INL/CON-21-64808-Revision-0

Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

January 2021

Changing the World's Energy Future

Andrew Wilkin Foss, Charles Forsberg

Idaho National Laboratory

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Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

INL/CON-21-64808
MIT-ANP-TR-191

Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

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March 2021

Massachusetts Institute of Technology

Idaho National Laboratory

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Abstract

Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

Fission batteries (FBs) are nuclear reactors defined by five characteristics which enable large-scale deployment: cost competitive, standardized sizes for economic mass production, easy installation and removal, secure and safe unattended operation, and high reliability. FBs are not defined by technology or power level. Technical and market considerations suggest most FBs will produce 20 to 30 MWt. These proceedings report on the outcomes of two workshops that were held in January 2021 to better define markets and economic challenges for FBs.

Three major markets were identified. The largest market is the industrial and commercial heat market. There are about 4,000 industrial users (excluding utilities) that require more than 1 MW of heat. The number of customers versus size of heat demand was determined. In a low-carbon world, there is the potential for many additional customers—including expanded biofuels production and district heat. The second market is for non-grid electricity. This includes cogeneration plants that produce heat and electricity for a single customer. The third market is the maritime market with ~100,000 ships worldwide.

In the United States, natural gas is the low-cost energy option today and will remain so unless constraints or taxes impact its use. If restrictions on greenhouse gas emissions exist, the FB competition includes natural gas with carbon capture, biofuels, hydrogen, and grid electricity. Natural gas with carbon capture is not economically viable on a small scale. Biofuels may be expensive but may be the economically preferred option for locations with small energy demands of a few megawatts. Hydrogen is a potential competitor with many of the characteristics of natural gas. Grid electricity is not a competitive source of heat.

For FBs to be economically competitive, the price of delivered heat must be \$20–50/MWh (\$6–15/million BTU). The economically competitive range for non-grid electricity is estimated at \$70–100/MWh. These electricity prices are competitive with the retail prices of electricity in many parts of the United States for the customer. FBs are not expected to be competitive selling wholesale electricity to the grid. To achieve the aforementioned cost targets for heat and electricity markets, FB designers must (1) maximize the power output within the constraints of a FB (e.g., truck transportability, passive decay heat removal), (2) drastically reduce the size of onsite staff, (3) adopt core designs with low fuel costs (enrichment and fabrication), and (4) develop a system design that is efficiently manufactured in factories.

The business case depends upon more than being just a replacement for natural gas. The largest incentives for adoption of FBs are where they create new markets and new sources of revenue. An example is the paper and pulp industry that burns biomass wastes to provide heat and electricity to make paper. An external heat source could meet the demand for heat and electricity by the paper process and enable converting waste biomass into liquid biofuels rather than burning to provide heat. Other

markets, such as data centers, are driven by special energy requirements such as extreme reliability. Most customers are not in the energy business but need heat and electricity to produce a product—a manufactured good, education, water treatment, hospitals, data storage, retail sales (shopping malls), marine transport or some other product. As a consequence, there will be large incentives to lease rather than own FBs. Leasing avoids the regulatory challenges that remain with the owner of the FB. Leasing creates large incentives for FB standardization of sizes and transportability to maintain the value of the FB at the end of the lease—similar to the leasing of jet engines and aircraft.

The economic constraints combined with technical constraints suggest competitive FBs will likely have outputs exceeding 10 MWt. There appear to be little incentives for very long-lived reactor cores because such machines require much larger inventories of fuel. Maintenance requirements and the options to provide technology updates may favor shorter lifetimes (~5 years). The assessment is there is the potential for FBs to be economically viable and play a major role in global decarbonization in three markets: heat, non-grid electricity, and maritime applications.

Acknowledgement

The authors would like to thank for their support the Idaho National Laboratory (INL) and the INL National Universities Consortium (NUC) Program under Department of Energy (DOE) Idaho Operations Contract DE-AC07-05ID14517. We would also like to thank the speakers who made the workshop a success and the audiences whose questions helped clarify the discussion on fission batteries.

Executive Summary

Fission batteries (FBs) are nuclear reactors defined by five characteristics which enable large-scale deployment: (1) cost competitive, (2) standardized sizes for economic mass production, (3) easily installed and removed, (4) secure and safe unattended operation, and (5) highly reliable. FBs are not defined by technology or power level. This proceeding reports on the outcomes of two workshops that were held in January 2021 to better define markets, economic requirements, and business models for FBs that, in turn, define some of the FB technical requirements. This summary and report are the first effort to understand these aspects of FBs; thus, the conclusions must be considered preliminary results. The report appendixes include the presentations to enable the reader to review the source material to draw their own conclusions independent of the report authors.

Fission Battery Definition

FBs are not defined by technology (water, sodium salt, and helium) or size (micro, small, modular, large, etc.) but rather by a set of attributes:

- *Economic* – Competes with the costs of other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable flexible deployment across many applications, integration with other energy sources, and use as distributed energy resources.
- *Standardized* – Developed in standardized sizes, power outputs, and manufacturing processes that enable universal use and factory production, thereby enabling low-cost and reliable systems with faster qualification and lower uncertainty for deployment.
- *Modular* –Installed readily and easily for application-specific use and removal after use. After use, FBs can be recycled by recharging with fresh fuel or responsibly dispositioned.
- *Unattended* – Operated securely and safely in an unattended manner to provide demand-driven power.
- *Reliable* – Equipped with systems and technologies that have a high level of reliability to support the mission life and enable deployment for all required applications. They must be robust, resilient, fault tolerant, and durable to achieve fail-safe operation.

Market, technical, and other constraints as discussed below imply power outputs of a few tens of megawatts.

Markets

Three major markets were identified. The largest market is the industrial and commercial heat market. The industrial heat demand by itself is more than twice the total electricity output of the U.S. There are about 4,000 industrial users (excluding power plants) that require more than 1 MW of heat. The number of customers versus size of heat demand is shown in Figure ES.1.

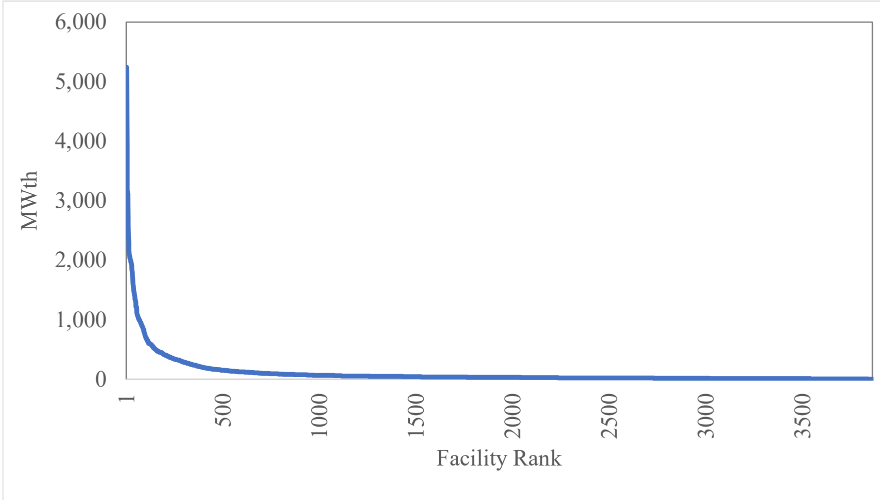

Figure ES.1. Industrial Market by Number of Industrial Customers Vs. Heat Demand.

Figure ES.2 shows the number of customers versus heat demand up to 250 MWt (excluding the largest 335 facilities in the full figure shown above). At 250 MWt, the industrial facility would have 3 to 25 FBs—depending upon individual FB size.

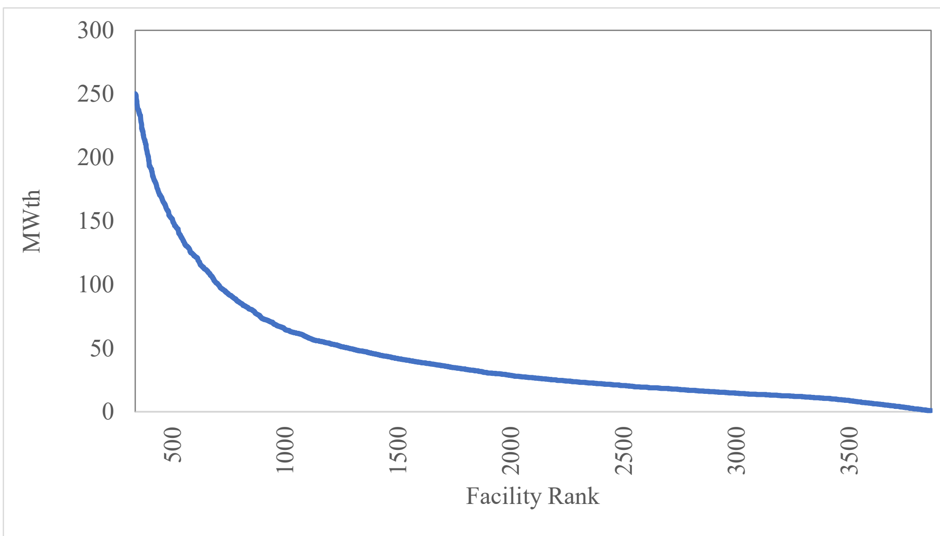

Figure ES.2. Industrial Market by Number of Industrial Customers Vs. Heat Demand up to 250 MWt.

A low-carbon world will require major changes in energy markets. The largest potential future market that was identified is biofuels production—drop-in replacements for gasoline, diesel, and jet fuel. Alternative hydrocarbon fuel sources could be implemented much more readily than wide-scale replacement of combustion systems. Biomass concentrates carbon from the atmosphere, but conversion processes from biomass to liquid fuels are energy intensive. Biomass can be the feedstock and the energy source for biofuels production. If external sources of heat and electricity are available (rather than burning biomass itself), the hydrocarbon fuel output per ton of biomass can be doubled. This market has three segments: conversion of starch or sugar into ethanol (today), conversion of cellulosic materials into hydrocarbon fuels, and conversion of biomass wastes that are currently burnt for energy, such as from paper and pulp plants, into biofuels. Total heat and electricity input could be 10% of total U.S. energy consumption. The first and third market segments could use FBs. The expected size and energy consumption of cellulosic biofuels plants are much larger and thus may not be a market for FBs.

The second FB market is for non-grid electricity with three segments. The first segment includes isolated communities, mining facilities, and military bases. The second segment is facilities with special electricity requirements such as data centers with extreme reliability requirements. The third segment is customers where self-generation is less expensive than grid electricity. The retail price of electricity is significantly higher than the wholesale price of electricity because of the electricity transmission and distribution's cost. This market includes cogeneration plants that produce heat and electricity for a single customer.

The third market is the worldwide maritime market with about 99,000 ships plus offshore platforms and some port facilities. This market's distinctive characteristic is the ships can travel to a port facility for change out of FBs. This removes many of the restrictions on the weight and size of the FB. However, maritime use imposes other requirements. Power for propulsion can be provided as electricity or coupling the power system to the propeller(s) with a transmission. The maritime market is split into many segments. Container ships may be the most attractive first market. Thirty ports handle most of the world's container freight; thus, relatively few port facilities would need to include nuclear-powered ships in their operations. Container ships spend a large fraction of time at sea relative to most ships, and thus, a larger fraction of their cost is associated with fuel. This favors FBs.

The Competition

The economic requirements for a FB are determined by the competition. In the United States, natural gas is currently the low-cost thermal energy option, and it will remain so unless constraints or taxes impact its use. Natural gas with carbon capture and sequestration is not economically viable on a small scale of a few tens of megawatts. It is not just the cost of carbon capture but the pipelines and sequestration of the carbon dioxide that become very expensive. If fossil fuels with carbon capture and sequestration (CCS) are used, the economic scenario will be large cogeneration facilities producing heat—most likely as steam delivered to multiple customers in an industrial park. Figure ES.3 projects natural gas prices with different carbon taxes that can also be viewed as the range of costs for large-scale CCS. Current large-scale CCS costs are between \$50 and \$100 per ton of carbon dioxide. For FBs to be economically competitive, the price of delivered heat must be \$20–50/MWh (\$6–15/million BTU). These prices are significantly higher than the current price of natural gas in most of the United States but similar to the prices of natural gas in the rest of the world.

Biofuels have the potential to be competitive with FBs—depending partly upon external energy sources to convert biomass into liquid and gaseous fuels. The potential low-carbon energy sources for biofuels plants are fossil fuels with CCS, nuclear heat, and hydrogen.

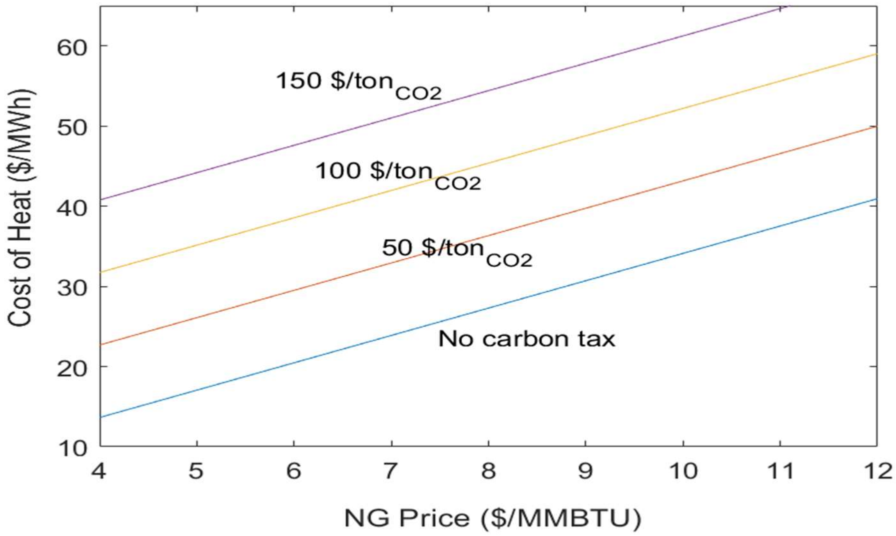

Figure ES.3. Cost of Heat versus Natural Gas Prices for Different Carbon Taxes.

Hydrogen as a heat source is potentially competitive in some parts of the U.S. in a low-carbon economy as a replacement for natural gas that is a carbon tax on natural gas or a requirement for CCS. There are two major routes to hydrogen. The first is steam methane reforming of natural gas with sequestration of the carbon dioxide. This is potentially competitive in locations with cheap natural gas and good carbon-dioxide sequestration sites. In steam methane reforming, natural gas is used as a feedstock and an energy source. The process produces hydrogen and a relatively pure carbon dioxide. The natural gas used as an energy source requires removing the carbon dioxide from the stack gas. In effect, there is carbon dioxide steam with low-CCS costs and a second stream with higher CCS costs. There are also process variants that produce only relatively pure CO_2 streams. This feature enables lower cost hydrogen production in some locations. However, hydrogen is more expense to transport than natural gas. The geographical variations of hydrogen prices will be larger than for natural gas. The other large-scale option is nuclear hydrogen production with the potential for economic hydrogen production that is not location dependent. The economics of nuclear hydrogen production favor very large hydrogen production facilities—similar in size to global refineries. This is dictated by both the economics of nuclear power and economics of hydrogen production.

The economically competitive range for non-grid electricity is estimated at $70–100/MWh. These electricity prices are competitive with the retail prices of electricity in many parts of the United States for the customer as shown in Table S1. Retail prices include generation, transmission, and distribution. FBs are not expected to be competitive selling wholesale electricity to the grid.

Grid electricity as a source of heat is likely to be uneconomic with heat demands of a few tens of megawatts. The laws of thermodynamics imply several units of heat are required to make one unit of electricity—but under most circumstances one unit of electricity with resistance heating makes one unit of heat. Heat is cheap and electricity (work) is more expensive. Because FBs produce heat, they have a competitive advantage in delivering heat to the customer relative to production of electricity. Electric heat is likely to be competitive for users with small energy demands.

Table ES.1. Retail Electricity Prices by Region for Different Sectors ($/MWh).

Region	Residential	Commercial	Industrial	Transportation	All Sectors
New England	210	163	131	92	178
Middle Atlantic	158	122	66	112	123
East North Central	134	102	69	71	101
West North Central	119	97	73	87	97
South Atlantic	119	94	65	79	100
East South Central	114	107	58	--	94
West South Central	112	82	54	66	84
Mountain	118	96	63	93	94
Pacific Contiguous	156	144	97	90	138
Pacific Noncontiguous	283	245	235	--	255
U.S. Total	130	107	68	97	105

The above analysis is based on energy as a commodity. However, there is a difference between the value of energy to a customer and its price. The value may be much higher than the commercial price of heat or electricity. There are two examples below that can clarify this.

First, the largest incentives for adopting FBs is where they create new markets and new sources of revenue. An example is the paper and pulp industry that burns biomass wastes to provide heat and electricity to make paper. An external heat source could enable these plants to produce paper (old business) and use the internally generated biomass wastes as a feedstock to produce biofuels rather than burn the wastes to produce heat.

A second example is data centers with special energy requirements such as extreme reliability and significant cooling demand; the latter of which may be provided through (heat-driven) sorption chilling technologies. The costs and risks of downtime results in decisions to choose more expensive energy sources if more reliable. The value of reliable electricity is more important than the cost of commodity electricity.

Business Models

Most FB customers are not in the energy business but need heat and electricity to produce a product—a manufactured good, education, retail sales (shopping malls), marine transport, or some other product. They are not in the business of producing electricity for sale but having a business arrangement can mitigate risks of energy availability and price. Moreover, businesses do not want to be dependent upon other businesses for energy—the holdup problem where the energy supplier can raise prices. They want competitive suppliers—like the competitive market for fossil fuels. This creates incentives to lease FBs to supply energy with multiple suppliers. Another, possibly stronger factor is the administrative and legal burden of nuclear operations. If responsibility for licensing, compliance, and working with the Nuclear Regulatory Commission could be carried by the leasing company, nuclear energy could become available to a much broader range of businesses. Leases are simple commercial agreements relative to other commercial agreements. As a consequence, they are widely used to leasing everything from trucks to train cars to jet engines to aircraft, although operational responsibility would be an important factor to work out (such as in a contract for dispatchable power within ranges that could be specified in the lease).

The leasing model imposes requirements on FBs. FBs must be transportable for delivery and return to the lessor. FBs must be standardized—partly for economics of mass production but also to maintain the value of the FB. If the FB is customized for a particular customer, at the end of the lease, it can't be quickly refurbished and sent to the next customer or repossessed for failure to pay leasing fees. Equally important, if there is a problem with a FB, and it is customized, there will not be a replacement at the factory.

Business decisions that consider risk will often lead to different conclusions than result from simple economic models. For example, a simple engineering economic model may show the most economical solution to provide heat would be a large nuclear reactor or fossil-fuel plant with CCS cogeneration plant that produces heat and electricity for multiple customers. The problem is the interests of the cogeneration plant owners and the different users of heat do not align over time. The industrial customer is concerned once he sites his plant in an industrial park with a large cogeneration plant, he will be hostage to the owner of cogeneration plant. This creates incentives to control his own energy sources. As a consequence, most large cogeneration plants with multiple customers have been built in the former Soviet Union with centrally planned economics. These types of considerations also create markets for FBs.

Implications for FB Design

A series of engineering assessments were undertaken to help define technical constraints based on the above economic constraints. To achieve the aforementioned cost targets for heat and electricity markets, FB designers must (1) maximize the power output within the constraints of a FB (e.g., truck transportability of the core with shielding and other modular units, as well as design constraints for passive decay heat removal), (2) drastically reduce the size of onsite staff, (3) adopt core designs requiring low fuel enrichment and fabrication costs, and (4) develop a system design that is efficiently manufactured in a factory. The other major conclusion is within the design envelope, the FB size should be maximized in size to be economically viable as shown in Figure ES.4. FBs under 5 MWt are unlikely to be economic.

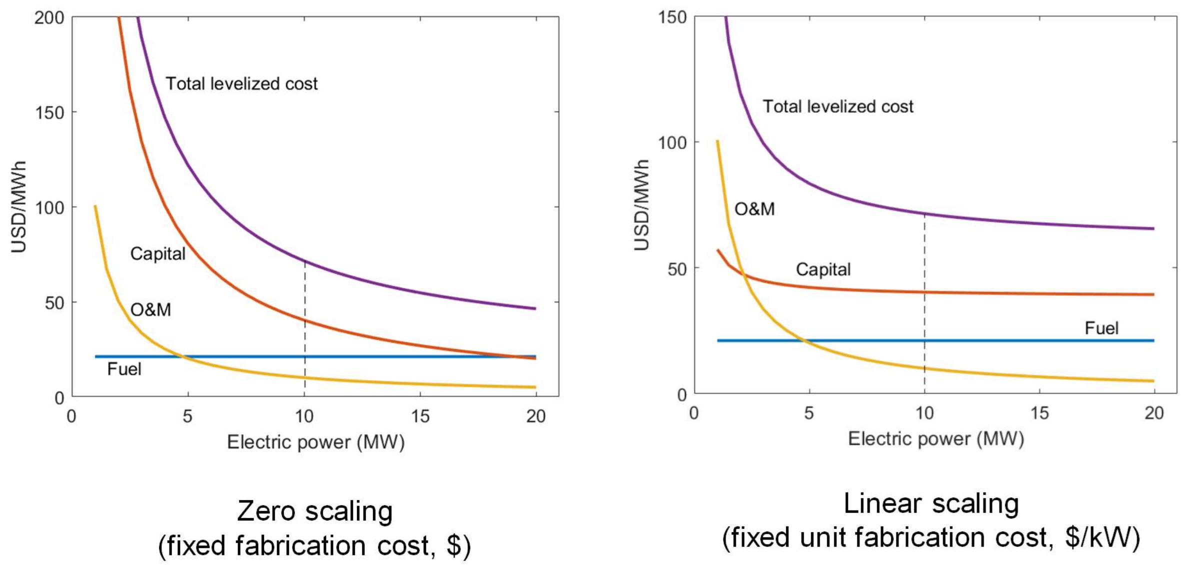

Figure ES.4. FB Cost Vs Size of FB for Different Sets of Assumptions.

Conclusions

The workshop and these proceedings are a first assessment of the markets, economics, and business models for FBs. This is a work in progress. FBs are defined by attributes—not technology or power levels. The attributes will limit power output to less than 100 MWt—and most likely between 20 to 30 MWt except for maritime and other such applications without the transport weight and size limits. The market size (1) is sufficient to support large-scale FB manufacturing similar to that for large jet engines and (2) may ultimately be 10 to 20% of total energy use. Most of the customers are energy consumers producing some other product such as manufactured goods, education, data processing, sales (shopping centers), or marine transport. They are not in the business of selling energy.

For FBs to be economically competitive, the price of delivered heat must be \$20–50/MWh (\$6–15/million BTU). The economically competitive range for non-grid electricity is estimated at \$70–100/MWh. The competition in a low-carbon world for energy demands of a few tens of megawatts includes hydrogen (and its derivatives such as ammonia) and biofuels. Grid electricity may be competitive at much smaller energy demands and fossil fuels with CCS competitive at much larger energy demands.

The likely business model is leasing FBs—similar to the model for leasing jet engines and aircraft. Presumably, the lessor would obtain and manage the reactor license with the Nuclear Regulatory Commission. The customer wants multiple suppliers to assure competitive prices—similar to multiple suppliers of fossil fuels. This requires transportability and standardized FBs to enable switching FB suppliers and retaining the value of used FBs after refurbishment for the next lessee. Manufacturing cost considerations imply very small FBs under a few megawatts are unlikely to be competitive.

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1. INTRODUCTION

Fission batteries (FBs) are a concept for nuclear reactors defined by five characteristics that enable large-scale deployment: (1) cost competitive, (2) standardized sizes for economic mass production, (3) easily installed and removed, (4) secure and safe unattended operation, and (5) highly reliable. FBs are not defined by technology or power level. This proceedings document reports on the outcomes of two workshops organized by the National University Consortium (Massachusetts Institute of Technology, North Carolina State University, The Ohio State University, the University of New Mexico, and Oregon State University) and Idaho National Laboratory (INL) that were held in January 2021 to better define markets, economic requirements, and business models for FBs that, in turn, define some of the FB technical requirements. The workshop and this report are the first effort to understand these aspects of FBs; thus, the results must be considered preliminary. The report appendixes include the workshop agenda (Appendix A), a breakdown of the participants by sector (Appendix B), the speaker biographies (Appendix C), and the presentations (Appendix D) to enable readers to review the source material and draw their own conclusions independent of the report authors.

The main report is an integration of the results of the workshop including added information from speakers, audience participants, and other sources. It includes references from the literature and reference to presentations by speakers [Example: Forsberg Appendix D].

2. FISSION BATTERY DEFINITION

FBs are not defined by technology (such as water, sodium, salt, or helium coolant) or size (micro, small, modular, large, etc.) but rather by a set of attributes [Ballout Appendix D; Agarwal 2021].

- *Economic* – Competes with the costs of other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable flexible deployment across many applications, integration with other energy sources, and use as distributed energy resources.
- *Standardized* – Developed in standardized sizes, power outputs, and manufacturing processes that enable universal use and factory production, thereby enabling low-cost and reliable systems with faster qualification and lower uncertainty for deployment.
- *Modular* –Installed readily and easily for application-specific use and removal after use. After use, FBs can be recycled by recharging with fresh fuel or responsibly dispositioned.
- *Unattended* – Operated securely and safely in an unattended manner to provide demand-driven power.
- *Reliable* – Equipped with systems and technologies that have a high level of reliability to support the mission life and enable deployment for all required applications. They must be robust, resilient, fault tolerant, and durable to achieve fail-safe operation.

Market, technical, and other constraints as discussed herein imply power outputs of a few tens of megawatts of heat—perhaps with an upper limit of 100 MWt. The requirements to be easily installed and removed imply transportability that imposes size and weight constraints on FBs.

3. MARKETS

Figure 3.1 shows the U.S. energy market in 2019 [LLNL 2021] from energy sources to final customers. The customers on the right in pink are broken into four categories: residential, commercial, industrial, and transportation. The electric sector in gold converts various forms of energy into electricity. About 17% of all energy consumed by customers is in the form of electricity (calculated by dividing the 12.7 quadrillion BTU of electricity generation over the sum of energy consumption by the four customer categories in pink). The rest of the energy, aside from minuscule contributions directly from solar and hydro to customer categories, is consumed in the form of heat [Forsberg and Bragg-Sitton 2020]. Heat is the primary energy market in the U.S. and globally. Nuclear reactors produce heat and thus could serve this demand.

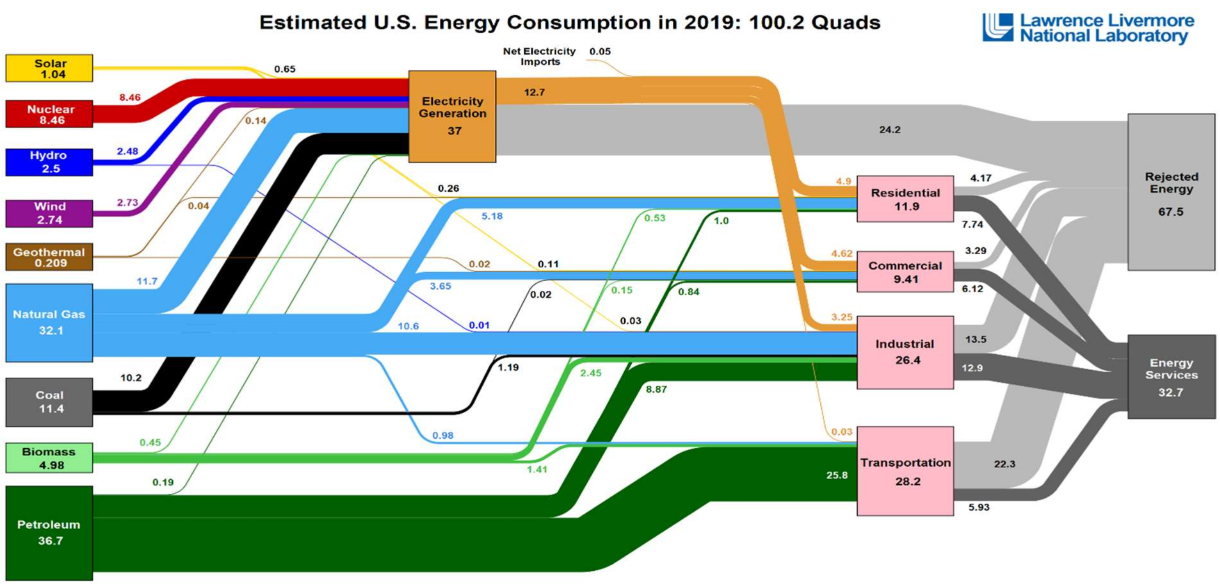

Figure 3.1. 2019 U.S. Energy Flow Diagram from Source to Customer

Three major markets were identified in the workshop: industrial heat markets, electricity markets, and maritime (ship) markets.

3.1 Industrial Heat Markets

The largest market is the industrial heat markets. Recent papers [Thiel 2021; Rissman 2020; Gates 2021] have examined the need for low-carbon heat sources for these markets from different perspectives. We examined the market from two perspectives: current markets and future markets. The goals of a low-carbon energy system will change markets. The largest potential change is the development of a biofuels industry to replace the existing oil industry in providing transportation fuels. Oil refining is the single largest industrial consumer of energy. As discussed in more detail below, any large-scale biofuels industry would also use massive amounts of energy and could quickly become the largest industrial consumer of energy in the production of liquid fuels.

3.1.1 Current Industrial Markets

The industrial heat demand by itself is more than twice the total electricity output of the U.S. A more detailed analysis of this market was undertaken by Foss [Appendix D] starting with the Environmental Protection Agency (EPA) Facility Level Information on Greenhouse Gases Tool (FLIGHT) database [EPA 2021] of carbon dioxide emissions in 2018 from ~6,000 large facilities. These are facilities with average heat consumption rates of 1 MW or more. This data base lists emission sources by company, addresses, and industrial codes. The emissions are linked by source: coal, natural gas, and oil consumption. Starting with carbon dioxide emissions, the energy consumed can be calculated using standard emissions per unit of coal (210 lbs/MMBtu), oil (174 lbs/MMBtu), and natural gas (117 lbs/MMBtu). This yields annual energy consumption at large facilities. The analysis assumed each facility operated for 90% of the year. This yielded the average thermal power load at large facilities. Table 3.1 shows the largest heat users by industrial sector. The largest sector is the utility sector followed by oil refining and the chemical industry. Similar previous analyses for industrial sectors in aggregate have been done by INL and National Renewable Energy Laboratory (NREL) [McMillan et al. 2016] and Massachusetts Institute of Technology (MIT) [Buongiorno 2018; Appendix F].

Table 3.1. Largest U.S. Industrial Sectors for Heat Demand in 2018.

	Industry	Facility Count	Total CO_2 (million metric t)	Total Energy (trillion Btu)	Total Thermal Load (MWt)
#1	Electric utilities	1,394	1,795	23,809	885,741
#2	Chemical manufacturing	650	176	2,487	92,536
#3	Pipeline transportation	630	29	388	14,452
#4	Oil and gas extraction	588	62	833	30,993
#5	Waste management	571	11	142	5,292
#6	Cement, glass, mineral mfg.	350	106	1,407	52,347
#7	Food manufacturing	327	33	474	17,649
#8	Primary metal manufacturing	275	87	1,155	42,967
#9	Paper manufacturing	216	35	516	19,203

#10	Petroleum manufacturing	171	209	2,797	104,067
	Other	641	45	673	25,049
	Total	**5,813**	**2,587**	**34,684**	**1,290,295**

Excluding electric utilities (because electricity applications for FBs are discussed separately below), there are about 4,000 industrial users that require more than 1 MW of heat. The number of non-utility customers versus the size of heat demand is shown in Figure 3.2. The customers are ranked from largest to smallest in terms of heat use.

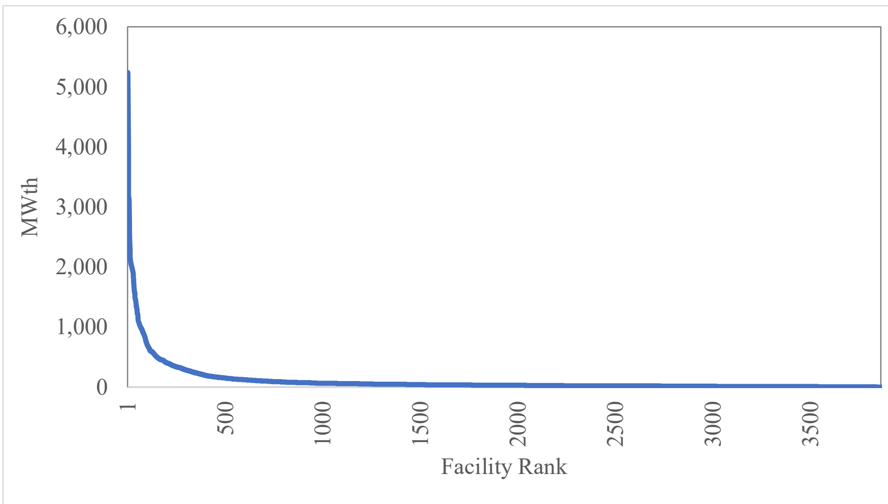

Figure 3.2. Industrial Market by Number of Industrial Customers Vs Heat Demand.

Figure 3.3 shows the number of customers versus heat demand up to 250 MWt (excluding the largest 335 facilities at the left side in the full figure shown above). At 250 MWt, the industrial facility would have 3 to 25 FBs—depending upon individual FB size.

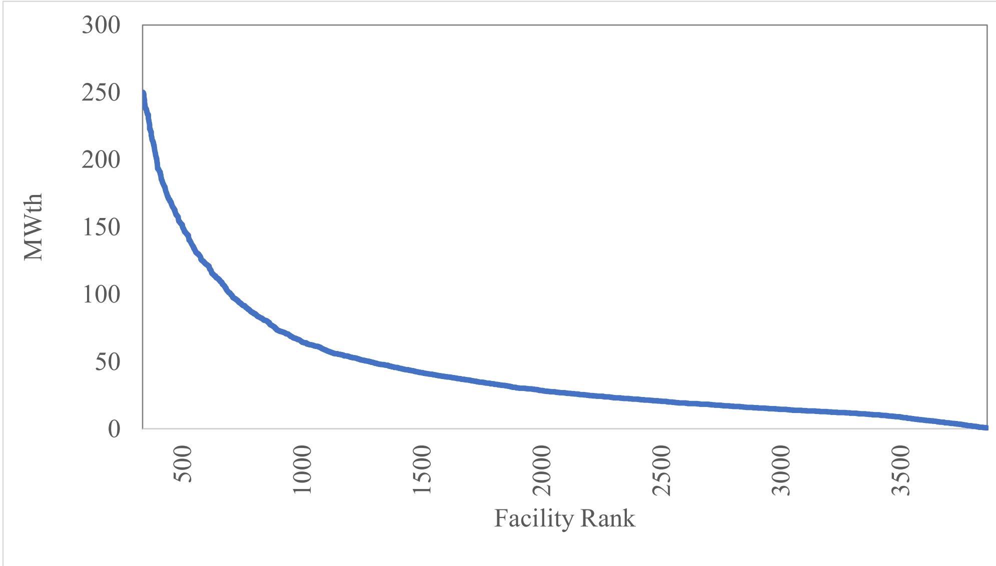

Figure 3.3. Industrial Market by Number of Industrial Customers Vs. Heat Demand up to 250 MWt.

The next four figures show histograms of the distribution of heat demand across facilities for four industrial sectors with temperature requirements that match well with nuclear capabilities [Buongiorno 2018, Appendix F]: petroleum manufacturing, chemical manufacturing, paper manufacturing, and food manufacturing. Other industrial sectors in Table 3.1 align less well with nuclear outlet temperatures and would be less suitable as markets for FBs.

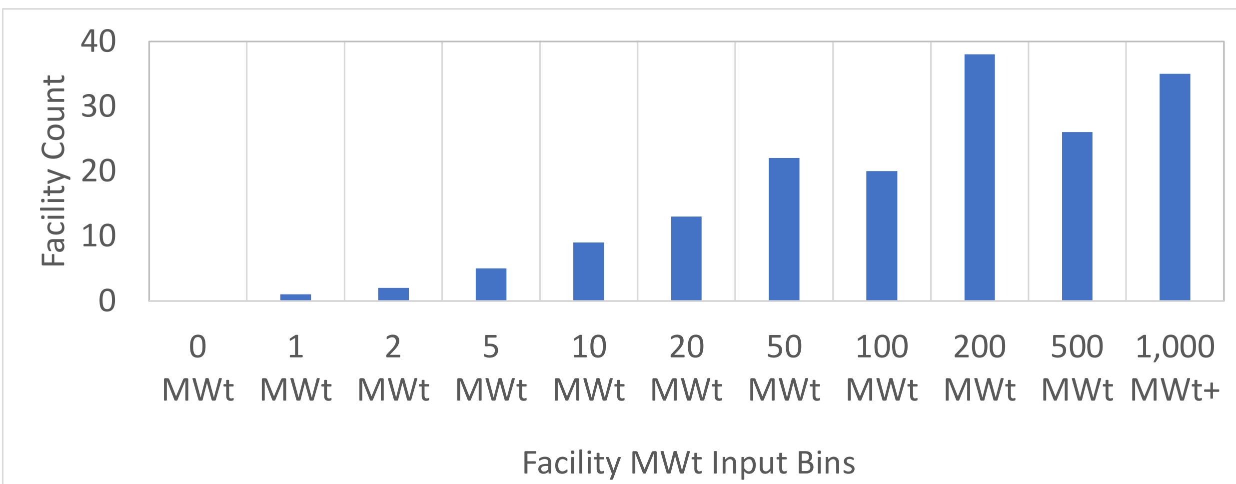

Figure 3.4. Petroleum Manufacturing by Number of Industrial Customers Vs. Heat Demand.

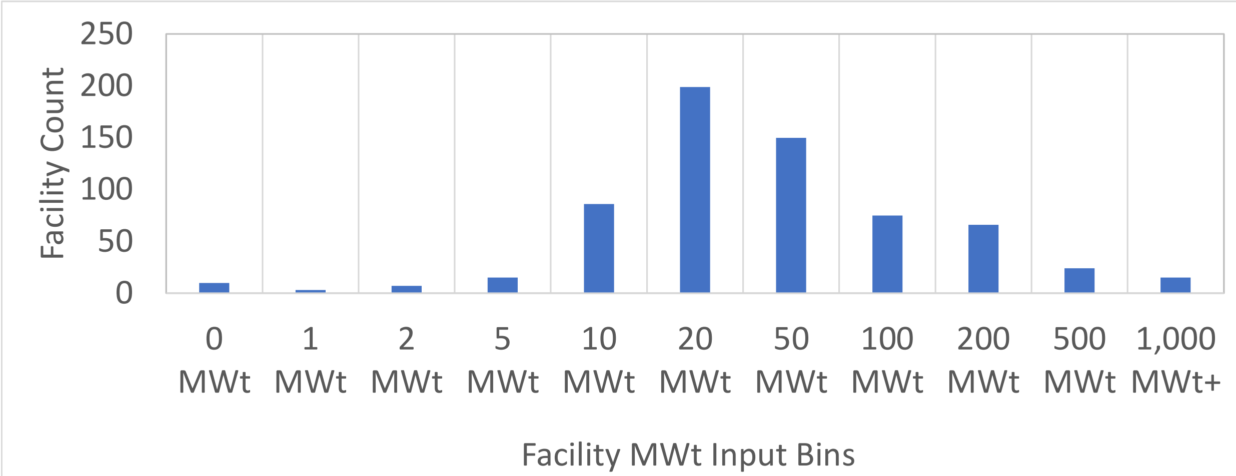

Figure 3.5. Chemical Manufacturing by Number of Industrial Customers Vs. Heat Demand.

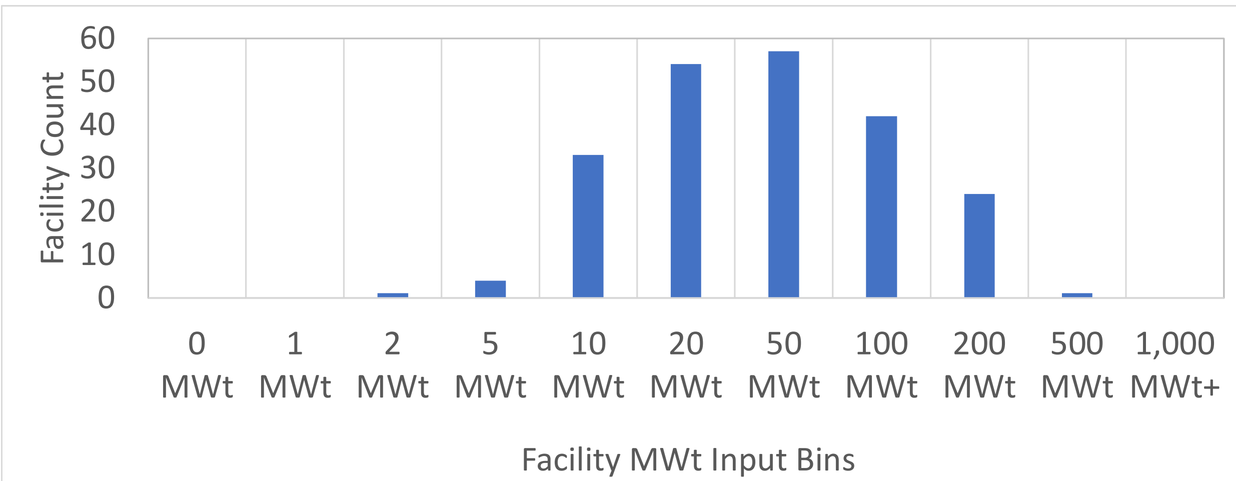

Figure 3.6. Paper Manufacturing by Number of Industrial Customers Vs. Heat Demand.

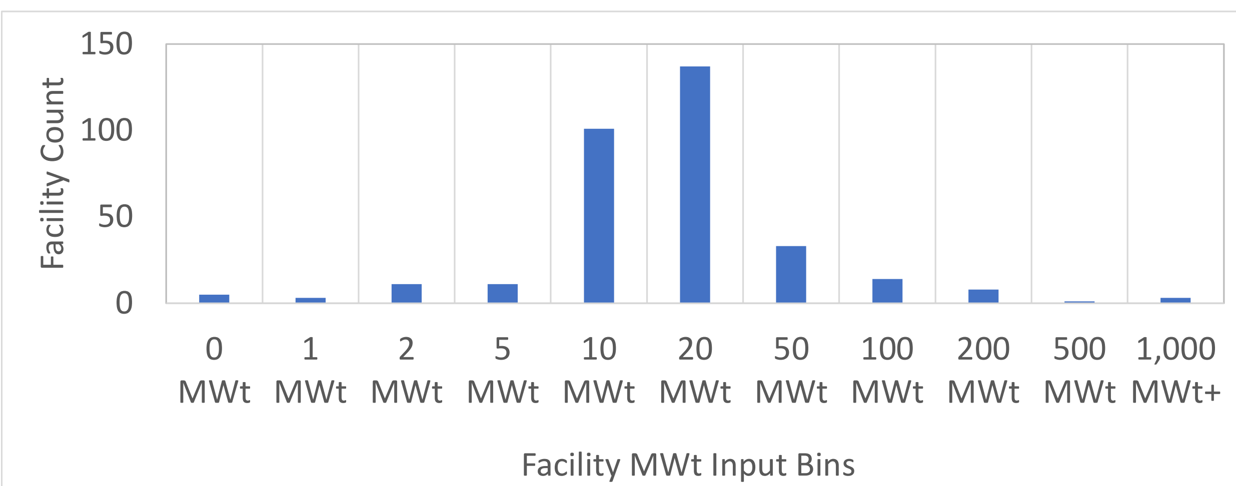

Figure 3.7. Food Manufacturing by Number of Industrial Customers Vs. Heat Demand.

3.1.2 Future Biofuels Markets

A low-carbon world will require large changes in energy markets. The question becomes: what are the added future customers for FBs and other energy-producing systems? The largest change may be in biofuels production—drop-in replacements for gasoline, diesel, and jet fuel. That is because (1) biofuels could potentially replace fossil liquid fuels used for transportation and (2) the transport sector is the largest energy-consuming sector of the United States (Table 3.1)—the oil refineries. Biomass removes carbon dioxide from the atmosphere as it grows; thus, the burning of biomass does not result in any net increase in atmospheric carbon dioxide levels over the long term if the plants and trees are eventually replaced. The energy input into biofuels production at bio-refineries, if used to replace liquid fossil fuels and hydrocarbon feedstocks to the chemical industry, could be 10% of total U.S. energy consumption.

The conversion of biomass into liquid fuels is energy intensive. Biomass can be (1) the carbon feedstock to produce hydrocarbon fuels and (2) the energy source for the bio-refinery. If external sources of heat and hydrogen are available (rather than burning biomass itself), the hydrocarbon fuel output per ton of biomass can be doubled. Recent studies [Forsberg and Dale 2020; Forsberg et al. 2021; Forsberg 2008] indicate low-carbon biofuels could fully replace liquid fuels (gasoline, diesel, and jet fuel) and hydrocarbon feedstocks for the chemical industry without large impacts on food or fiber production. This requires biofuels be primarily used as a carbon feedstock for biofuels production—not as an energy source to operate biofuels plants converting biomass to liquid biofuels.

The market has three segments [Dale Appendix D]: conversion of starch or sugar into ethanol (today), conversion of cellulosic materials into hydrocarbon fuels, and conversion of biomass wastes that are currently burnt for energy, such as from paper and pulp plants, into biofuels. The first market exists today; the second and third markets do not currently exist. The first and third market segments could use FBs. The expected size and energy consumption of individual cellulosic biofuels plants are much larger and thus may not be a market for FBs.

Starch and Sugar to Ethanol

Figure 3.8 shows the breakdown for a typical ethanol plant that converts corn into ethanol. Such plants consume about 90 MW of heat and produce 100 million gallons of fuel ethanol per year. Most of the energy input is in the form of natural gas. The facilities operate year round, and the heat demand could be met by several FBs. There are about 200 ethanol plants in the United States as shown in Figure 3.9. In addition to producing ethanol, the process produces distiller's grain and other byproducts. Almost half the energy input is drying of these byproducts that are high-value protein feeds for cattle and other species. The next largest heat demand is the distillation process that convert the alcohol-water mixture from fermentation into pure ethanol for use as a fuel. Most of the heat demand is at temperatures below 200°C.

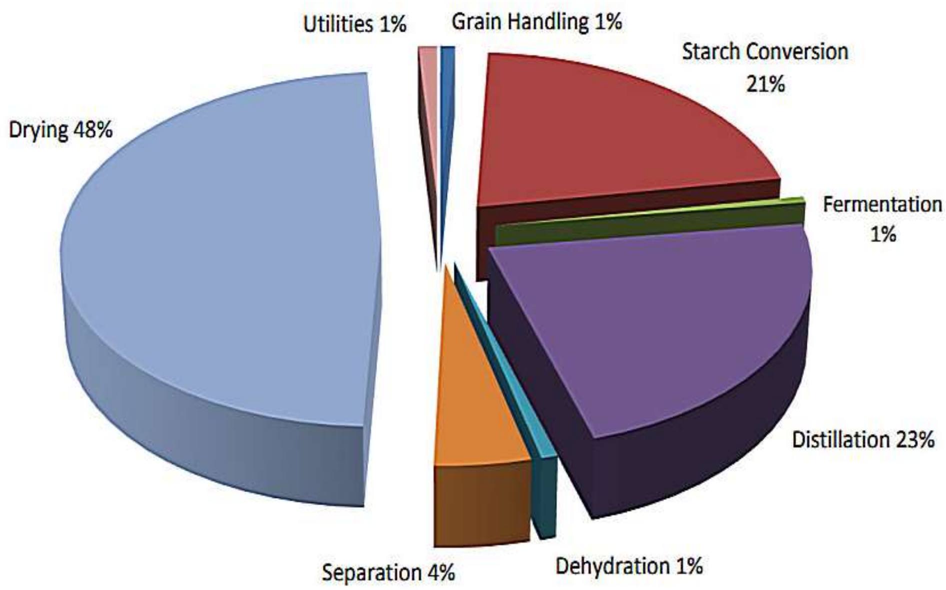

Figure 3.8. Energy Inputs into Ethanol Production [Focus on Energy 2009].

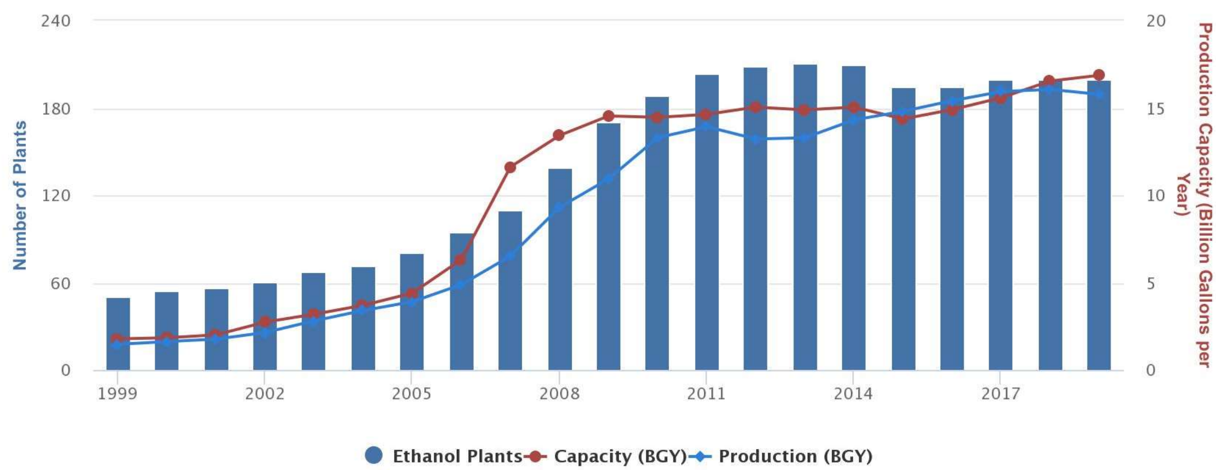

Figure 3.9. U.S. Ethanol Plant Count, Capacity, and Production [U.S. DOE 2021].

Cellulosic Biomass to Hydrocarbon Fuels

Work is underway to develop a second class of biofuels plants that convert cellulosic feedstocks into drop-in fuels and hydrocarbon feedstocks for chemical plants. Most of the biomass on earth is cellulosic. Fossil fuels and chemical feedstocks can in simplified form be represented by $(CH_2)_xH_2$ where the value of X determines whether the fuel is gasoline, diesel, or jet fuel—or a feedstock to the chemical industry. Biomass has a composition near $CH_{1.44}O_{0.66.}$ Converting biomass into hydrocarbons involves removing oxygen and adding hydrogen. The oxygen can be removed in the form of water in which case the process requires a source of external hydrogen. Alternatively, the oxygen can be removed as carbon dioxide, however, that implies less hydrocarbon fuel per unit of biomass feedstock. A fraction of the biomass is being used as an energy source for the biofuels conversion process. In practical systems, external energy in the form of heat and hydrogen can double hydrocarbon fuel per unit of biomass versus using the biomass as a feedstock and the energy source to convert biomass into a hydrocarbon fuel

While the potential for large-scale biomass is substantial, the first generation of biofuels plants failed for multiple reasons. The industrial model was to collect local biomass and convert it to liquid fuels. However, the low density of unprocessed biomass (in bales) limits the economic distance of transport; that, in turn, severely limits bio-refinery size. The small scale makes the plants uneconomic. Second, unprocessed bales of biomass can easily burn, and the biomass degrades while in storage. This is in contrast to ethanol production from corn. Corn is a dense uniform feedstock that is cheap to store, does not quickly degrade in storage, and is cheap to move long distances. Third, the bio-refineries envisioned produced niche market fuels; that is, they were not able to produce variable fuels to match changing market demands.

Earlier research developed an alternative strategy—local depots that convert local cellulosic biomass into a dense, storable, shippable product. Those processes have been demonstrated at the pilot-plant scale and enable large-scale bio-refineries. The schematic of a nuclear bio-refinery is shown in Figure 3.10. Local biomass is converted into a dense storable form close to where it is harvested and shipped by unit train to large bio-refineries. The concentrated heat requirements for such a bio-refinery imply the only viable heat sources are nuclear or fossil fuels with CCS. If biomass (the feedstock) is used as the energy source instead, the quantities of biofuels that can be produced from existing biomass resources are much less. Furthermore, biomass as a fuel source for the bio-refinery is more expensive than the alternative energy sources in most locations.

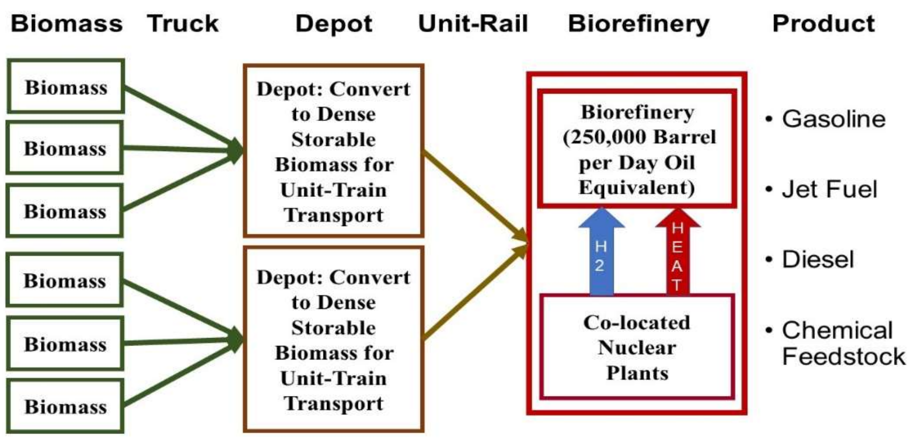

Figure 3.10. Integrated Nuclear Bio-refinery with Depots.

The conversion of biomass at the bio-refinery is a two-step process: (1) production of a hydrocarbon crude oil from biomass and (2) refining the hydrocarbon into the required products—primarily gasoline, diesel, and jet fuel. There is a century of experience in oil refining that shows massive economics of scale. Part of this is the traditional enhanced economics of larger-scale production systems. However, more important is the ability of integrated refineries to efficiently produce variable quantities of different products over time from variable feedstocks to match changing market needs. The front-end conversion of biomass to hydrocarbons can be a general purpose process such as Fischer-Tropsch or processes that convert specific feedstocks into hydrocarbons. The Fischer-Tropsch process is used today to convert coal and natural gas into liquid hydrocarbon fuels and can accept almost any carbon-based feedstock.

A large integrated cellulosic bio-refinery will have heat demands larger than a large oil refinery—partly because of the requirement to remove water from the feedstock. In addition, a large cellulosic bio-refinery will have massive demands for hydrogen to remove the oxygen from the biomass feedstock and convert the biomass into a hydrocarbon fuel. Large integrated oil refineries measure heat input in gigawatts and energy input into hydrogen production in similar units. In a low-carbon economy the demand for concentrated energy sources, excluding electricity from renewables, can only be met by (1) nuclear reactors or (2) fossil fuels with CCS. Of the 66 non-utility industrial facilities in the United States with heat demands over 1 GW, 35 of them are oil refineries. The energy inputs for such facilities implies they would likely choose reactors considerably larger than FBs.

Biofuels from Paper and Pulp Facilities

The third class of potential future biofuels plants are associated with the forest industry—particularly the paper and pulp plants. Earlier Figure 3.6 showed the external heat demands for the paper and pulp industry. However, that is only a third of the energy consumption. In the paper process, pulp wood is digested, and the fiber is converted to paper. The bark and other waste from the paper process are burnt to provide most of the energy for the papermaking process—including drying the paper. Figure 3.11 shows the total energy input into the paper industry by source [Schwartz Appendix D]. Two thirds of the energy input is from burning biomass—not external sources of energy.

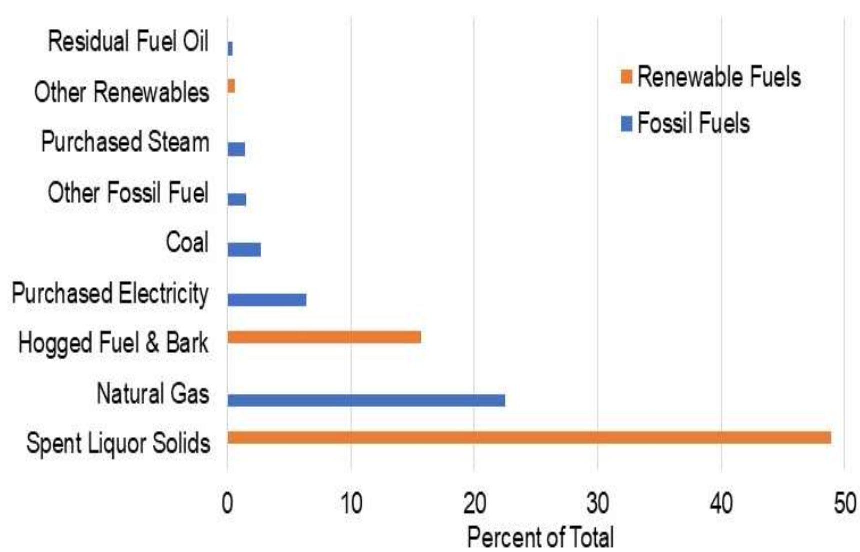

Figure 3.11. 2018 Energy Inputs into the Paper and Pulp Mills.

Research is underway to convert biomass that is burnt in paper mills into biofuels for transportation or other end-use sectors. If FBs can provide the required energy to operate the paper and pulp facilities, paper plants can then convert biomass that is currently burnt for energy into biofuels. This would result in plants that produce paper and biofuels. Paper plants burn two major biomass wastes to produce heat—each with its own characteristics.

- *Hogged fuel and bark.* This waste stream is created when bark and other materials are stripped from the pulpwood and not used in the papermaking process. It also includes secondary wastes from harvesting of pulpwood used as an energy source for paper and pulp mills. There are many options to convert this waste into liquid biofuels. This is a form of cellulosic biomass and thus processes being developed to convert other cellulosic feedstocks into liquid fuels can be used. If FBs were a commercial product, this market could develop quickly because processes exist to convert hogged fuel and bark into liquid fuels.

- *Spent liquor solids.* The second waste stream is the spent liquor solids from the pulping process. This stream contains the non-fiber components of pulpwood that cannot be converted into paper. The burning of this waste stream produces heat and recovers chemicals from the papermaking process that are recycled back to the plant. If this stream is to be converted into biofuels, the process must also allow recovery of the chemicals for the paper plant.

The economics for biofuels in this application may be highly favorable for two reasons. First, FB heat would enable production of a second product—biofuels. Second, in all other biofuels systems one must pay for the biomass to be grown and delivered to the biofuels plant. In a paper and pulp mill, the feedstock is free if an alternative heat source for the paper plant can be provided. Both markets could be served by FBs rather than larger nuclear plants or large fossil-fueled plants with CCS because the size of paper and pulp plants is limited by the economics of shipping pulpwood from the forest to the paper and pulp mill. The U.S. and Canada would be the major markets.

Electrical Markets

The second FB market is for non-grid electricity. This can be broken into several markets. First are the traditional non-grid electricity markets such as isolated communities, mining facilities, and military bases. Second, there are customers with special electricity requirements such as data centers with extreme reliability requirements. Last, this market includes traditional electricity grid customers that chose to generate their own electricity because it is less expensive than purchased electricity. In this context, it is important to understand the cost structure of grid electricity where a significant fraction of electricity's cost is the transmission and distribution costs, as shown in Figure 3.12. Avoidance of transmission and distribution costs for onsite electricity generation may allow FBs with relatively high generation costs (in comparison to grid-connected sources) to be economically viable.

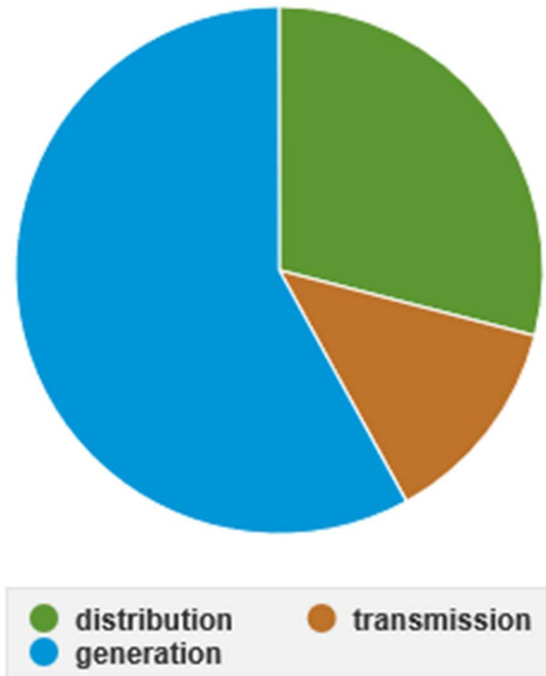

Figure 3.12. Major Components of the Average Price of Electricity in 2019 [U.S. EIA 2021].

Today the United States has several thousand cogeneration sites that produce heat and electricity for their owners with a total electric generating capacity of about 80 GWs (DOE EERE 2021). Most of these facilities currently use natural gas as the fuel. The natural gas is burnt in a steam boiler, gas turbine, or diesel engine to produce electricity with the lower temperature exhaust heat used for building heat, adsorption air-conditioning, and/or industrial processes. Most of these facilities are coupled to the grid; that is, they are grid optional. They may buy and sell electricity, but the economics are based on lower production costs than electricity from the grid. This is an existing market where many sites are potential customers for FBs. There are also a smaller number of micro grids that just generate electricity.

Table 3.2 shows the retail electricity prices by region for different sectors of the economy [Buongiorno Appendix D]. The Pacific noncontiguous region comprises Alaska and Hawaii, which have high-electricity prices because of their remoteness from larger energy systems. There are specific electric markets that are potential markets for FBs to directly provide electricity for the customer—but not the main grid.

Table 3.2. Retail Electricity Prices by Region for Different Sectors ($/MWh).

Region	Residential	Commercial	Industrial	Transportation	All Sectors
New England	210	163	131	92	178
Middle Atlantic	158	122	66	112	123
East North Central	134	102	69	71	101
West North Central	119	97	73	87	97
South Atlantic	119	94	65	79	100
East South Central	114	107	58	--	94
West South Central	112	82	54	66	84
Mountain	118	96	63	93	94
Pacific Contiguous	156	144	97	90	138
Pacific Noncontiguous	283	245	235	--	255
U.S. Total	130	107	68	97	105

Maritime Market

The third market is the worldwide maritime market with about 99,000 ships plus offshore platforms and some port facilities [Burton Appendix D]. The total carbon dioxide emissions are about 2.5% of global emissions with 45% of those emissions from about 3,000 ships. There are three distinctive characteristics of this market. First, ships can travel to a port facility for change out FBs. This removes many of the restrictions on the weight and size of the FB. Second, because of the action of waves, there are a set of requirements imposed by the motions of the ship on the FB. Third, most ships travel between countries, and thus one must consider international law and the regulations of the specific port facilities.

Power for propulsion can be provided as electricity or via steam or other power cycle. However, typical propeller rotational speed is 76 revolutions per minute. This implies large transmissions to match power cycle rotational speed (typically at much higher rates) to propeller rotational speed and places large incentives to minimize the rotational speed of the power cycle if directly coupled to the propellers. In addition to the demand for propulsion, there is a need for auxiliary power. Table 3.3 shows the auxiliary power (electricity) demand for a typical ship with a 26,900 kW propulsion demand. In most cases auxiliary power demand is small with two major exceptions—passenger cruise ships and some military vessels. On cruise ships, passenger services can consume more energy than propulsion because one has a small city on board. Aboard military vessels the crew, radar and various weapons create major demands for electricity.

Table 3.3. Auxiliary Electricity Demand (kW) with Type of Operation for a Ship with a Propulsion Demand of 26,900 kW (Burton Appendix D).

	At Sea	Maneuvering	Cargo Ops. Loading	Cargo Ops. Unloading	Harbor	Emergency
Average Continuous Load	868	1,608	1,136	1,573	660	118
Intermediate Load	259	290	256	295	266	0
Equivalent Intermediate Load	104	116	102	118	106	0
Total Required Power	972	1,724	1,238	1,691	766	118
Generating Capacity	1,150	2,300	2,300	2,300	2,300	300

The maritime market is split into many segments. Container ships may be the most attractive first market for FBs. There are about 5,000 container ships currently in service. Container ships spend a larger fraction of time at sea relative to most ships, and thus, a larger fraction of their cost is associated with fuel. They are the largest energy users. Figure 3.13 shows fuel usage by ship type in millions of tons of heavy fuel oil equivalent today and projected into the future.

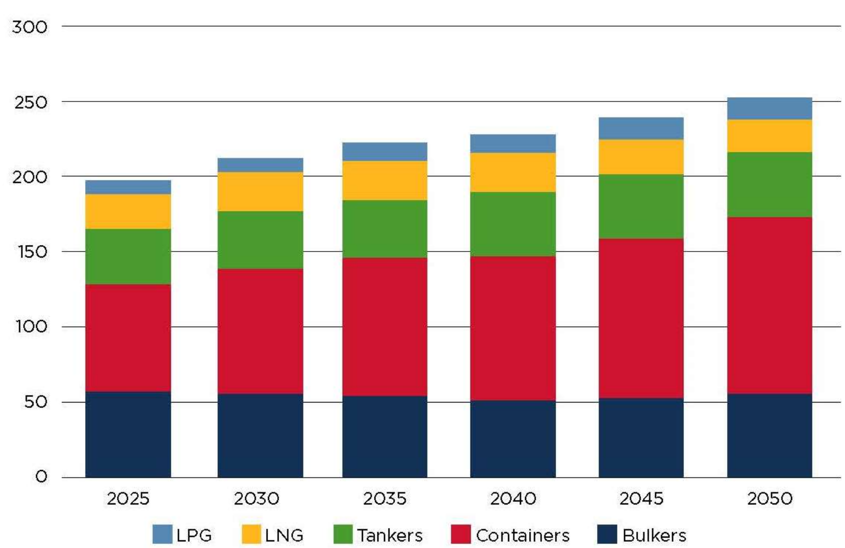

Figure 3.13. Fuel Consumption (Millions of Tons of Heavy Oil Equivalent) by Ship Type (ABS 2020).

Thirty ports (Table 3.4) handle most of the world's container freight; thus, relatively few port facilities would need to include nuclear-powered ships in their operations to create a large market for FBs. Container freight volume is measured in millions of 20 foot equivalent units (TEUs). The standardized containers are either 20 or 40 feet long. A 40 foot unit is treated as two 20-foot units. The table includes several port facilities (such as Keihin Ports, Japan) that do not have a ranking or volume. These entries are for locations with several ports close together that are operated as a single container port and where the total number of TEUs per year is between the TEUs listed above and below that entry. In 2019, the total container shipping volume was about 800 million TEUs.

Table 3.4. World's Largest Container Ports (World Shipping Council 2021).

Rank	Port	Volume (Million TEU/y)	Rank	Port	Volume (Million TEU/y)
1	Shanghai, China	42.01	17	Los Angeles, U.S.A.	9.46
2	Singapore	36.60	18	Tanjung Pelepas, Malaysia	8.96
3	Shenzhen, China	27.74	19	Hamburg, Germany	8.73
4	Ningbo-Zhoushan, China	26.35	20	Long Beach, U.S.A.	8.09
5	Guangzhou Harbor, China	21.87	21	Laem Chabang, Thailand	8.07
6	Busan, South Korea	21.66		Keihin Ports, Japan	
7	Hong Kong, S.A.R, China	19.60	22	Tanjung Priok, Jakarta, Indonesia	7.64
8	Qingdao, China	18.26	23	New York-NJ, U.S.A.	7.20
9	Tianjin, China	16.00	24	Colombo, Sri Lanka	7.05
10	Jebel Ali, Dubai, UAE	14.95	25	Yingkou, China	6.50
11	Rotterdam, Netherlands	14.51	26	Ho Chi Minh City, Vietnam	6.33
12	Port Klang, Malaysia	12.32	27	Bremen/Bremerhaven, Germany	5.42
13	Antwerp, Belgium	11.10		Hanshin Port, Japan	
14	Kaohsiung, Taiwan	10.45	28	Manila, Philippines	5.05
15	Xiamen, China	10.00	29	J. Nehru Port, India	5.05
16	Dalian, China	9.77	30	Piraeus, Greece	4.91

There are specific harbor regulations for ships that depend upon the country and international regulations for ships through the International Maritime Organization, which is part of the United Nations. Nuclear-powered cargo ships have been built in the past (such as the NS *Savannah*); thus, there is some experience. There are four major IMO conventions whose rules must be followed:

- *Load Line*. Amount of cargo a vessel may safely carry.
- *Tonnage*. The carrying capacity of a ship based on volume.
- *SOLAS (Safety of life at sea)*. Construction, communications, lifesaving, fire protection, and firefighting.
- *MARPOL (Marine pollution)*. Pollution prevention from onboard lubricants, cargoes, or emissions.

4. THE COMPETITION

The economic requirements for a FB are determined by the competition. We divide the market into two segments—the heat market and the electricity market. Heat from fossil fuels is much less expensive than electricity, as shown in Figure 4.1. Typically, the cost of electricity is about six times the cost of heat. That is because of three factors. First, it takes several units of heat to produce one unit of electricity because of the laws of thermodynamics. Second, there is the high cost to transport electricity, as shown above in Figure 3.8. Last, electricity is expensive to store—it must be used the moment; it is produced in the absence of large-scale low-cost storage technology. Because FBs provide heat, they will be more competitive in most heat markets than electricity markets.

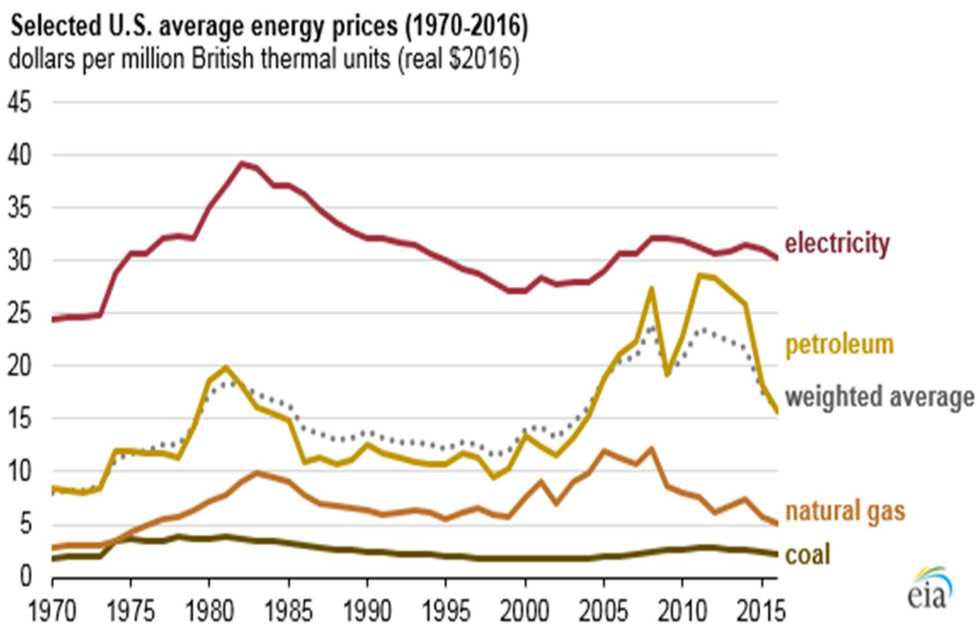

Figure 4.1. Cost of Different Energy Sources over 45 years (U.S. EIA).

In the United States, coal and natural gas are currently the low-cost thermal energy options, and they will remain so unless constraints or taxes restrict their use. Our analysis assumes there will be restrictions on greenhouse gas releases and thus the question is: what is the competition in a world with some types of restrictions on carbon dioxide emissions?

In a low-carbon world, we conclude, based on multiple considerations as described below, for FBs to be economically competitive, the price of delivered heat must be $20–50/MWh ($6–15/million BTU). These prices are significantly higher than the current price of coal and natural gas in most of the United States but similar to their prices in much of the rest of the world.

The economically competitive range for non-grid electricity is estimated at $70–100/MWh. The important caveat is "non-grid" electricity. That is because a significant fraction of the cost of electricity is delivery—from the generator by the transmission and distribution grid.

The analysis below is based on economics. However, that is not the only basis for FBs [Roege 2021; Roege Appendix D]. National security, law enforcement, or commercial/civil security represent a category for which value tends to be exposed through risk assessments and ultimately collective judgment about alternative actions and anticipated costs. Just like fences, lights, and guard force size, entities consider life cycle cost of energy assurance alternatives (backup generators, microgrids, etc.) as a risk/cost tradeoff. Commercial operations such as data centers, chemical processing, or logistics facilities often can calculate financial opportunity and recovery costs that can help inform the value of reliability. It is easy to underestimate real impacts, especially related to human aspects–such as safety, attitude, or community goodwill. Recent rolling blackouts in California and Texas have emphasized the value of high-reliable energy may be much higher than the price of commodity energy. These types of facilities have very different economics.

4.1. Heat Source Competition

As shown earlier in Figure 3.1, heat is ~83% of total U.S. energy demand [Forsberg and Briggs-Sitton 2020]. The primary source of heat for stationary non-electric-generating applications is natural gas; thus, the primary market for FBs is replacement of natural gas. Coal is used for electricity generation and steel production—markets where FBs are not expected to be competitive. Oil is used for transport where FBs are not applicable except for maritime applications. There are multiple alternatives.

4.1.1. Electric Heating

Electric heating is very expensive as shown in Figure 4.1. It may be competitive where the heat demand is small (less than 1 MW) or where there are special requirements such as high-temperature induction heating used for melting steel scrap. It is not expected to be competitive in the larger heat market.

Grid electricity as a source of heat is likely to be uneconomic for significant heat demands (tens of megawatts or more). The laws of thermodynamics imply several units of heat are required to make one unit of electricity—but under most circumstances one unit of electricity with resistance heating makes only one unit of heat. Heat is cheap and electricity (work) is more expensive. Because FBs produce heat, they have a competitive advantage in delivering heat to the customer relative to production of electricity.

4.1.2. Fossil Fuels

Natural gas with CCS is not economically viable on a small scale of a few tens of megawatts. It is not just the cost of carbon capture [Brandl 2021; Herzog 2018] but the pipelines and sequestration of the carbon dioxide that become very expensive [Smith 2021] at small scales. If fossil fuels with CCS are used, the economic scenario will be large cogeneration facilities producing heat—most likely as steam delivered to multiple customers in an industrial park. Figure 4.2 projects natural gas prices with different carbon taxes that can also be viewed as the range of costs for large-scale CCS. For reference, current large-scale CCS costs are between \$50 and \$100 per ton of carbon dioxide. Based on the cost of natural gas with large-scale CCS as the competition, the price of FB delivered heat must be \$20–50/MWh (\$6–15/million BTU). These prices are significantly higher than the current price of natural gas in most of the United States without a carbon tax, as shown in Figure 4.2, but similar to the prices of natural gas in the rest of the world.

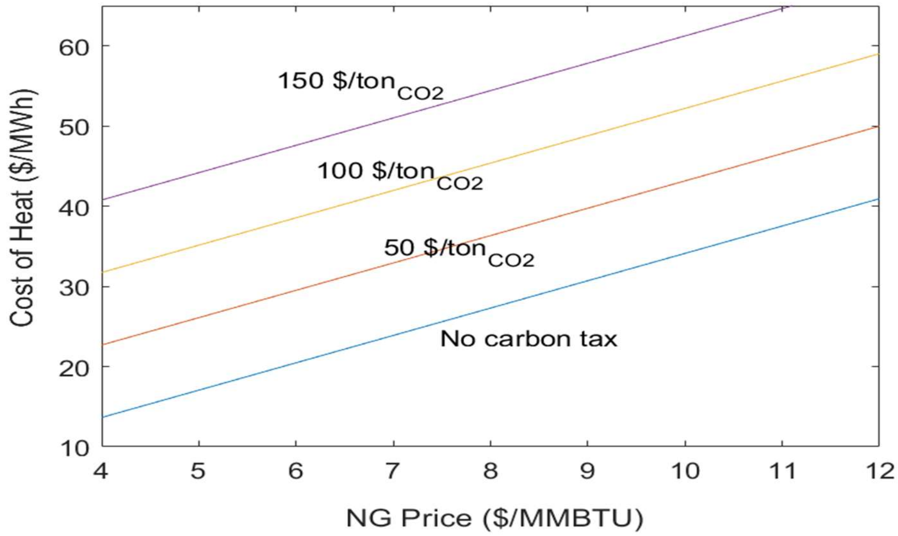

Figure 4.2. Cost of Heat versus Natural Gas Prices for Different Carbon Taxes.

4.1.3. Biofuels

Biofuels have the potential to be competitive with FBs—depending partly upon external energy sources to convert biomass into liquid and gaseous fuels (see Section 3.1.2). They would be most competitive in supplying heat to smaller users with heat demands of a few megawatts or less because of the low capital cost of smaller combustion systems compared to other alternatives to produce low-carbon heat. At the same time, biofuels production facilities may be a major market for FBs as discussed earlier.

As discussed earlier, biomass has a composition near $CH_{1.44}O_{0.66}$. Converting biomass into hydrocarbons involves removing oxygen and adding hydrogen to produce a hydrocarbon fuel—$(CH_2)_xH_2$. The oxygen can be removed in the form of water, in which case the process requires a source of external hydrogen. Alternatively, the oxygen can be removed as carbon dioxide. That option implies less hydrocarbon fuel per unit of biomass feedstock but allows sequestration of carbon dioxide from biomass—a method to remove carbon dioxide from the atmosphere and sequester it underground. The nuclear-bio-refinery options can produce variable ratios of hydrocarbon fuel and a relatively pure carbon dioxide stream with low-cost sequestration. There is an economic competition between using biomass to produce hydrocarbon fuels and using biomass to remove carbon dioxide from the air if society is willing to pay for removal of carbon dioxide from the air.

At the same time, the available supply of biomass depends upon the energy input into the bio-refinery. There is the potential to replace all liquid hydrocarbon fuels with biofuels. Traditionally biomass has been considered an energy source. By several estimates, biomass can meet about a quarter of future global low-carbon energy demands [Dale 2014]. The estimated U.S. harvestable biomass (carbon content about 80% that of petroleum) is at least a billion tons per year [DOE 2016] without significantly increasing prices of food or fiber. However, in a bio-refinery biomass is a carbon feedstock. There are many added sources of biomass that have a low-energy content but a high-carbon content. Traditional estimates of available biomass exclude such biomass carbon feedstocks (e.g., sewage sludge, municipal trash, and paper mill byproducts) that can be used for biofuels production if there are added energy inputs at the bio-refinery.

This is not the entire story. Agriculture is flexible—*it is designed primarily for food and animal feed production.* But agriculture can be redesigned [Dale 2010] to produce the same quantities of food and larger quantities of biomass for fuel and chemicals. This is because we do not use land primarily to grow human food. Instead, over 80% of human use of land is to produce animal feed, mostly in low-productivity pastures. Increasing the productivity of pasture [Cherubin 2021] would greatly decrease the land demand of food/feed production and free up land for bioenergy production. There are also options such as double cropping [Dale 2010] (growing two crops in one year) that are not used today because of the lack of sufficient demand for plant matter but could provide hundreds of millions of additional tons annually of biomass with significant environmental benefits [Kim 2005]. Moisture tolerant logistics systems for bioenergy crops are possible that could enable double cropping [Wendt 2018]. Last, there are the continuing productivity gains of American agriculture. For example, corn yields have gone from 20 to 180 bushels per acre from 1936 to 2019 [Nielson 2021]. It may be possible to double the biomass yield of the corn plant if we design a corn plant with a 20% lower starch yield (the corn grain) but with much more corn stalks and leaves.

The conclusion is that biofuels are potentially a major competitor to FBs—particularly for facilities with smaller heat demands. Biofuels feedstock costs are similar to crude oil prices. There is the potential for the cost of heat from biofuels to be \$15 to \$20 per million BTU. This would be significantly under the price of electricity but above current natural gas prices. At the same time, bio-refineries are potentially a major market for nuclear energy.

4.1.4. Hydrogen

In a low-carbon economy, hydrogen as a heat source may be competitive in some parts of the U.S. as a replacement for natural gas. Hydrogen is transported by pipeline and can be stored in the same facilities used for natural gas at low costs. Currently hydrogen is stored commercially in man-made salt caverns with work underway to enable storage in many other geological media (Heinemann 2021). The United States produces about 10 million tons of hydrogen per year for the production of fertilizer, oil refining, and the chemical industry. Large quantities are transported along the Gulf coast via pipeline. The cost of hydrogen transport is significantly greater than natural gas because of the lower volumetric energy density of hydrogen relative to natural gas. This implies the potential for larger regional differences in hydrogen costs compared to natural gas. Recent studies [Mallapragada 2020; Lucid Catalyst 2020; Ruth et al. 2020] have examined various hydrogen production methods.

The primary production method for hydrogen today is steam methane reforming of natural gas—a process that converts natural gas and steam into hydrogen and carbon dioxide. With the addition of CCS, it can be a low-carbon source of hydrogen. The cost of CCS for this process can be very low in locations such as Texas with low-cost natural gas and good carbon-dioxide sequestration sites.

The economics of CCS is carbon capture is expensive but the cost of sequestration is low if one has appropriate local geology [Smith 2021]. The process chemistry of traditional steam methane reforming results in two thirds of the carbon dioxide leaving the process as a relatively pure stream. Variants of the process result in essentially all of carbon dioxide leaving the process as a relatively pure stream of carbon dioxide. The carbon capture cost can be very low. In contrast, in a conventional natural gas furnace the exit steam is typically near 10% carbon dioxide implying high costs to capture the carbon dioxide. The cost of carbon sequestration can be significantly below \$10/ton if transport distances are short and good sequestration sites are available. Parts of Texas, Ohio, and North Dakota appear to have these characteristics. However, hydrogen is expensive to transport long distances relative to natural gas.

There are several programs to optimize steam methane reforming with CCS. At the current time, it appears that the first large-scale commercial plant will be built in the United Kingdom [Duckett 2021; Hynet 2020; French 2020; Cotton 2019]. The 750 million pound project will use the Johnson Matthey's variant of steam methane reforming to produce 3 TWh/year of hydrogen. The site is at an existing refinery where the refinery and local chemical plants will provide the initial market for hydrogen.

The alternative hydrogen production routes are electrolysis—low temperature electrolysis of water and high-temperature electrolysis of steam [Lucid Catalyst 2020; Terra Praxis 2021; Ingersoll Appendix D]. It takes more energy to convert water (oxidized hydrogen) into hydrogen than to convert methane (a reduced form of hydrogen) into hydrogen. High-temperature electrolysis is more efficient, and the cost of heat from converting water into steam is much less than the cost of electricity. Hydrogen plants using electrolytic cells are relatively expensive and thus the economics requires operating the electrolysis plants at high-capacity factors. There are also large economics of scale associated with the balance of plant (compressors, safety systems, etc.). Figure 4.3 shows projected hydrogen costs in 2030 as a function of capacity factor for different energy sources: solar PV, wind, and clean heat (nuclear and geothermal). Solar, for example, produces expensive hydrogen because of the low capacity factors of the hydrogen production facilities for spreading capital costs over hydrogen output. Nuclear hydrogen plants have potentially lower production costs because of higher capacity factors.

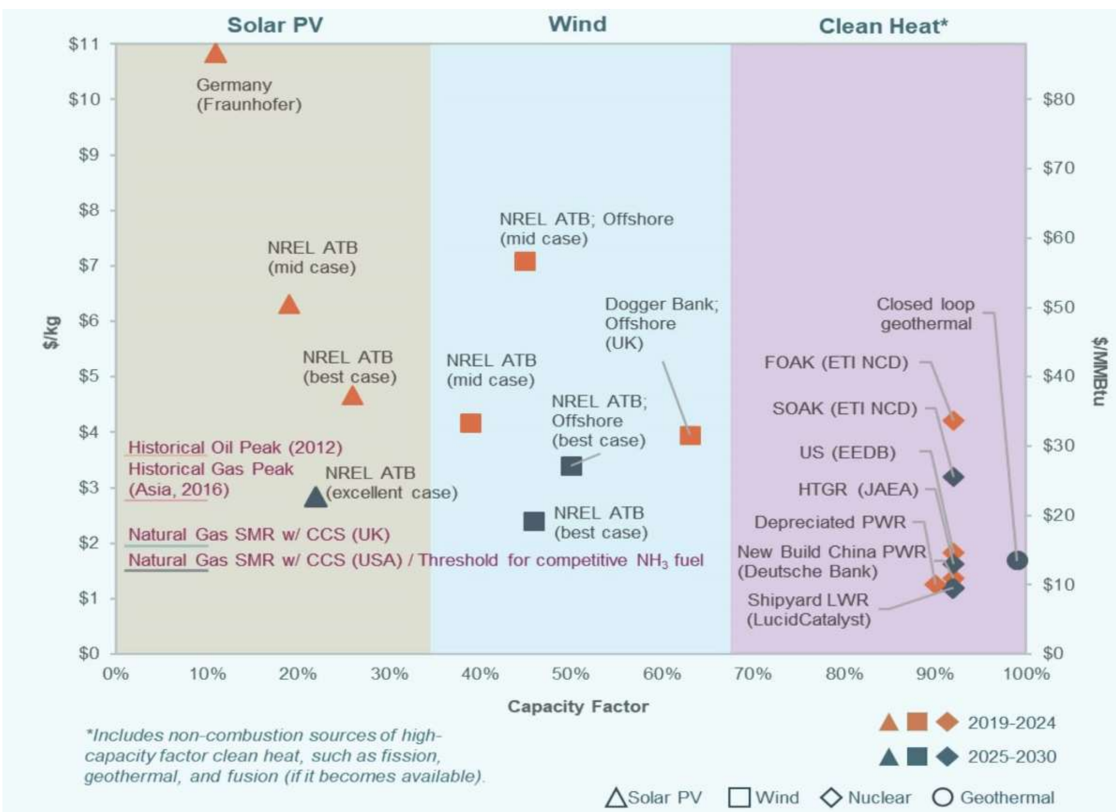

Figure 4.3. Projected Cost of Hydrogen as a Function of Capacity Factor [Courtesy of Lucid Catalyst; Ingersoll 2021; Appendix D].

The ability to move large amounts of hydrogen via pipeline, like natural gas, creates fundamentally new nuclear hydrogen production options. The energy carrying capacity of a single natural gas or hydrogen pipeline is an order of magnitude larger than an electricity transmission line. As discussed in Lucid Catalyst [2020], this creates the option of a gigafactory for hydrogen production at the energy production scale of a modern refinery. The site would contain a factory to build modular nuclear plants for onsite energy production with economics of mass production over a period of decades. The factory would replace nuclear plants as needed. Many modular reactors would be co-sited, and the hydrogen production plant would be co-located. Figure 4.4 shows a conceptual site plan where the manufacturing plant is in the upper part of the picture, the reactors are in the middle of the picture, and the hydrogen production facilities are located at the bottom. In many respects, this concept is similar to FBs except the reactors are sited at the production site that reduces the size and weight shipping constraints for the reactor. Shipyard cranes are capable of lifting thousands of tons. Other FB constraints are also reduced by a central site. These features may enable very low-cost hydrogen production by mass production of the reactors that provide electricity and heat combined with large hydrogen production facilities.

Figure 4.4. Hydrogen Gigafactory [Courtesy of Lucid Catalyst 2020] with Co-located Modular Reactor Deployment and Hydrogen Production.

There is a longer-term hydrogen production option [Saint John 2021]—hydrogen from methane through a pyrolysis process that converts methane to hydrogen and carbon. The carbon would be sequestered by burial. In theory, the costs could be low assuming low-cost natural gas because it takes relatively little energy to break up methane (CH_4) into its constituents if a successful process can be developed.

4.2. Electricity Source Competition

The economically competitive range for non-grid electricity is estimated at $70-100/MWh. These electricity prices are competitive with the retail prices of electricity in many parts of the United States for the customer as shown earlier in Table 3.2. Retail prices include generation, transmission, and distribution. FBs are not expected to be competitive selling wholesale electricity to the grid.

Conventional analysis for grid systems is based on energy as a commodity. However, there is a difference between the value of energy to a customer and its price. The value may be much higher than the commercial price of heat or electricity that creates markets for FBs. There are two examples below that can clarify this:

First, the largest incentives for adoption of FBs relate to creating new markets and new sources of revenue. An example is the paper and pulp industry that burns biomass wastes to provide heat and electricity to make paper. An external heat source could enable these plants to produce paper (old business) and use the internally generated biomass wastes as a feedstock to produce biofuels rather than burn the wastes to produce heat and electricity.

A second example are data centers with special energy requirements such as extreme reliability and significant cooling demand; the latter of which may be provided through (heat-driven) sorption chilling technologies. The costs and risks of downtime result in decisions to choose more expensive energy sources if more reliable. The value of reliable electricity is more important than the cost of commodity electricity.

5. BUSINESS MODELS

Most FB customers are not in the energy business but need heat and electricity to produce a product—a manufactured good, marine transport, data processing, retail sales (shopping malls), education (university campuses), or some other product. They are not in the business of producing electricity for sale but having a business arrangement can mitigate risks of energy availability and price. Moreover, businesses do not want to be dependent upon single suppliers for energy—the holdup problem where the energy supplier can raise prices. They want competitive suppliers—like the competitive market for supplying fossil fuels. Customers do not want to be in the business of licensing nuclear reactors.

These practical business considerations help define business models for FBs. These real-world constraints create incentives to lease FBs to supply energy with multiple suppliers of FBs. It also creates disincentives for other business structures such as large reactors with cogeneration to supply heat to multiple customers.

5.1. Leasing Fission Batteries

Leasing may avoid the administrative and legal burden of nuclear operations [Teplinsky Appendix D]. If responsibility for licensing, compliance, and interactions with the Nuclear Regulatory Commission (NRC) is carried by the leasing company, nuclear energy could become available to a much broader range of businesses. Leases are relatively simple compared to other commercial agreements. As a consequence, they are widely used to lease everything from trucks to train cars to jet engines to aircraft, although operational responsibility would be an important factor to work out. Table 5.1 summarizes lease options.

Table 5.1. Type of Lease and Characteristics.

Type of Lease	Key Aspects
Capital or Finance Lease (similar to bank loan)	• Customer owns equipment, lessor takes security interest • Equipment = asset, lease payments = liability • Customer can depreciate the equipment as an asset to provide a tax benefit • Customer can purchase equipment for discounted price at end of lease term
Operating Lease	• Lessor owns equipment, customer rents at a fixed monthly payment • Rental payments = operating expenses, tax deductible • End of lease term -> customer can extend lease, purchase equipment for fair market value, or return equipment
Solar Lease	• Similar to operating lease • Different options of down payment • Tax incentives/rebates normally are retained by developer

Given the above characteristics of different leases, operating leases will likely be the preferred lease form. This is the easiest structure from NRC licensing perspective–FB's owned by the developer where the customer rents at fixed periodic payment. The maintenance could be done by the owner or a specialty company. In this context, it is noted we have many existing nuclear plants where the operator is not the owner. For example, Exelon operates nuclear power plants for multiple utility owners. The capital or finance lease would require extensive discussions with the NRC and perhaps enabling legislation. The NRC regulations that apply to leasing are in 10 CFR §50.81:

> The Commission consents, without individual application, to the creation of any mortgage, pledge, or other lien upon any production or utilization facility not owned by the United States which is the subject of a license or upon any leasehold or other interest in such facility, provided:
>
> (1) That the rights of any creditor so secured may be exercised only in compliance with and subject to the same requirements and restrictions as would apply to the licensee pursuant to the provisions of the license, the Atomic Energy Act of 1954, as amended, and regulations issued by the Commission pursuant to said Act; and
> (2) That no creditor so secured may take possession of the facility pursuant to the provisions of this section prior to either the issuance of a license from the Commission authorizing such possession or the transfer of the license.

The current NRC licensing framework is not designed for large-scale deployment of nuclear batteries. Licensing solutions are necessary to enable large-scale deployment—key to success of leasing model from a market perspective. There are a variety of solutions to enable leasing.

- **Manufacturing Licenses**
  - Allow for pre-fabrication of nuclear power plants and then installation and operation at separately approved sites
  - Appendix N to Parts 50 and 52 provides for construction and operation of nuclear power reactors of identical design at multiple sites
- **Non-power reactors (NPRs)**
  - Simplified licensing process
  - NUREG-1537, "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors"—includes Standard Review Plant for licensing NPRs
  - Although nuclear batteries may not qualify as non-power reactors under the current system, regulations could be changed in the future to allow them to be licensed in a manner similar to NPRs
  - NRC has already included suggested modifications to NUREG-1537 Part 1 in a report titled "Regulatory Review of Micro-Reactors – Initial Considerations."
- **Part 53**
  - Performance-based licensing regime with technology-inclusive framework
  - Significant engagement with NRC required to provide for a licensing framework allowing for large-scale deployment of nuclear batteries.

Separate but coupled to leasing and licensing FBs is the licensing basis for FBs. The NRC has historically had a modified licensing strategy for small research reactors under 10 MW. This is because the small fission product inventory implies that large accidents are impossible. This is parallel to the EPA regulations on hazardous materials—there are different rules for small quantities of hazardous materials because the maximum possible accident consequence is small. To use a simple example, most cars have gasoline tanks but the risks and maximum consequence of an accident from the gasoline in those tanks is small compared to a tanker truck delivering gasoline to the local gasoline station. The regulations for the gasoline in the tank in your car are different than a truck hauling large quantities of gasoline or an oil tank farm.

The NRC, through the definitions in 10 CFR 170.3 and NUREG 1537, defines 10 MWt for non-power reactors (Class 104) as the dividing line between research reactors and testing facilities subject to the results of accident analysis in 10 CFR 20.1001 through 20.2404 and appendices. The licensing burden and requirements are less for small research reactors. The 10 MWt criterion is being replaced via revisions to NUREG 1537 that reflect a new criterion [ACRS 2019; NRC 2019] introduced in the non-power production or utilization facility (NPUF) rule. Under the NPUF rule, non-power reactors are classified as a research reactor if the accident radiation doses are $\leq$ 1 rem Total Effective Dose Equivalent (TEDE)—the sum of the effective dose equivalent for external exposures and the committed effective dose equivalent for internal exposures. These doses are coupled to the EPA Protective Action Guidelines for radiation release protocol and mitigation. The practical implication is the regulatory burden and siting requirements may be simplified for FBs provided it can be shown the maximum accident consequences are small and localized. This may create a separate limit on the power output of a FB independent of power limits imposed by transportation constraints. Depending upon design, that limit may be a few tens of megawatts.

If the customer is not in the United States, there is the question of spent nuclear fuel (SNF) takeback—where the SNF goes at end of FB lifetime. This includes ships not owned by U.S. companies. If the foreign country has its own nuclear program and repository program, wastes can be returned to the country that leases FBs. From an economic and non-proliferation perspective, there are massive incentives for SNF takeback for FBs. The FB factory and associated jobs would be in the United States.

Last, the leasing model imposes requirements on FBs. FBs must be transportable for delivery and return to the lessor. FBs must be standardized—partly for economics of mass production but also to maintain the value of the FB. If the FB were instead customized for a particular customer, at the end of the lease it could not be quickly refurbished and sent to the next customer. Its value would be limited if repossessed for failure to pay leasing fees. Equally important, if there were a problem with a FB and it were customized, there would not be a replacement unit available at the factory.

5.2. Other Business Models

Business decisions that consider risk often lead to different conclusions than decision-making from simple economic models [Parsons Appendix D]. For example, a simple engineering economic model may show the most economical solution to provide heat would be a large nuclear reactor or fossil-fuel plant with CCS designed to provide heat and electricity for multiple customers. The problem is the interests of the cogeneration plant owners and the different users of heat do not align over time. The industrial customers are concerned once they site the plant in an industrial park with a large cogeneration plant, the industrial customers will be hostage to the plant owner of cogeneration plant that can raise the price of energy. This creates incentives for industrial facilities to control their own energy sources. As a consequence, most large nuclear cogeneration plants with multiple customers were built in the former Soviet Union with centrally planned economics. In the United States, the number of fossil-fired cogeneration plants with multiple customers is far below academic projections of cogeneration based on economic studies for these reasons. These types of considerations also create markets for FBs where the company has potentially multiple supply options.

Separate from these considerations is the fact that a large fraction of the industrial facilities is sited based on logistical or other cost drivers that are more important than the cost of energy. Food processing plants, paper and pulp mills, mines, and many other facilities cannot be moved. They are located near the resources they process to produce final products. The energy must be delivered to them.

6. IMPLICATIONS FOR FB DESIGN

A series of engineering assessments [Buongiorno Appendix D] were undertaken to help define technical constraints based on the above economic constraints. To achieve the aforementioned cost targets for heat and electricity markets, FB designers must (1) maximize the power output within the constraints of a FB (e.g., truck transportability and passive decay heat removal), (2) drastically reduce the size of onsite staff, (3) adopt core designs requiring low fuel enrichment and fabrication costs, and (4) develop a system design that is efficiently manufactured in a factory. The other major conclusion is within the design envelope, the FB size should be maximized to be economically viable as shown in Figure 6.1. FBs under 5 MWt are unlikely to be economic. The assumptions used in this analysis are in Table 6.1.

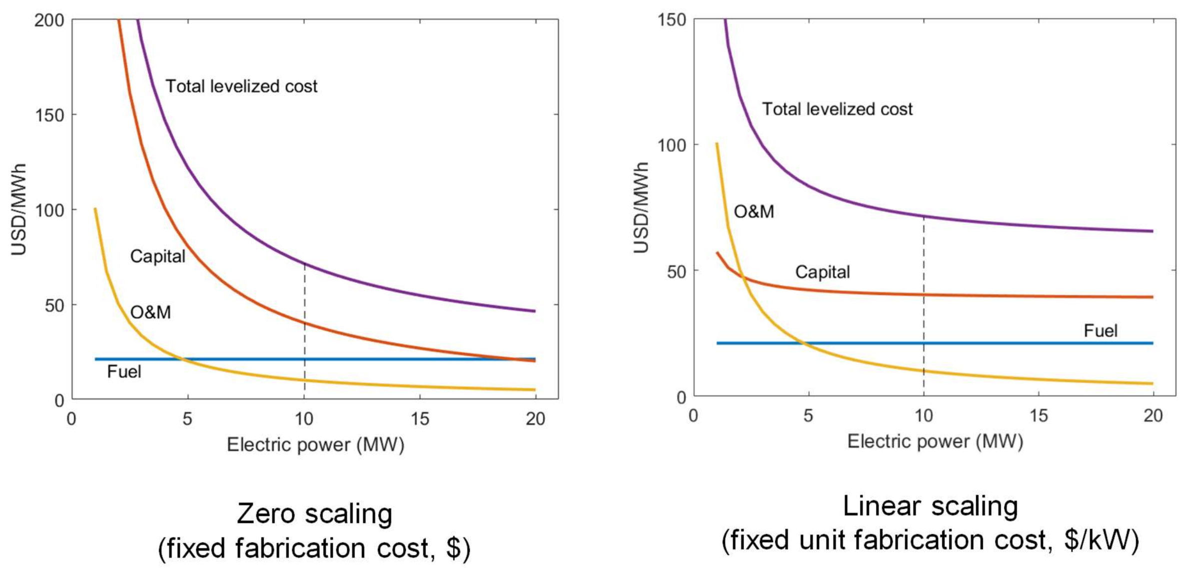

Figure 6.1. FB Cost Vs Size of FB for Different Sets of Assumptions.

Table 6.1. Economic Assumptions Used in Analysis.

Parameter	Value	Comments
electric power output	10 MWe	Reasonable value for many NB applications
thermal efficiency	35%	Estimated for open-air Brayton cycle with losses
core power	28.6 MWt	= electric power/thermal efficiency
capacity factor	85%	NB and co-located applications must be operated continuously for good economics
fuel enrichment	5%	Does not require relicensing of U.S. fuel cycle facilities
discharge burnup	20 MWd/kg_U	Lower than light water reactor because of small cartridge core
refueling interval	5 yrs.	From fresh fuel load in central facility to spent fuel return

cost of uranium	40 $/lb. of U_3O_8	Conservative assumption for cost of yellowcake
cost of uranium conversion	6 $\$/kg_U$	Conservative assumption for cost of converting yellowcake into UF_6
cost of uranium enrichment	160 $/SWU	Conservative assumption in current U market
cost of fuel fabrication	500 $\$/kg_U$	2x higher than traditional LWR fuel fabrication
cost of SNF disposal	1 $/MWh	U.S. SNF disposal fee
# of FTE for O&M	5	Same FTE/MW of current U.S. fleet
wages per FTE	150,000 $/yr.	Includes benefits and taxes
cost of fabrication	30 M$	3000 $/kW, excluding fuel
other capital costs	1.7 M$	Includes site preparation, NB vault, electric transformer, office container, NB shipment to/from site, installation and connection
NB economic lifetime	20 yrs.	NB technical lifetime likely longer
cost of decommissioning	½ cost of NB fabrication	Incurred at the end of the project
discount rate	5%/yr.	Reasonable for small project

The economic analysis led to several quantitative conclusions:

- Power output should be maximized within FB constraints (truck transport, passive decay heat, and licensing).
- The allowable staff is in the range of 0.5–1.5 FTE/MW.
- The economic benefits for long-lived reactor cores are limited beyond 5 years.
- Higher enrichments require higher burnups. The fuel enrichment should be <10% ^{235}U with a burnup >20 MWd/kg_U. Higher enrichments require higher burnups and higher specific power densities to avoid high interest costs associated with the fuel.
- FB fabrication cost (excluding fuel) should be less than 5000 $/kW.
- Requires a discount rate less than 10 %/yr.

7. CONCLUSIONS

The workshop and this proceedings document are first assessments of the markets, economic goals, the competition, and the business models for FBs. This is work in progress. FBs are defined by attributes—not technology or power levels. The attributes will limit power output to 100 MWt—and most likely between 20 to 30 MWt except for maritime and other such applications without the transport weight and size limits. The market size (1) is sufficient to support large-scale FB manufacturing similar to that for large jet engines and (2) could ultimately be 10 to 20% of total energy use. Most of the customers are energy consumers producing some other product such as manufactured goods, marine transport, data processing, retail sales (shopping centers), or education (university campuses). They are not in the business of selling energy.

For FBs to be economically competitive, the price of delivered heat must be \$20–50/MWh (\$6–15/million BTU). The economically competitive range for non-grid electricity is estimated at \$70–100/MWh. The competition in a low-carbon world for heat demands of megawatts to multiple tens of megawatts includes hydrogen (and its derivatives such as ammonia) and biofuels. FBs become less competitive than grid electricity at smaller energy demands, they become less competitive than fossil fuels with CCS at larger energy demands in locations with cheap natural gas and good low-cost carbon dioxide sequestration sites.

The likely business model is leasing of FBs—similar to the model for leasing jet engines and aircraft. The lessor would obtain and manage the reactor license with the NRC. The customer wants multiple suppliers to assure competitive prices—similar to multiple suppliers of fossil fuels. This requires transportability and standardized FBs to enable switching FB suppliers and retaining the value of used FBs after refurbishment for the next lessee. Manufacturing cost considerations imply very small FBs under a few megawatts are unlikely to be competitive.

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Appendix A: AGENDA and FLYER

Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

January 13 and Jan 27, 2021: Two Webinars (10:00 to 1:00 Eastern)

[1]Charles Forsberg (cforsber@mit.edu) and [2]Andrew W. Foss (Andrew.Foss@inl.gov)
[1]Massachusetts Institute of Technology; [2]Idaho National Laboratory

Fission batteries (FBs) are a new vision for nuclear power to address smaller markets in a low-carbon world. Fission batteries are defined by a set of attributes—not technology. There are five attributes. First, FBs must be cost competitive with other distributed energy sources (electricity and heat) used for a particular application. Second, FBs are developed in standardized sizes and power outputs to enables universal use and factory production at a manufacturing scale similar to jet engines and aircraft. Third, FBs are designed for easily installation, use and removed after use. This creates a competitive energy market where user is not an economic hostage to the suppler. Fourth, they are designed to operate securely and safely while unattended to provide demand-driven power. Last, the systems and technologies mush have a high level of reliability to provide a long life and enable wide-scale deployment for multiple applications. These are aspirational goals. It is not known if FBs can be built.

Micro reactors and small modular reactors may have several of these attributes but not all of these attributes. The power output of the FB is not defined. There are proposals for FBs that vary from less than a megawatt to 100 MWt. For technical and market reasons, larger FBs are considered unlikely. The markets include heat to industrial and other customers. The industrial heat demand is more than twice the total electricity produced in the U.S. FBs may be used to produce electricity for specialty markets with special requirements such as ships and data centers with high reliability requirements. It is not expected that FBs will be competitive for the production of grid electricity. The workshop is to address several questions.

What is the Market for Fission Batteries?

What is the total size of the market? What heat output is required for different sectors; that is, what would be the market size for units of 2, 5, 10, 25, 50, 75 and 100 MWt? What are the technical requirements (temperature of delivered heat, special requirements such as for marine applications, etc.)? The expectation is that many customers would have multiple FBs to meet local demands and reliability goals. What is the commercial model—own or lease? What are the implications of the business model?

What is the Competition and at What Price?

What is the competition: natural gas with no carbon constraints; natural gas with carbon tax, fossil fuels with carbon capture and sequestration, low-carbon hydrogen, biofuels and electricity? What is competitive at different facility heat demands? What are the regional differences in the price of different fuels? Some options such as electricity and hydrogen may have very large geographical differences in price.

What are the Reactor Requirements Driven by Economics and Markets?

What do cost constraints imply in terms such as design choices such as power density and allowable uranium enrichments? What do the economic goals imply in terms of operations, maintenance and security—such as manpower levels? If high reliability heat is required, how many fission batteries are required to meet specific reliability goals?

Agenda (10:00 to 1:00 Eastern)

January 13, 2021 (Wednesday): Question and Answer after Each Speaker

10:00: Charles Forsberg (MIT) / Andrew Foss (INL): Welcome

10:05: Youssef A. Ballout (INL): Fission Battery Initiative

10:15: Charles Forsberg (MIT): Defining Markets, the Competition and Economic Design Constraints for Fission Batteries

10:40: Andrew Foss (INL): Market Opportunities for Fission Batteries

11:05: Eric Ingersoll (Lucid Catalyst): Nuclear hydrogen futures: The Competition

11:30: Break

11:45: Gareth Burton (American Bureau of Shipping): Fission Battery Initiative Workshop: Maritime Perspective

12:10: Bruce Dale (Michigan State University): Liquid Biofuels Energy Markets

12:35: Roundtable and Discussion

January 27, 2021 (Wednesday): Question and Answer after Each Speaker

10:00: Charles Forsberg (MIT) / Andrew Foss (INL): Welcome

10:05: Youssef A. Ballout (INL): Fission Battery Initiative

10:15: Jacopo Buongiorno (MIT): Can Nuclear Batteries Be Economically Competitive In Large Markets?

10:40: Paul E. Roege, P.E. (Partner, Creative Erg, LLC): The Resilience Value Proposition

11:05: Elina Teplinsky (Partner: Pillsbury Winthrop Shaw Pittman LLP): Legal feasibility of leasing of Fission Batteries

11:30: Break

11:45: Jerry Schwartz (American Forest & Paper Association): Pulp and Paper Industry Perspectives

12:15: John Parsons (MIT Sloan School of Management): Business Models: Enterprise Controls FB versus Large-scale Cogeneration with Multiple Heat Customers

12:35: Workshop Roundtable

Appendix B: WORKSHOP PARTICIPANTS

A total of 250 people attended all or part of the two session webinar including 74 participants from the national laboratories, 20 from government agencies, 72 from universities, and 84 from industry.

Appendix C: SPEAKER BIOGRAPHIES

Youssef A. Ballout (Idaho National Laboratory)

Dr. Youssef Ballout is the Director of the Reactor Systems Design and Analysis Division in the Nuclear Science and Technology Directorate at the Idaho National Laboratory. Dr. Ballout began his engineering studies in Limoges, France and holds bachelor's, master's and doctoral degrees in engineering from Wichita State University, Kansas. Prior to joining INL he was the President of Elysium Industries Limited where he engaged in the design and development of a molten chloride salt fast reactor. He spent 26 years at the Naval Nuclear Laboratory/Knolls Atomic Power Laboratory where he worked on several aspects of naval reactor design and analysis including core materials fundamentals, computational fluid dynamics and advanced computational techniques development, advanced reactor programs, and core systems integration. Dr. Ballout also worked as the structural materials manager for the Jupiter Icy Moon Orbiter (JIMO/ Prometheus) project for space nuclear propulsion.

Jacopo Buongiorno (Massachusetts Institute of Technology)

Jacopo Buongiorno is the TEPCO Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology (MIT), and the Director of Science and Technology of the MIT Nuclear Reactor Laboratory. He teaches a variety of undergraduate and graduate courses in thermo-fluids engineering and nuclear reactor engineering. Jacopo has published 90 journal articles in the areas of reactor safety and design, two-phase flow and heat transfer, and nanofluid technology. For his research work and his teaching at MIT he won several awards, among which the ANS Outstanding Teacher Award (2019), the MIT MacVicar Faculty Fellowship (2014), the ANS Landis Young Member Engineering Achievement Award (2011), the ASME Heat Transfer Best Paper Award (2008), and the ANS Mark Mills Award (2001). Jacopo is the Director of the Center for Advanced Nuclear Energy Systems (CANES). In 2016-2018 he led the MIT study on the Future of Nuclear Energy in a Carbon-Constrained World. Jacopo is a consultant for the nuclear industry in the area of reactor thermal-hydraulics, and a member of the Accrediting Board of the National Academy of Nuclear Training. He is also a member of the Secretary of Energy Advisory Board (SEAB) Space Working Group, a Fellow of the American Nuclear Society (including service on its Special Committee on Fukushima in 2011-2012), a member of the American Society of Mechanical Engineers, past member of the Naval Studies Board (2017-2019), and a participant in the Defense Science Study Group (2014-2015).

Gareth Burton (American Bureau of Shipping)

Gareth Burton is Vice President Technology at ABS (American Bureau of Shipping). He began his career with a consulting engineering company before joining ABS in 2001. During his time with the organization, he has held various roles in engineering, client relationship management and product development in the US, Mexico and Singapore. In his current role, he is responsible for the development and execution of the ABS research program. Gareth holds a Bachelor's Degree from the University of Manchester, England and a Masters' and Doctorate of Engineering from the University of Ulster, Belfast, Northern Ireland. In addition he has completed the Executive MBA program through Texas A&M University.

Bruce Dale (Michigan State University)

Professor Dale is University Distinguished Professor of chemical engineering at Michigan State University and the Founding Editor of Biofuels, Bioproducts and Biorefining. He has published more than 300 archival journal papers and has 63 US and international patents. He is interested in understanding how long term prosperity can be based on sustainable agroenergy systems.

Charles Forsberg (Massachusetts Institute of Technology)

Dr. Charles Forsberg is a Principle Research Scientist at MIT. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. Dr. Forsberg was the Executive Director of the MIT Future of the Nuclear Fuel Cycle study and one of three co-inventors of the Fluoride-salt-cooled High-temperature Reactor. He has been awarded 12 patents and published over 300 papers

Andrew Foss (Idaho National Laboratory)

Andrew Foss is Technical Program Lead - Nuclear Energy Markets, Economics, and Systems Analyses at Idaho National Laboratory. He works with national laboratory teams to ensure the cost competitiveness and market viability of advanced nuclear concepts in future energy systems. Before joining INL in 2020, Andrew performed numerous energy consulting projects at NERA Economic Consulting (2005-2007 and 2009-2014) and LucidCatalyst (2014-2020). His areas of expertise include innovative nuclear technologies, energy market modeling, and commercialization strategies. He participated as a cost expert in the MIT study on The Future of Nuclear Energy in a Carbon-Constrained World (2018) and wrote report chapters for the International Atomic Energy Agency on nuclear cost drivers (2019). He has also worked with the US Advanced Research Project Agency-Energy (ARPA-E), the UK Department for Business, Energy, and Industrial Strategy (BEIS), the Electric Power Research Institute (EPRI), the UK Energy Technologies Institute, the UK Energy Systems Catapult, ClearPath, EDF, Duke, Entergy, and NV Energy, as well as developers of fission and fusion technologies. He earned a bachelor’s degree in physics from Amherst College and a master’s degree in public policy with concentration in environment and natural resources from the Harvard Kennedy School.

Eric Ingersoll (Lucid Catalyst)

Eric Ingersoll is the Managing Director of LucidCatalyst (LC) is a strategic advisor and entrepreneur with deep experience in the commercialization of new energy technologies. He has extensive project and policy experience in renewables, energy storage, oil & gas, and nuclear, with a special emphasis on advanced nuclear technologies. At LC, Eric works with clients to develop commercialization and market entry strategies for advanced energy technologies such as advanced nuclear power generation, carbon capture, and zero-carbon liquid fuels. Eric has led the LC team in completing an array of projects related to regulatory, financing, and project delivery barriers in the nuclear sector for a variety of clients, including government agencies in the US and abroad. LC conducted a definitive cost study on advanced nuclear technology and maintains one of the industry's most comprehensive advanced nuclear cost models. Eric was on the study team for MIT's Study: The Future of Nuclear Energy in a Carbon-Constrained World, and a principal author of ETI’s Nuclear Cost Drivers Report. He leads multiple decarbonization modeling efforts, and advises governments and private sector on electricity and fuels applications of advanced nuclear and fusion energy systems. Eric is also co-founder of the NGO Energy Options Network (EON): a group of technologists, engineers, entrepreneurs, and scientists providing rigorous thought leadership and hands on support to accelerate the commercialization and deployment of Real Climate Options most aren’t paying attention to. As most future energy system growth will likely take place in the developing world, EON focuses heavily on technologies practical for deployment there.

John E. Parsons (Massachusetts Institute of Technology)

Dr. Parsons is Senior Lecturer at the Sloan School of Management. His research focuses on the valuation and financing of investments in energy markets, as well as the problems of risk in energy and environment markets, the role of trading operations in energy companies. He is currently an Associate Director at MIT’s Center for Energy and Environmental Policy Research (CEEPR) and the co-Director of the MIT Energy Initiative’s Low Carbon Energy Center focused on advanced nuclear generation. He was a co-Director of the recent MIT study on the Future of Nuclear Energy in a Carbon Constrained World. Dr. Parsons serves as an Associate Member of the U.S. CFTC’s Energy and Environmental Markets Advisory Committee. Dr. Parsons has been a Visiting Scholar at the U.S. Federal Energy Regulatory Commission. He holds a BA in Economics from Princeton University and a PhD in Economics from Northwestern University.

Paul Roege (Partner, Creative Erg, LLC)

Colonel (retired) Paul Roege (P.E.) has over 40 years of experience leading engineering, construction, and research. He currently balances ongoing research and advocacy about energy and resilience with direct engagement with innovative energy startups, including service as Director of the Advanced Nuclear and Production Expert Group (ANPEG). As a US Army engineer officer, Colonel Roege managed construction programs in Europe, Asia, Africa and Central America, including reconstruction of Iraqi oil production systems in 2003. He later was recalled to active duty to develop operational energy doctrine and catalyzed early resilience discussion in the Pentagon. While serving as a DARPA program manager, he initiated a program to build a very small deployable reactor for military use. In his civilian career, Colonel Roege led engineering and nuclear safety activities in nuclear fuel cycle facilities, waste management, and infrastructure systems on the Department of Energy sites. Paul is a registered professional engineer and a West Point alumnus with graduate degrees from Boston University (Business) and the Massachusetts Institute of Technology (Nuclear Engineering).

Jerry Schwartz (American Forest & Paper Association)

Jerry Schwartz has been with the American Forest & Paper Association for over twenty five years and currently is the Senior Director of Energy and Environmental Policy. He is responsible for managing energy, water, and other policy issues for the association. Jerry also is the Sustainability Team Leader for AF&PA, and he led the effort to develop and implement its sustainability initiative, Better Practices, Better Planet 2020. Before joining AF&PA, he owned a litigation support consulting firm, traveled around the world for a year with his wife, and worked in the Environmental Enforcement Section of the Department of Justice for four years. He also worked in various offices in the U.S. Environmental Protection Agency for six years. He graduated with honors from Harpur College with a Bachelor of Arts degree and he has a juris doctor degree from the George Washington University National Law Center.

Elina Teplinsky (Pillsbury Winthrop Shaw Pittman LLP)

Elina Teplinsky, a leading member of Pillsbury's International Nuclear Projects team and Energy Industry Group deputy leader, focuses on international nuclear energy matters, including advice to U.S. and global clients on transactional and regulatory issues. She is a co-chair of the World Nuclear Association's Law Working Group.

Appendix D: Presentations

January 13, 2021

Youssef Ballout, Ph.D.
Director of the Reactor Systems Design and Analysis Division

Fission Battery Initiative

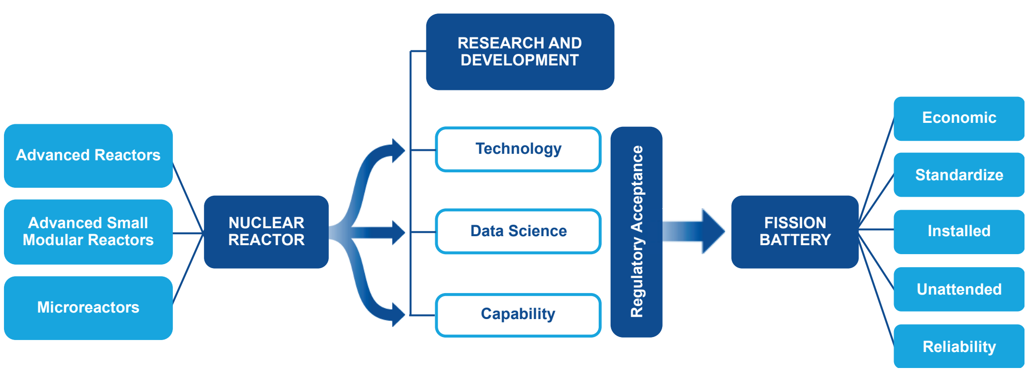
Nuclear Science and Technology

Idaho National Laboratory

Fission Battery Initiative

Vision: Developing technologies that enable nuclear reactor systems to function as batteries.

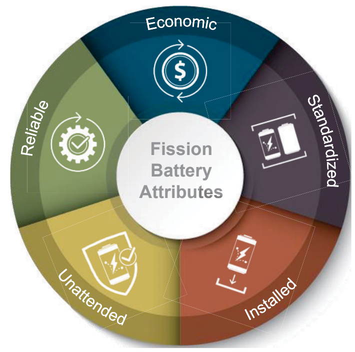
Outcome: Deliver on research and development needed to provide technologies that achieve key fission battery attributes and expand applications of nuclear reactors systems beyond concepts that are currently under development.



Research and development to enable nuclear reactor technologies to achieve fission battery attributes

Fission Battery Attributes

- **Economic** – Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable flexible deployment across many applications, integration with other energy sources, and use as distributed energy resources.
- **Standardized** – Developed in standardized sizes, power outputs, and manufacturing processes that enable universal use and factory production, thereby enabling low-cost and reliable systems with faster qualification and lower uncertainty for deployment.
- **Installed** – Readily and easily installed for application-specific use and removal after use. After use, fission batteries can be recycled by recharging with fresh fuel or responsibly dispositioned.
- **Unattended** – Operated securely and safely in an unattended manner to provide demand-driven power.
- **Reliable** – Equipped with systems and technologies that have a high level of reliability to support the mission life and enable deployment for all required applications. They must be robust, resilient, fault tolerant, and durable to achieve fail-safe operation.



Fission Battery Workshop Series

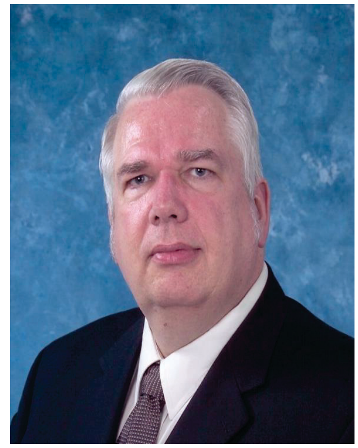
- **Jointly INL and National University Consortium are organizing workshops across five areas:**
  - Market and Economic Requirements for Fission Batteries and Other Nuclear Systems
  - Technology Innovation for Fission Batteries
  - Transportation and Siting for Fission Batteries
  - Security Scoping for Fission Batteries
  - Safety and Licensing of Fission Batteries
- **Expected outcomes:**
  - Each workshop outcomes are expected to outline the goals of each fission battery attribute

INL

Idaho National Laboratory

Defining Markets, the Competition and Economic Design Constraints for Fission Batteries

Charles Forsberg
Massachusetts Institute of Technology
Email: cforsber@mit.edu



Workshop: Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

January 13 and Jan 27, 2021

Outline

- Fission Batteries: What Are They and What They Are Not
- Who Are the Potential Customers?
  - Heat Demand, Temperature Requirements, Reliability Requirements
  - How Many FBs by Category for the U.S.
- What Is the Competition?

Fission Batteries

Defined By a Set of Characteristics

Do Not Know If Can Achieve Full Set of Characteristics

Fission Battery (FB) Attributes

Small Modular Reactors and Microreactors May Have 2 or 3 Attributes

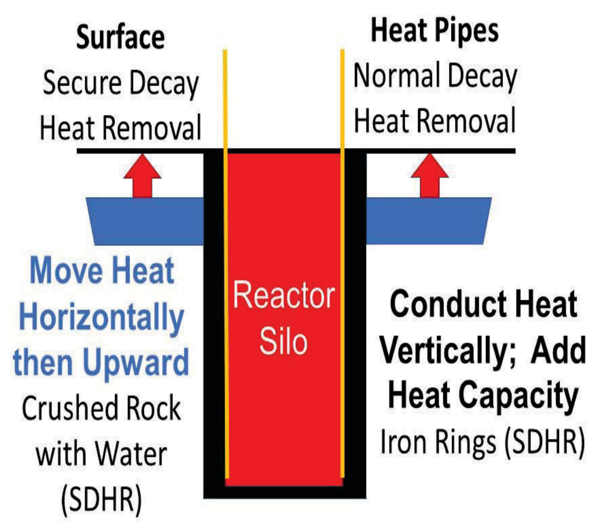
- *Economic:* Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular location.
- *Standardized*: Developed in standardized sizes and power outputs with manufacturing processes that enable universal use and factory production to lower costs and more reliable systems (Manufacturing scale similar to jet engines and aircraft).
- *Installed*: readily and easily installed for use and removed after use. Creates a competitive energy market where user is not an economic hostage to the suppler.
- *Unattended*: Operate securely and safely while unattended to provide demand-driven power
- *Reliable*: Systems and technologies must have a high level of reliability to provide a long life and enable wide-scale deployment for applications.

Fission-Battery Customer Interface

- Drop-in reactor with minimum site infrastructure; may replace reactor rather than refuel reactor (Battery model)
- Most customers are not in the energy or power business—they do not sell heat or electricity as a business
- Customers need energy to heat buildings, produce products and other purposes
- Customer may own or lease fission batteries

The Fission Battery (FB) Is Not Defined By Power Output

- Different viewpoints on FB size
  - Proposals from <1 to 100 MWt
  - Technical challenges with larger power output
  - Example: Assured decay heat removal if no local security to assure decay heat rejection to atmosphere
- **Economic questions (Speaker: Andrew Foss)**
  - **What is the market size (number of units) for different power levels? May deploy multiple FBs per customer**
  - **Is market sufficiently large to support factory production?**

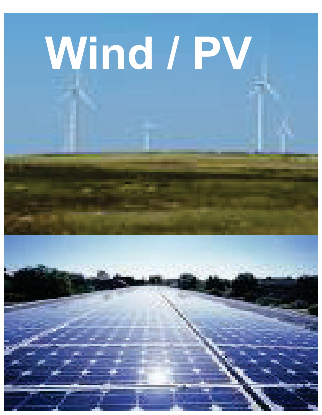


Secure Decay Heat Removal System With Ground Heat Sink

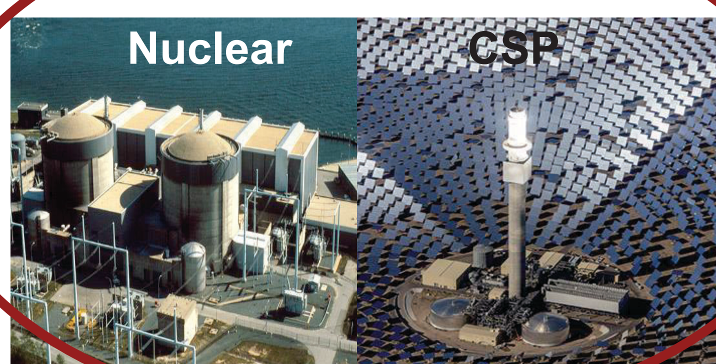
Who Are the Potential Customers?

Two Primary Energy Production Systems: Electricity and Heat

Produce Electricity



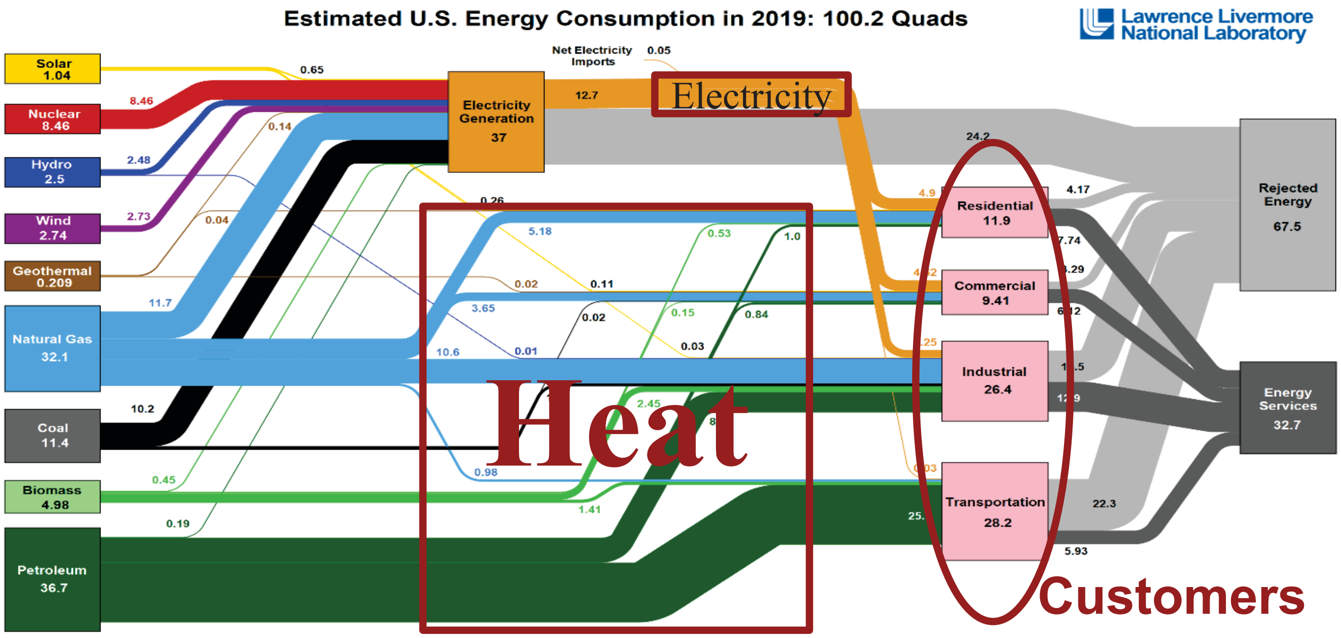
Produce Heat



Nuclear Reactors Produce Heat

Most Energy Is Consumed As Heat

Industrial Heat Demand Twice Total Electricity Production



Making Electricity from Heat is Expensive:

Thermodynamics of Power Cycles

Multiple Units of Heat → One Unit Electricity

+ Power Plant

1 Unit of Electricity → One Unit of Heat

+ Electric Resistance Heater

Heat Generating Technologies Tend to Produce Low-Cost Heat;

Electric Generating Technologies Tend to Produce Low-Cost Electricity

Expected Fission Battery Markets

- *Heat:* Competitive advantage
- *Work (Electricity):* Non-utility markets with special requirements
  - Ships
  - Ultra-high reliability or quality (Data centers, etc.)
  - Off-grid locations
- **May sell excess energy to grid (cogeneration) but not likely to be economic basis to buy or lease fission battery**

There Are Many Markets and a Large Numbers of Potential Customers

- Existing U.S. heat users (Speaker: Andrew Foss)
  - Industry, schools, agriculture, etc.
  - Over 6000 users with heat demand greater than 1 MWt
- Biofuels (Speaker: Bruce Dale)
- Chemicals
- Ships and other maritime applications (Speaker: Gareth Burton)
- Special electricity markets (data centers, others)

Fission Battery Has a Different Ownership Model

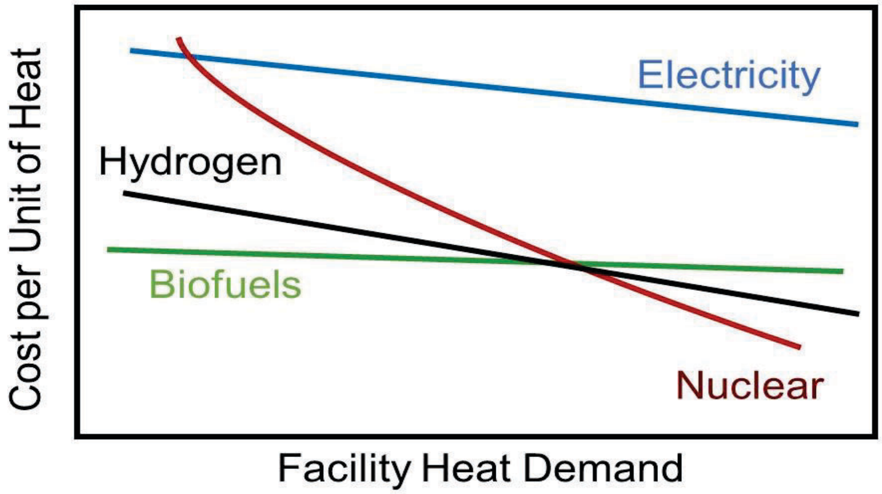
- **Most fission battery customers are not in the energy business** —just need heat and/or electricity for their business (Speaker: J. Parsons)
- May own or lease fission battery—like leasing trucks or other equipment (Speaker: Elina Teplinsky)
- If a problem, call the vendor to fix

What Is the Competition?

Defines Fission Battery Economic Goals

There are Multiple Potential Competitors

Hypothetical Cost of Heat Vs Customer Energy Demand



Fission Battery Goal to Move Nuclear Line Down

Workshop To Begin to Define Real-World Numbers

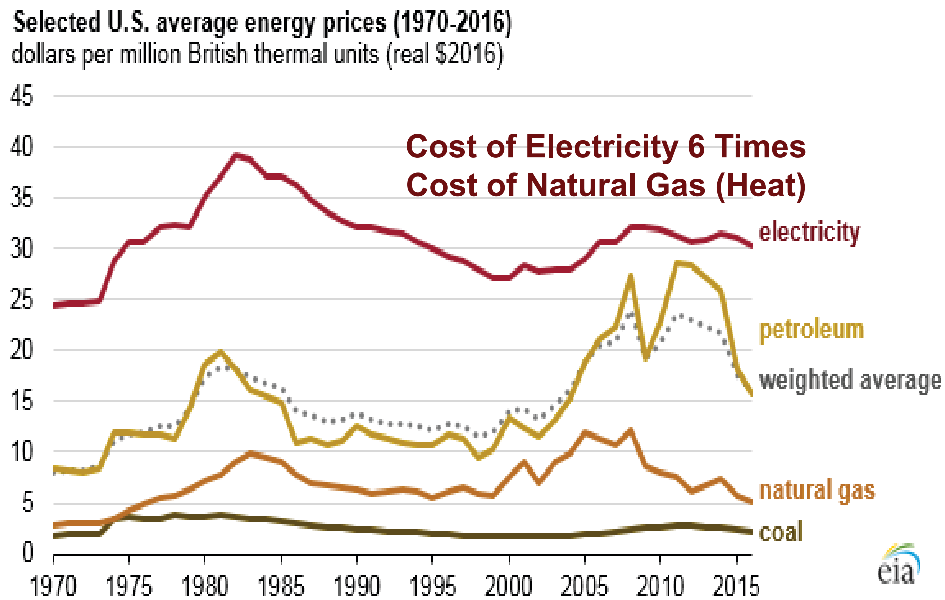
The Competition: Grid Electricity

Expensive Energy Source

Really Expensive Heat Source

Electricity Six Times More Expensive than Heat

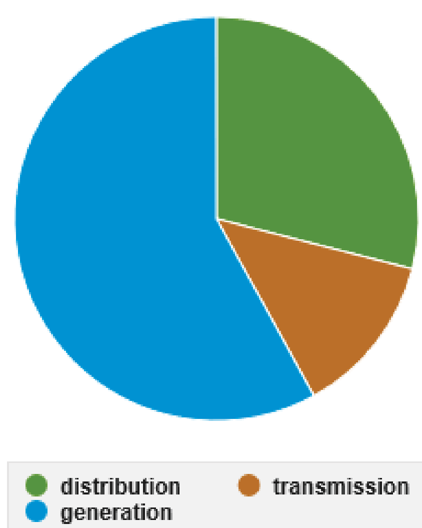
- Electricity is great except:
  - Expensive to produce
  - Expensive to ship
  - Expensive to store
- We use heat because it is cheap to produce and store



http://www.eia.gov/todayinenergy/detail.cfm?id=36754c

Delivered Electricity Price (2019) Has Three Components

- Components
  - Generation (blue)
  - Transmission (brown)
  - Distribution (green)
- Transmission and Distribution Costs increase with Wind & Solar
- **Electricity is more expensive than heat even if the cost to produce electricity was zero**



https://www.eia.gov/energyexplained/electricity/prices-and-factors-affecting-prices.php

The Competition:
Co-Generation Using Large Nuclear Reactors or Fossil Fuels with Carbon Capture and Sequestration

Co-Generation With Large Central Heat-Generating Technology and Distributed Heat to Customers

- Co-generation enables large-scale energy sources to provide heat and electricity to multiple customers
- Two options
  - Large nuclear plants (Any location)
  - Fossil fuels with carbon capture and sequestration (Locations with sequestration sites)
- **Economic heat but implies rebuilding much of U.S. industry to collocate with heat sources**
- Business challenge of how to organize such systems creates incentives for fission batteries (Speaker: J. Parsons)

The Competition
Hydrogen (Speaker: Eric Ingersoll)

Hydrogen Can Replace Natural Gas But at What Price?

- Production options
  - Steam methane reforming with CCS
  - Low or high-temperature electrolysis
- Can be cheaply stored like natural gas in underground facilities
- Premium energy source like electricity but two important differences
  - Cheap storage
  - Transport via pipeline

Chevron-Phillips Clemens Terminal
(160' X 1,000' Cylinder Salt Cavern)

What Are The Constraints?

Multiple Constraints for Fission Batteries

- Small output places major economic constraints on operations
  - Must minimize manpower and allowable fuel costs to be economically competitive (Speaker: Jacopo. Buongiorno)
  - Rethink manpower-intensive security (Speaker: Paul Roege)
- Major business questions
  - Leasing and Liability (Speaker: Elina Teplinsky)
  - Licensing (Separate Workshop in this series)
- Technical challenges (Separate Workshops in this series)

Conclusions

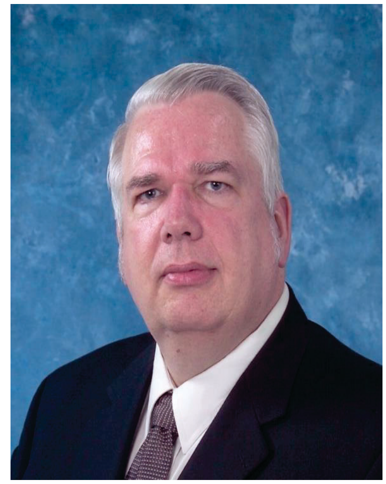
- Low-carbon world implies radical changes in energy systems
- Fission batteries are one solution
  - Defined by attributes, not technology
  - We do not know the maximum output of a fission battery
- Economics workshop goals (Two webinars)
  - Define the market—number of customers for different heat demands at different temperatures
  - Understand the competition
  - Understand the constraints
    - Business and legal (Leasing, licensing and liability)
    - Economic constraints on technical choices

Backup / Other Information

Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES). He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.



Fission Battery (FB) Attributes

- *Economic:* Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable distributed energy resources through flexible deployment across many applications and integration with other energy sources.
- Standardized: Developed in standardized sizes and power outputs with manufacturing process that enables universal use and factory production. This will lower costs and produce more reliable systems that achieve faster qualification
- Installed: readily and easily installed for use and removed after use. After use they can be recycled by recharging with fresh fuel or responsibly dispositioned
- Unattended: Operate securely and safely while unattended to provide demand-driven power
- Reliable: Systems and technologies mush have a high level of reliability to provide a long life and enable wide-scale deployment for applications. To support the concept of remove monitoring, they must be robust, resilient, fault tolerant and durable, and provide advance notification when replacement is needed

Thermodynamics Defines Two Types of Energy

- Heat is produced by
  - Burning fossil fuels
  - Nuclear power plants
  - Concentrated solar power (CSP) plants
- Work (electricity, mechanical movement, etc.) produced by
  - Hydroelectric plants
  - Solar Photovoltaic
  - Wind

Nuclear and Fossil with Carbon Capture and Sequestration Co-generation Have Many Similarities

- Safety case is important
  - Nuclear: radioactive source term
  - Fossil fuels: carbon dioxide heavy gas that can asphyxiated people
- Two options
  - Large nuclear plants (Any location)
  - Fossil fuels with carbon capture and sequestration (Locations with sequestration sites)
- Likely the primary competition in a zero-carbon world but implies rebuilding most U.S. industry to collocate with heat source

A Low-Carbon World Changes Energy Markets

- Major heat users—future directions
  - Paper, pulp and forestry
  - Chemicals
- Liquid Biofuels May Replace Liquid Fossil Fuels (Bruce Dale Talk)
  - Zero-carbon liquid hydrocarbon fuels, carbon from air via plants
  - **Liquid fuels yield per ton of biomass doubled with external heat and hydrogen input—10 to 20% total U.S. energy consumption and major nuclear energy market**
  - **Nuclear Biofuels Workshop (Forsberg / Dale contact)**

Market Opportunities for Fission Batteries

Andrew Foss
INL Technical Program Lead –
Nuclear Energy Markets, Economics, and Systems Analyses

Fission Battery Economics Workshop

January 2021

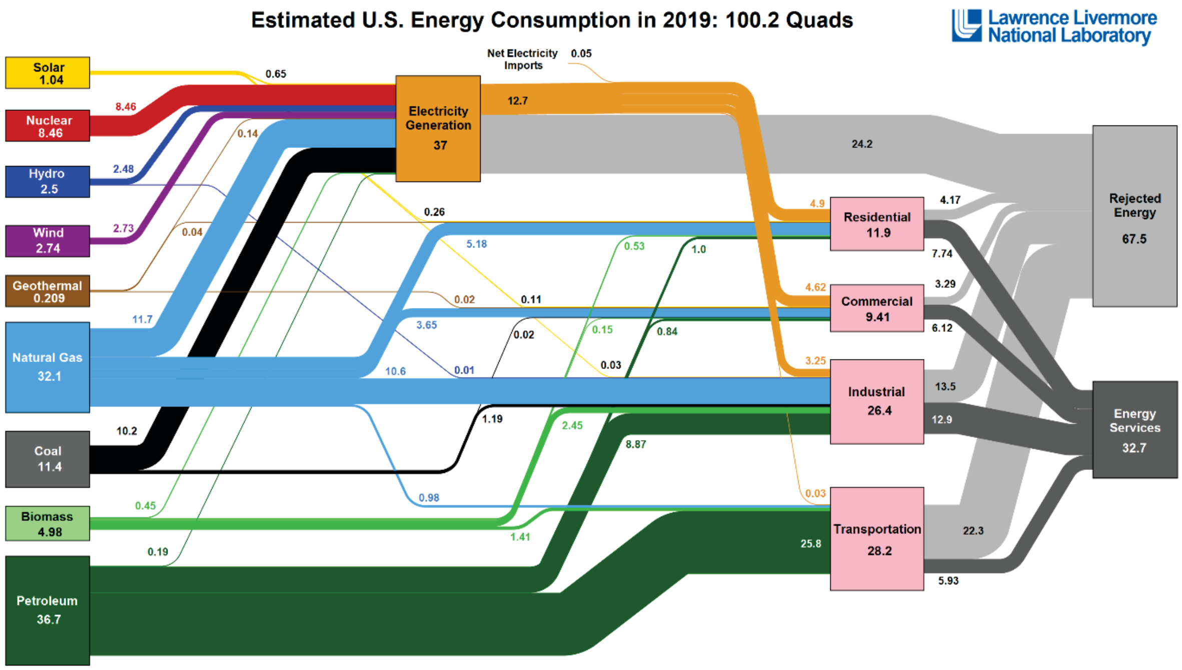
www.inl.gov

Idaho National Laboratory

Key Questions for Fission Battery Development

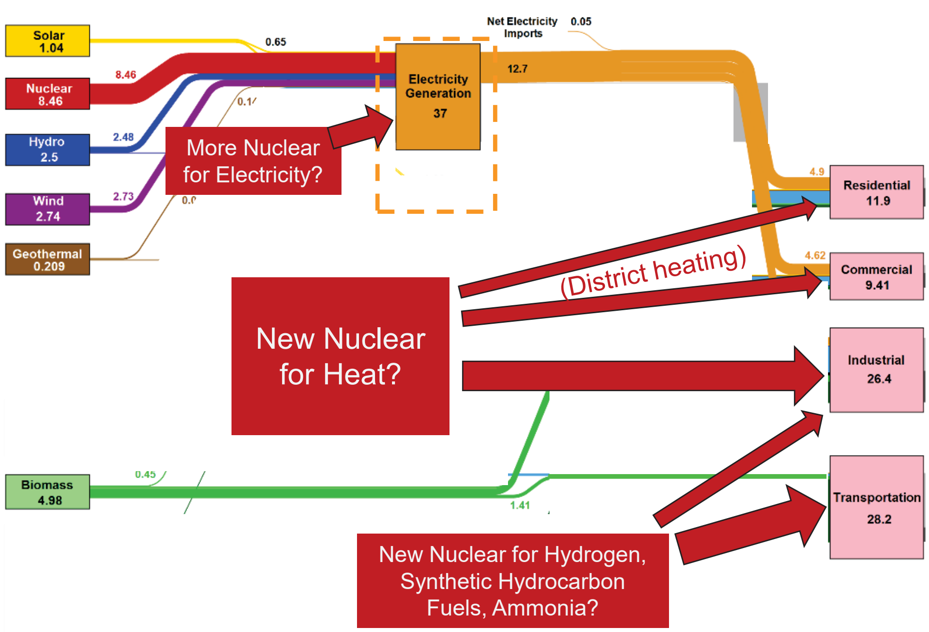
1. **What are the markets and customers?**
   – Meeting societal needs for more clean energy
2. **What is the optimal unit size?**
   – Alignment with customer needs
3. **What is the total market opportunity?**
   – Unit size (and revenue) per customer x number of customers
4. **What is the optimal outlet temperature?**
   – Alignment with customer needs

US Electricity and Heat Consumption



Source: Lawrence Livermore National Laboratory
https://flowcharts.llnl.gov/content/assets/docs/2019_United-States_Energy.pdf

What Roles for Nuclear in Deep Decarbonization?



(Removal of fossil energy is only for illustrative purposes, not a prediction – and CCS is also a decarbonization option)

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Electricity Markets for Fission Batteries

- Regional grid
- Microgrids
- Remote communities
- Military bases
- Mines

Sources: New Atlas, Sandia National Lab, Alaska Dispatch News, ABC News, Teck Resources

4

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Analysis of Industrial Heat Demand

What is the typical thermal load at facilities within each industrial sector, and what is the spread? -> Histograms

1. EPA FLIGHT database of CO_2 emissions from ~6,000 large facilities
   - Companies, addresses, industry codes (NAICS)
   - Emissions linked to coal, natural gas, and oil consumption
2. CO_2 emission factors (lbs per MMBtu) for coal, natural gas, and oil
3. Combine 1 and 2 -> Annual energy consumption at large facilities
4. Annual facility utilization assumption (90%)
5. Combine 3 and 4 -> Average thermal power load at large facilities

Similar previous analyses (for industrial sectors in aggregate rather than histograms of facility loads): INL and NREL, *Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions*, 2016; MIT, *The Future of Nuclear Energy in a Carbon-Constrained World*, 2018 (Appendix F)

5

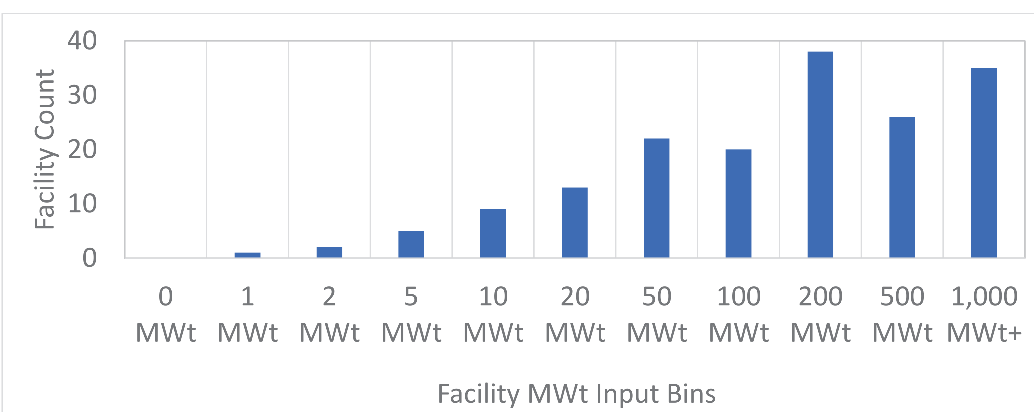
Largest Industrial Sectors for Heat Demand

(Data for 2018 ranked by facility count; asterisk denotes sectors with histograms on next slides)

	Industry	Facility Count	Total CO_2 (million metric t)	Total Energy (trillion Btu)	Total Thermal Load (MWt)
#1	Electric utilities	1,394	1,795	23,809	885,741
#2 *	Chemical manufacturing	650	176	2,487	92,536
#3	Pipeline transportation	630	29	388	14,452
#4	Oil and gas extraction	588	62	833	30,993
#5	Waste management	571	11	142	5,292
#6	Cement, glass, mineral mfg.	350	106	1,407	52,347
#7 *	Food manufacturing	327	33	474	17,649
#8	Primary metal manufacturing	275	87	1,155	42,967
#9 *	Paper manufacturing	216	35	516	19,203
#10 *	Petroleum manufacturing	171	209	2,797	104,067
	Other	641	45	673	25,049
	Total	**5,813**	**2,587**	**34,684**	**1,290,295**

Heat Demand for Petroleum Manufacturing

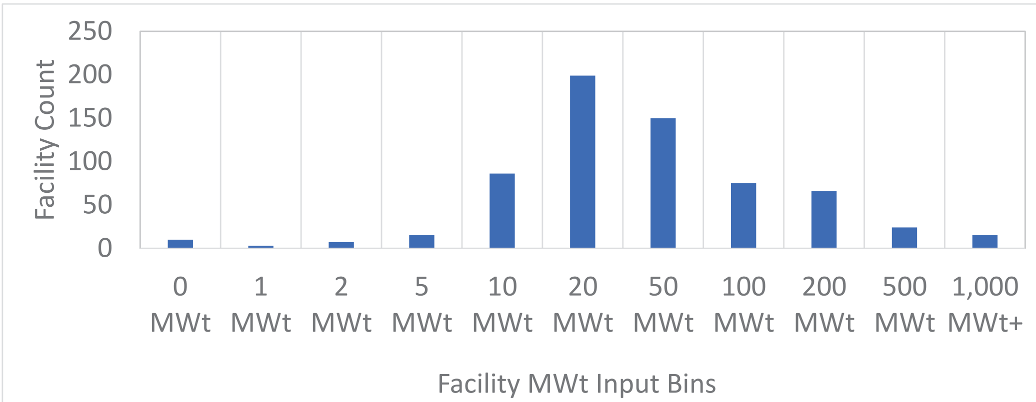
		Facility Count	Total CO_2 (million metric t)	Total Energy (trillion Btu)	Total Thermal Load (MWt)
#10	Petroleum manufacturing	171	209 (avg 1.2 per facility)	2,797 (avg 16 per facility)	104,067 (avg 609 per facility)



Temperature needs: Up to 750 C (fluid catalytic cracker)

Heat Demand for Chemical Manufacturing

	Industry	Facility Count	Total CO_2 (million metric t)	Total Energy (trillion Btu)	Total Thermal Load (MWt)
#2	Chemical manufacturing	650	176 (avg 0.3 per facility)	2,487 (avg 3.8 per facility)	92,536 (avg 142 per facility)

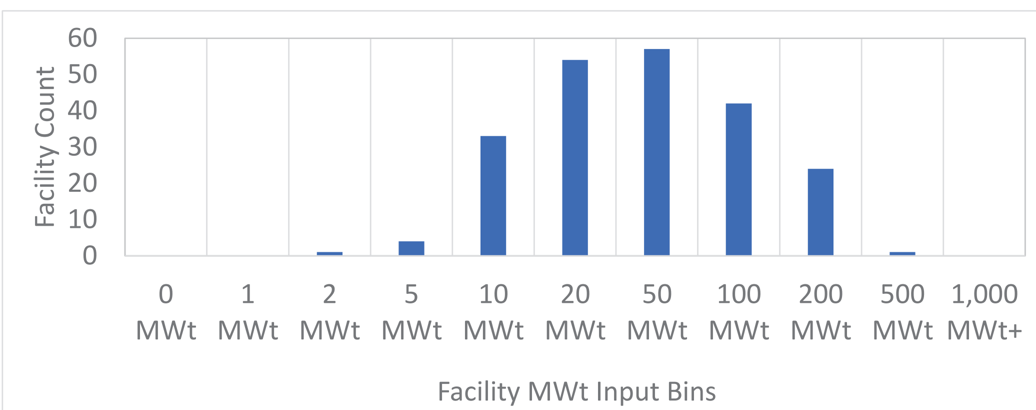


Several processes around 500 C

We have invited chemical industry representatives for the second session (Jan 27)

Heat Demand for Paper Manufacturing

	Industry	Facility Count	Total CO_2 (million metric t)	Total Energy (trillion Btu)	Total Thermal Load (MWt)
#9	Paper manufacturing	216	35 (avg 0.2 per facility)	516 (avg 2.4 per facility)	19,203 (avg 89 per facility)



Most processes 200 - 300 C

We have invited a paper industry representative for the second session (Jan 27)

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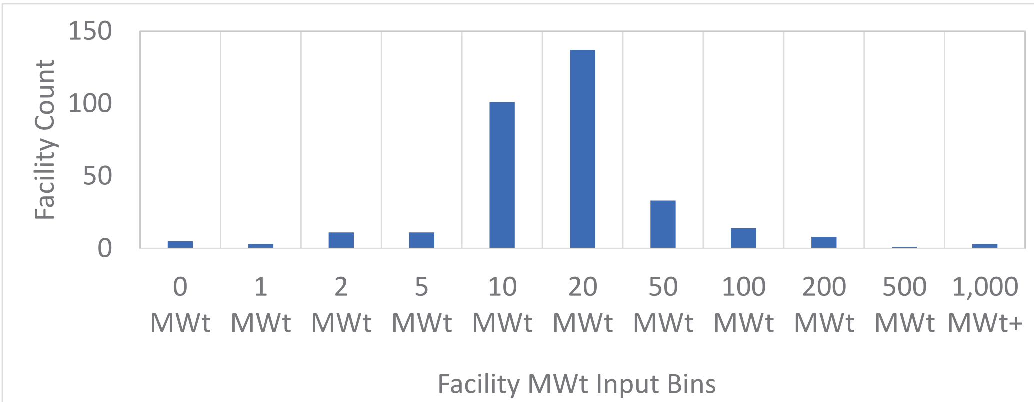
Heat Demand for Food Manufacturing

	Industry	Facility Count	Total CO_2 (million metric t)	Total Energy (trillion Btu)	Total Thermal Load (MWt)
#7	Food manufacturing	327	33 (avg 0.1 per facility)	474 (avg 1.5 per facility)	17,649 (avg 54 per facility)



Most processes around 200 - 300 C

10

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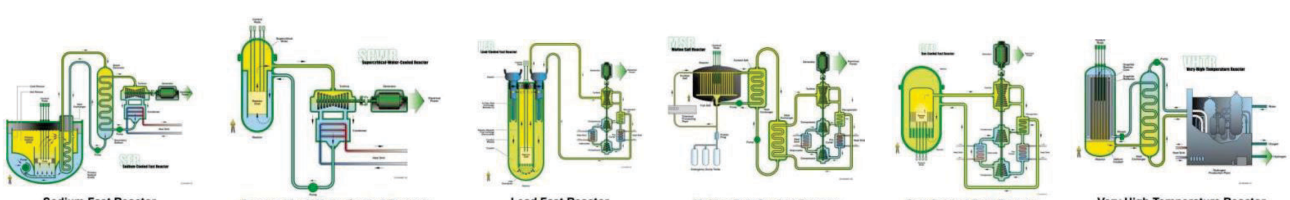
Nuclear Reactor Temperatures

Light-water reactors	300 C
Sodium fast reactors	500 C
Supercritical-water-cooled reactors	500 - 550 C
Lead-cooled fast reactors	500 - 800 C
Molten salt reactors	600 - 700 C
Fluoride-salt-cooled high-temperature reactors	600 - 700 C
High-temperature gas-cooled reactors	700 - 850 C
Very high-temperature reactors	900 - 1000 C

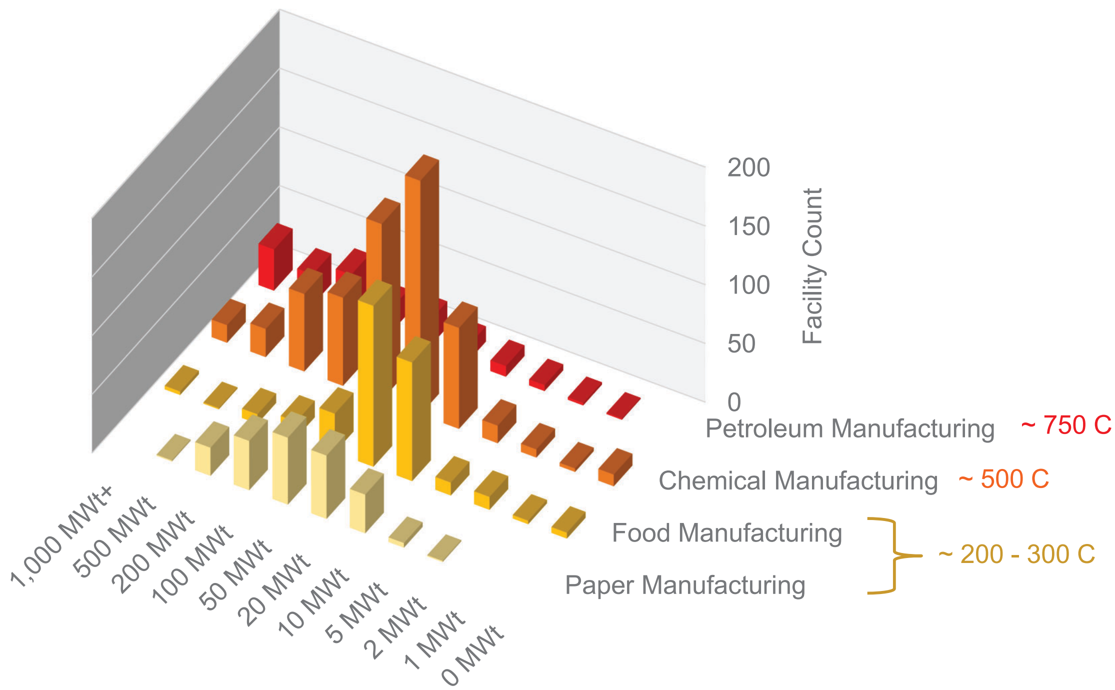
If temperature is too high for customer needs, just pass fluid through turbines to cool it



Sources: MIT, *The Future of Nuclear Energy in a Carbon-Constrained World*, 2018
Generation IV International Forum

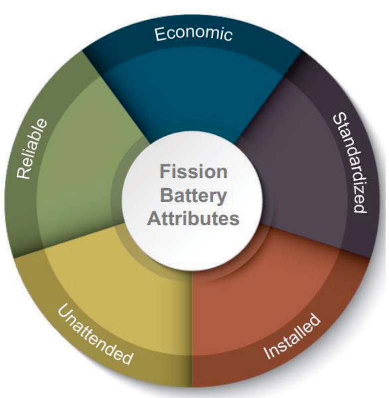
11

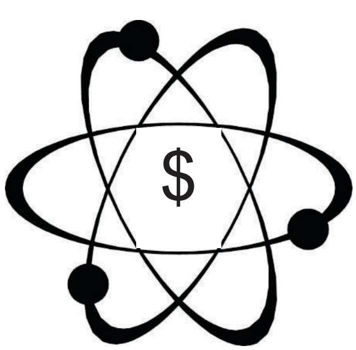
Aligning FB Temps and Sizes with Sector Needs



12

Cost Competitiveness of Fission Batteries





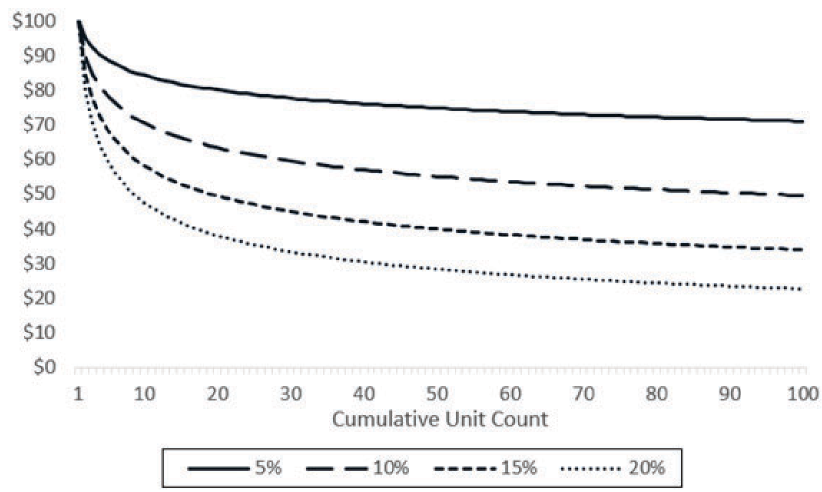
- **Standardization**
  - Avoid customization engineering
  - Streamline site-specific review and permitting
- **Factory manufacturing**
  - Modular components or entire units
  - Efficient inspection in factory
- **Economies of multiples**
  - Fast first-to-N^{th} reductions if many units
  - Multiple units per site? Multiple customers?
- **Quick and easy installation**
  - Avoid long construction, financing
  - On-site energy better than hydrogen pipelines/trucks?
- **Unattended autonomous operation**
  - Automation and robotics, not workers
  - Remote multi-unit monitoring and control centers
- **Nuclear energy as *products*, not *projects***

13

Illustrative Learning Rates for Cost Reduction

$$C_i = C_1 \times (1 - r)^{\log_2 i}$$

r is the percentage reduction in cost per doubling in cumulative unit deployments



Global onshore wind learning rate *r* from 1985 to 2015 = **19%** (87% cost reduction cumulatively)
Global solar PV module learning rate *r* from 1976 to 2015 = **24%** (99% cost reduction cumulatively)

Source for global wind and solar learning rates: Bloomberg New Energy Finance (http://cgcan.org/wp-content/uploads/2016/07/Learning-curves-for-wind-PV-BNEF-2016.png)

Summary for Fission Battery Development

1. **What are the markets and customers?**
   – Many: **Electricity** (regional grid, microgrids, remote communities, military, mines), **heat** (refineries, chemicals, paper, food, commercial, residential), **other** (hydrogen, synthetic hydrocarbon fuels, ammonia, desalination, …)

2. **What is the optimal unit size?**
   – Wide range, but many industrial facilities require 20 - 200 MW_t (multiple units could be deployed per site, multiple customers)

3. **What is the total market opportunity?**
   – Very large, especially if transition away from fossil must accelerate

4. **What is the optimal outlet temperature?**
   – Many industrial processes require 200 - 750 C

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Nuclear Hydrogen Futures

Eric Ingersoll

LUCID
CATALYST

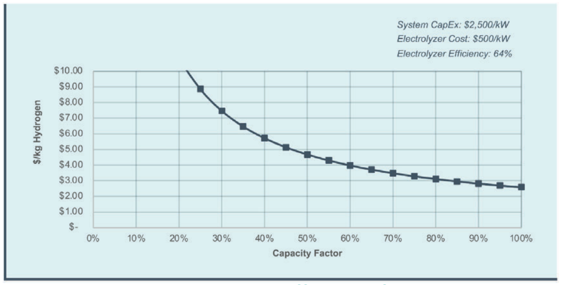
January 2021

Zero emissions hydrogen in the transition to a zero emissions energy system—examples

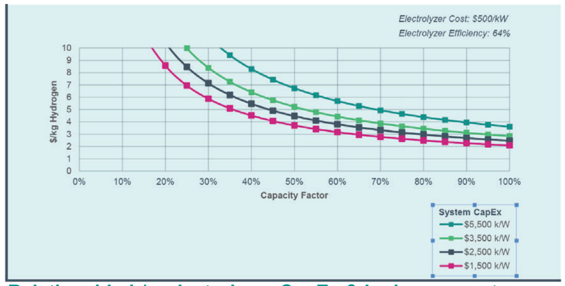
- Todays markets—but clean
  - Competitors: natural gas (SMR) and coal gasification
  - Add to gas networks
- Medium-term direct use (may be substituted later)
  - Heavy trucking, long-distance buses, locomotives
  - Onsite fuel cell cogen
- Long-term direct use (depends on converting end uses)
  - Long-distance aviation
- Feedstock for fuels and chemicals (substitute)
  - Synthetic hydrocarbons
  - Hydrocarbon substitutes, e.g., ammonia

Hydrogen cost drivers

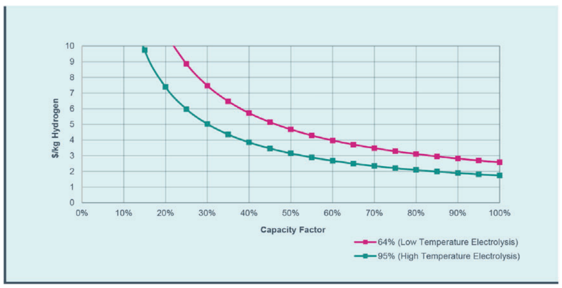
Relationship b/w capacity factor & hydrogen cost



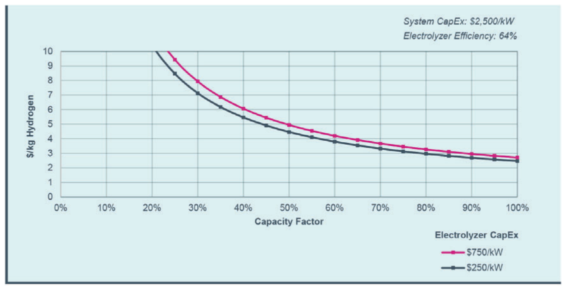
Relationship b/w energy system CapEx & hydrogen cost



Relationship b/w electrolyzer efficiency & hydrogen cost

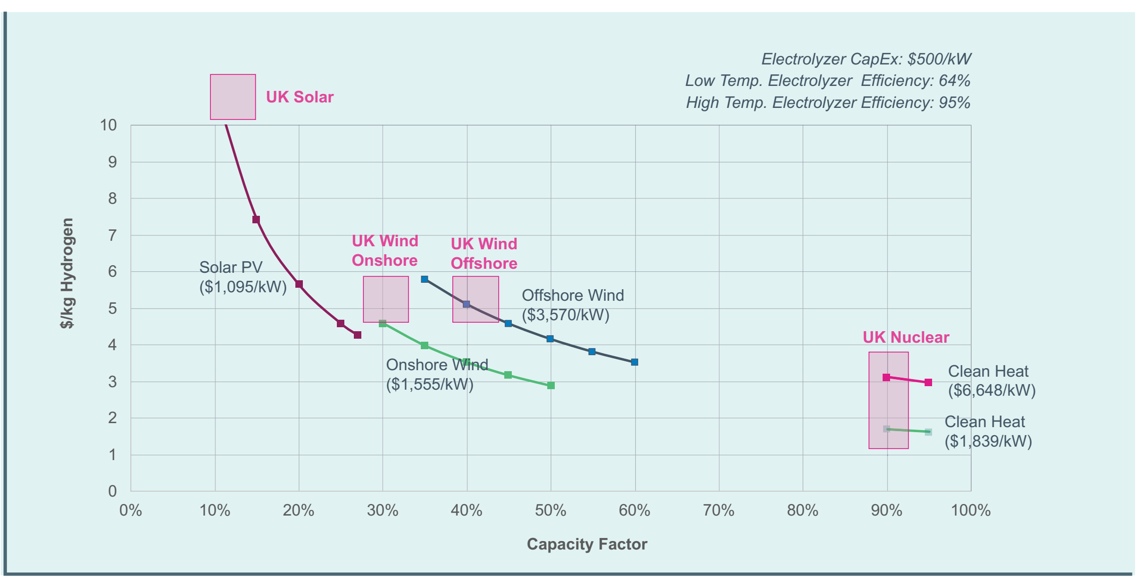


Relationship b/w electrolyzer CapEx & hydrogen cost



Source: LucidCatalyst, "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals," 2020.

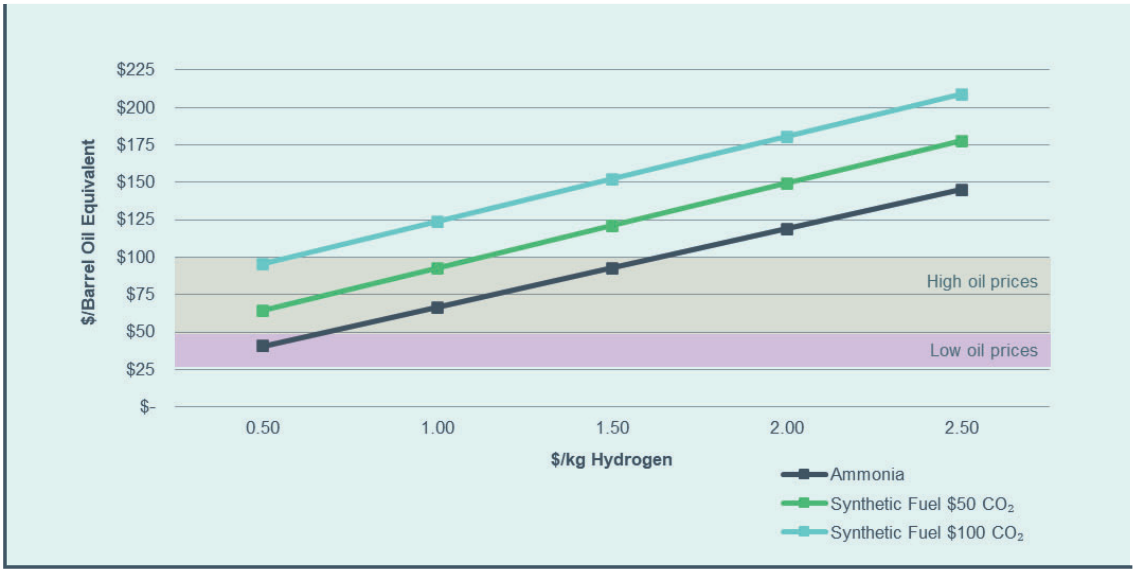
Hydrogen production costs



Current hydrogen production costs of different energy technologies in the UK

Source: LucidCatalyst, "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals," 2020.

Target price for clean hydrogen



Oil price 'guardrails' of the hydrogen economy ($0.50–1.50/kg hydrogen)

Source: LucidCatalyst, "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals," 2020.

Key innovations for low cost hydrogen made from nuclear energy

- Requires very low cost energy as input
- Exportable commodity, not tied to local grid scale demand
  - Enables much larger projects
  - A refinery, not a power plant
- Manufacturing-based delivery model
  - Bring the factory to the project: Gigafactory
  - Bring the project to the factory: Shipyard manufacturing

Gigafactory

Hydrogen/Synfuel Gigafactory

Source: LucidCatalyst

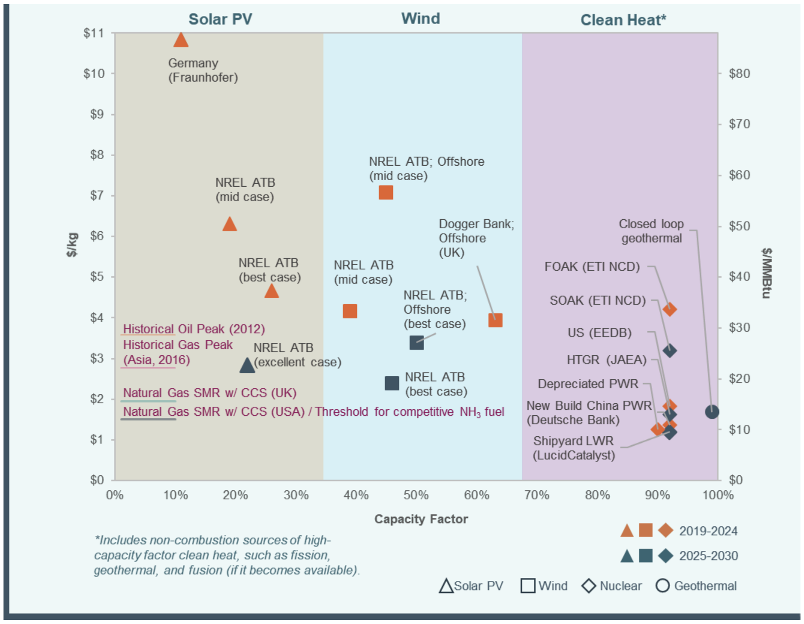
Ship-manufactured ammonia platform

Ammonia bunker offloading ammonia from production platform

Shipyard manufacturing of fuels production platforms

Source: LucidCatalyst

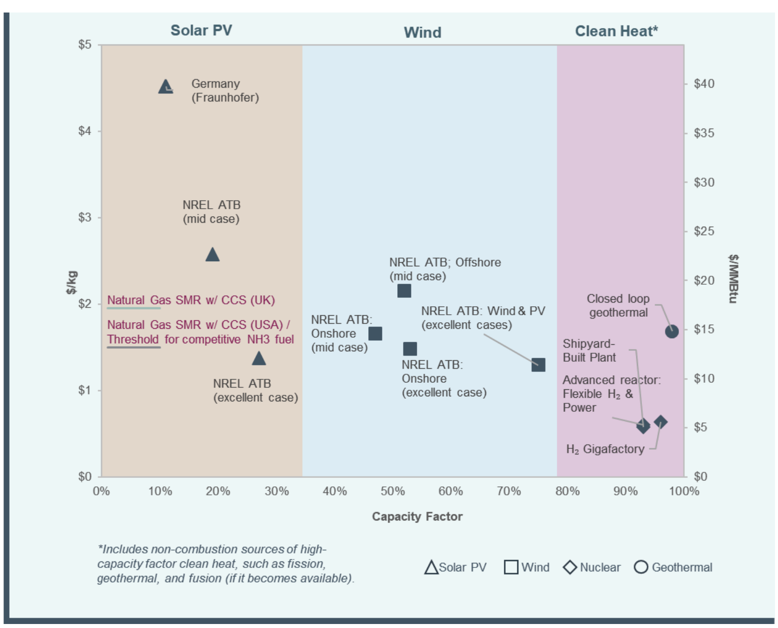
Projected hydrogen production cost in 2030



Cost of hydrogen production from different energy technologies in the real world now and in 2030

Source: LucidCatalyst, "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals," 2020.

Projected hydrogen production cost in 2050



Projected cost of hydrogen production from different energy technologies in 2050

Source: LucidCatalyst, "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals," 2020.

Nuclear batteries are unlikely to compete with gas or electric grid supplied energy

- Bulk electricity and hydrogen will get very cheap
- Zero emissions ammonia will flatten the global variation in hydrogen prices
  - $250–200/tonne ammonia production cost (forthcoming EPRI study)
    - $13.44–10.75/GJ or $84.40-67.50/bbl-finished product
    - $48.40–38.7/MWt
  - Fuel production platforms can be close to end-use markets
  - Longer-distance delivery costs should drop to match LNG transportation costs ~$1/GJ
  - Ammonia pipelines cost less than natural gas and have higher energy density
- Opportunity: places where you cannot deliver bulk energy easily
- What about a small ammonia plant?

LucidCatalyst delivers strategic thought leadership to enable rapid decarbonization and prosperity for all.

Eric Ingersoll

eric.ingersoll@lucidcatalyst.com

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Fission Battery Initiative Workshop – Maritime Perspective

Gareth Burton | January 13 2021

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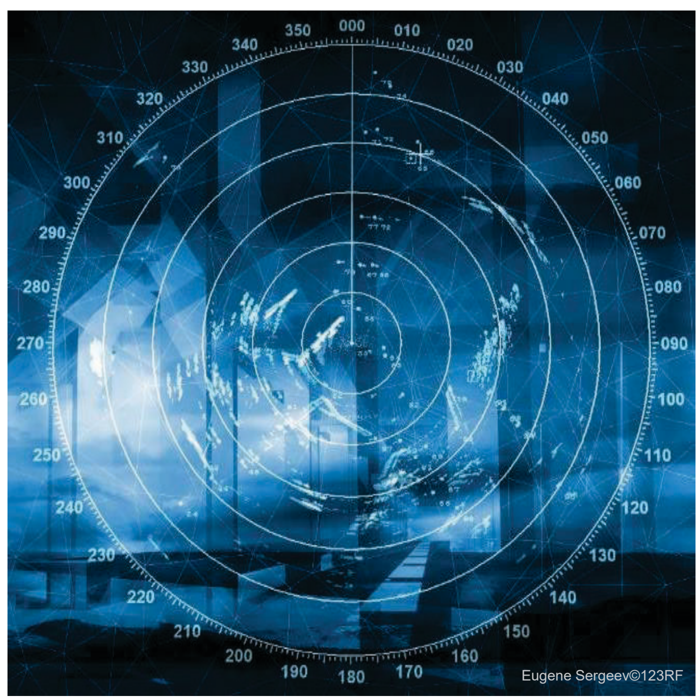
Discussion Items

- Introduction to ABS
- Overview of the Marine Industry
- Safety Network in the Marine Industry
- Current Industry Drivers



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Introduction to ABS

- ABS Organization
- ABS Mission
- Standards Development

Introduction to ABS

- Not-for-profit classification society
- Headquarter: Houston, Texas
- Independent arbiters of standards
- Achieved by establishing and administering standards known as rules for marine vessels and structures
  - Design
  - Construction
  - Operational Maintenance
- Worldwide presence at ports, shipyards, and manufacturing facilities
  - 200 overs in 70 countries

Marine Standards

- Class Requirements
- Guidance Documents
- Focus
  - Practical
  - Authoritative
  - Impartial

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Overview of Marine Industry

- Industry Size, Vessel Types
- Operating Profile, Power Requirements
- Power Options
- Nuclear Power in Marine

Maritime Industry: Industry Size

SELF-PROPELLED SHIPS

World Fleet	Cargo Carrying Ships
99,031 SHIPS **2097.1** Million Dwt	**61,384** SHIPS **2012.7** Million Dwt

MARITIME
- Bulk Carriers
- Tankers
- Containerships
- Passenger, Ferries, Ro-ro

OFFSHORE
- Exploration
- Production
- Offshore Support

GAS
- FLNG (Floating Liquified Natural Gas)
- FSRU (Floating Storage & Regassification Unit)

Navy
- Combatants
- Auxiliaries

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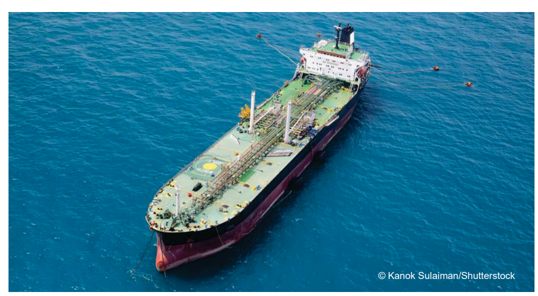
Maritime Industry: Vessel Types

Bulk Carriers: Carry dry cargo in bulk, such as ore, grain, or coal

Vessel Deadweight (DWT)	Category of Bulk Carrier
>=200K	Very Large Ore Carrier (VLOC) Very Large Bulk Carrier (VLBC)
120K-200K	Capesize
83K-120K	Post Panamax
80K-83K	Kamsarmax
65K-80K	Panamax
40K-65K	Handymax
10K-40K	Handysize
<10K	Small Bulker

Tankers: Carry liquid such as crude oil



Vessel Deadweight (DWT)	Category of Tanker
>=200K	Very Large Crude Carrier (VLCC)
125K-200K	Suezmax
85K-125K	Aframax
55K-85K	Panamax
25K-55K	Medium Range (MR)
<25K	Short Range (SR)
>=10K	Handysize
<10K	Small Tanker

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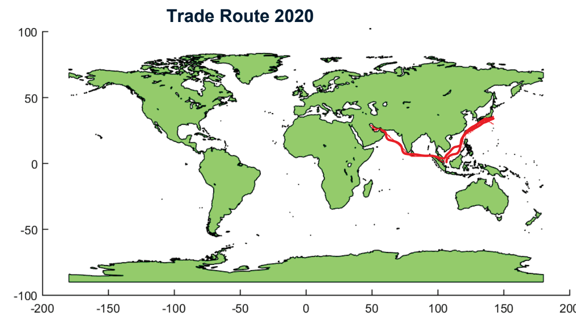
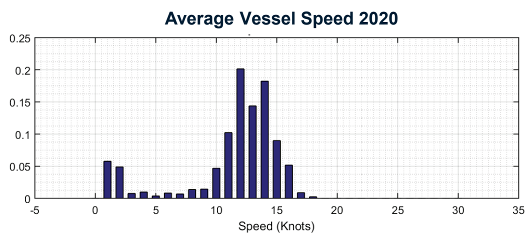
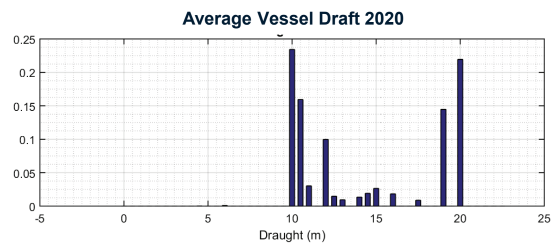
Crude Oil Tanker: Operating Profile







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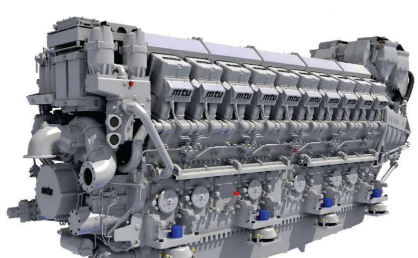
Crude Oil Tanker: Power Arrangements

Propulsion Power:



© 3dhorse

Installed Propulsion Power	
Maximum Continuous Rating (kW)	26,900
# of Cylinders	10
Engine Cycle	2 Stroke
Revolutions (RPM)	75.8

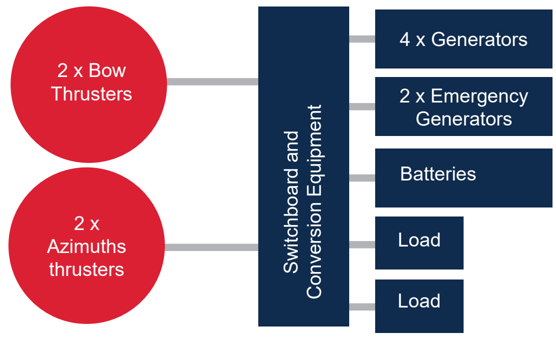
Other Shipboard Loads:

	At Sea	Maneuvering	Cargo Ops. Loading	Cargo Ops. Unloading	Harbor	Emergency
Average Continuous Load (KW)	868	1,608	1,136	1,573	660	118
Intermittent Load (KW)	259	290	256	295	266	0
Diversity Factor (%)	40	40	40	40	40	40
Equivalent Intermittent Load (KW)	104	116	102	118	106	0
Total Required Power (KW)	972	1,724	1,238	1,691	766	118
Generating Capacity (KW)	1,150	2,300	2,300	2,300	2,300	300
Notes	1 GEN.	2 GEN.	2 GEN.	2 GEN.	2 GEN.	1 GEN.
Generator Loading	0.84	0.75	0.54	0.74	0.33	0.39

Platform Support Vessel: Power Arrangements

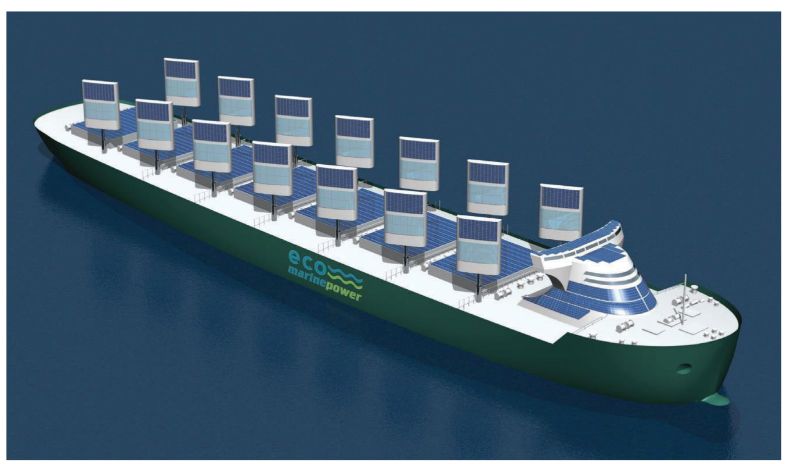
- Diesel Electric
- Total Installed Power: 7600 KW
- Propulsion
  - 2 x Bow Thrusters
  - 2 x Azimuth Thrusters

Power	
Propulsion	Diesel Electric
Main Engines	4 x 1900 KW
Main Generators	4 x 480VAC, 2282 KVA
Total Installed Power	7,600 KW
Emergency Generators	2 x 470KW



Power Options

- Internal Combustion Engine
- Diesel Electric
- Steam turbine
- Gas Turbine
- Hybrid Systems (Battery)
- Fuel Cell
- Wind Propulsion
- Solar
- Nuclear



Nuclear Maritime History

- United States
  - 1940: Research on application in marine propulsion
  - 1953: The first test reactor
  - 1955: First nuclear submarine, USS Nautilus (SSN-571)
  - 1962: U.S. Navy 26 nuclear submarines operational and 30 under construction
  - 1959: N.S. Savannah, 1st nuclear-powered merchant vessel
- USSR / Russia
  - 1955: 1st Soviet nuclear submarine, K-3 Leninsky Komsomol
  - 1957: World's 1st nuclear icebreaker, "Lenin"
  - Current: Ice Breaker fleet

NS (Nuclear Ship) Savannah, enroute to the World's Fair in Seattle, 1962

Current Military Use of Nuclear Power	
US Navy	• 73 Submarines (55 Attack, 18 Ballistic/ Guided Missile) • 11 Aircraft Carriers
Russian Navy	• 21 Submarines (13 Attack, 8 Ballistic/ Cruise Missile) • 1 Battlecruiser
China	• 14 Submarines (9 Attack, 5 Ballistic)
British Navy	• 10 Submarines (6 Attack, 4 Ballistic)
France	• 9 Submarines (5 Attack, 4 Ballistic) • 1 Aircraft Carrier
Indian Navy	• 1 Submarine

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Safety Network in the Maritime Industry

- Stakeholders
- International Maritime Organization

Maritime Safety Network

- Multiple Stakeholders

International Maritime Organization (IMO)

- Part of the United Nations – members are representative of individual governments
- Commercial and other interested organizations (IACS) have observer status
- Conventions must be adopted by individual flag states within their national laws
- IMO Conventions:
  - LOAD LINE: amount of cargo a vessel may safely carry
  - TONNAGE: the carrying capacity of a ship based on volume
  - SOLAS (Safety of Life at the Sea): construction, communications, lifesaving, fire protection, firefighting
  - MARPOL (Marine Pollution): pollution prevention from onboard lubricants, cargoes or emissions

Current Industry Drivers

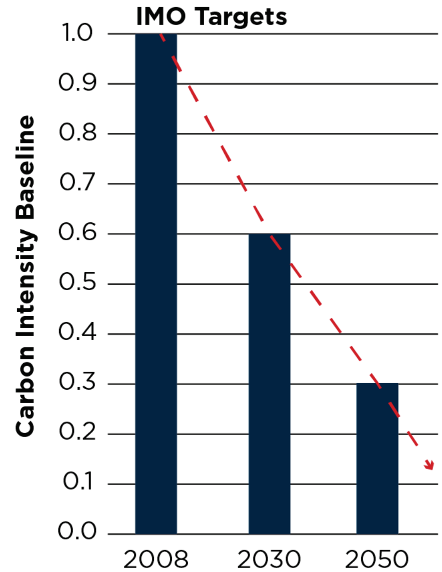
- Sustainability Focus
- Alternative Fuels

Industry Drivers

- **Regulatory**: IMO policies are requiring reduced carbon and GHG emissions
- **Social**: Societal pressures on companies to operate sustainably in all aspects
- **Financial**: Requiring sustainability initiatives to reduce long-term risk in investments
- **Corporate Governance and Shareholders**: Board rooms are pushing for targeted strategies to reduce emissions
- **Charterers**: Looking for assurance that vessels will be compliant and as efficient as possible
- **Other Stakeholders**: Regional Authorities, Insurers, brokers, etc.

IMO Strategy for Reduction of GHG Emissions from Shipping

- IMO initial strategy set ambitious goals for future pollution reduction targets compared to 2008 levels:
  - Reduce carbon intensity by 40% by 2030
  - Reduce carbon intensity by 70% by 2050
  - Reduce GHG emissions 50% by 2050



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Decarbonization Solutions

Alternative Fuels and Energy Sources

- LNG
- Hydrogen
- LPG/Ethane
- Ammonia
- Methanol (Regional)
- Nuclear
- Biofuels (Regional)
- Biofuels (Global)

Technology Improvements

- Air Lubrication
- Improved Hull & ESD Options
- Wind/Solar
- Hybrid
- Fuel Cells
- Electric Propulsion
- Cold Ironing
- Carbon Capture (Shore/Ship)

Operational Efficiency

- Weather Routing
- New Charter Arrangements
- Speed Optimization
- Just in Time Shipping
- Vessel Performance Reporting
- Smart Vessel/ Improved Reliability
- Fleet Interactive Performance/ Optimization

Pathway to 2050

2050

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Alternative Fuels/Energy Sources with GHG Reduction Potential

Fuel Type	Infrastructure	Security of Supply	Energy Density	CO_2	SOx	Safety
Heavy Fuel Oil	●	●	●	○	○	●
Marine Diesel	●	●	●	○	◕	●
LNG	◑	●	◑	◑	●	◕
LPG	◑	◑	◑	◔	●	◑
Methanol (from Methane)	◑	◑	◔	◔	●	◕
Methanol (from biomass)	◔	◔	◔	●	●	◕
Ammonia (from methane)	◑	◑	◔	◔	●	◑
Ammonia (from renewable)	◔	◔	◔	●	●	◑
Hydrogen (from methane)	◔	◑	◔	◔	●	◑
Hydrogen (from renewable)	○	◔	◔	●	●	◑
Biofuels	◔	◔	●	◑ ●	●	◕

Notes:
- **Infrastructure** refers to existing bunkering infrastructure or facilities that can be adapted to support bunkering (e.g. import/export terminals)
- **Security** of supply refers to the availability of sufficient global production to meet significant demand from the marine sector for bunkers
- **Energy density** refers to the volumetric energy content of the fuel and on-board storage requirements
- **CO_2 and SOx** refers to impact on emissions
- **Safety** refers to handling, storage and consumption risks

Source: ABS/MSI study

THANK YOU

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Liquid Biofuels and Energy Markets

Bruce E. Dale
University Distinguished Professor
Michigan State University. East Lansing, MI

Workshop:
Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

January 13 and Jan 27, 2021

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Outline

- Market and Biomass Resource Base for Liquid Fuels
- Ethanol (corn and sugar cane) Biofuels
- Cellulosic Biofuels
- Paper, Pulp and Liquid Fuels
- Conclusions

2

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Market and Biomass Resource Base for Liquid Fuels

3

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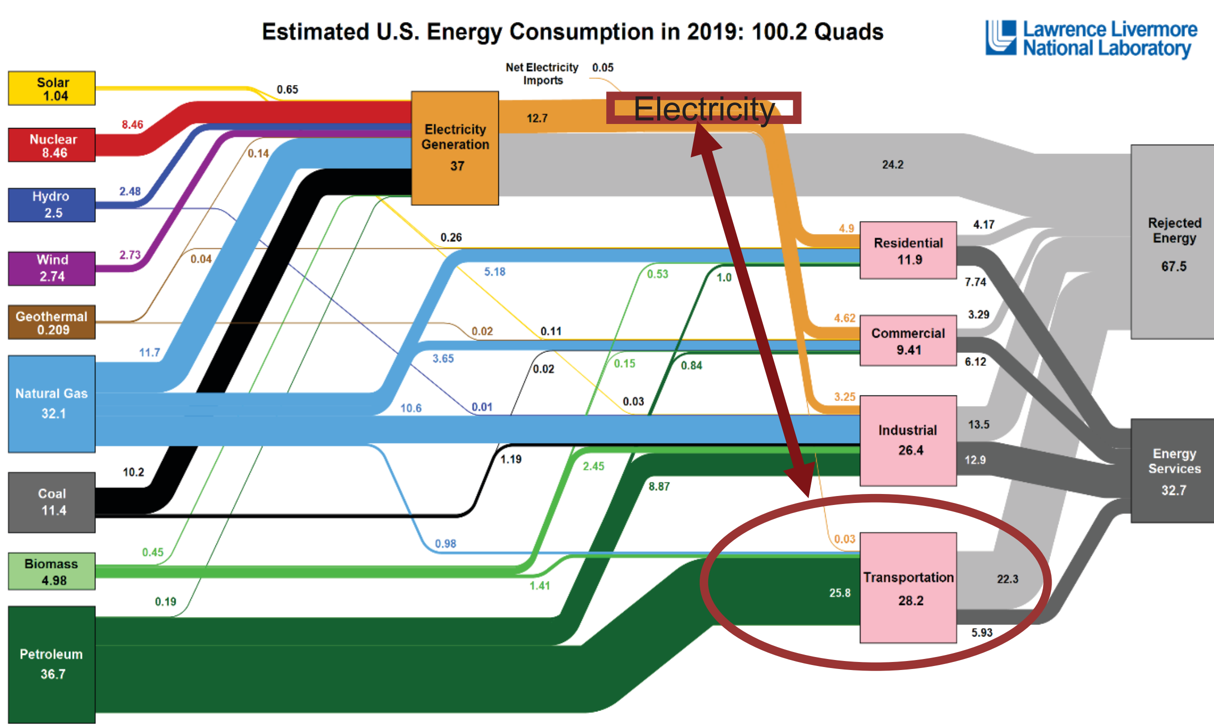
Liquid Fuels Are Central to the Economy

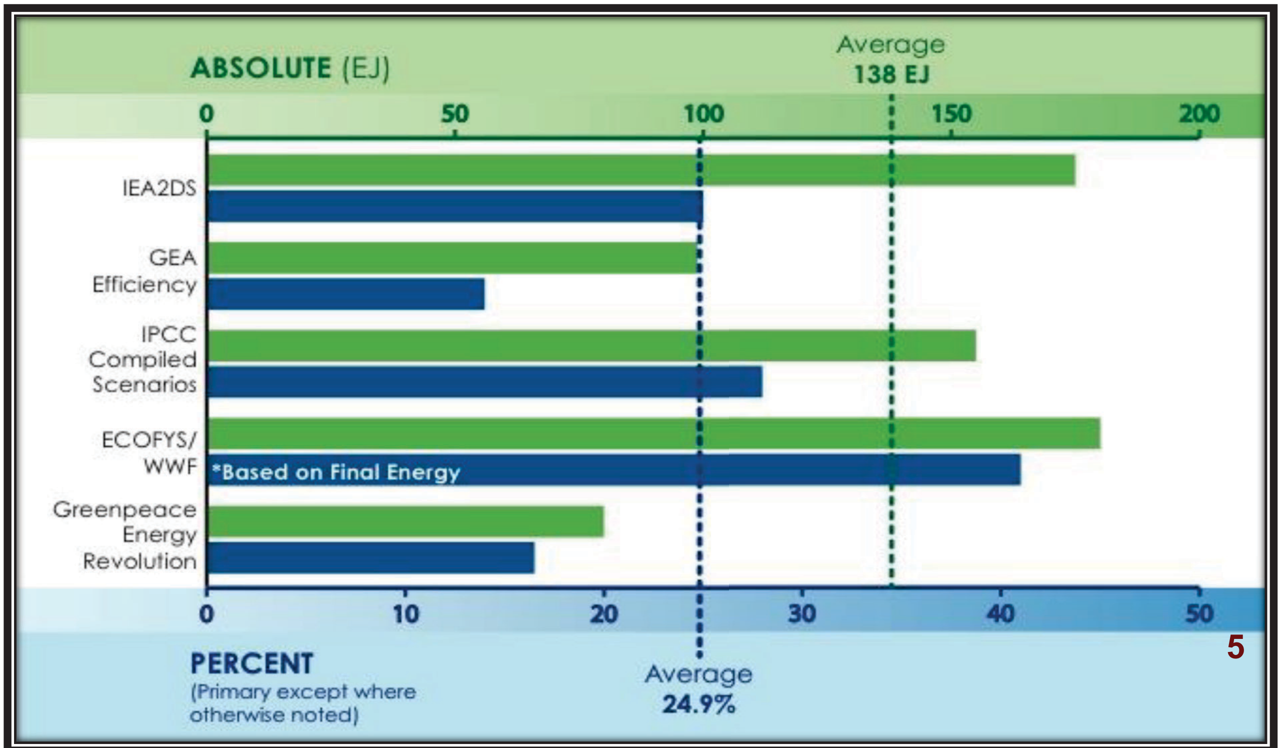
Bigger and More Difficult to Decarbonize than Electricity



4

Bioenergy Contribution in 2050:

Five Low-Carbon Energy Scenarios Suggest it is about 25% of Global Energy Needs



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Dale et al., ES&T, 2014

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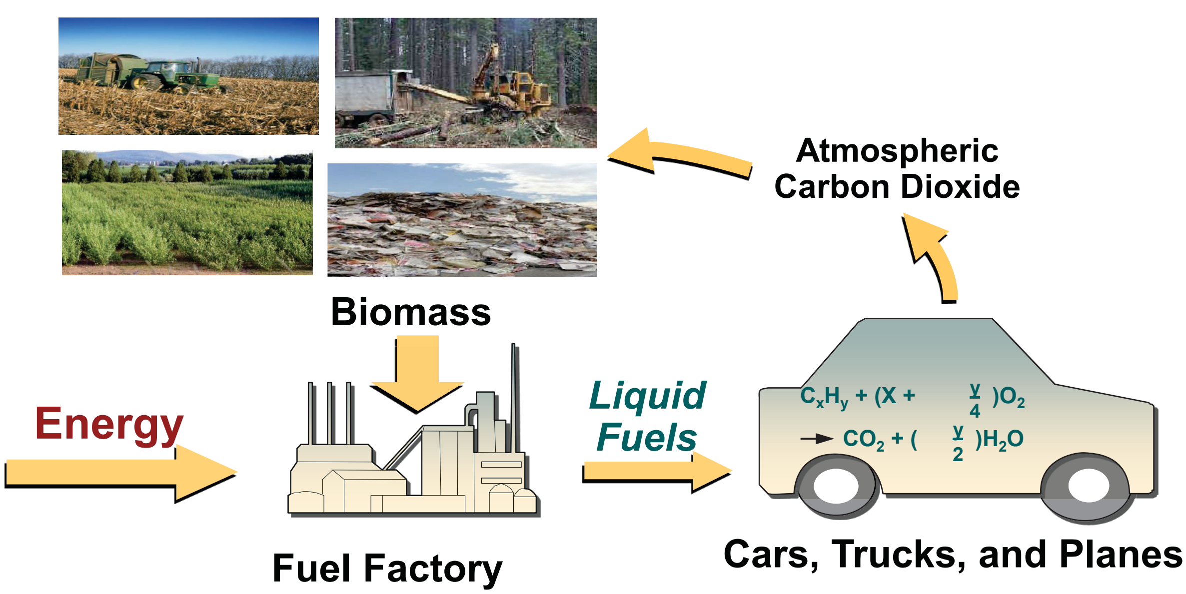
External Energy Sources Can Double Liquid Fuel Yields Per Ton of Biomass

Choice: Burn Biomass or Supply External Energy Heat/H_2 for Biorefinery?



9

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Biomass Is Both an Energy Source & a Carbon Source

- If external energy sources are used, liquid fuels per ton of biomass can be doubled
- *Thus reducing biofuel land footprint by 2x*
- Multiple biofuels processing options available with different energy requirements
- Preferred choices driven by economics
- ***External energy inputs could be in excess of 10% of the total U.S. energy consumption***

7

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Market A

Ethanol (corn & sugar cane) Biofuels

Current Biofuels Industry

United States, Canada and Brazil

8

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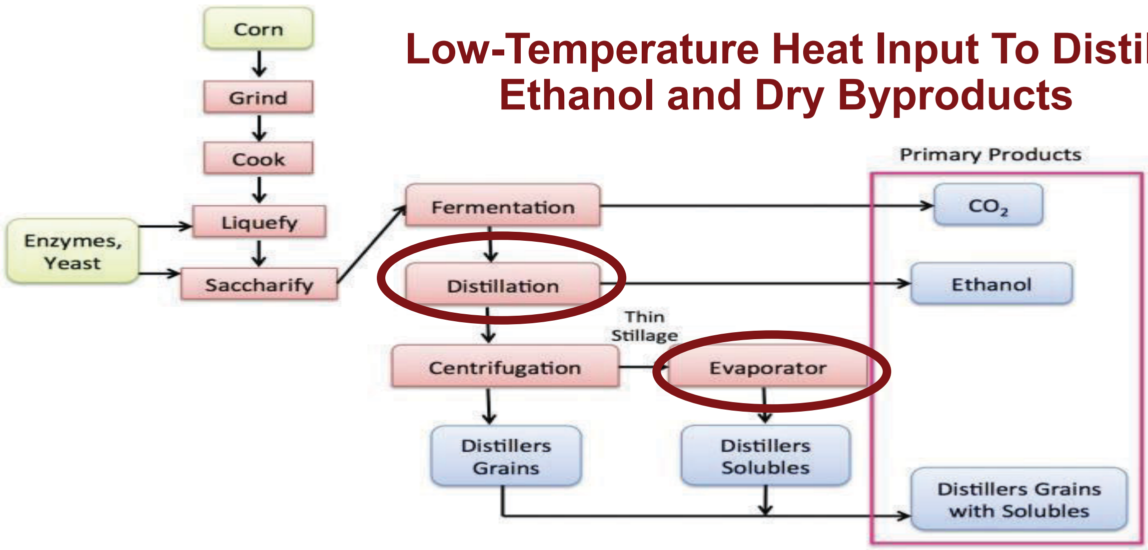
Ethanol Plants (Modified Beer Brewing) Produce Multiple Products



Low-Temperature Heat Input To Distill Ethanol and Dry Byproducts

https://www.e-education.psu.edu/egee439/node/673; Credit: Caroline Clifford

9

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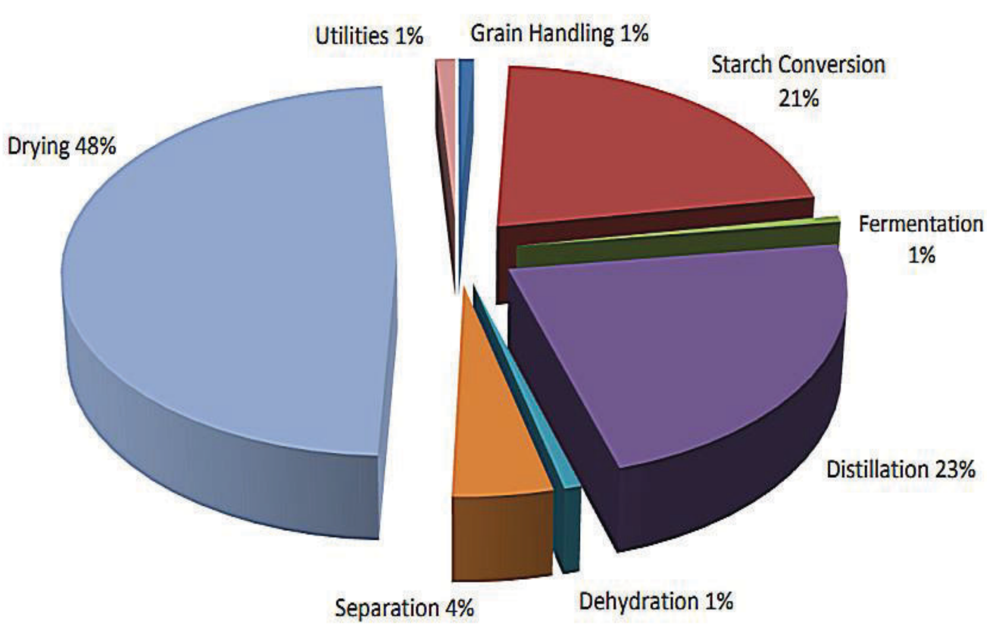
Energy Inputs for Ethanol Production

FIGURE 5: ENERGY USES IN A TYPICAL ETHANOL PLANT



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https://focusonenergy.com/sites/default/files/ethanol_guidebook.pdf

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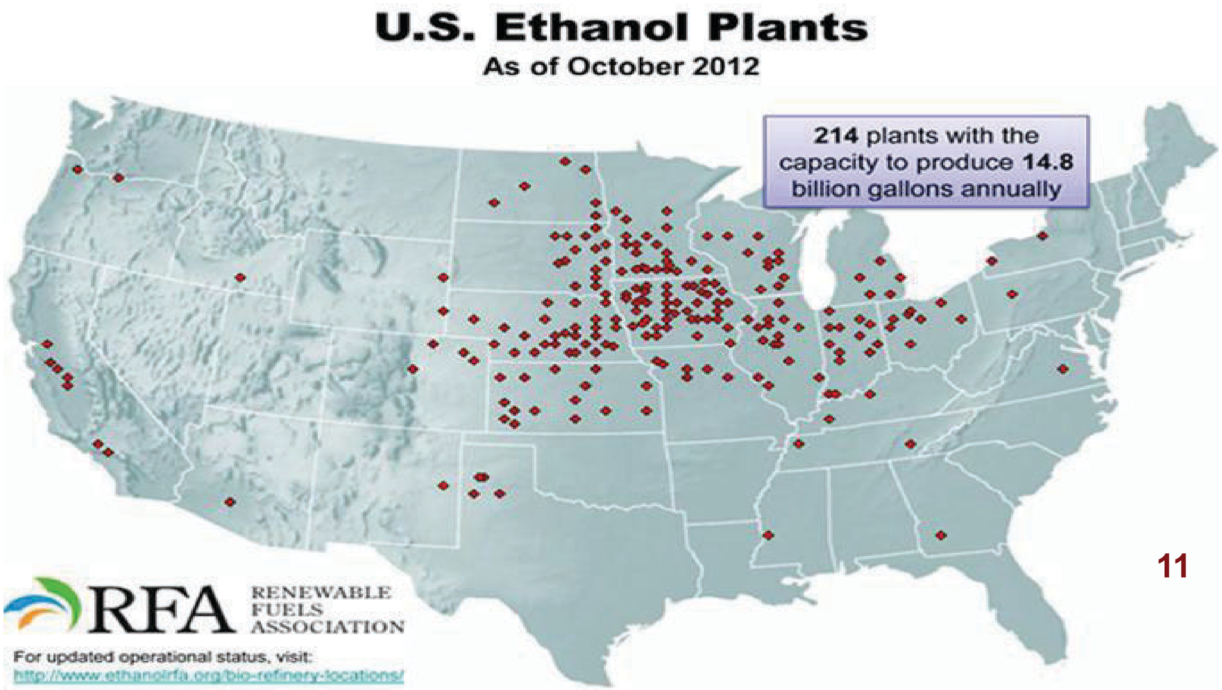
Corn Ethanol Plant Heat Input ~90 MWt (per 100 MM gal/year plant)



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Market B
Cellulosic Biofuels

Objective: Convert <u>All</u> Carbon In Biomass To Drop-In Hydrocarbon Fuels (Gasoline, Diesel & Jet)

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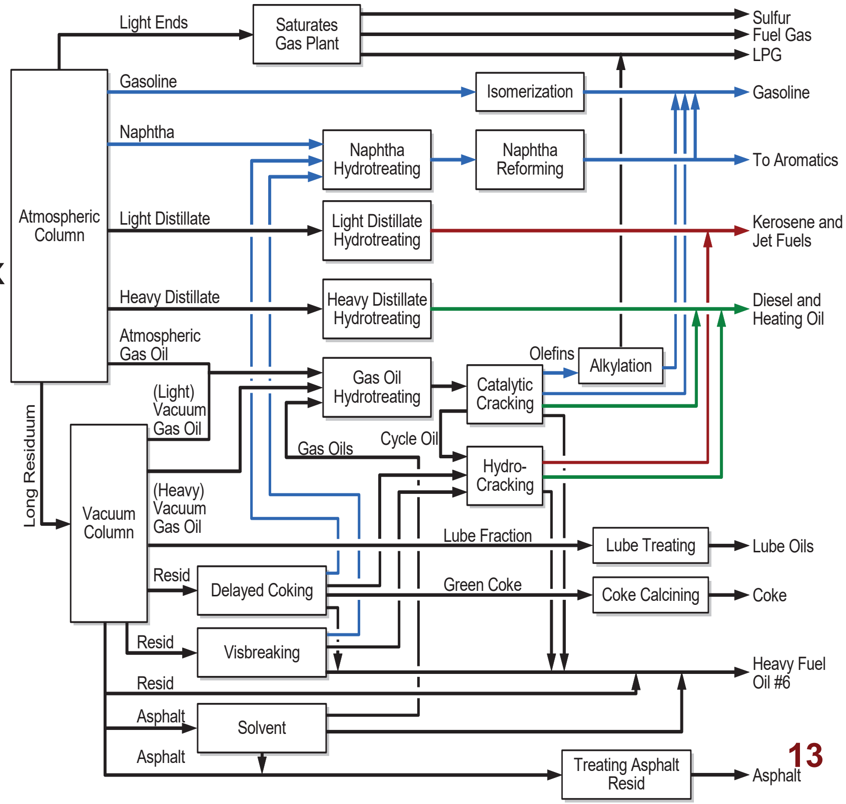
Biorefineries Must Compete Head On with Oil Refineries on Scale and Flexibility

- **Required properties:**
- Accept variable feed-stocks & produce variable products over time--requires complex flowsheets (right)
- Massive economies of scale—not competitive at small scale
- ***Integrated economic refinery input of 250,000 barrels of oil or larger***



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Large-Scale Conversion of Cellulosic Biomass to Hydrocarbon Fuels

- Total conversion of biomass to hydrocarbon fuels requires huge inputs of heat and hydrogen
  - Biomass: $CH_{1.44}\ O_{0.66}$
  - Hydrocarbon fuel (gasoline, diesel, jet fuel): CH_2
- Coal liquefaction (Fischer-Tropsch) and many other processes can be used to convert biomass feedstocks into liquid fuels
- Economics requires massive economies of scale—equivalent to 250,000 barrel/day oil refinery
- Current cellulosic biorefinery designs are less than one-tenth this scale–*mostly constrained by logistics* (***and perhaps reluctance to face the facts of logistics and scale…☺***)

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Major Logistics Challenge for Large-Scale Cellulosic Biofuels Production

- Cellulosic biomass has low density and is not stable/safe if stored outside
- Uneconomic to ship most cellulsoic biomass long distances (except for dense, flowable grains such as corn)
- Solution: *densify biomass by processing in local "depots" into stable, storable densified intermediate product for shipment to large scale biorefinery*
- Achieving these economics requires system integration/integrators: this will be a challenge
- ***But not less of a challenge than continuing with the current unworkable logistics model***

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Biomass Logistics Challenge Visualized

Biomass stacked up and ready to go at the Abengoa Biorefinery in Hugoton, Kansas

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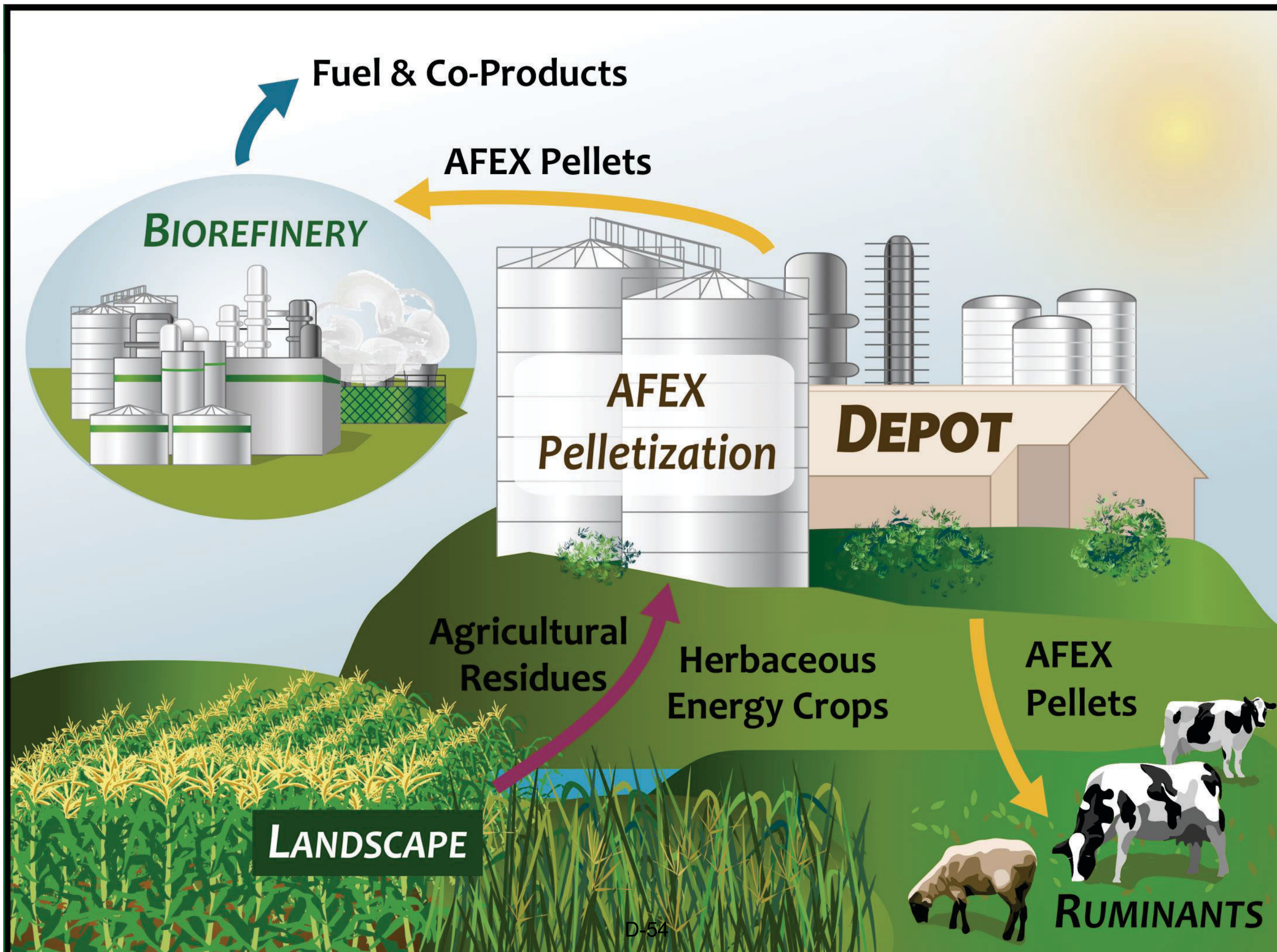
Another problem, biomass burns very easily:
So we need to store it under protected conditions



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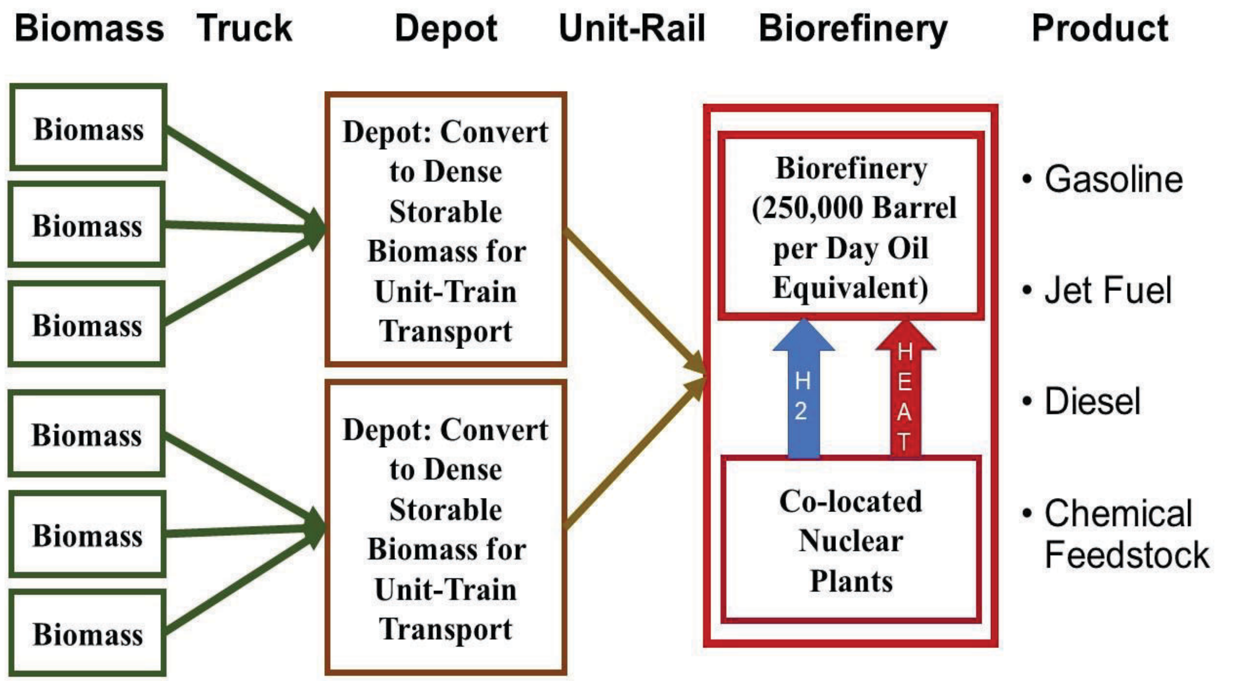
Integrated System Required for Large-Scale Nuclear Biofuels Production



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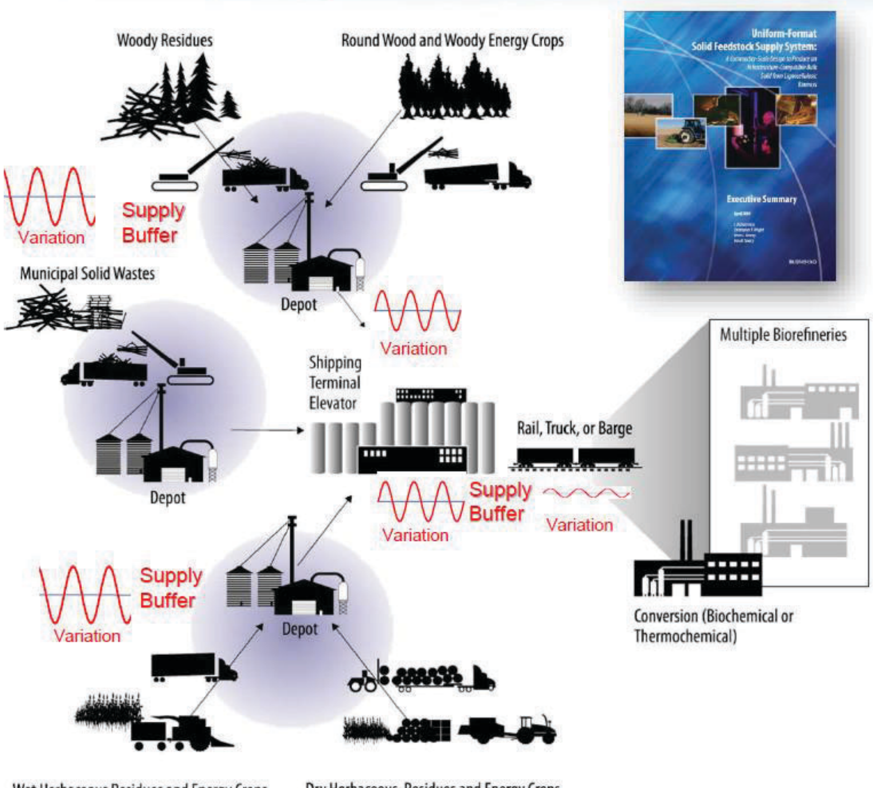
Decoupling Feed Processing from Conversion



- Wide-spread, interconnected supply network
- Stable, flowable, consitent, and conversion-ready feedstocks
- Reduced feedstock variability in quantity, quality, cost
- Decoupling does not eliminate the feed handling problem, but it does reduce conversion plant downtime.

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Future Biofuels Options May Use Massive Quantities of Hydrogen

Comparisons of Options to Produce Hydrocarbon Fuels from Biomass		
Platform	Yield, Kg Octane per Kg Cellulose	Input Energy from Hydrogen (%)
Thermochemical	**0.310**	0
Sugar	**0.352**	4.9
Carboxylate (Kolbe)	**0.422**	23.4
Carboxylate (2°Alcohol)	**0.469**	32.3
Carboxylate (1° Alcohol)	**0.528**	40.8

Almost Doubles Liquid Fuels per Ton of Biomass and Gives Higher-Quality Fuels with Hydrogen Addition

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Summer Workshop On Large-Scale Nuclear Biorefineries

- Biorefineries equivalent to 250,000 barrel per day oil refinery
- Gigawatt heat demands and massive hydrogen demand (existing single large oil refinery heat demand measured in gigawatts)
- Reduce land footprint (and associated environmental impacts) by 2x compared to BAU
- Joint Michigan State, MIT, North Carolina State University and Idaho National Laboratory workshop
- **Invitation to workshop participants**

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Market C
Paper, Pulp and Liquid Fuels

Coproduction of Paper and Fuels

2
3

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Paper and Pulp Industry

- Paper mills separate fiber and from other wood components
  - Fiber becomes paper
  - Burn remaining biomass for energy
- Large-scale lower-temperature heat Input
  - Digest wood
  - Dry paper
- **Paper and pulp plant size limited by economic transport distance of pulp wood**

International Paper Company's Kraft pulp and paper mill in Georgetown, South Carolina

4

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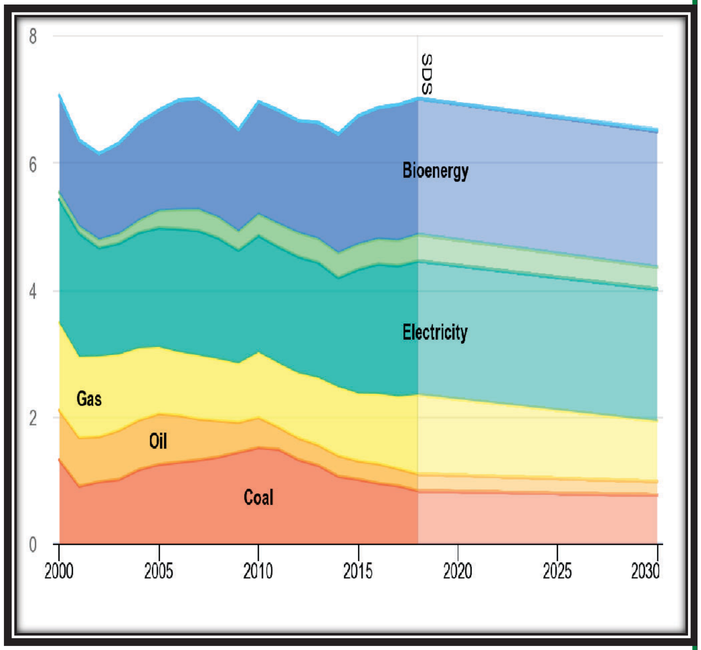
Paper & Pulp Energy Use
(~6% of Global Energy Demand)

- Large total biomass and fossil fuel input (EJ)
- Biomass in large plants produces required electricity
- Nuclear heat can replace biomass & fossil fuel energy input: Chemical pulping uses more heat, Mechanical pulping uses more electricity
- **Can convert biomass that is burnt from heat source to liquid fuels**



IEA, *Final energy demand in pulp and paper in the Sustainable Development Scenario, 2000-2030*, IEA, Paris https://www.iea.org/data-and-statistics/charts/final-energy-demand-in-pulp-and-paper-in-the-sustainable-development-scenario-2000-2030

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Conclusions

- Drop-in Biofuels Can Replace Liquid Fossil Fuels
- Quantities and Quality of Liquid Biofuels Depend Upon External Energy Inputs: *Up 10-20% of total U.S. energy demand*
- Two applications:
  - Replace fossil fuel inputs to biofuels, paper and pulp plants
  - Replace burning of biomass for stationary heat supply and convert that biomass into liquid fuels for transport
- Different parts of market require different sizes of nuclear reactor heat inputs
- Most markets are not in urban areas

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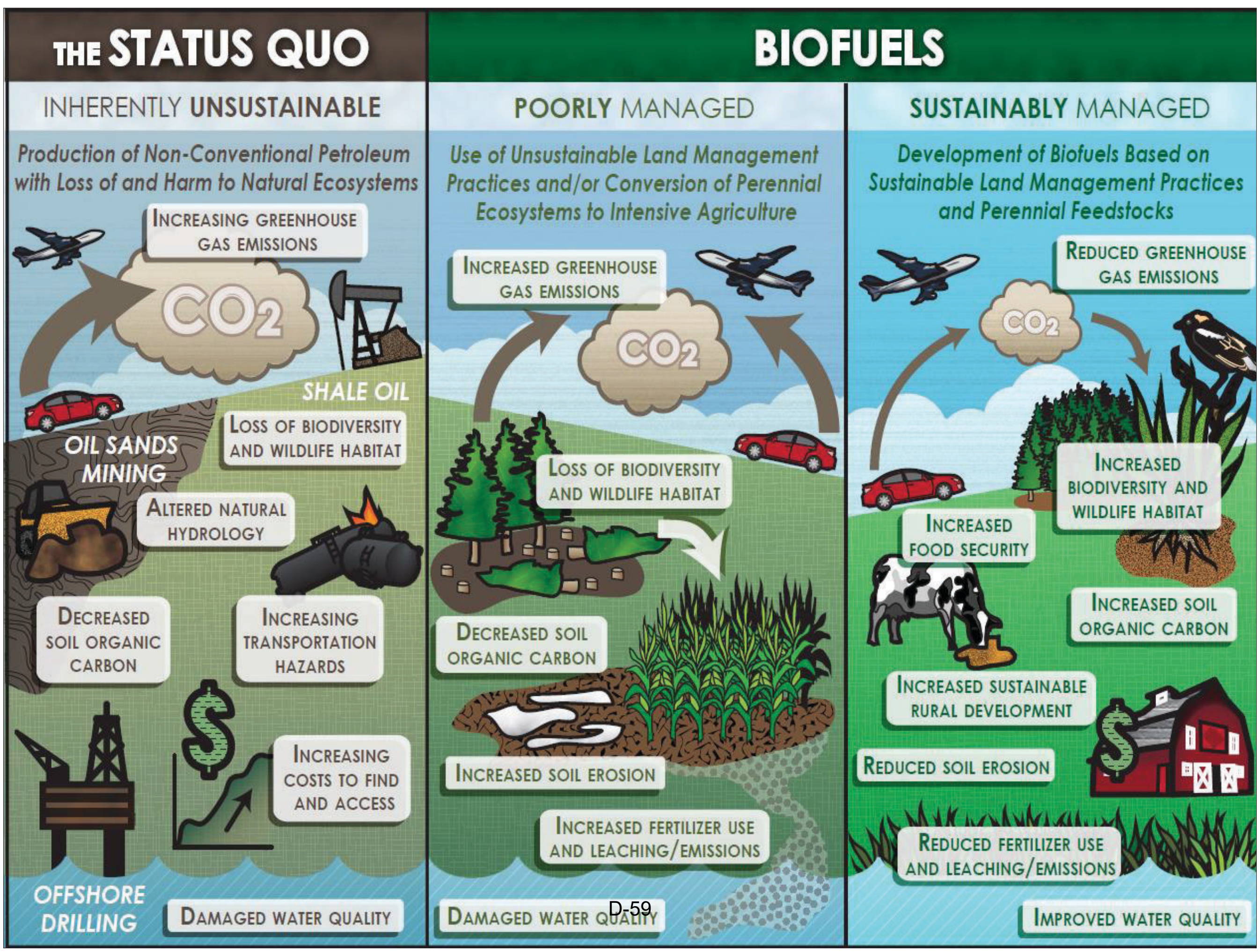
Questions ??



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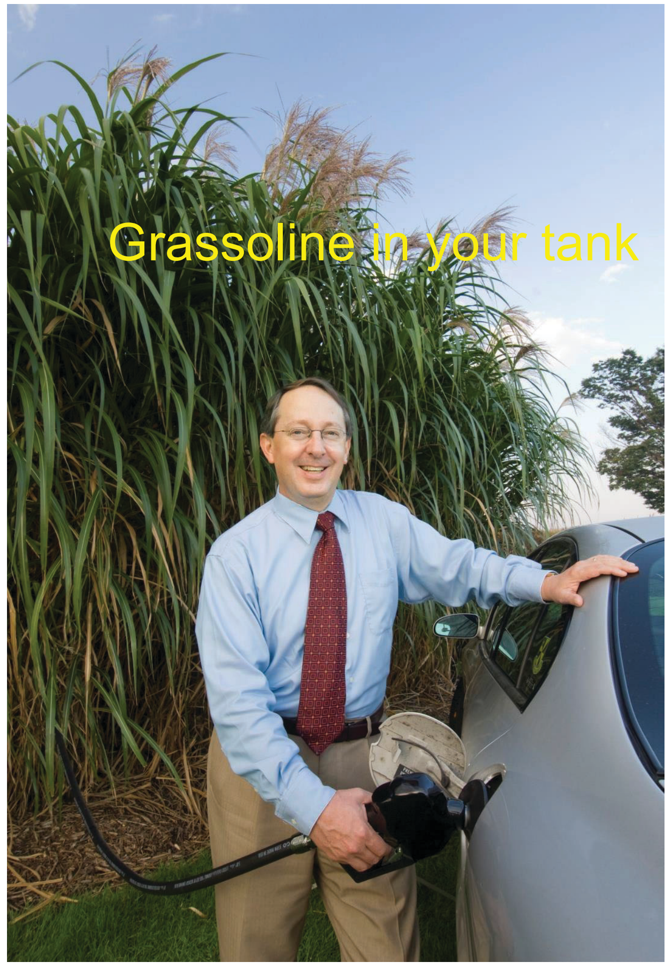
"The Stone Age did not end for lack of stone, and the Oil Age will end long before the world runs out of oil."

Sheikh Zaki Yamani
Former Saudi Arabia Oil Minister



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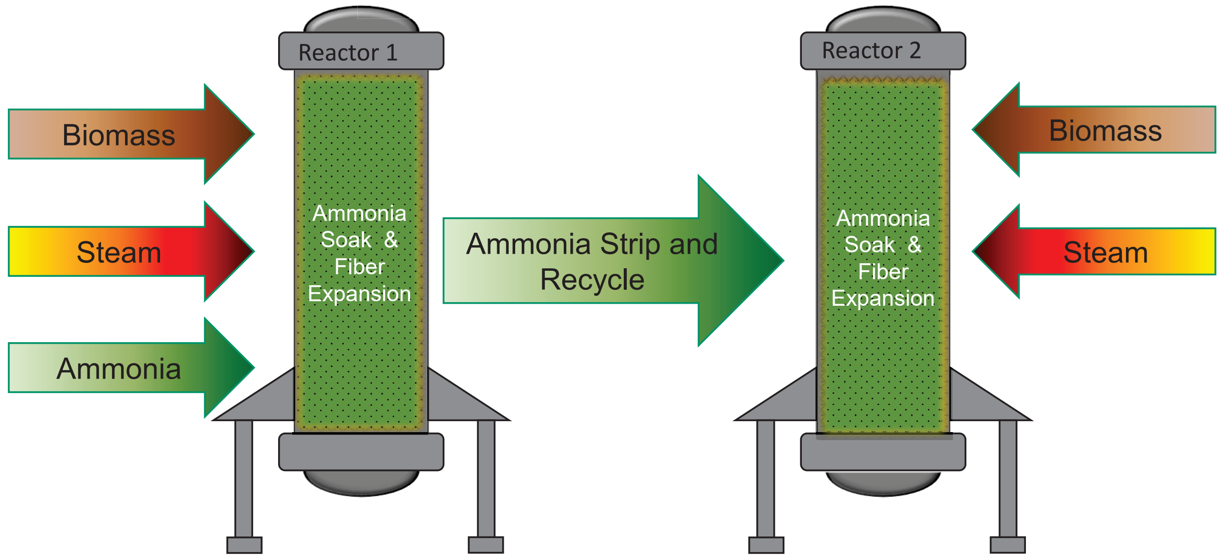
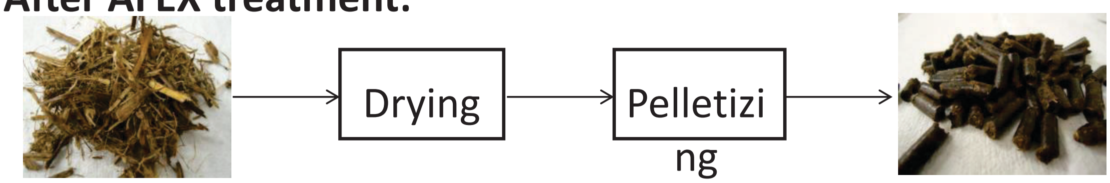
Added Information

THE AFEX PROCESS



After AFEX treatment:



Treated biomass **AFEX pellets**

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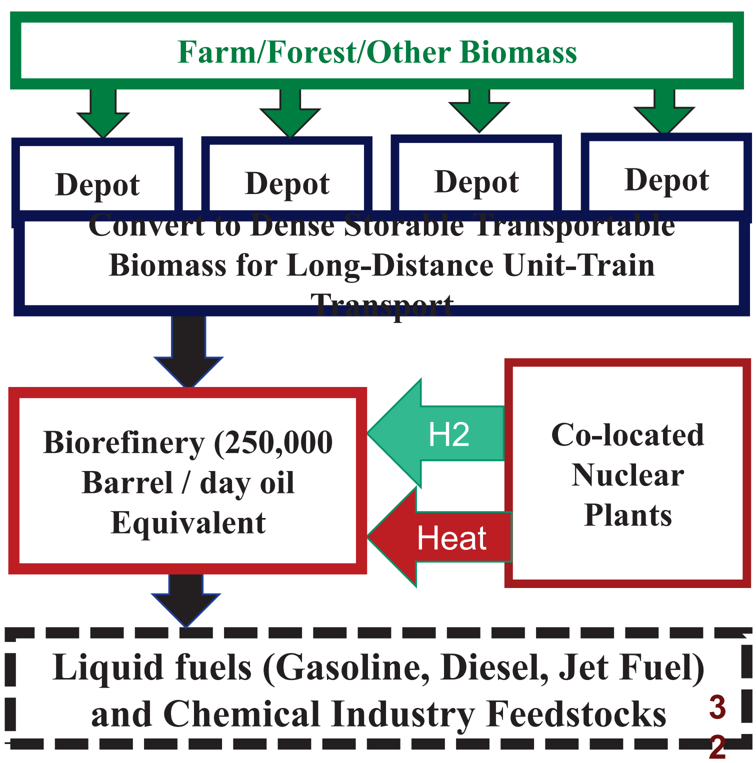
Nuclear Biorefinery System

- Depots consolidate and densify local biomass for economic storeable long-distance transport of biomass
- Unit-train shipment to large-scale biorefineries to enable:
  - Economics of scale
  - Full slate of products
- Nuclear reactors to provide heat and hydrogen to refinery
  - Biomass as renewable carbon source
  - More than double liquid drop-in hydrocarbon biofuels per unit of biomass
  - Enables processing of renewable carbon sources (sewage sludge, etc.) with high carbon content but low energy content
- Replace all fossil-fuel liquid hydrocarbon fuels and chemical feedstocks



January 13, 2021

Youssef Ballout, Ph.D.
Director of the Reactor Systems Design and Analysis Division

Fission Battery Initiative

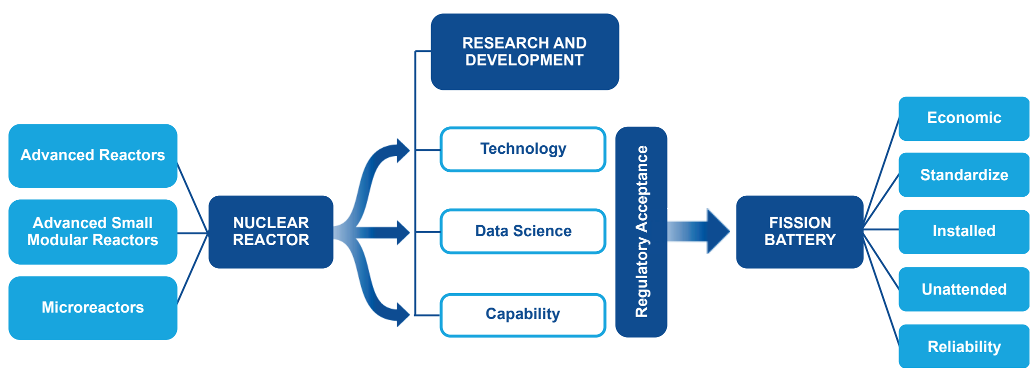
Nuclear Science and Technology

Idaho National Laboratory

Fission Battery Initiative

Vision: Developing technologies that enable nuclear reactor systems to function as batteries.

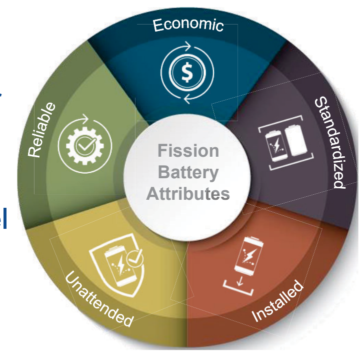
Outcome: Deliver on research and development needed to provide technologies that achieve key fission battery attributes and expand applications of nuclear reactors systems beyond concepts that are currently under development.



Research and development to enable nuclear reactor technologies to achieve fission battery attributes

Fission Battery Attributes

- **Economic** – Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable flexible deployment across many applications, integration with other energy sources, and use as distributed energy resources.
- **Standardized** – Developed in standardized sizes, power outputs, and manufacturing processes that enable universal use and factory production, thereby enabling low-cost and reliable systems with faster qualification and lower uncertainty for deployment.
- **Installed** – Readily and easily installed for application-specific use and removal after use. After use, fission batteries can be recycled by recharging with fresh fuel or responsibly dispositioned.
- **Unattended** – Operated securely and safely in an unattended manner to provide demand-driven power.
- **Reliable** – Equipped with systems and technologies that have a high level of reliability to support the mission life and enable deployment for all required applications. They must be robust, resilient, fault tolerant, and durable to achieve fail-safe operation.



Fission Battery Workshop Series

- **Jointly INL and National University Consortium are organizing workshops across <u>five</u> areas:**
  - Market and Economic Requirements for Fission Batteries and Other Nuclear Systems
  - Technology Innovation for Fission Batteries
  - Transportation and Siting for Fission Batteries
  - Security Scoping for Fission Batteries
  - Safety and Licensing of Fission Batteries
- **Expected outcomes:**
  - Each workshop outcomes are expected to outline the goals of each fission battery attribute

INL

Idaho National Laboratory

CAN NUCLEAR BATTERIES BE ECONOMICALLY COMPETITIVE IN LARGE MARKETS?

Jacopo Buongiorno

TEPCO Professor of Nuclear Science and Engineering
Director, Center for Advanced Nuclear Energy Systems
Science and Technology Director, Nuclear Reactor Laboratory

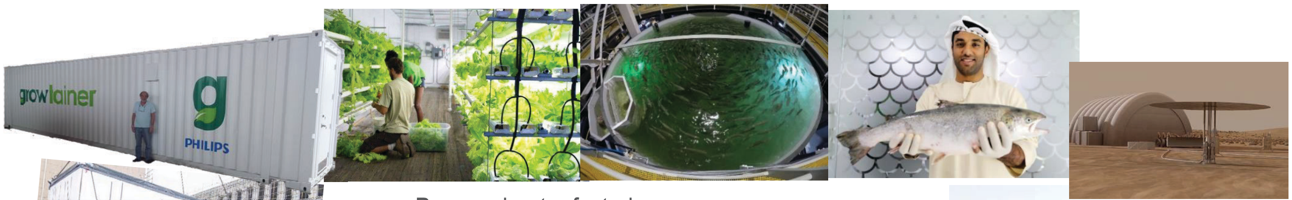
MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

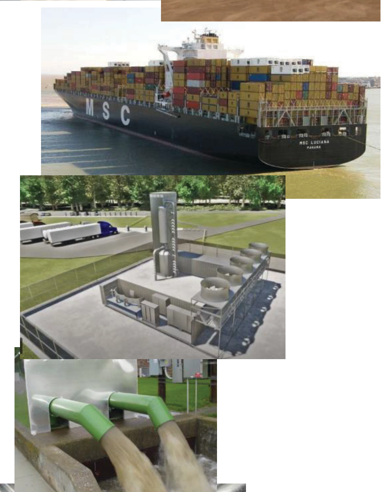
OBJECTIVES

- Identify *cost targets* for heat and electricity delivered by Nuclear Batteries (NB)
- Identify and quantify *cost drivers* for NB

WHAT ARE THE POTENTIAL MARKETS?



- Process heat = factories
- Charging stations = e-trucks, hydrogen vehicles
- District heating = home heating
- Desalination = fresh water
- Micro-grids = towns, islands, military bases
- Large pumps = flood protection
- Propulsion = freight ships
- Portable data centers = support local businesses
- Portable farms = fresh produce
- Indoor aquaculture = fresh fish
- Portable biopharma = synthetic insulin, vaccines
- Portable 3D printers = manufacturing
- Space = surface power and propulsion



Heat, electricity and much more

COST TARGET (ELECTRICITY)

- For electricity the main competition is the grid, but NB are NOT on the grid.
- NB obviate the need for transmission and distribution charges, thus must be compared to retail prices (not generation cost).

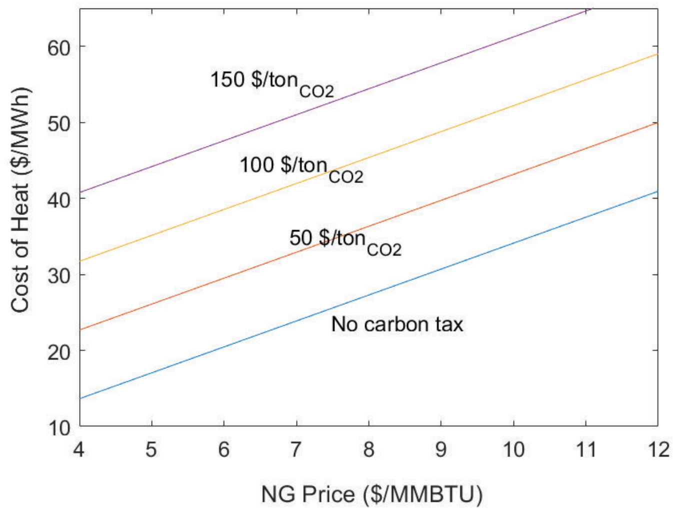
US Electricity Retail Prices 2019 ($/MWh) (includes generation, transmission, distribution)

Region	Residential	Commercial	Industrial	Transportation	All Sectors
New England	210	163	131	92	178
Middle Atlantic	158	122	66	112	123
East North Central	134	102	69	71	101
West North Central	119	97	73	87	97
South Atlantic	119	94	65	79	100
East South Central	114	107	58	--	94
West South Central	112	82	54	66	84
Mountain	118	96	63	93	94
Pacific Contiguous	156	144	97	90	138
Pacific Noncontiguous	283	245	235	--	255
U.S. Total	130	107	68	97	105

Cost target for electricity 70-100 $/MWh

COST TARGET (HEAT)

- For heat the main competition is NG-fired boilers.
- NG boilers are too small for CCS*, so burning NG will incur a carbon tax in a carbon-constrained world



*The cost of CO_2 capture from a large NG-fired boiler at around 10%mol concentration in the flue gas and 99% efficiency could be up to 100 $/t_{CO2}$, including compression, but excluding transport and storage, which might add 3-30 $/t_{CO2}$ depending on location.
(Int. J. Greenhouse Gas Control 105, 2021, 103239)

NG price does not include the cost of the boiler

Cost target for heat 20-50 $/MWh (6-15 $/MMBTU)

LCOE AND LCOH – BASELINE ASSUMPTIONS

NB is shipped to site with a fueled core, operated continuously for several years, shipped back to a central facility for refueling and refurbishment.

Parameter	Value	Comments
electric power output	10 MW	Reasonable value for many NB applications
thermal efficiency	35%	Estimated for open-air Brayton cycle with losses
core power	28.6 MW	= electric power / thermal efficiency
capacity factor	85%	NB and co-located applications must be operated continuously for good economics
fuel enrichment	5%	Does not require relicensing of U.S. fuel cycle facilities
discharge burnup	20 MWd/kg_U	Lower than LWR because of small cartridge core
refueling interval	5 yrs	From fresh fuel load in central facility to spent fuel return
cost of uranium	40 $/lb of U_3O_8	Conservative assumption for cost of yellow cake
cost of uranium conversion	6 $\$/kg_U$	Conservative assumption for cost of converting yellow cake into UF_6
cost of uranium enrichment	160 $/SWU	Conservative assumption in current U market
cost of fuel fabrication	500 $\$/kg_U$	2x higher than traditional LWR fuel fabrication
cost of spent fuel disposal	1 $/MWh	U.S. spent nuclear fuel disposal fee
# of FTE for O&M	5	Same FTE/MW of current US fleet
wages per FTE	150,000 $/yr	Includes benefits and taxes
cost of fabrication	30 M$	3000 $/kW, excluding fuel
other capital costs	1.7 M$	Includes site preparation, NB vault, electric transformer, office container, NB shipment to/from site, installation and connection
NB economic lifetime	20 yrs	NB technical lifetime likely longer
cost of decommissioning	½ cost of NB fabrication	Incurred at the end of the project
Discount rate	5%/yr	Reasonable for small project

LCOE AND LCOH ESTIMATES

$$\text{LCOE [\$/MWh]} = \frac{\text{Annualized Fuel + O\&M + Fabrication + Deployment + Decommissioning Costs}}{(\text{electric power} \times \text{capacity factor} \times 8760)}$$

$$\text{LCOH [\$/MWh]} = \frac{\text{Annualized Fuel + O\&M + Fabrication + Deployment + Decommissioning Costs}}{(\text{thermal power} \times \text{capacity factor} \times 8760)}$$

Baseline case results:

LCOE = 71 $/MWh

LCOH = 25 $/MWh (7.3 $/MMBTU)

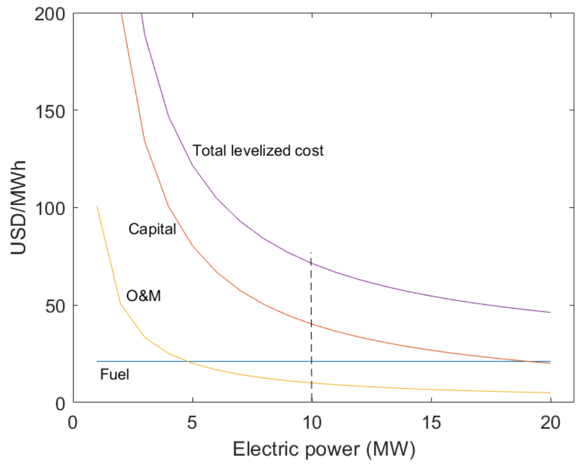
Depending on specific applications and business models, NB will be used for electricity only, heat only or cogeneration, requiring more sophisticated FOMs than LCOE and LCOH

LCOE PARAMETRIC STUDY

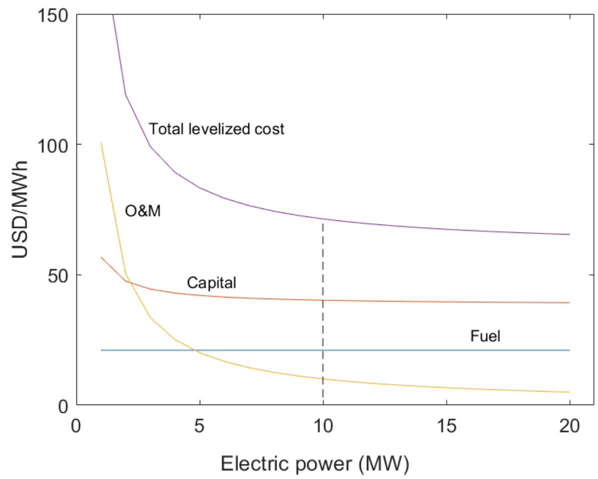
Parameters varied one at a time:

- Power output: 1 to 20 MW
- Fuel enrichment: 5 to 20%
- Discharge burnup: 5 to 30 MWd/kg_U
- Refueling interval: 3 to 10 years
- NB fabrication cost (excluding fuel): 1000 to 10000 $/kW
- # of FTEs for O&M: 2 to 15
- Discount rate: 2 to 15 %/yr

THE EFFECT OF POWER OUTPUT



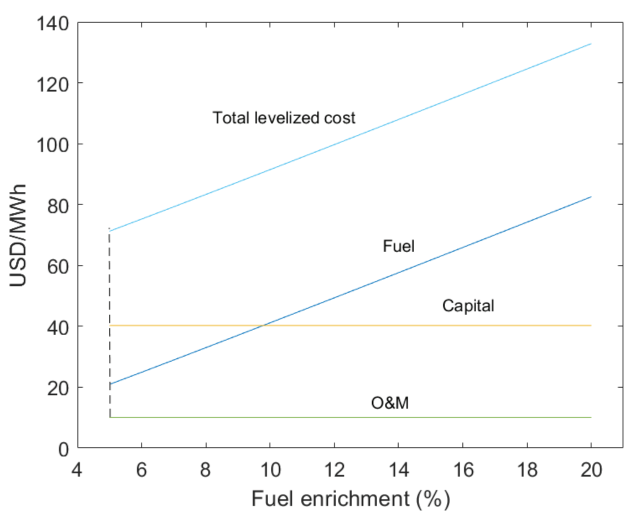
Zero scaling
(fixed fabrication cost, $)



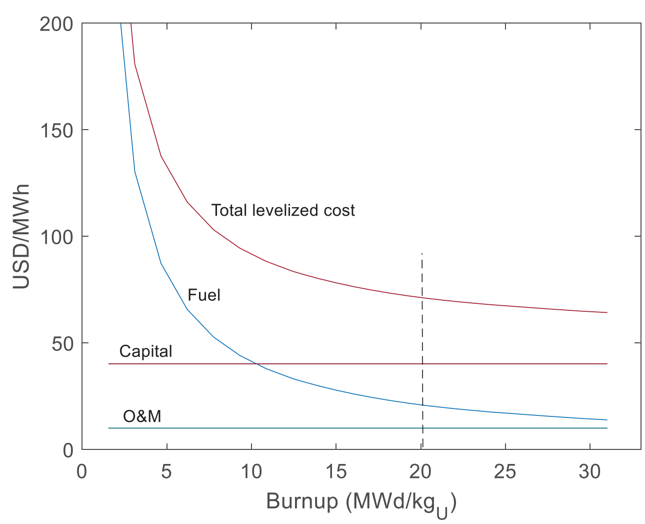
Linear scaling
(fixed *specific* fabrication cost, $/kW)

Economy of scale applies also to micro-reactors!

THE EFFECT OF FUEL PARAMETERS

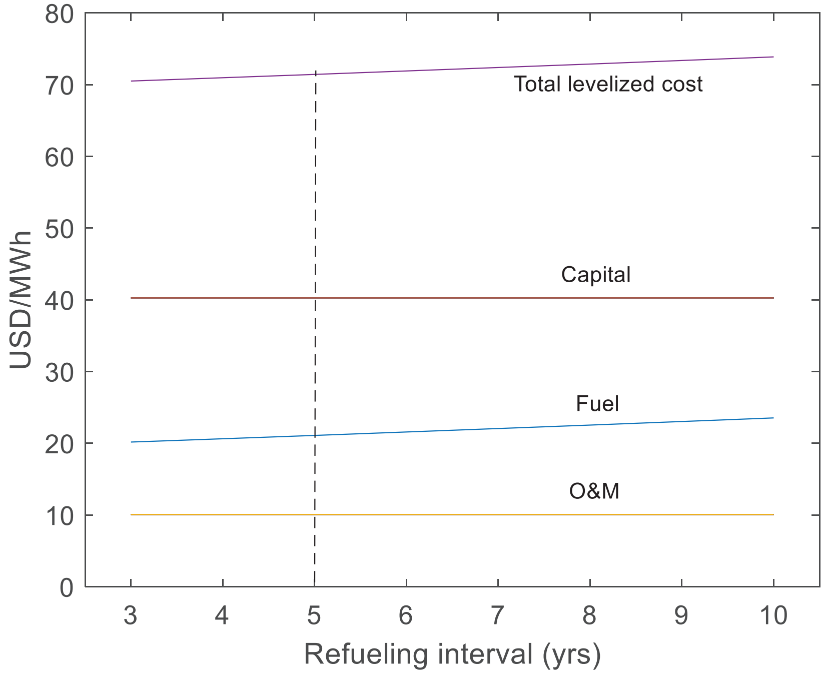


>5% enrichment requires relicensing of U.S. fuel cycle facilities



Fuel costs can quickly become unreasonable

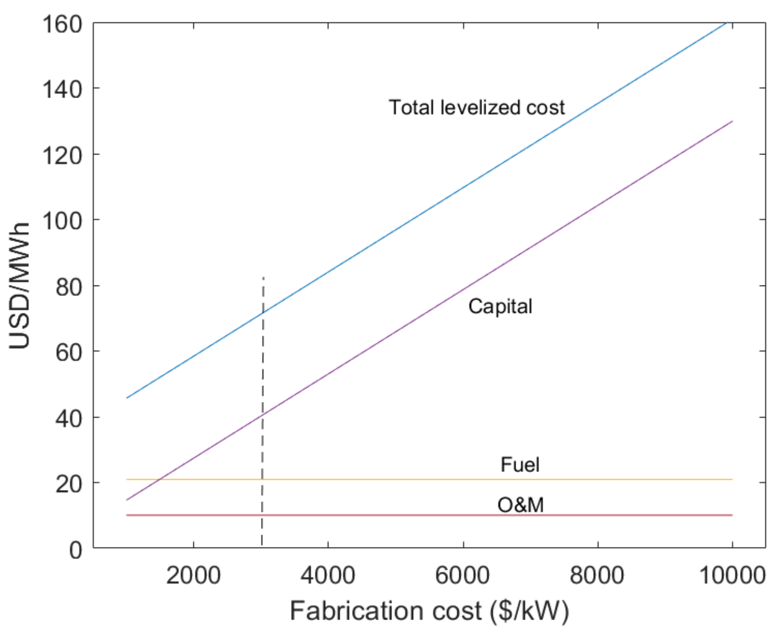
THE EFFECT OF REFUELING INTERVAL



⇐ High power density Low power density ⇒

Weak sensitivity wrt refueling interval, BUT fuel mass in the core and core dimensions are inversely proportional to refueling interval (for given core power and discharge burnup)

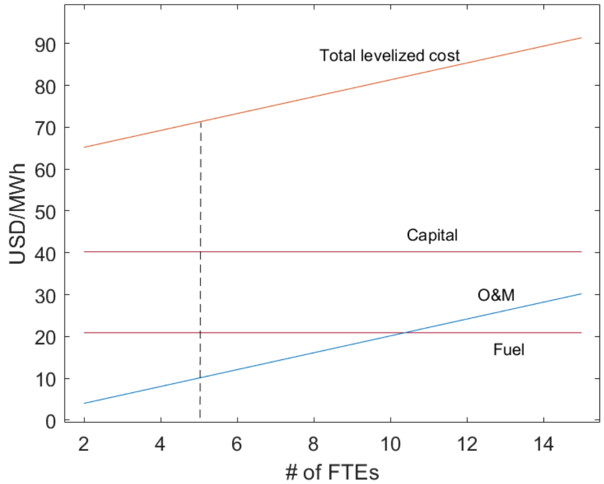
THE EFFECT OF FABRICATION COST



Fabrication cost makes a big difference, as expected

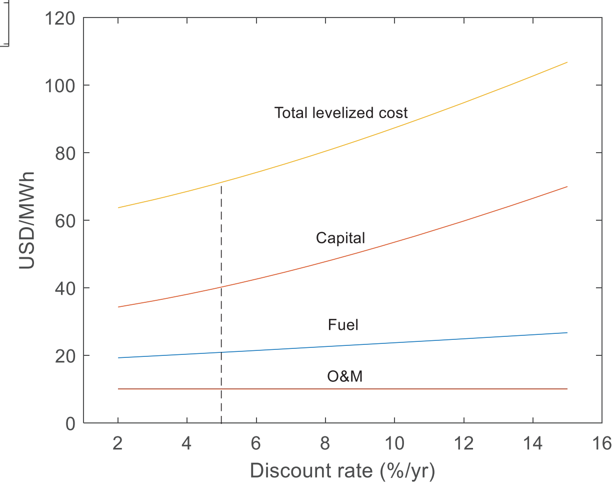
Compare to large jet engines (delicate and complex machines built in factories) generating 50 MW peak mechanical power at takeoff: cost $25M or 500 $/kW.

THE EFFECT OF STAFF SIZE AND DISCOUNT RATE



LCOE not overly sensitive to # of FTEs within the range explored. 8 FTEs translates to two staff onsite 24/7.

Low cost of financing is key. Should be achievable with small, low-risk project.

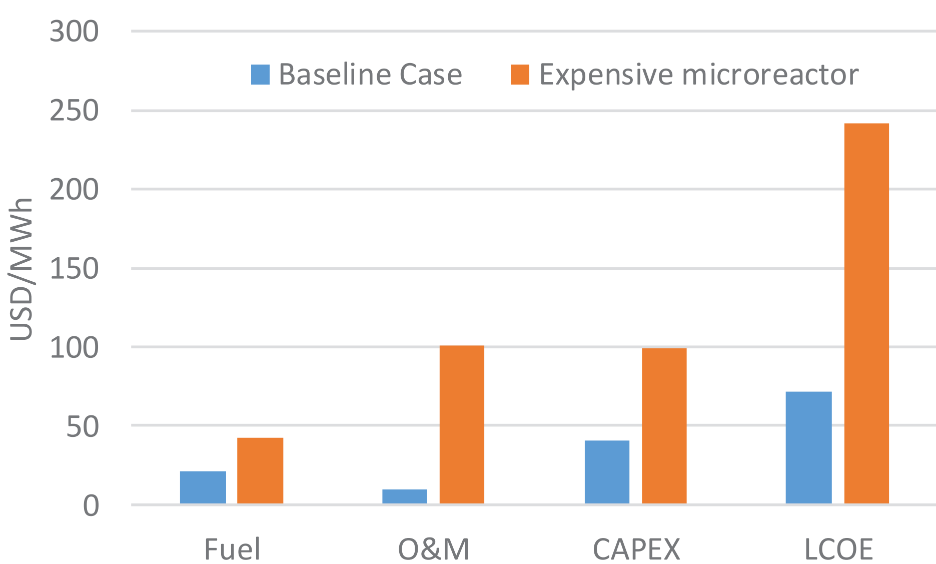


COST CAN EASILY GET OUT OF HAND

Notional example of "expensive design"

Electric output: 2 MW
TRISO fuel: 2500 $/kg_U$
Burnup: 50 MWd/kg$_U$
# of FTEs: 10

NB fabrication: 7000 $/kW
Enrichment: 15%
Refueling interval: 20 yrs



TAKEAWAY MESSAGES

- Cost targets for Nuclear Batteries in large markets are 70-100 \$/MWh for electricity, and 20-50 \$/MWh or 6-15 \$/MMBTU for heat
- It appears that NB can meet those targets, if:
  - Power output is maximized, within NB constraints (e.g., truck transportability, passive decay heat removal)
  - Staff is in the 0.5-1.5 FTE/MW range
  - Enrichment <10% and burnup >20 MWd/kg_U
  - NB fabrication cost (excluding fuel) <5000 \$/kW
  - Discount rate <10 %/yr
- No cost incentive for very long refueling intervals (>10 yrs)

BACKUP SLIDES

SITE PREP AND INSTALLATION – ASSUMPTIONS

- Dig hole for micro-reactor vault: $150k at $200/cubic yard (Home Advisor 2020a)
- Prepare lot (assumed to be 300 m^2 per micro-reactor) (McClure 2013): $50k (Home Advisor 2020a)
- Cost of the micro-reactor vault: $1M, assumed to be equivalent to the cost of a SNF dry cask (Wald 2011)
- Electric transformer: $100k (Switchgear 2020)
- Office container: $5k (includes shipment) (Container Alliance ca 2017)
- Fence: $23k (high-end fences run at about $100/ft (Home Advisor 2020b)
- Shipment fresh micro-reactor: $50k, similar to fresh fuel shipment, conservatively calculated from recommended estimates in Feizollahi et al. (1995)
- Shipment spent micro-reactor: $200k, based on spent fuel shipment cost of $\$50/kg_{HM}$ (NEA 1994)
- Micro-reactor installation, connection and on-site testing: $170k (crew of 5 × 14 days × 8 hours × $300/hour)

LIKELY COST DRIVERS

- Core design: combo of fuel enrichment, specific power and burnup.
- Fabrication: materials availability in codes (Ni-based alloys, ferritic SS, Ti-alloys), supply chain, fabrication equipment suitability of desired size components (<10 ft, 3-4 tons forging), off-the-shelf BOP equipment.
- Transportability: weight and size compatible with standard ISO containers (<14’x14’).
- Installation: requirements for onsite excavation, concrete structures, special crane or handling equipment.
- O&M: onsite manpower required for normal ops, unique daily ops requirements (e.g., chemistry monitoring/control), routine ops/maintenance with high exposure potential, unique sensing requirements (e.g., pump sensors/release monitoring for tritium), high replacement periodicity for any parts/materials, readily available sensors for remote or online monitoring and operations, safety systems hardened against cyber intrusion, diagnostic/prognostic/degradation algorithms availability.

The Resilience Value Proposition

- Fission Battery Economics Workshop
- January 2021

- Paul E. Roege, P.E., Creative Erg, LLC

Value

The regard that something is held to deserve; the importance, worth, or usefulness of something.

(Oxford)

Historical manifestation

- Anthropological pattern - creation, guarding, barter, and conflict over items or services of "value"
- Currency systems facilitated negotiation and transactions
- Price (arbitrary) ≠ Value (fundamental)
- Value is exposed in a decision
- What's the value of
  - Pork bellies
  - Energy
  - Concert tickets?

Energy is now treated a commodity . . . *but*

Value derives from application and circumstances of use!

to illustrate. . .

The military concept of *Energy-Informed Operations:*

Using energy to the greatest net operational benefit.

Energy provides the operational edge

Dismounted Maneuver

Capability Priorities:
- Increased Mobility, lethality
- Decreased Resupply and Operational Interruptions

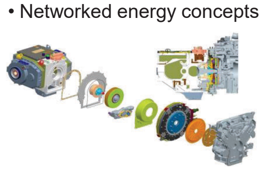
Trend:
- More Systems = Net increase in power demand
- Networked Communications to the Soldier level

Soldier-Worn Integrated Power Equipment System (SWIPES)

Mounted Maneuver

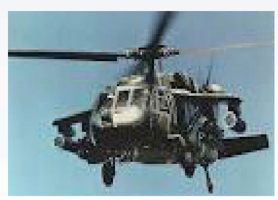
Capability Priorities:
- Flexibility for rapidly changing operating environment
- Endurance/sustainability

Trend:
- Diversification of threats
- Proliferation of onboard systems
- Networked energy concepts



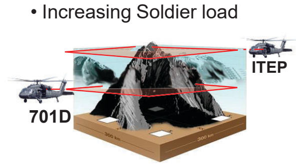
Integrated Starter-Generator (ISG)

Air Maneuver



Capability Priorities:
- 424 Km Radius of Action without Refuel
- Operational coverage 6K/95°

Trend:
- Extended distances, remote locations
- Increasing Soldier load



Improved Turbine Engine Program (ITEP)

Contingency Basing

Capability Priorities:
- Interoperate with systems, Soldiers, partners
- Increase efficiency to provide more resources for operations

Trends:
- Extended operations – quality of life improvements
- Increased use of contracted support

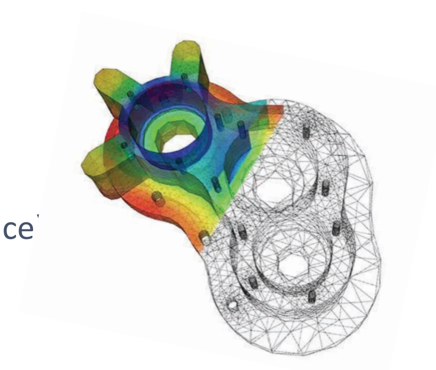
Microgrids

Complicating the equation

What if. . . ?

Factoring in Uncertainty (19^{th}-20^{th} Centuries)

- *Risk Management based upon confidence (or arrogance?)*
- Maximize Expected Value (EV)
- Decisions based upon actuarial information (predictability)
- Institutionalized indemnification (legal) / risk sharing (insurance)
- Life cycle strategy
  - Optimize system design for performance
  - Protect system as designed (*stasis*)



Optimize . . .

Risk Management (the rest of human history)

- *Adaptive management based upon humility*
- Seek Resilience (capacity to thrive in face of change)
- Acknowledge change and unknowns
- Focus on desired outcome rather than the system
- Life cycle strategy
  - Balance effectiveness and agility for incremental improvement
  - Sense, respond, recover, and adapt

Improvise!

Why resurrect Resilience?

- Increasingly dynamic and complex world
- New phenomenologies
- Recognition of knowledge gaps
- Shortcomings in EV model
- Growing dissatisfaction with outcomes

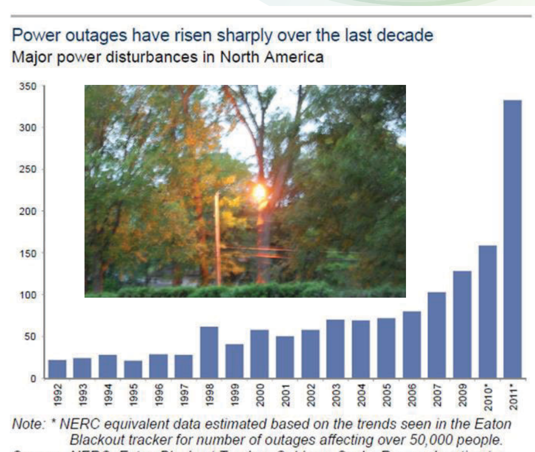


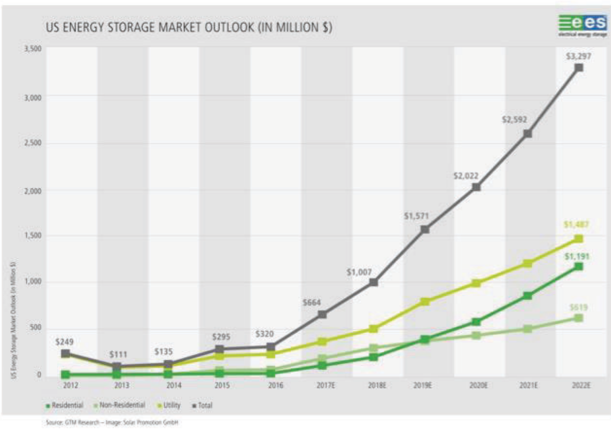
Illustration – Fukushima tsunami

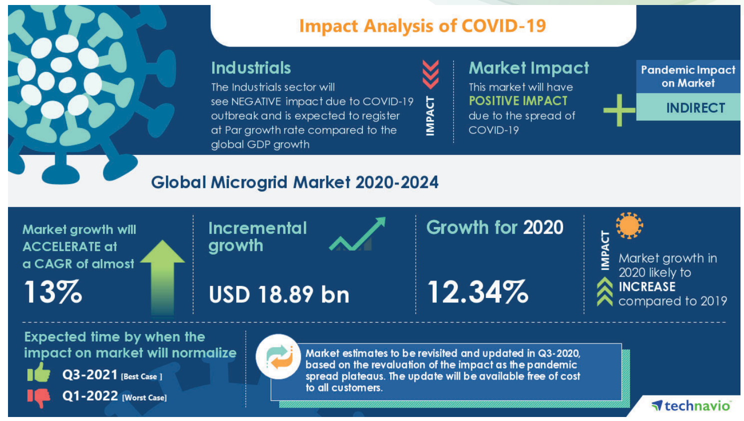
- Complex system
- Single-point vulnerabilities
- Extraordinary consequences
- Mitigated by operator initiative

Illustration – Puerto Rico hurricane

- Centralized system
- Limited local capacities
- Service restoration 1 >yr
- Consequences mitigated by local initiative

Indicators of change





Energy storage and microgrid investment growth – not driven by “lowest LCOE.”

How can we value (and afford) Resilience?

- Shift focus from maintaining system stasis to assuring outcomes
- Reform design emphasis from point optimization to agility
- Adopt systemic resilience metrics
- Cultivate proactive, entrepreneurial posture
- Expand decision processes to address real value

Alternative design approaches

Deterministic

- Optimize @design condition
- Maximize expected return
- Anticipated stressors
- System features
  - Protective barriers
  - Deterministic control
  - Prescriptive procedures

Resilient

- Characterize via contingency & sensitivity analyses
- Embrace sensing, stability, flexibility, adaptability
- System features
  - Open architecture
  - Alternative configurations
  - Intelligent systems
  - Situational awareness
  - Operational options

LEGO® Model – INL Photo

Resilience Metrics (model)

Domain	Prepare	Absorb	Recover	Adapt
Physical				
Information				
Cognitive				
Social				

Develop specific measures based upon system/objectives

From Roege, P.E. et al., Metrics for energy resilience, Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.012

Philosophical shift required

- Reform value proposition
- Adopt abundance mentality
- Accept humble attitude
- Embrace change
- Encourage/empower entrepreneurship

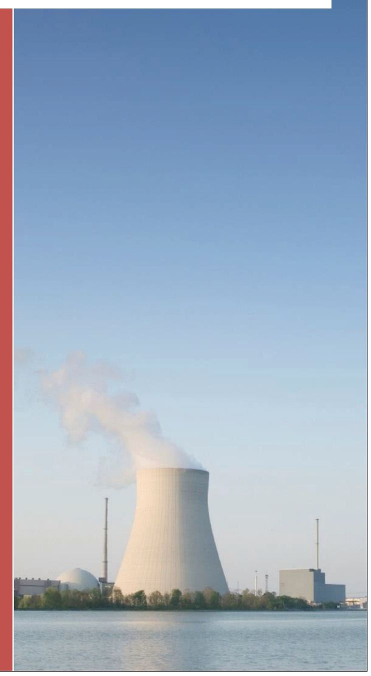
Leasing Nuclear Batteries: Opportunities and Considerations

Elina Teplinsky
Partner
Pillsbury Winthrop Shaw Pittman LLP

presented at

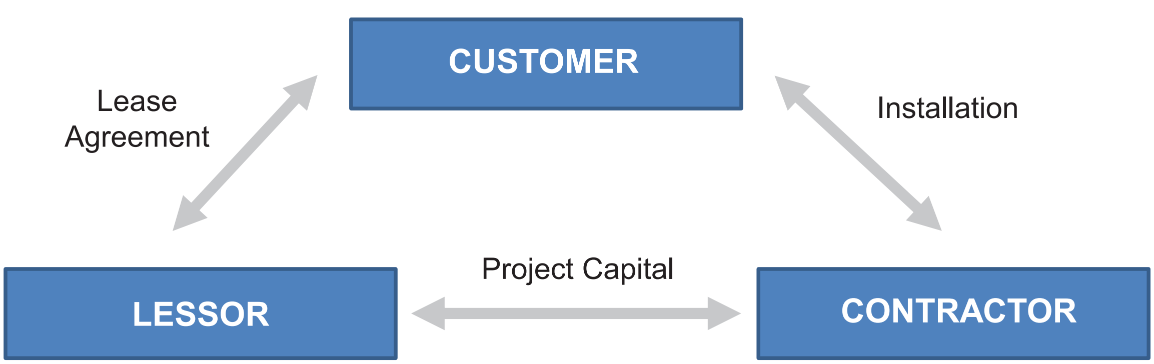
Workshop on Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

January 27, 2021



Leasing in the Energy Sector: An Overview

- **Lease:** financing structure that allows a customer to use equipment without purchasing it outright
  - Commonly used for solar systems and battery storage
  - Simpler than a PPA + possible tax & accounting benefits
  - Terms flexible – 3-15+ years

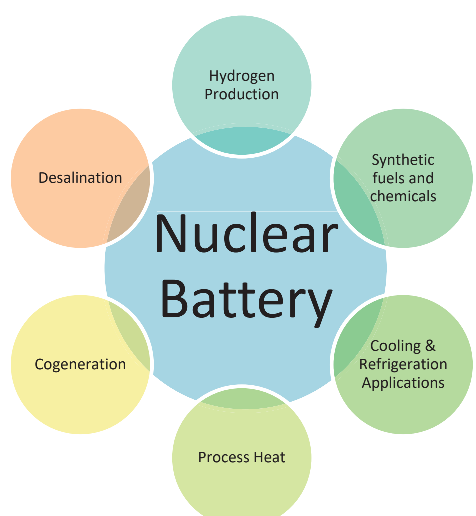


Types of Leases

Type of Lease	Key Aspects
Capital or Finance Lease (similar to bank loan)	• Customer owns equipment, lessor takes security interest • Equipment = asset, lease payments = liability • Customer can depreciate the equipment as an asset to provide a tax benefit • Customer can purchase equipment for discounted price at end of lease term
Operating Lease	• Lessor owns equipment, customer rents at a fixed monthly payment • Rental payments = operating expenses, tax deductible • End of lease term -> customer can extend lease, purchase equipment for fair market value, or return equipment
Solar Lease	• Similar to operating lease • Different options of down payment • Tax incentives / rebates normally are retained by developer

Leases in the Context of Nuclear Batteries

- Primary customers will be industrials – purchasing heat, not electricity
  - Diverse customer base relative to utilities
  - No interest in licensing and operating nuclear facilities
- Leases v. PPAs
- Highly manufactured content and short deployment times may allow for involvement of additional players, such as financial institutions



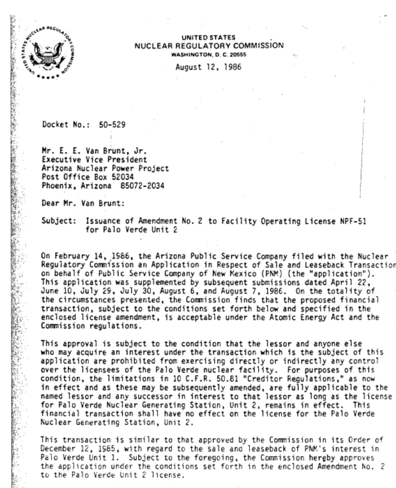
Feasibility of Leasing Nuclear Batteries

- **NRC Creditor Regulations at 10 CFR §50.81:**
  - The Commission consents, without individual application, to the creation of any mortgage, pledge, or other lien upon any production or utilization facility not owned by the United States which is the subject of a license or upon any leasehold or other interest in such facility: Provided:
    - (1) That the rights of any creditor so secured may be exercised only in compliance with and subject to the same requirements and restrictions as would apply to the licensee pursuant to the provisions of the license, the Atomic Energy Act of 1954, as amended, and regulations issued by the Commission pursuant to said Act; and
    - (2) That no creditor so secured may take possession of the facility pursuant to the provisions of this section prior to either the issuance of a license from the Commission authorizing such possession or the transfer of the license.

History of Regulation of Nuclear Leasing in the U.S.

- **1970s and 80s: various "sale leaseback" transactions**
  - Nuclear power plant owners in the United States sold facilities to equity investors, leased back same interest sold
  - Refinancing and tax equity transactions – sale of credits to institutional investors

- **NRC applied 10 CFR §50.81 to these transactions:**
  - Approved the applications with no impact on licenses, but with conditions:
    - Facilities to operate in conformity with applications
    - Lessor and anyone else who may acquire an interest under the transaction are **prohibited from exercising directly or indirectly any control over the licensees**
    - Licensees required to notify NRC of any changes in the sale leaseback agreements



UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

August 12, 1986

Docket No.: 50-529

Mr. E. E. Van Brunt, Jr.
Executive Vice President
Arizona Nuclear Power Project
Post Office Box 52034
Phoenix, Arizona 85072-2034

Dear Mr. Van Brunt:

Subject: Issuance of Amendment No. 2 to Facility Operating License NPF-51 for Palo Verde Unit 2

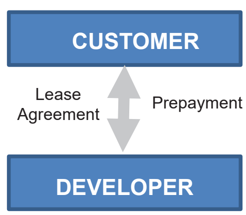
On February 14, 1986, the Arizona Public Service Company filed with the Nuclear Regulatory Commission an Application in Respect of Sale and Leaseback Transaction on behalf of Public Service Company of New Mexico (PNM) (the "application"). This application was supplemented by subsequent submissions dated April 22, June 10, July 29, July 30, August 6, and August 7, 1986. On the totality of the circumstances presented, the Commission finds that the proposed financial transaction, subject to the conditions set forth below and specified in the enclosed license amendment, is acceptable under the Atomic Energy Act and the Commission regulations.

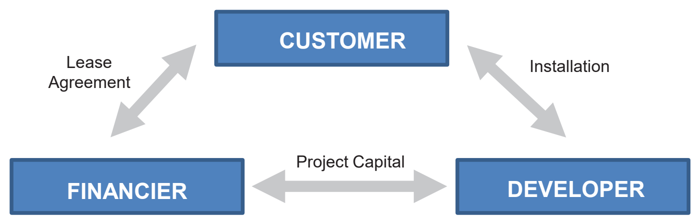
This approval is subject to the condition that the lessor and anyone else who may acquire an interest under the transaction which is the subject of this application are prohibited from exercising directly or indirectly any control over the licensees of the Palo Verde nuclear facility. For purposes of this condition, the limitations in 10 C.F.R. 50.81 "Creditor Regulations," as now in effect and as these may be subsequently amended, are fully applicable to the named lessor and any successor in interest to that lessor as long as the license for Palo Verde Nuclear Generating Station, Unit 2, remains in effect. This financial transaction shall have no effect on the license for the Palo Verde Nuclear Generating Station, Unit 2.

This transaction is similar to that approved by the Commission in its Order of December 12, 1985, with regard to the sale and leaseback of PNM's interest in Palo Verde Unit 1. Subject to the foregoing, the Commission hereby approves the application under the conditions set forth in the enclosed Amendment No. 2 to the Palo Verde Unit 2 license.

Framework for Leasing

- Facility licensed and operated by project developer
- Easiest structure from NRC licensing perspective is operating lease – facility owner by developer, customer rents at fixed periodic payment
- Capital lease may be possible, but likely subject to significant NRC scrutiny – may not be compatible with large-scale deployment model, unless blanket approval of concept can be secured
- Lessor can be project developer (build, own, operate, lease) or financial institution (if a derisked project)
  - In absence of financier involvement, partial pre-payment or downpayment of lease will help offset capital costs

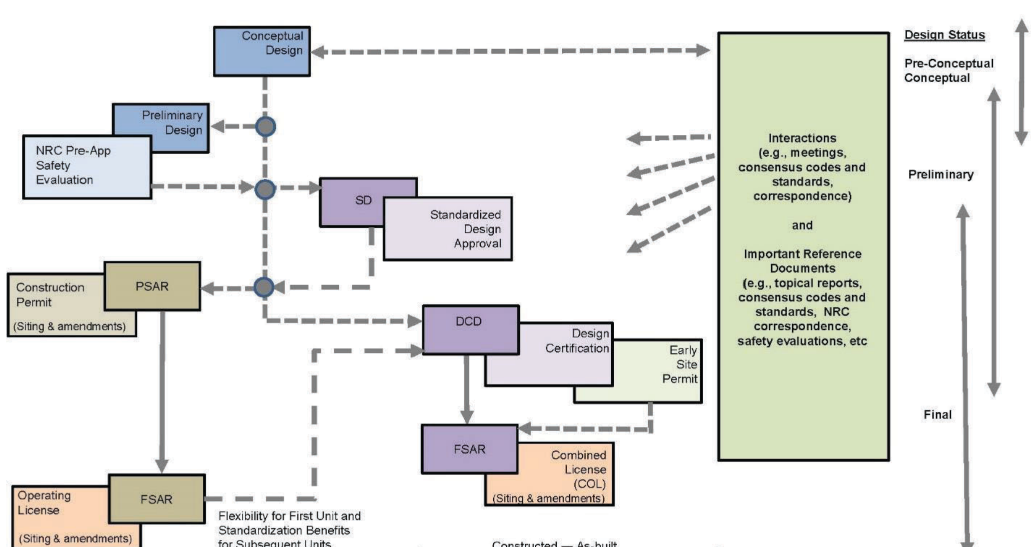




Licensing Challenge

Current NRC licensing framework is not designed for large-scale deployment of nuclear batteries

Licensing solutions necessary to enable this large-scale deployment – key to success of leasing model from a market perspective



Licensing Challenge – Possible Solutions

- **Manufacturing Licenses**
  - allows for pre-fabrication of nuclear power plants and then installation and operation at separately approved sites
  - Appendix N to Parts 50 and 52 provides for construction and operation of nuclear power reactors of identical design at multiple sites
- **Non-power reactors (NPRs)**
  - Simplified licensing process
  - NUREG-1537, "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors" – includes Standard Review Plant for licensing NPRs
  - Although nuclear batteries may not be nonpower reactors, regulations could be changed in the future to allow them to be licensed in a manner similar to NPRs
  - NRC has already included suggested modifications to NUREG-1537 Part 1 in a report titled "Regulatory Review of Micro-Reactors – Initial Considerations"
- **Part 53**
  - Performance-based licensing regime with technology-inclusive framework
  - Significant engagement with NRC required to provide for a licensing framework allowing for large-scale deployment of nuclear batteries

Leasing Model – Liability Considerations
Price-Anderson Act (PAA) Key Principles

Omnibus coverage protects all who may be liable

- The owner
- Contractors, vendors and suppliers
- Anyone else with liability

Covers <u>any legal liability</u> arising from a nuclear incident

- Negligence
- Gross negligence
- Willful misconduct

Economically channels all liability to the plant owner

- Owner holds insurance policies

Provides cap on liability equal to the coverage

- Total amount of primary + secondary insurance

Requirements for Reactors with Rated Capacity of > 100MWe

- Must have two tiers of nuclear liability security:
  - Primary nuclear liability insurance of $450 million
  - Must participate in a secondary retrospective insurance plan
- Modular units of 100 MWe to 300 MWe at single site with combined capacity up to 1300 MWe treated as single unit

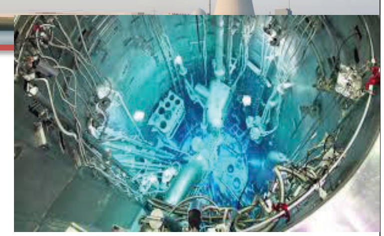
Primary nuclear liability insurance: $450M

+

Secondary retrospective insurance: $131M / reactor / incident

10

Requirements for Reactors with Rated Capacity <100 MWe



- Maintain primary insurance as required by NRC
  - Required amount ranges from $1-$74M, depending on capacity or established by a formula
  - Requirement does not apply to non-profit university reactors
- No secondary retrospective premiums are required
- Government indemnification required where licensee maintains financial protection of less than $560M
  - Maximum amount of indemnification is $500M; amount reduced by the amount licensee's financial protection exceeds $60M
  - Indemnity in excess of $250M available for non-profit university reactors

Primary nuclear liability insurance: $1-74M

+

NRC indemnification

11

Leasing Model and Liability

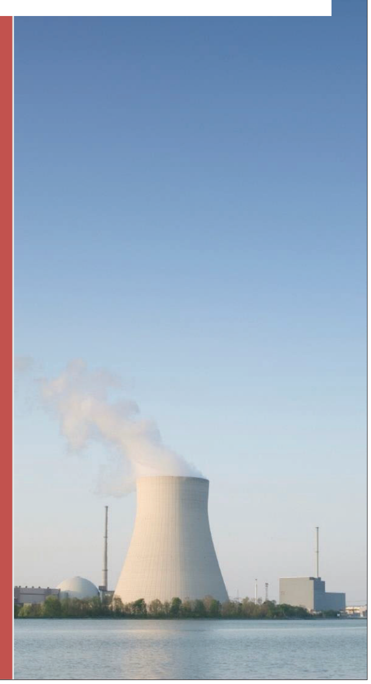
- Operating lease model fully compatible with Price Anderson framework
  - Owner holds insurance policies, lessor covered under the policies, lessor has no control over facility or owner
- Capital lease model would require discussion with NRC
- Some industry recommendations:
  - Threshold for requiring maximum primary financial protection and participation in the secondary financial protection program (100 MWe too low)
  - Changing the existing 300 MWe threshold for treating a combination of facilities as a single facility for financial protection purposes;
  - Developing variable requirements for primary and/or retrospective premiums (e.g., a sliding scale for reactors with output between 100 MWe and 500 MWe)
  - Creating new thresholds for non-electricity generating reactors; and
  - Changing the amount of property insurance required under 10 CFR 50.54(w).

Conclusions

- Leasing models widely used in the energy sector
- NRC precedent for treatment of financial transactions
- Leasing models need to be developed with input from regulators and financial community
- Licensing presents the biggest challenge
- Liability framework works with leasing model, but financial requirements should be better adapted to nuclear batteries

QUESTIONS?

Thank you for your attention



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AF&PA's Energy Profile

January 27, 2020

Workshop: Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems

BETTER PRACTICES BETTER PLANET 2020
Continuing AF&PA's Commitment to Sustainability

Overview

- AF&PA
- Description of Industry
- Energy Profile Today
  - Energy Sources
  - Costs
  - Key Attributes
- Where Are We Going?
  - Industry Commitments/Trends
  - Technology Development
  - 2050

AF&PA's Mission

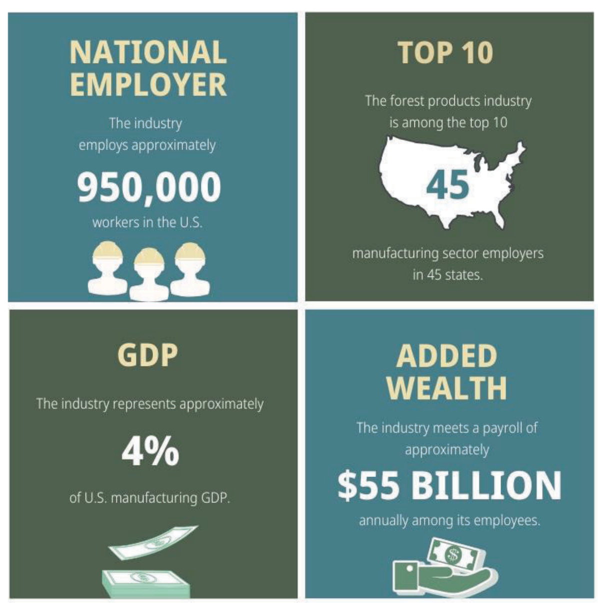
Advance a sustainable U.S. pulp, paper, packaging and wood products manufacturing industry through fact-based public policy and marketplace advocacy.

American Forest & Paper Association

Our Industry Supports Nearly One Million Jobs Nationwide

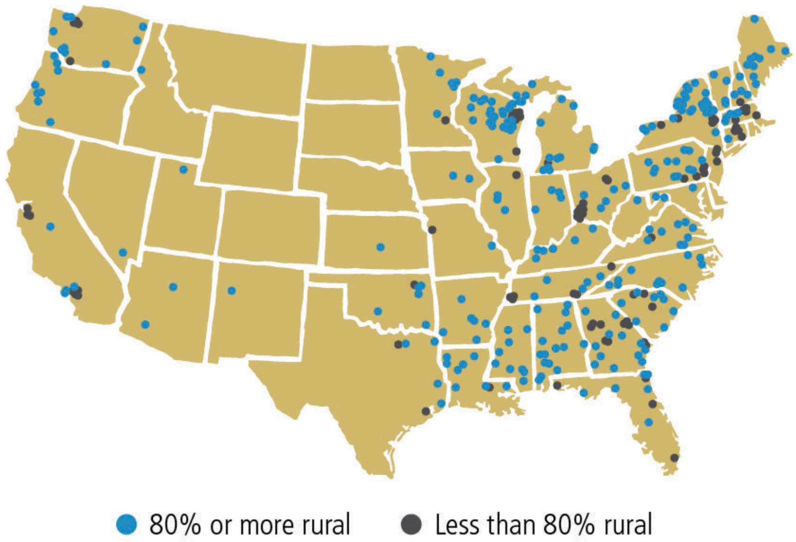
WE ARE AMERICAN
MANUFACTURING JOBS

Forest products manufacturers are an important source of year-round, well-paying jobs in many rural American communities and often serve as economic-development engines for entire regions. Given the industry's size, the economic vitality of forest products companies is essential to these local communities and regions, as well as to the nation's manufacturing base and overall economy.



American Forest & Paper Association

More Than 75 Percent Of All U.S. Pulp And Paper Mills Are Located In Rural Counties



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U.S. Forest Products Industry

6

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Typical Pulp and Paper Mill

7

In the Mill

PCA's Wallula mill in Washington state and Greif's Riverville mill in Virginia.
Photo Credit: AF&PA

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Data Sources

- AF&PA—For members in 2018
- U.S. Government—As indicated

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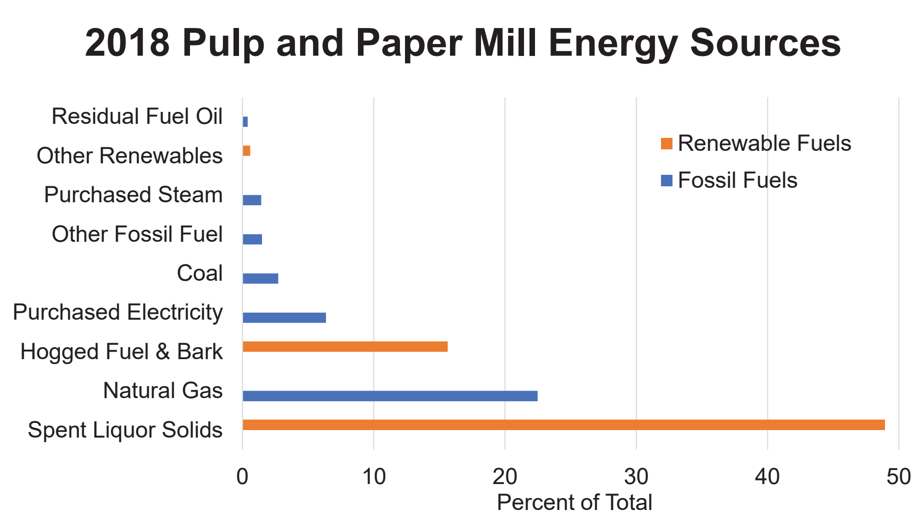
Pulp and Paper Mill Energy Sources—AF&PA Members

Meet About 2/3 of Overall Energy Demand with Carbon Neutral Biomass



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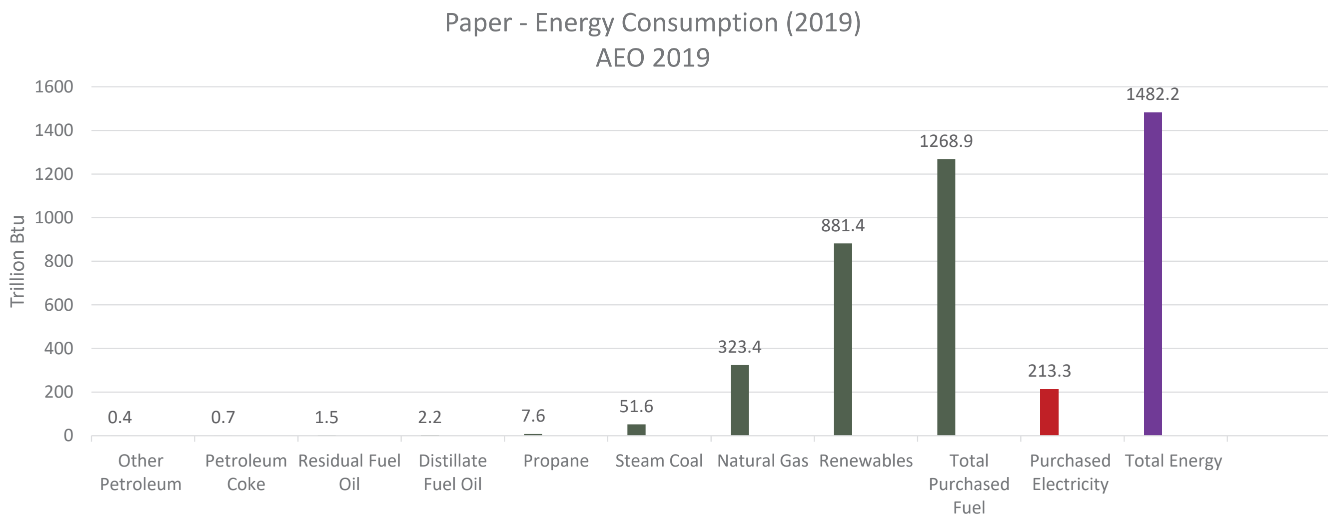
Paper Industry Energy Consumption



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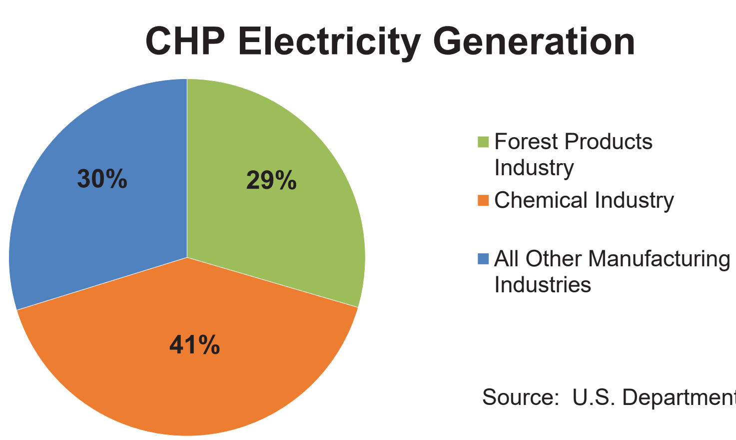
Combined Heat & Power (CHP) Electricity Generation

98.9% of electricity produced in 2018 by the paper and wood products industry was generated using CHP technology

29% of industrial CHP was generated by the paper and wood products industry



Source: U.S. Department of Energy

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AF&PA Member CHP Capacity

- About 300 units (note one facility can have more than one generator).
- Range: from less than 1 MW to about 90MW
- Median: 22 MW
- Average: 26 MW

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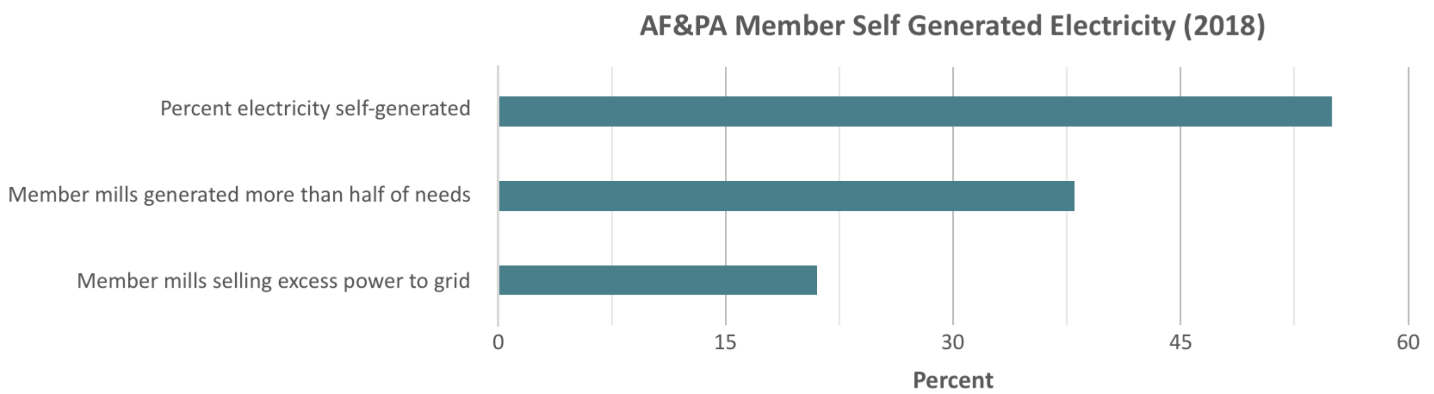
CHP Benefits

- Power is byproduct for industrial CHP; main product for other QFs
- Integral to pulp and paper manufacturing
- CHP provides benefits to society through higher efficiency, lower emissions, resilience, transmission relief (distributed generation), more competitive manufacturing and jobs

American Forest & Paper Association

AF&PA Pulp And Paper Mills Self-generated 55% Of Electricity Needed To Power Mills In 2018



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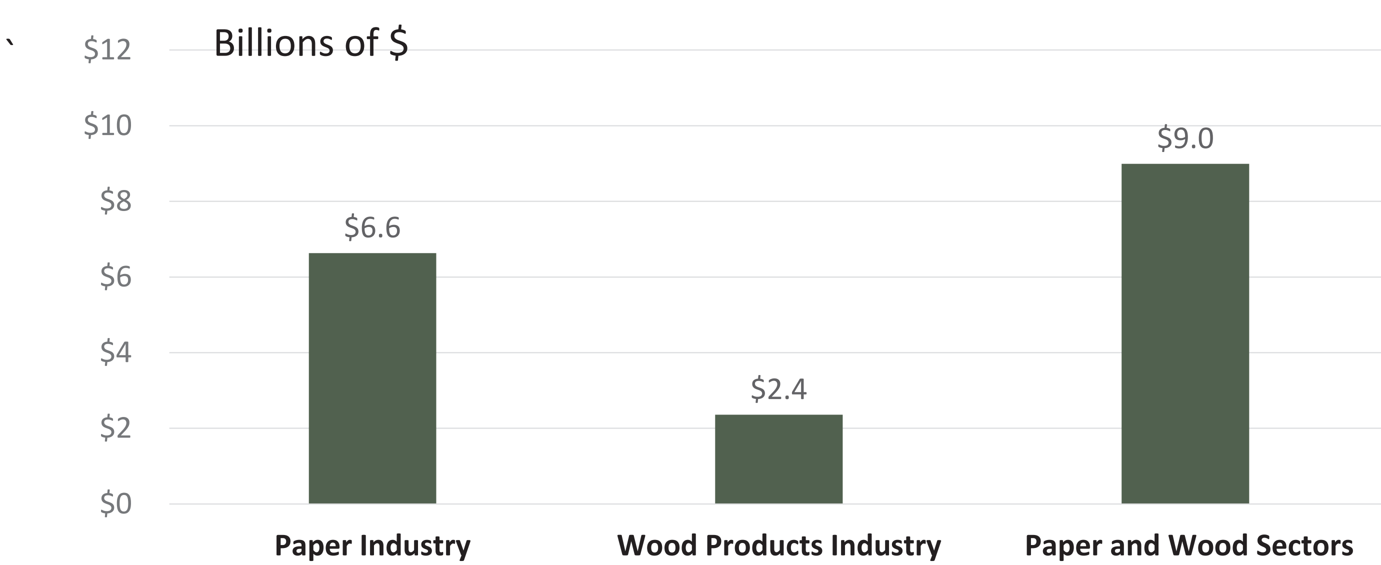
Annual Energy Expenditures - 2018



Source: Annual Survey of Manufactures

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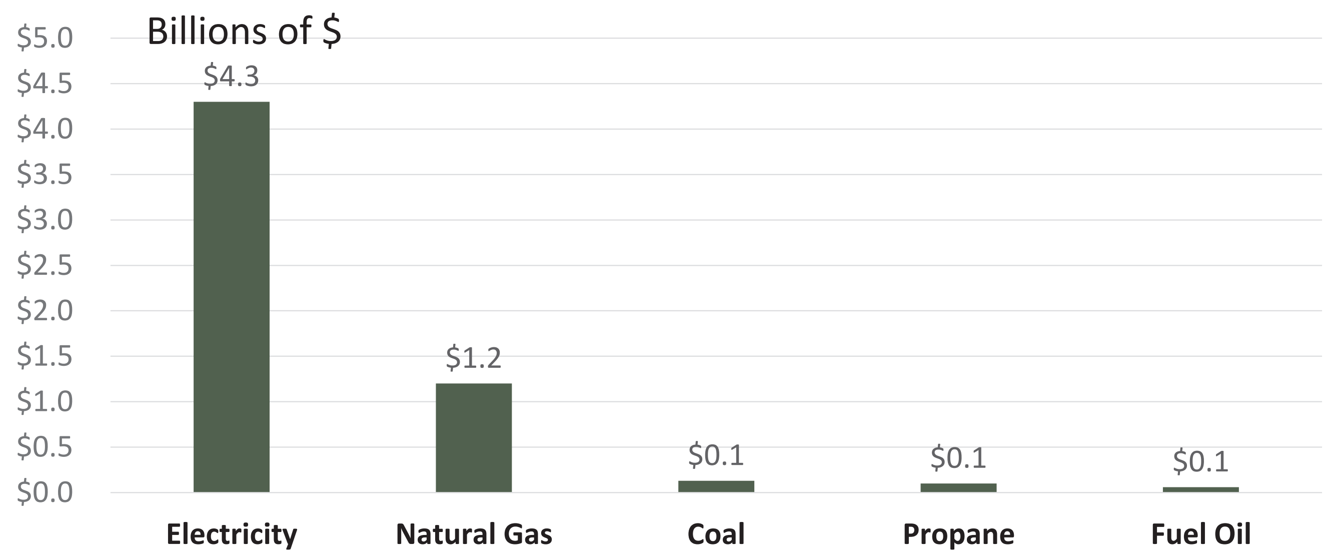
Paper Industry Energy Expenditures by Category



Source: Estimated based on 2019 Energy Information Administration data

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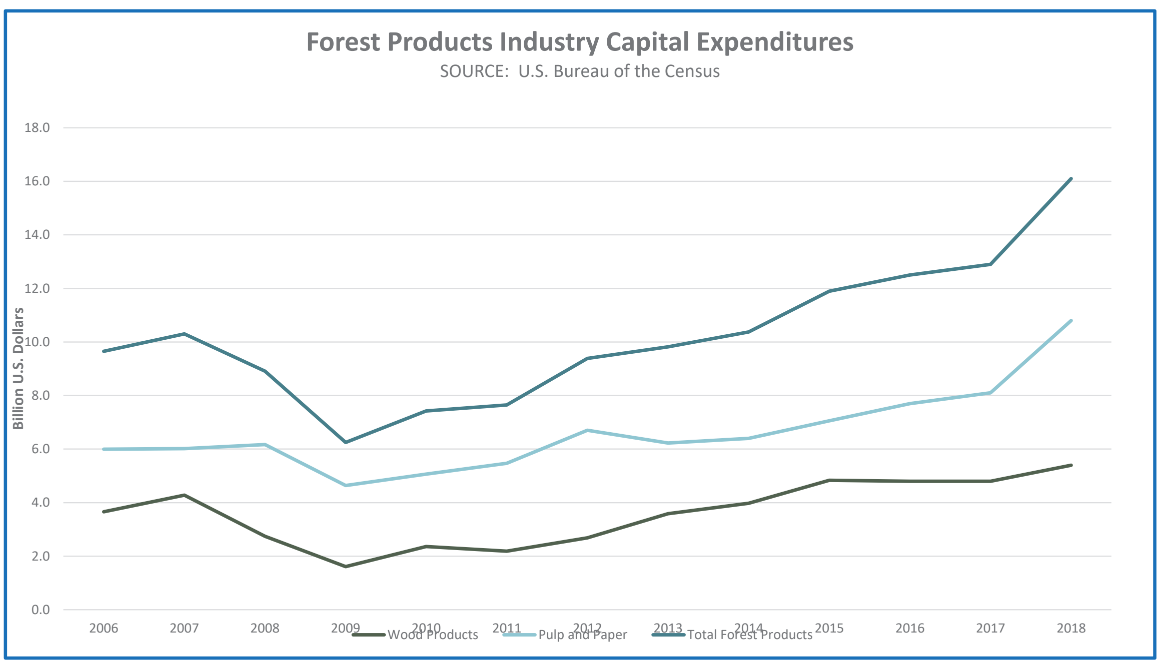
Economics-Capital Expenditures



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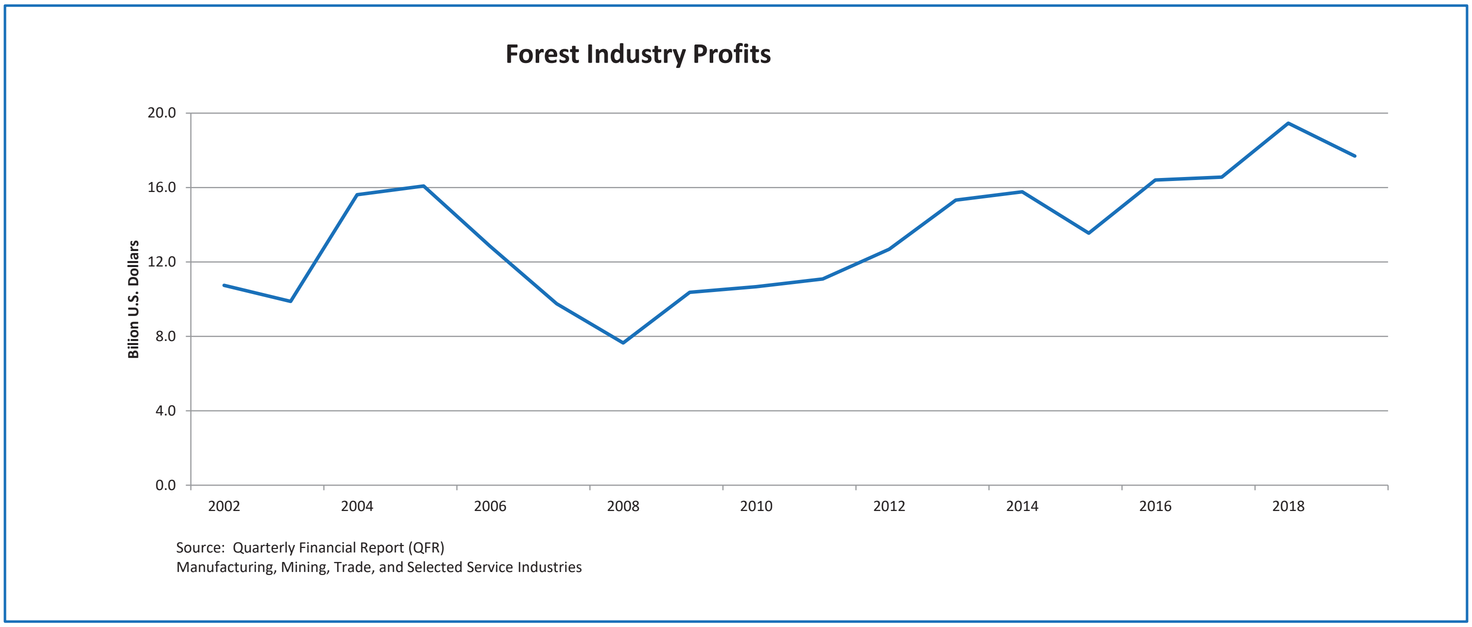
Economics-Profits



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Industry Needs v Initiative Key Attributes

- Economic
- Standardized
- Installed
- Unattended
- Reliable

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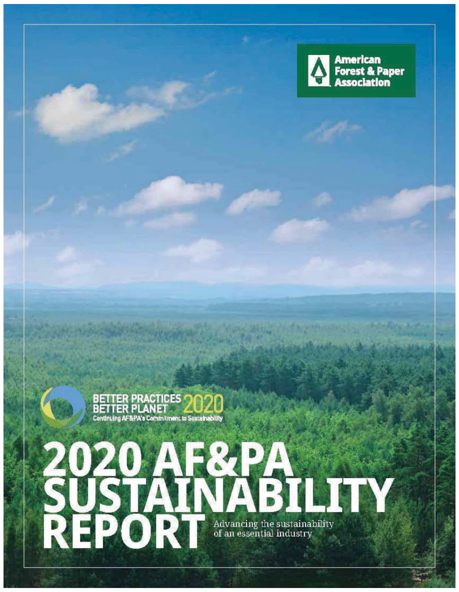
Better Practices, Better Planet 2020



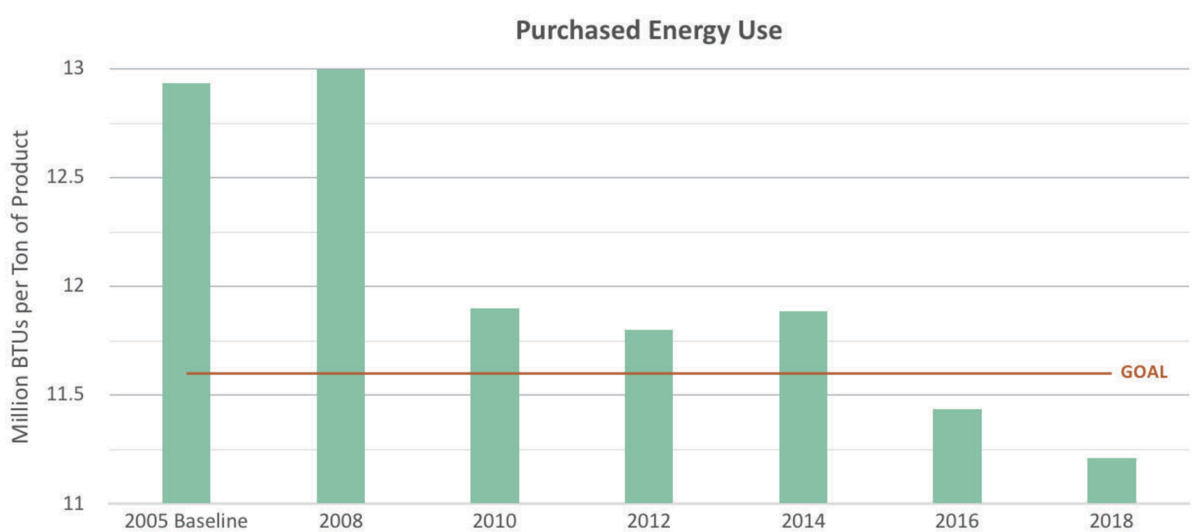
PROGRESS BY THE NUMBERS

AF&PA Sustainability Goal	2018 Performance*	Baseline (2005*)	Progress from baseline year
Improve safety incidence rate by 25%, while working to achieve zero injuries	1.617 recordable cases per 200,000 hours worked	2.625 recordable cases per 200,000 hours worked (2006)	38.4% improvement in recordable incidence rate GOAL SURPASSED
Increase wood fiber procurement from certified forestlands and certified fiber sourcing programs; decrease illegal logging	99% from certified fiber sourcing programs; 28.1% from certified forestlands	87% from certified fiber sourcing programs; 23% from certified forestlands	12 percentage point improvement from certified sourcing programs; 5.1 percentage point improvement from certified forestlands GOAL ACHIEVED
Improve purchased energy efficiency by at least 10%	11.21 million BTUs per ton of product	12.94 million BTUs per ton of product	13.3% decrease in purchased energy GOAL SURPASSED
Reduce greenhouse gas emissions by at least 20%	0.636 ton CO_2eq per ton of product	0.828 ton CO_2eq per ton of product	23.2% decrease in GHG emissions GOAL SURPASSED
Reduce pulp and paper mill water use by at least 12%	10,503 gallons per ton of product	11,281 gallons per ton of product	6.9% reduction in water use
Exceed 70% paper recovery for recycling	66.2% (2019)	51.5%	14.7 percentage point increase in paper recycling rate

* unless otherwise indicated

American Forest & Paper Association

Energy Efficiency: 13.3% decrease in purchased energy (Goal Surpassed)



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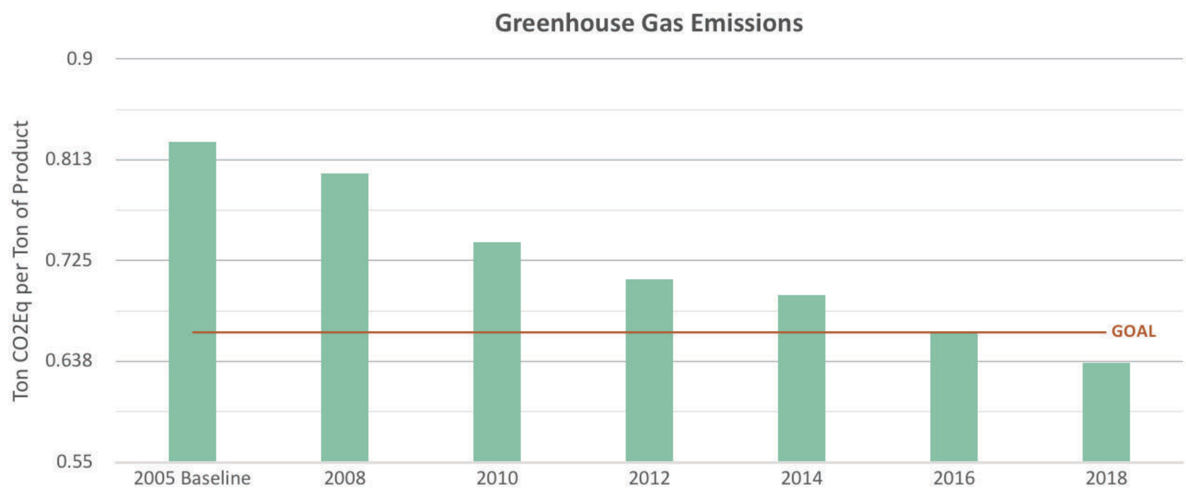
Greenhouse Gas Emissions: 23.2% reduction (Goal Surpassed)



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Alliance for Pulp & Paper Technology Innovation

Mission:

- Promote development of advanced manufacturing technologies for the pulp and paper industry and platforms to enable new revenue streams from forest-based biomass

Identify	*Communicate*	*Deliver*
• Technology needs • R&D priorities	• Funding entities • Solution providers	• Projects • Partnerships

appti

Transforming Manufacturing Through Innovation

American Forest & Paper Association

Next-Generation Pulping

Goal **Reduce total energy 25%. Increase yield 5 percentage points.**

Value $900 MM, Energy 70 trillion BTU
($6MM/yr 1000 tpd mill)

Black Liquor Concentration

Goal **Develop a more energy-efficient method to remove water from kraft black liquor**

Value $95 MM, 23 trillion BTU
($2-3 MM per year for a 2,000 tpd mill)

Drier Web before Dryer Section

Goal **Increase dryness of paper webs entering dryer section by ~ 30%** ***(from 45-55% up to 65%)***

Value $250 MM, 80 TBTU

appti

Transforming Manufacturing Through Innovation

American Forest & Paper Association

Reuse of Process Effluents

Goal **Reduce average water usage by half**

Value ~ 5K gal/ton, >$300MM, 45 TBTU, 480B Gal

appti

Transforming Manufacturing Through Innovation

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2050—Industrial Decarbonization

2030 Goals

2050?

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BETTER PRACTICES BETTER PLANET 2020
Continuing AF&PA's Commitment to Sustainability

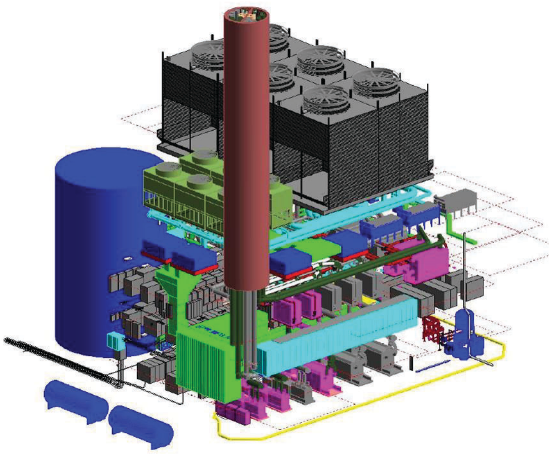
BUSINESS MODELS, FINANCING MODELS

JOHN PARSONS
January 27, 2021
Fission Battery Initiative Workshop, INL

WHO WILL BUY A NUCLEAR BATTERY?

CAN MULTIPLE USERS SHARE AN ASSET?

Harvard's New District Energy Facility

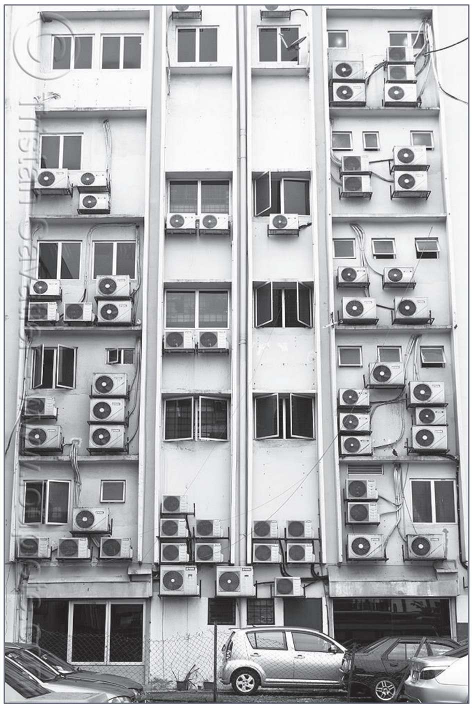


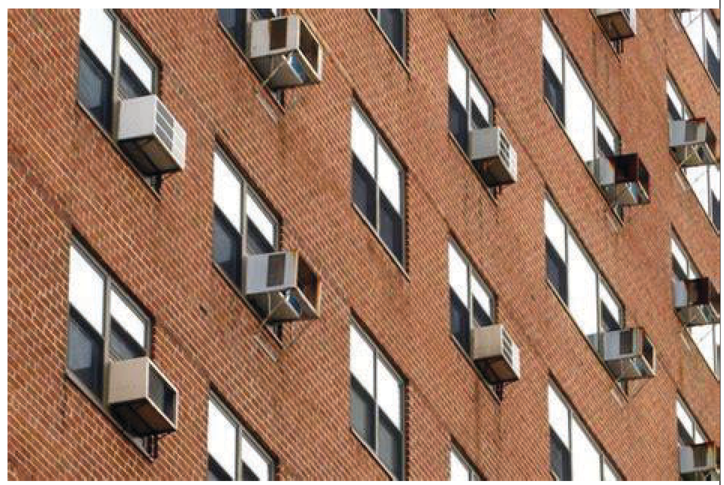
City of Boston – Major Parcel Development

7 years ago, new district heating systems were a part of Boston's climate plan.

No longer. Fear of stranded NG asset.
But also…developer opposition to central sys.

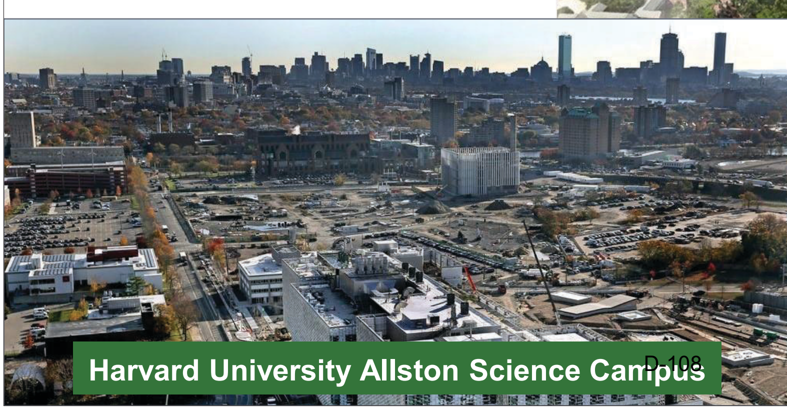
Central AC is More Efficient, but…





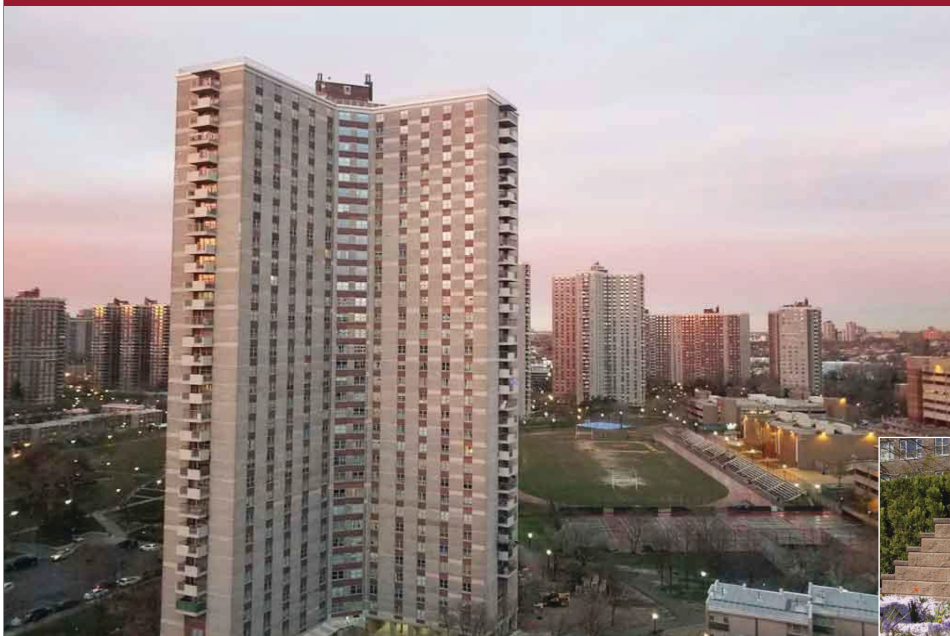
Why is One a Campus and Not the Other?

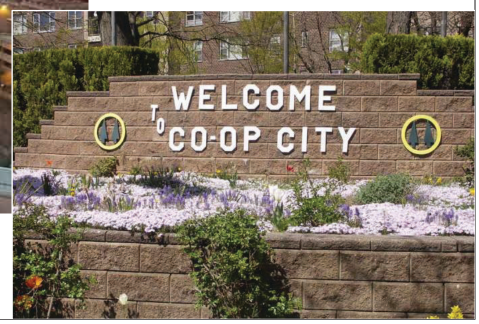
It's not because one is a university.



Boston has a medical campus with a district heating system.

On the other hand…





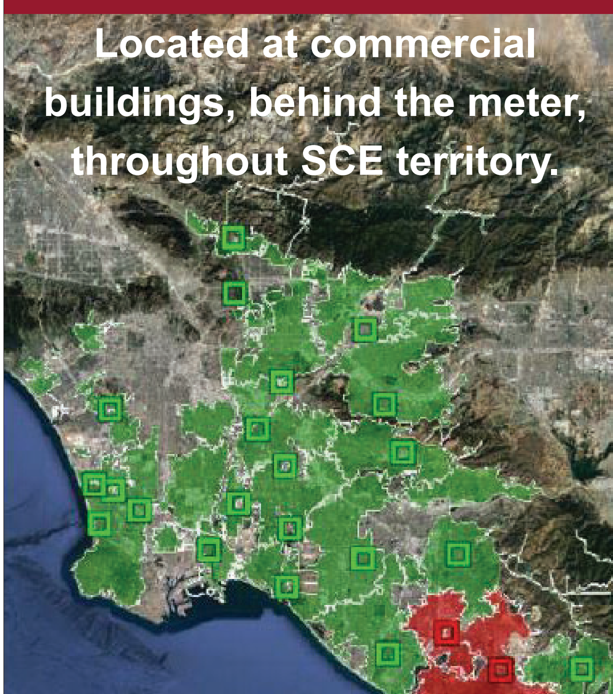
OWNERSHIP AND FINANCING ARE ADAPTABLE TO OPERATIONAL CONTEXT

Project Financing: Carlsbad Desalination Plant

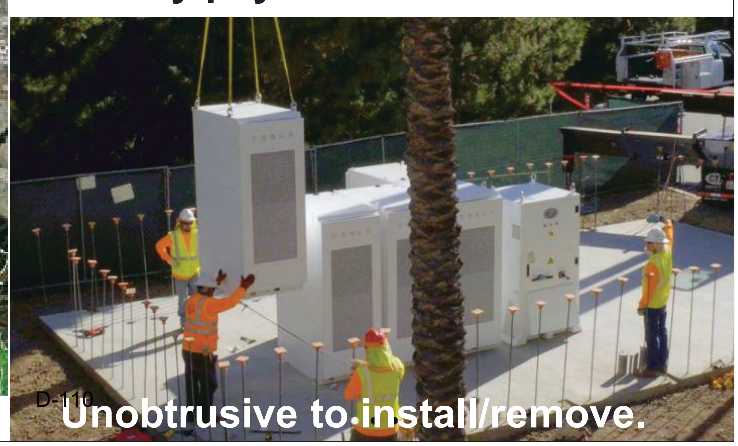
- $1 billion investment
- 82% debt financed
- County water authority pays for the plant on an installment plan

- The asset is dedicated and cannot be repurposed.

Ownership is Flexible: Battery Installations



- Owned by special purpose entity--financier.
- Managed by specialist company.
- Hosted by building owner.
- Utility pays a fee.



THANK YOU