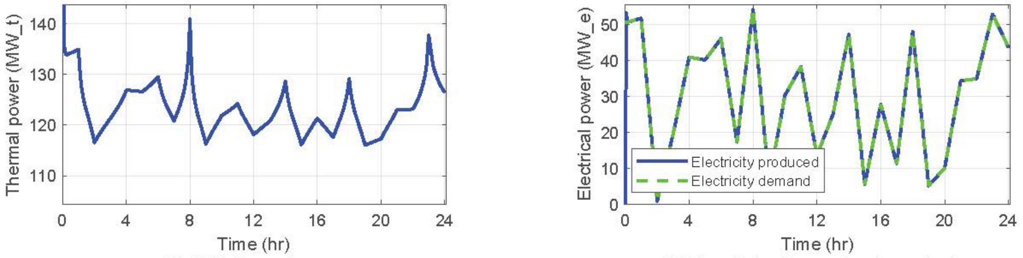


Fig. 4 Scenario I: SMR to directly fulfill the microgrid electricity demand

In Fig. 5, the upper subplots depict the mass flow rate of the SMR with an average flow rate of 61 kg/s, an inlet specific enthalpy of 2.9 e6 J/kg, an outlet specific enthalpy of 9.4 e5 J/kg, an output operating temperature of 290 °C, and an input operating temperature of 148 °C. The power demand is interpolated from the hourly curves in the two graphs in Fig. 5. The SMR's maximum output power is approximately 50 MWe, and increasing the number of SMRs will meet the higher power demand.



(a) SMR enthalpy and mass flow (b) SMR inlet and outlet temperature



(c) SMR thermal power (d) Electricity demand and production

Fig. 5 **Results of scenario I: SMR to directly fulfill the microgrid electricity demand**

3.3 Scenario II (Normal Mode): SMR with Surplus Energy for Hydrogen Production

In this case study, we present a scenario in which the SMR generates thermal energy to meet the microgrid electricity demand while also producing hydrogen (Fig. 6). As in Scenario I, we ran a 24-h simulation to simulate daily electricity production. By leveraging the existing models, the simulation was built using a four-loop power plant, which is available in the Hybrid library. This nuclear power plant has a nominal thermal power of 1,600 MWt and an electricity capacity of 500 MWe. We have leveraged ten SMRs in total to satisfy the electricity demand. Figures 7 and 8 depict the production of electricity and hydrogen, respectively.

Figure 7 depicts a nuclear power plant with a mass flow rate of 886 kg/s, an inlet specific enthalpy of 2.7 e6 J/kg, an outlet specific enthalpy of 1 e6 J/kg, an output operating temperature of 285 °C, and an input operating temperature of 185 °C. The hourly curves in the lower two graphs interpolate the power demand. Nuclear power plants can generate up to 500 MWe of electricity and can meet peak demand. Regarding hydrogen generation as shown in Fig. 8, the output enthalpy of steam entering the hydrogen production module is 2.7e6 J/kg, the return enthalpy is 9.6e5 J/kg, and the mass flow rate is 10.5 kg/s. Figure 7c depicts the electricity consumed from the grid, while Fig. 7d depicts the hydrogen production rate of 0.32 kg/s.

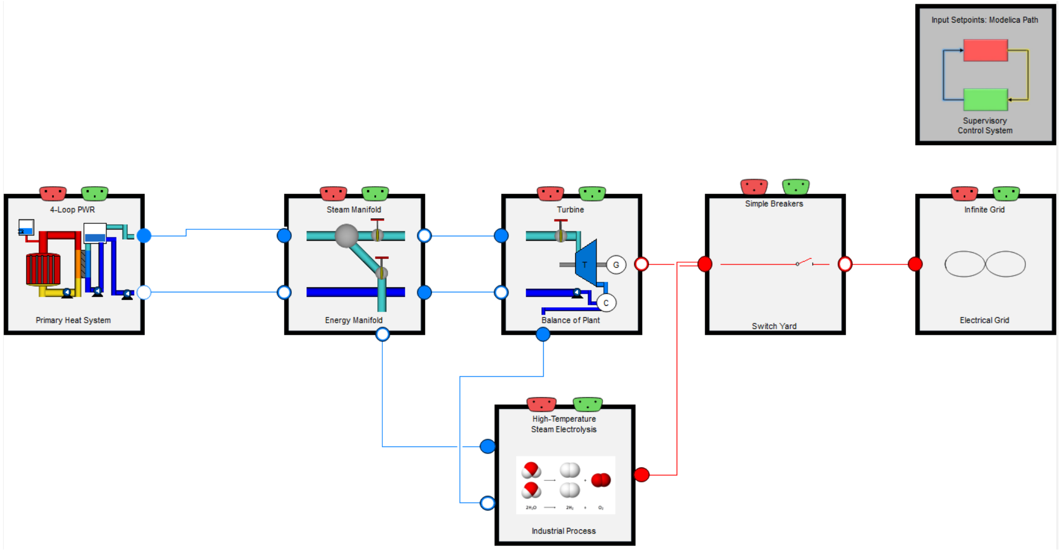
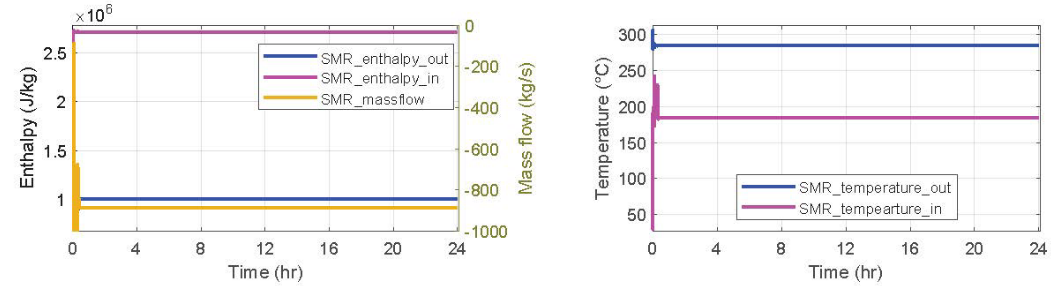
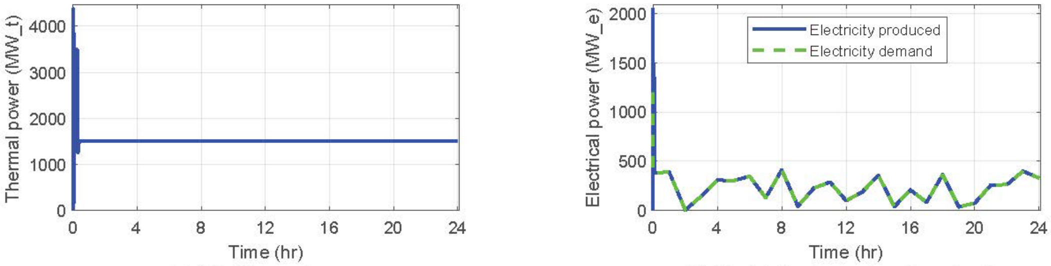


Fig. 6 Scenario II: SMR to fulfill the microgrid electricity demand and produce hydrogen with surplus energy



(a) SMR enthalpy and mass flow

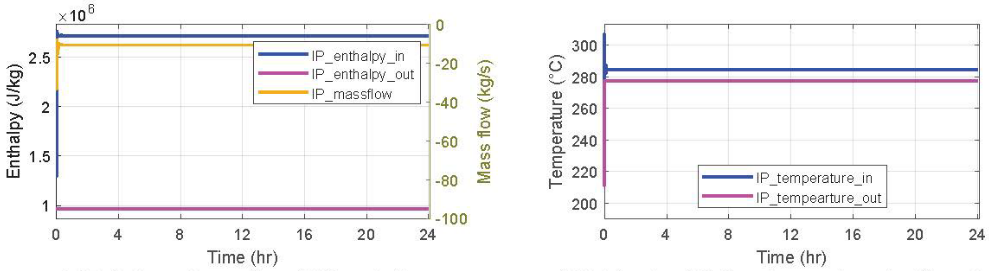
(b) SMR inlet and outlet temperature



(c) SMR thermal power

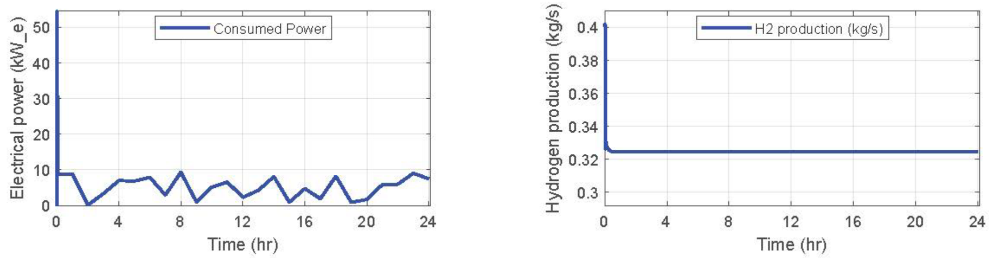
(d) Electricity demand and production

Fig. 7 Results of scenario II: SMR to fulfill the microgrid electricity demand



(a) Enthalpy and mass flow of H2 production

(b) Inlet and outlet steam temperatures for H2 production



(c) Consumed electricity for H2 production

(d) H2 production speed

Fig. 8 Results of scenario II: SMR to support hydrogen production

3.4 Scenario III (Stealth Mode): Hydrogen and Fuel Cell Storage to Fulfill Microgrid Electricity Demand

The purpose of this scenario is to demonstrate the idea that a number of hydrogen-based fuel cells can generate the total electricity to meet the demand of the microgrid (Fig. 9). The hydrogen could be transported off site. This scenario assumes that electricity is produced in a stealth mode. Therefore, hydrogen is assumed to be already charged for the fuel cell system. Within the project timeframe, we utilized an existing open source fuel cell library for proof of concept.

In this case setup, the grid electricity usage is an input to the meter as the fuel cell discharge demand. In the simulation, we use the same power profile as in Scenario 1 and scale it to match the capacity of the fuel cell system. A current source was used in the simulation setup to simulate the fuel cell discharge current based on the power demand and the filtered fuel cell voltage. Due to the limitations of the existing fuel cell, the simulation was run for a time period of 6 h. The SINTEF fuel cell model was developed to simulate a fuel cell vehicle with an assumption that the hydrogen is stored in a 350-bar compressed hydrogen tank. The system parameters are summarized next. In future studies, the fuel cell system will need to be properly configured, and modeling the actual hydrogen storage and fuel cell system techniques is required.

- Fuel cell stack mass = 42 kg
- Rated current = 450 A

- Hydrogen tank volume = 0.13 m^3
- Hydrogen tank pressure = 350 bar

In order to run the profile on a hydrogen fuel cell system, the electricity demand is scaled down by a factor of 1/1800. As shown in Fig. 10, the system follows a scaled current demand. The fuel cell model is quite small and does not have the capacity to power a microgrid. The required power demand can be met by increasing the capacity and number of fuel cells.

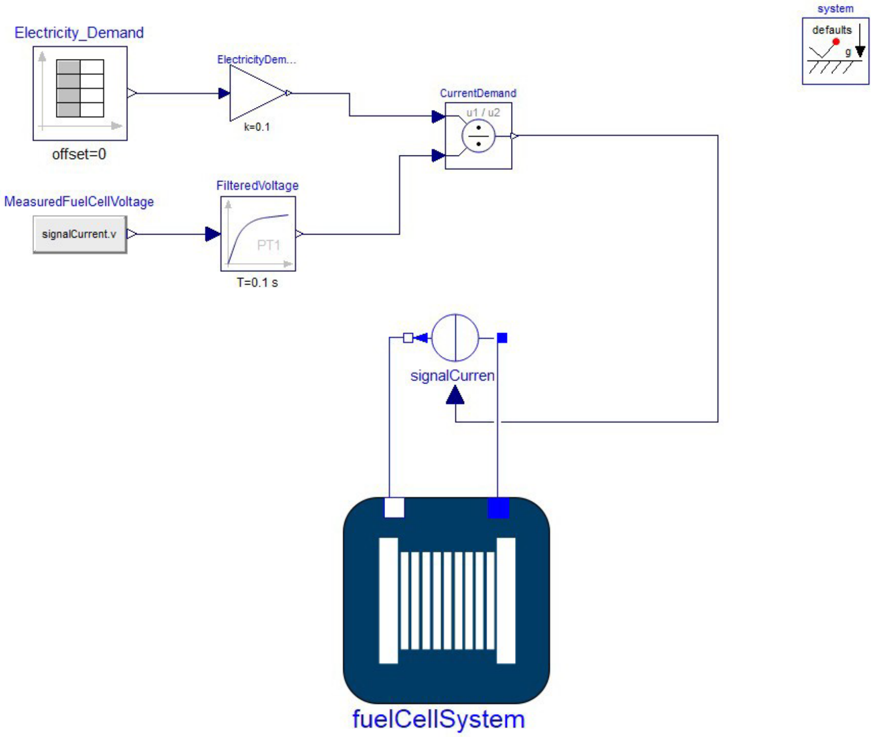
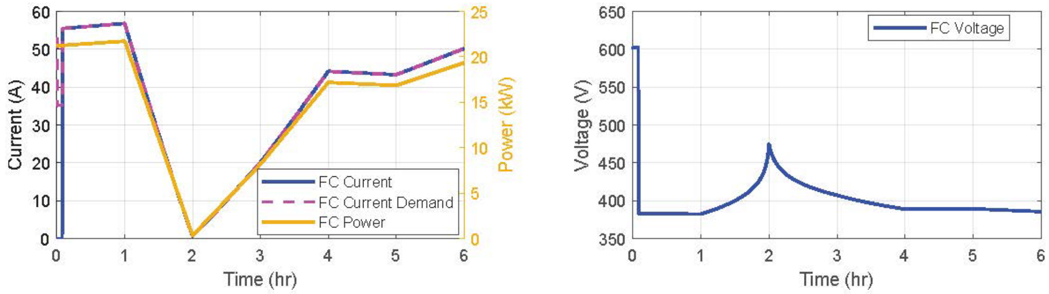


Fig. 9 Scenario III: Hydrogen fuel cell system to fulfill the microgrid electricity demand



(a) Fuel Cell Current and Power

(b) Fuel Cell Voltage

Fig. 10 Results of scenario III: Fuel cell to satisfy the microgrid electricity demand

4. Conclusion

In this technical report, we discussed the various hydrogen storage technologies and the ongoing development of SMR products in the literature. Compression and cryogenic hydrogen storage technologies remain the most advanced methods of hydrogen storage to date. Recent research has focused on absorption materials and metal hydrides for hydrogen storage, and significant progress has been made in hydrogen storage technology. However, more research and development are still required before hydrogen can be used in a wide range of applications. Several of the existing SMR projects have focused on military applications. Prototypes are expected to be ready in 2027. Progress and test data, as well as lessons learned, will be useful for assessing the actual use of SMR.

We present three cases in the simulation study that may fit the military use model. The simulations are carried out using available models from the open-source libraries Hybrid and VirtualFCS. SMR and hydrogen have been demonstrated as potential energy sources in a combat environment. The SMR can be used as an energy source in the normal mode, producing electricity and hydrogen. In the stealth mode, the SMR can be disconnected and the military community can be powered by hydrogen and fuel cells. Potential future studies will build and test comprehensive models (e.g., fuel-cell chemistry type, hydrogen storage techniques, and so on) and profiles that are closer to combat situations.

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List of Symbols, Abbreviations, and Acronyms

AlH_3	aluminum hydride
$CaAlH_4$	calcium aluminum hydride
COF	covalent organic framework
DOD	Department of Defense
DOE	US Department of Energy
H_2	hydrogen
HTSE	high-temperature steam electrolysis
HySA	Hydrogen South Africa
IES	integrated energy systems
INL	Idaho National Laboratory
iPWR	Integral/Compact Pressurized Water Reactor
$LaNi_5$	lanthanum-nickel alloy
$LiAlH_4$	lithium aluminum hydride
$LiBH_4$	lithium borohydride
LH2	liquid hydrogen
LOHC	liquid organic hydrogen carrier
$Mg(BH_4)_2$	magnesium borohydride
MgH_2	magnesium hydride
MOF	metal organic framework
MWe	megawatt electrical
$NaAlH_4$	sodium aluminum hydride
NRC	Nuclear Regulatory Commission
O_2	oxygen
PEMFC	proton-exchange membrane fuel cell
PID	proportional-integral-derivative
PIM	intrinsically microporous polymer

SMR	small modular reactor
SOEC	solid oxide electrolytic cell
SOFC	solid oxide fuel cell
TRISO	triple coated isotropic
USNC	Ultra Safe Nuclear Corp
VirtualFCS	Virtual Fuel Cell System
vSMR	very small modular reactor
$Zn(BH_4)_2$	zinc borohydride

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(PDF) FCDD RLD DCI
TECH LIB

1 DEVCOM ARL
(PDF) FCDD RLS CC
D BAKER

2 UNIV TEXAS DALLAS
(PDF) J WANG
J ZHANG