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Integrated Nuclear-Renewable Hybrid Energy Systems: Current Energy Market Status Report

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Richard D. Boardman
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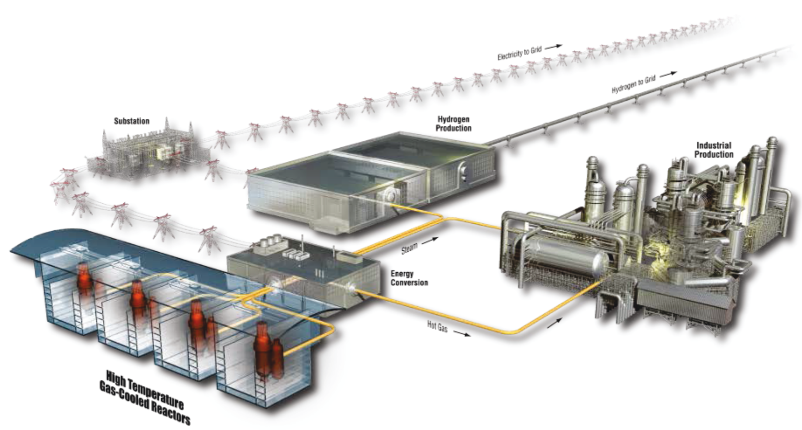
June 2015



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ABSTRACT

In the present work, a study is conducted on the economic market available to Integrated Nuclear-Renewable Hybrid Energy Systems (HES). Specifically, the markets available for the integrated industrial manufacturing plant are presented and discussed for near-term and far-term applications. The purpose of this work is to allow HES researchers to fully understand this secondary product market (the primary HES product is assumed to be electricity) and to provide recommendations for future research direction.

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ACRONYMS

HES	Integrated Nuclear-Renewable Hybrid Energy System
LPG	Liquefied Petroleum Gases
LWR	Light Water Reactor
MECS	Manufacturing Energy Consumption Survey
NGL	Natural Gas Liquids
NRC	Nuclear Regulatory Commission
SMR	Small Modular Reactor

Integrated Nuclear-Renewable Hybrid Energy Systems: Current Energy Market Status Report

1. Introduction and Problem Definition

In order to properly create a program surrounding the development of any technological concept it is necessary to fully understand the market for which it is being developed. In the case of Integrated Nuclear-Renewable Hybrid Energy Systems (HES), there are two economic markets in which it must be able to participate: the electricity market and the secondary product market associated with the specific system. This report focuses on characterizing the secondary product markets in the U.S. and provides recommendations for further developing the HES program.

While HESs have been discussed in depth in other reports, it is helpful to discuss them briefly relative to the present work [1]. The HES is simply defined as a system that features integration of a nuclear power plant, a renewable energy source, and an industrial manufacturing plant. The system is designed in a fashion that allows it to either produce electricity to meet grid demand or to apportion energy (thermal and/or electric) to manufacture a secondary product as needed. The primary benefit of this concept lies in its ability to maximize economic performance of the integrated system and to manufacture products in a carbon-free manner. A secondary benefit is the enhanced supply-side flexibility gained by allowing the HES to economically provide grid services.

A key tenet to nuclear power plant economics in today's electricity market is their ability to operate at a very high capacity factor. Unfortunately, in regions with a high penetration of renewable energy, the carbon-free energy produced by nuclear power may not be needed at all times. This forces the nuclear power plant either reduce power or to find a user for its excess capacity. This may include paying the electric grid to find a user, releasing energy to the environment, or reducing thermal power. If the plant is unable to economically or safely do any of these actions, the plant is at risk of being shut down permanently. In order to allow nuclear power plants to continue to contribute carbon-free electricity to the grid in a future with high renewable energy penetration, HESs would divert excess capacity to a chemical process. Additionally, if a currently operating manufacturing plant was modified to be an HES component, then the products would now be produced with reduced emission of carbon and other greenhouse gases.

There are several key economic barriers that must be surmounted for HESs to be developed. Two primary barriers are the increased capital cost associated with coupling and controlling the HES components and the opportunity cost associated with decreased utilization of the manufacturing plant if operated in a variable manner [a] . Because of this, manufacturing plants that are less complex and have smaller non-variable operations and capital costs may be more attractive for integration. A secondary economic barrier for the HES is the market availability for its products. The system must operate in a region where there is either an intermittent demand for its electricity, an intermittent demand for its secondary product, or both. In a region with an intermittent demand, product prices should shift accordingly, making it less attractive to produce one of the products. The HES then can shift production in order to maximize profit. Without an intermittent demand for at least one of its products, there would be little need to expend the extra capital required for integration as an HES.

Other barriers to the construction of HES include regulatory challenges associated with nuclear power plants providing heat and challenges associated with complex integration of manufacturing processes [2]. If the HES is functioning as reserve capacity for the grid, it is particularly important the manufacturing

[a] This may not be an issue if an auxiliary heat source is included to supply energy to the manufacturing plant when the nuclear plant is sending electricity to the grid. This could be a heat storage system or fossil fuel source.

plant be capable of changing operational load during a short period of time. If it is able to vary load on the order of seconds, it may be able to provide regulatory response for the electric grid [3]. If the HES is designed to provide carbon-free electricity to the grid in a 'day-ahead' fashion, then the nuclear plant must be scaled accordingly to support the integrated renewable energy farm. This allows the system to load-follow as required while producing the requested amount of electricity for the grid. Additionally, if the HES is designed to prevent the nuclear plant from needing to significantly reduce its power output (via reactor control maneuvers or turbine bypass), then the manufacturing plant must be scaled accordingly to absorb all excess capacity. This may make large scale manufacturing plants (hundreds of MWth power usage) more attractive for integration.

Economic benefits are anticipated for HESs. The two primary benefits include the hedge against future natural gas prices for the electric grid and manufacturing plant, and any future incentives that could be offered by the government for the systems environmental friendliness. In order for the successful implementation of HESs nationwide, these economic benefits will need to outweigh the aforementioned barriers.

2. Secondary Product Market Analysis

As discussed in the introduction, one of the main purposes of the manufacturing plant component in the HES is to absorb excess capacity from the nuclear plant when it is not supplying energy to the grid. While the scale of the plant itself is important, the scale of the secondary market energy usage is more important, as it directly correlates to the amount of capacity it is capable of absorbing for the electric grid. In this section, the power usages of different manufactured products are compared, along with their relative impact within U.S. regions.

2.1 Selection of Near-Term Secondary Products

In the near-term, it is important for the manufacturing plant to be easily integrated with a nuclear power plant without significant modification to the design or operation of either plant. For the first developed HESs, one preference may be that at least one of the HES components is already in place and that a local infrastructure is available to transport the secondary product to market. Additionally, there should be a suitable climate for the selected renewable energy component.

The secondary products considered in the present work were selected based on their integration potential. To provide a good starting point, data was compiled from the 2010 Manufacturing Energy Consumption Study (MECS) and the listed subindustries were ranked according to their Net Demand for Electricity [4]. This method of selection is summarized below:

- Focus on particular subindustries versus larger collective industries allows an emphasis on particular plant types.
- Subindustries are ranked solely by their average yearly **electric** power requirement to identify which industries would be capable of integrating with a near-term HES. In the near-term, it is assumed that plants could be integrated by electricity only, allowing currently built manufacturing plants and nuclear power plants to take advantage of integration with minimal capital expense. Additionally, there are currently no operating nuclear power plants in the United States that are capable of providing steam to adjacent manufacturing plants, and the regulatory structure that would allow this operation is currently not in place. It is assumed that currently operating nuclear plants will not undergo system modification to allow the direct sharing of heat with a manufacturing plant.

The results of this ranking are shown in Figure 1. Within Figure 1, the fraction of electricity that is generated onsite is called out in order to further advise which subindustries may be more interested in integrating with an HES. If a subindustry produces a large fraction of their energy onsite, they are most likely doing so to take advantage of a particular byproduct of the process. Of the industries and subindustries studies in the 2010 MECS, industries with larger than 2000 MW total electricity usage were selected for study.

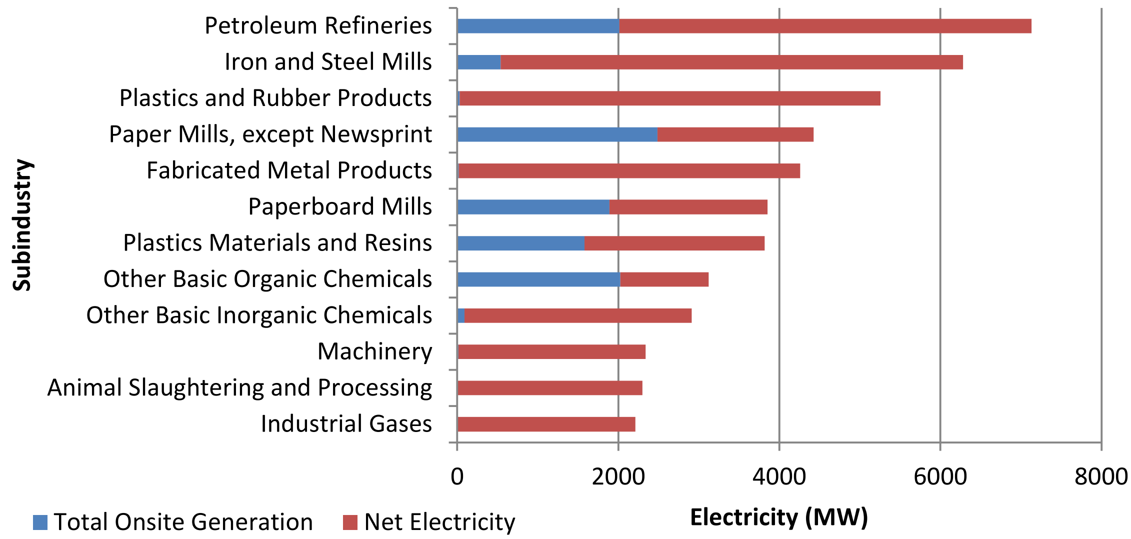

Figure 1. Manufacturing subindustries with greater than 2000 MW total electricity demand.

Using further data from the 2010 MECS, it is possible to show the total power requirement for each selected subindustry. This is shown in Figure 2, which depicts net electricity as a small component of the total energy requirement of most subindustries. The data is shown in units of average power rather than total energy per year in order to allow easier comparison to excess power plant capacity integrated with these subindustries in HESs. The energy requirements shown in Figure 2 are used only for the manufacturing process and do not include energy sources consumed as manufacturing feedstock.

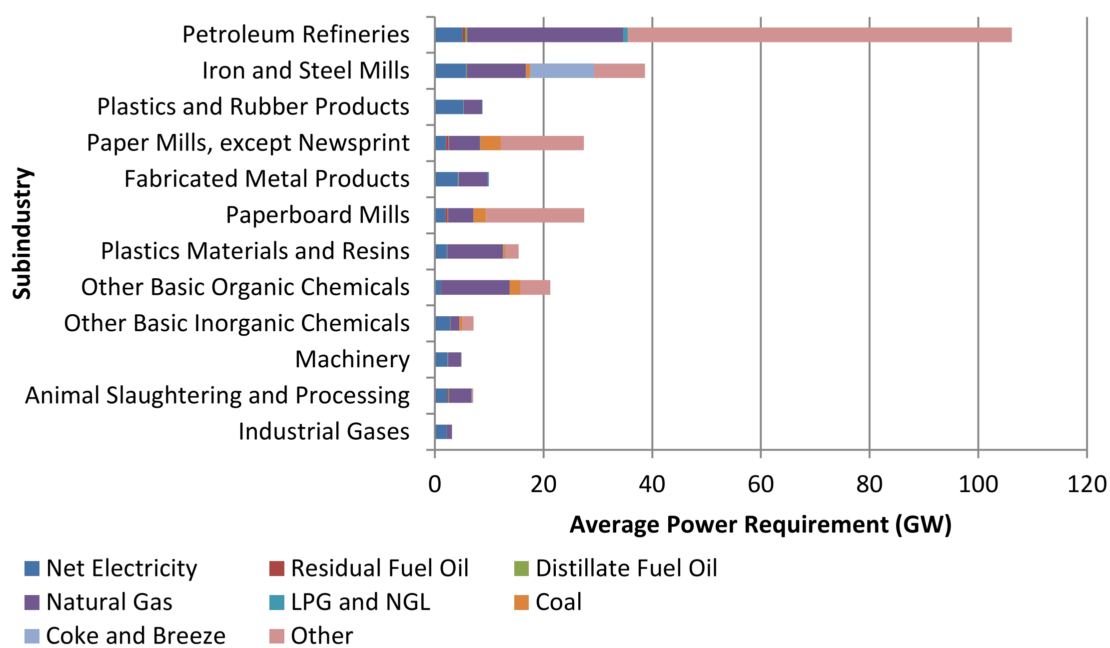

Figure 2. Reorganization of manufacturing subindustries to show total external energy requirements and their component sources.

It is also possible to depict this data in a way that shows the fraction of each power component. This is depicted in Figure 3.

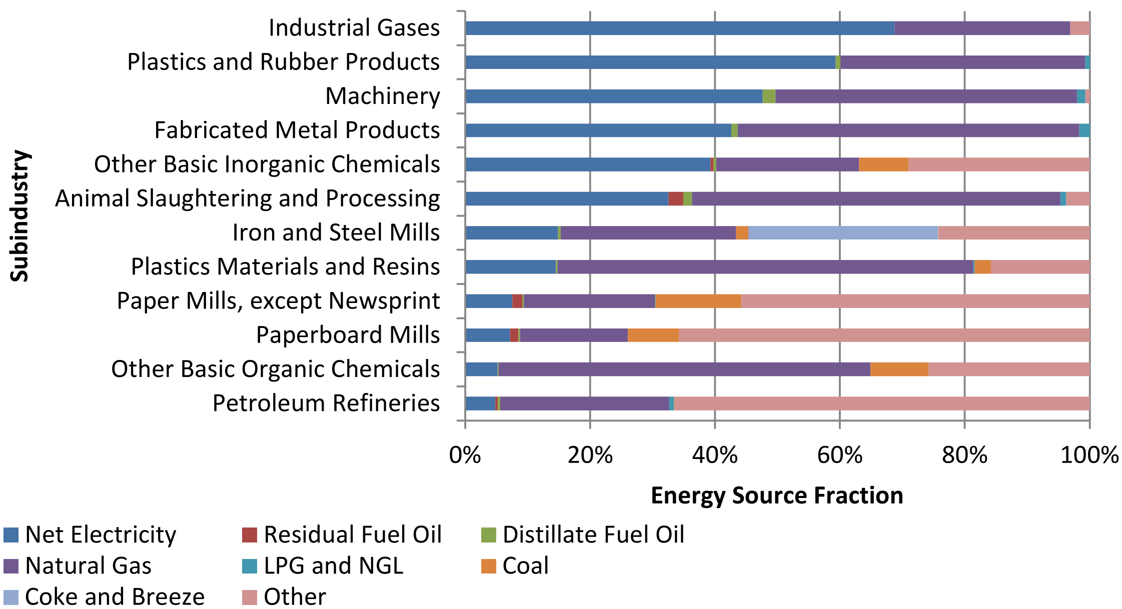

Figure 3. Reorganization of manufacturing subindustries to show fraction of each energy component source used.

By examining Figure 3, we can see that several of the selected subindustries look more attractive for integration with an HES by electricity only. Subindustries with a larger fraction of their energy through off-site electricity purchases (denoted as 'Net Electricity' in Figure 3) will attribute a larger fraction of their variable cost to electricity, increasing their potential for cost savings due to integration with an HES. This cost savings attributed to a reduced variable cost of electricity is crucial to the economic performance of the HES. Since its primary purpose is to absorb the excess capacity from the nuclear plant, it must function independent from the electric grid, varying its output accordingly or producing its own electricity when needed to maintain a constant output. While this may seem excessively complex, it may be what is required to maintain continued operation of the current fleet of nuclear reactors in the presence of a changing electric market and increasing environmental concerns.

The particular subindustries called out from Figure 3 are 'Industrial Gases', 'Plastics and Rubber Products', 'Machinery', and 'Fabricated Metal Products'. Integration with an HES will provide decreased carbon and other greenhouse gas emissions by removing their electricity load from the electric grid and placing it either partially or completely on electricity from the nuclear plant, which provides carbon-free generation.

2.2 Selection of Far-Term Secondary Products

In the far-term, the options available for greenfield implementations of HESs expand greatly for a number of reasons. First and foremost, the option of nuclear power plants to consider sending steam and high-temperature process heat to an integrated manufacturing plant becomes available. Additionally, manufacturing plants that produce alternative fuels (e.g. hydrogen, methanol, syngas) may have a higher technical readiness and assuming its construction continues to be incentivized, the penetration of renewable energy in the local electric grid will be higher—increasing the need for 'load-following' electric plants [5].

In general, sharing of heat between a nuclear power plant and a manufacturing plant—direct thermal integration of the plants—will require a fairly significant modification of both systems with respect to today's plants. If the manufacturing plant requires heat in different locations and at different temperatures, the heat transfer system must be designed accordingly.

For current processes, we can use the data from the 2010 MECS to determine what industries use the most energy that could be replaced using process heat from HESs. Since the range of potential applications is much larger for deployment that could occur over a longer-term time span, we can start by looking at the broadest classification of subindustries as studied in the 2010 MECS. The energy requirements for these subindustries are depicted in Figure 4. Figure 4 shows that the potential energy needs that could be met by HES is quite large, provided the technical feasibility and economic incentives are present. The data is shown in units of average power rather than total energy per year in order to allow easier comparison to excess power plant capacity integrated with these subindustries in HESs. The energy requirements shown in Figure 4 are used only for the manufacturing process and do not include energy sources consumed as manufacturing feedstock.

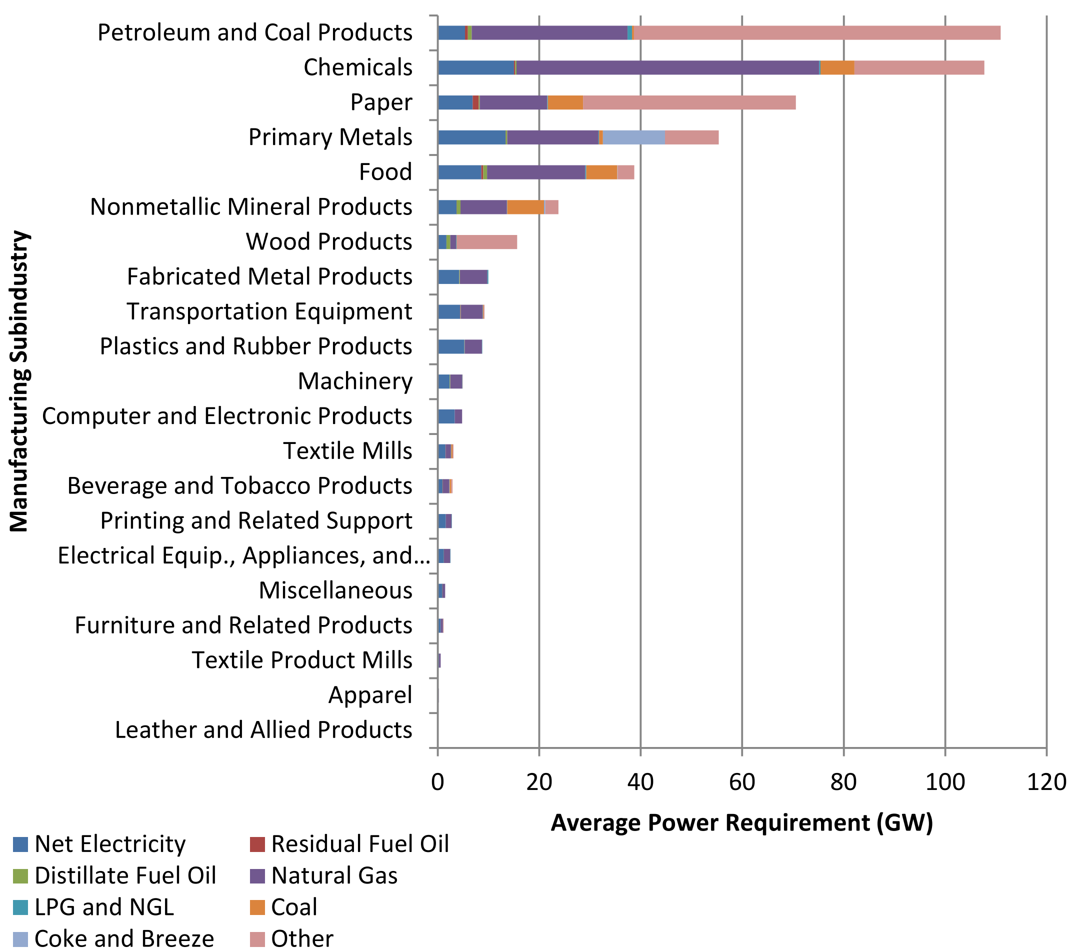

Figure 4. Total external energy requirements of all manufacturing subindustries and their component sources.

By narrowing down the list of subindustries, a chart similar to that depicted in Figure 2 can be created, with the primary difference being attributed to a ranking based on total energy requirement, versus only the Net Electricity component. This list of specific subindustries is depicted in Figure 5.

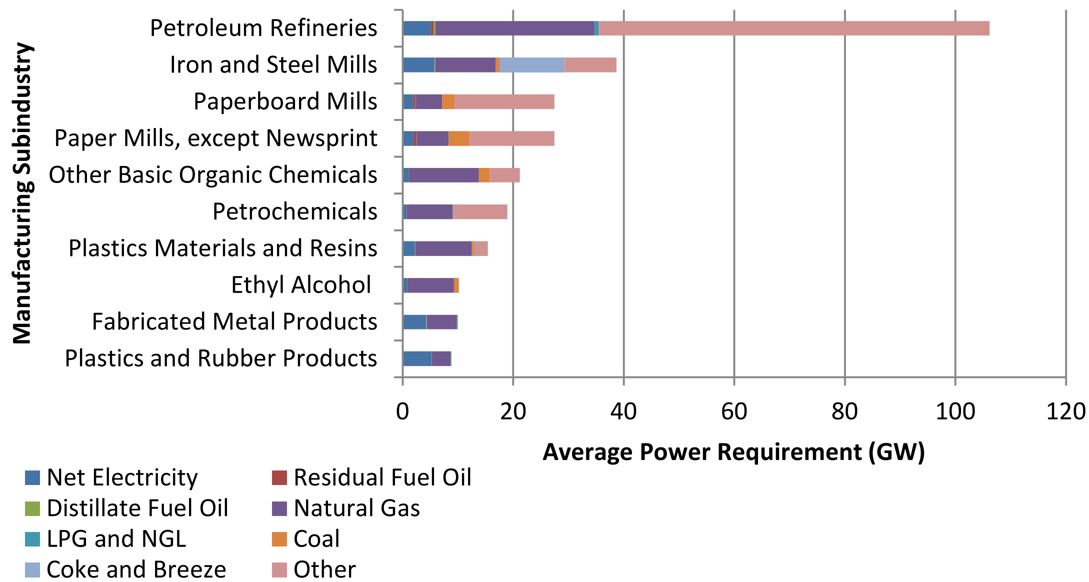

Figure 5. Total external energy requirements of a reduced list of manufacturing subindustries and their component sources.

Again, similar to Figure 3, the list of subindustries can be shown as a function of Energy Source Fraction. This is depicted in Figure 6 where the emphasis on Energy Source Fraction is placed on the fraction of natural gas sourced energy is required in the chemical process.

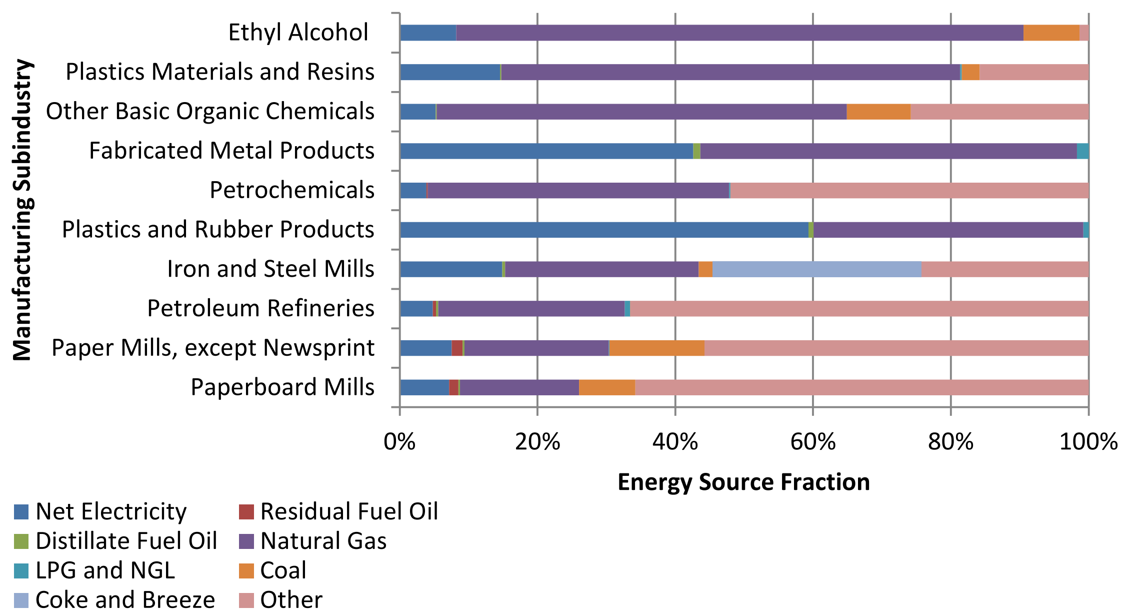

Figure 6. Reorganization of manufacturing subindustries to show fraction of each energy component used.

The reason for this method of listing is to call out subindustries that could allow for more economic integration in an HES. Processes that do not use natural gas for a large fraction of process heating energy are likely to do so for economic or technical reasons. In particular, manufacturing plants in the forestry products industry burn a byproduct, black liquor, for energy use. In the iron industry, coke is burned as a source of heat and carbon monoxide for the reduction of iron ore. In the petroleum industry, low-worth gases produced as byproducts are burned as a heat source. Because of the integral worth of these products to their specific manufacturing plant (relative to their worth in the market) replacing their use through nuclear-generated heat may be difficult.

The four particular subindustries that can be called out from Figure 6 are ‘Ethyl Alcohol’, ‘Plastics Materials and Resins’, ‘Other Basic Organic Materials’, and ‘Fabricated Metal Products’. Similar to the near-term secondary product subindustries selected in the previous subsection, integration of these with an HES will provide decreased emission of carbon and other greenhouse gases by removing or reducing the energy requirement of the plant on the energy market and placing it either partially or completely on energy from the nuclear plant.

2.3 Large Scale Integration in the United States

In order to understand the full impact that the previously selected subindustries will have on the electric grid through the use of HES, it is necessary to compare their energy usage with electricity usage statistics for different regions of the U.S. By obtaining data from the 2012 Economic Census, and combining it with data from the 2010 MECS, it is possible to estimate the electricity usage per state for each selected subindustry [6]. Specifically, the number of institutions listed for each industry in each state is listed in the 2012 Economic Census. This number was then used to weight the electricity usage data from each selected subindustry. Some error is introduced through the assumption that all plants in all states are the same plant size, but since this estimate is just being used to understand approximate trends, it is assumed to be acceptable. The calculated electricity usage for the selected subindustries can then be compared to the average retail electricity sales for each state, providing a perspective on their significance as regional electrical capacity sinks [7]. These estimates are provided in Table 1.

Table 1. Relative significance of four selected subindustries based on electricity requirements from Figure 3 in Section 2.1.

State/District	Average Retail Electricity Sales (GWe)	Industrial Gases Electricity Req. (GWe)	Plastics and Rubber Products Electricity Req. (GWe)	Machinery Electricity Req (GWe)	Fabricated Metal Products Electricity Req. (GWe)	Total of Selected Subindustries (GWe)	Fraction of State Average Retail Electricity Sales
New Hampshire	1.24	0.00	0.04	0.02	0.03	0.08	6.60%
Connecticut	3.37	0.01	0.07	0.04	0.09	0.21	6.36%
Michigan	11.96	0.04	0.26	0.20	0.23	0.73	6.09%
Rhode Island	0.88	0.00	0.02	0.01	0.02	0.05	6.06%
Wisconsin	7.85	0.03	0.18	0.10	0.15	0.46	5.86%
Ohio	17.39	0.11	0.38	0.16	0.27	0.92	5.31%
California	29.61	0.23	0.57	0.23	0.50	1.54	5.19%
Minnesota	7.76	0.03	0.14	0.08	0.11	0.37	4.71%
Massachusetts	6.31	0.03	0.12	0.05	0.10	0.29	4.66%
New Jersey	8.58	0.08	0.16	0.06	0.09	0.39	4.57%
Illinois	16.38	0.07	0.27	0.15	0.24	0.74	4.51%
Utah	3.39	0.02	0.06	0.02	0.04	0.15	4.39%
Indiana	12.00	0.08	0.21	0.08	0.13	0.51	4.21%
Pennsylvania	16.51	0.09	0.25	0.12	0.22	0.69	4.16%

Vermont	0.63	0.00	0.01	0.01	0.01	0.03	4.09%
Oregon	5.33	0.04	0.07	0.03	0.07	0.21	4.04%
Maine	1.32	0.00	0.02	0.01	0.02	0.05	3.86%
Kansas	4.60	0.04	0.06	0.03	0.04	0.18	3.83%
Iowa	5.22	0.03	0.06	0.04	0.05	0.18	3.54%
New York	16.33	0.06	0.21	0.09	0.18	0.54	3.30%
Idaho	2.71	0.03	0.02	0.01	0.02	0.09	3.22%
Oklahoma	6.77	0.04	0.06	0.04	0.07	0.21	3.15%
Nebraska	3.52	0.03	0.03	0.02	0.02	0.11	3.07%
Colorado	6.12	0.02	0.07	0.03	0.06	0.19	3.07%
South Dakota	1.34	0.00	0.02	0.01	0.01	0.04	3.07%
Delaware	1.31	0.01	0.02	0.00	0.01	0.04	3.02%
Tennessee	11.00	0.05	0.13	0.04	0.08	0.31	2.81%
Missouri	9.40	0.02	0.11	0.05	0.08	0.26	2.76%
West Virginia	3.51	0.04	0.02	0.01	0.02	0.10	2.73%
Mississippi	5.52	0.05	0.05	0.01	0.03	0.15	2.65%
North Carolina	14.61	0.04	0.18	0.06	0.10	0.38	2.63%
Washington	10.54	0.05	0.09	0.04	0.09	0.27	2.55%
Texas	41.69	0.24	0.32	0.16	0.33	1.05	2.52%
Alabama	9.83	0.07	0.07	0.03	0.07	0.24	2.41%
Louisiana	9.67	0.10	0.04	0.02	0.06	0.23	2.35%
Arkansas	5.35	0.01	0.05	0.02	0.04	0.12	2.30%
South Carolina	8.87	0.03	0.08	0.03	0.06	0.19	2.18%
Georgia	14.94	0.05	0.15	0.04	0.08	0.33	2.18%
Arizona	8.56	0.02	0.07	0.03	0.07	0.18	2.11%
Kentucky	10.16	0.04	0.08	0.03	0.05	0.20	1.96%
Florida	25.17	0.06	0.20	0.08	0.13	0.48	1.90%
Montana	1.58	0.00	0.01	0.01	0.01	0.03	1.79%
Wyoming	1.94	0.02	0.00	0.00	0.01	0.03	1.78%
North Dakota	1.68	0.00	0.01	0.01	0.01	0.03	1.74%
Virginia	12.30	0.05	0.07	0.03	0.06	0.20	1.64%
Nevada	4.01	0.00	0.03	0.01	0.02	0.06	1.62%
Maryland	7.05	0.02	0.04	0.01	0.03	0.11	1.61%
Alaska	0.73	0.00	0.01	0.00	0.00	0.01	1.51%
New Mexico	2.64	0.00	0.01	0.01	0.02	0.04	1.44%
Hawaii	1.10	0.00	0.01	0.00	0.00	0.01	1.02%
District of Columbia	1.28	0.00	0.00	0.00	0.00	0.00	0.03%

To emphasize the comparison of different values for each state, color fills were added to each column to show which states have the highest relative value of that particular column. In each column, darker color fills show higher relative values than lighter color fills. Examining Table 1, several key points stand out:

- The total electricity usage of the selected subindustries does not exceed 7% when compared to electricity usage of any state or district. Because of this, electricity-only integration of these four selected subindustries within an HES likely will not make a significant impact by absorbing excess capacity on the electricity market. Complete integration with heat sharing or energy transfer through other means will be required to displace more electrical capacity.

- Since the primary purpose of the selected subindustries from Section 2.1 is to absorb excess capacity from current nuclear plants, it is possible that electric-only integration with HES, particularly in the Northeast region of the U.S., may be attractive. However, it is unlikely that the size of any one manufacturing plant will be of a large enough scale to absorb all of the excess capacity from a single plant. Additionally, if the manufacturing plant must operate at full capacity to justify economical operation, energy storage will be needed to provide electricity when the nuclear plant is providing electricity for the grid.

- The four subindustries selected based on electricity requirement as shown in Figure 3 appear to be attractive for integration in an electric-only HES and were among the top electricity using subindustries studied in the 2010 MECS. It is important to note that the list tallied in Table 1is not inclusive of all possible manufacturing plants that could be integrated in an HES.

Next, using the four subindustries of interest selected from Figure 6 in Section 2.2, it is possible to conduct the same analysis shown in Table 1 for far-term integration in an HES, which would include direct thermal integration of the nuclear and manufacturing plants. Since the combined thermal energy usage will be compared to electricity usage, an assumption for conversion between thermal energy and electricity is required. A conversion factor of 0.33 was assumed to take into account standard power cycle inefficiencies. The results of this analysis are provided in Table 2.

Table 2. Relative significance of four selected subindustries based on natural gas use, as shown in Figure 6 from Section 2.2.

State/District	Average Retail Electricity Sales (GWe)	Ethyl Alcohol Total Energy Req. (GWt)	Plastics Material and Resin Total Energy Req. (GWt)	All Other Basic Organic Chemical Total Energy Req. (GWt)	Fabricated Metal Products Total Energy Req. (GWt)	Total of Selected Subindustries (GWt)	Fraction of State Average Retail Electricity Sales (0.33*GWt = GWe)
South Dakota	1.34	0.81	0.00	0.00	0.03	0.83	20.57%
Iowa	5.22	1.81	0.12	0.43	0.11	2.47	15.66%
Nebraska	3.52	1.26	0.05	0.10	0.05	1.46	13.73%
Rhode Island	0.88	0.00	0.19	0.00	0.05	0.24	9.12%
Kansas	4.60	0.75	0.11	0.20	0.10	1.17	8.39%
Wisconsin	7.85	0.55	0.49	0.48	0.35	1.87	7.87%
Connecticut	3.37	0.00	0.29	0.28	0.21	0.77	7.59%
New Jersey	8.58	0.00	0.46	1.26	0.22	1.95	7.49%
Minnesota	7.76	1.06	0.33	0.10	0.27	1.76	7.47%

Illinois	16.38	0.81	0.94	1.19	0.57	3.51	7.07%
Michigan	11.96	0.25	0.85	0.83	0.55	2.48	6.83%
Ohio	17.39	0.35	1.12	1.41	0.64	3.53	6.70%
Indiana	12.00	0.70	0.49	0.35	0.31	1.86	5.12%
Massachusetts	6.31	0.00	0.56	0.15	0.23	0.94	4.93%
Texas	41.69	0.40	1.42	3.61	0.79	6.22	4.92%
New Hampshire	1.24	0.00	0.11	0.00	0.07	0.18	4.81%
California	29.61	0.35	1.47	1.29	1.18	4.30	4.79%
Pennsylvania	16.51	0.00	0.75	1.06	0.53	2.34	4.67%
North Dakota	1.68	0.20	0.00	0.00	0.02	0.22	4.40%
Oregon	5.33	0.15	0.22	0.18	0.16	0.71	4.37%
West Virginia	3.51	0.00	0.08	0.33	0.05	0.46	4.30%
Louisiana	9.67	0.00	0.29	0.83	0.14	1.26	4.29%
South Carolina	8.87	0.00	0.30	0.63	0.13	1.06	3.95%
Georgia	14.94	0.20	0.63	0.71	0.20	1.73	3.82%
Missouri	9.40	0.25	0.20	0.43	0.19	1.08	3.78%
North Carolina	14.61	0.00	0.70	0.63	0.24	1.57	3.55%
Colorado	6.12	0.15	0.12	0.23	0.14	0.64	3.44%
New York	16.33	0.20	0.46	0.61	0.43	1.70	3.43%
Kentucky	10.16	0.00	0.42	0.51	0.12	1.05	3.42%
Alabama	9.83	0.00	0.30	0.45	0.17	0.92	3.09%
Utah	3.39	0.00	0.14	0.08	0.10	0.32	3.08%
Mississippi	5.52	0.00	0.20	0.20	0.06	0.47	2.82%
Idaho	2.71	0.00	0.07	0.10	0.05	0.22	2.72%
Tennessee	11.00	0.00	0.25	0.40	0.19	0.84	2.52%
Arkansas	5.35	0.00	0.11	0.20	0.09	0.40	2.45%
Oklahoma	6.77	0.00	0.12	0.20	0.18	0.50	2.44%
Arizona	8.56	0.00	0.19	0.28	0.16	0.63	2.41%
Delaware	1.31	0.00	0.07	0.00	0.02	0.08	2.12%
New Mexico	2.64	0.00	0.00	0.13	0.04	0.17	2.10%
Washington	10.54	0.00	0.11	0.33	0.21	0.64	2.02%
Florida	25.17	0.00	0.41	0.51	0.32	1.23	1.62%
Virginia	12.30	0.00	0.15	0.30	0.14	0.59	1.58%
Maryland	7.05	0.00	0.08	0.18	0.07	0.33	1.55%
Maine	1.32	0.00	0.00	0.00	0.05	0.05	1.15%
Nevada	4.01	0.00	0.08	0.00	0.05	0.13	1.10%
Vermont	0.63	0.00	0.00	0.00	0.02	0.02	0.97%
Montana	1.58	0.00	0.00	0.00	0.03	0.03	0.67%
Alaska	0.73	0.00	0.00	0.00	0.01	0.01	0.44%
Wyoming	1.94	0.00	0.00	0.00	0.02	0.02	0.31%
Hawaii	1.10	0.00	0.00	0.00	0.01	0.01	0.25%
District of Columbia	1.28	0.00	0.00	0.00	0.00	0.00	0.02%

Examining Table 2, several key points stand out:

- The total energy usage of the selected subindustries is still relatively low, with the exception of subindustries in South Dakota, Iowa, and Nebraska. Those states feature a lower overall electricity usage with a relatively high amount of energy being used for distillation of ethyl alcohol. Except for this specific subindustry, the remainder of the selected subindustries does not appear have the potential to absorb a significant amount of excess capacity on the electric market. Thus, in order to absorb a larger amount of excess capacity, integration with less attractive subindustries must be considered. For already developed subindustries, such as the petroleum industry, the paper industry, or the iron and steel industry, heavy modification of the production process will be required for integration. Another option that should be considered is development of an alternative energy economy, where hydrogen or methanol are produced and used to provide energy for manufacturing and transportation. It may be easier to modify a manufacturing plant to use hydrogen or methanol as part of the process than to use steam or high-temperature heat from a nuclear reactor.
- The development of small modular reactors (SMRs) will enable simpler, thermal integration with the selected subindustries due to the smaller scale of the reactor system.
- States from the southeast U.S., stand out by having a relatively high retail electricity sales, but relatively low presence of easily integrated subindustries. These regions may be ideal for development of an alternative energy economy based on hydrogen or methanol. Additionally, if biofuels are adopted more readily by the transportation industry, then these regions may be suitable for production of biomass intensive crops, such as sorghum, switchgrass, or energy cane.

3. Conclusions and Recommendations

In the present work, market conditions for the integration of HESs were studied for near-term (electric-only integration with existing plants) and far-term (electric or thermal integration with either existing plants or for greenfield installations) conditions. The major conclusions are summarized below:

Near-Term HES Opportunities

- Limited integration using current nuclear power plants may be possible with several subindustries if collaboration with local political and industry leaders is properly coordinated and incentivized. Specifically, the 'Ethyl Alcohol', 'Plastics Materials and Resins', 'Other Basic Organic Materials', and 'Fabricated Metal Products' subindustries appear to be attractive for integration due to their large electricity usage and the large fraction of electricity usage with respect to other energy sources used in each subindustry. Further research will be required to determine how the plants will be integrated in the HES in order to serve as a capacity sink for a current nuclear power plant.
- The subindustries selected based on Figure 3 use a small amount of energy relative to the total electricity sold on the grid. Specifically, no state or region could accommodate more than 7% of electricity usage using these plants as capacity sinks for current nuclear power plants. Further research may reveal other options, not excluding the production of alternative fuel or energy carriers, such as hydrogen or methanol.
- It is unlikely that any one manufacturing plant will be able to use electricity to the scale required to absorb all the excess capacity from a current nuclear power plant. Because of this, many plants may need to be integrated within a single HES. Additionally, if the plant is required to operate at all times, onsite electricity storage may be needed.

Far-Term HES Opportunities

- Significant integration (electrical and thermal) using a future fleet of SMRs and large LWRs is possible with several subindustries if collaboration with local political and industry leaders is properly coordinated and incentivized. Specifically, the 'Ethyl Alcohol', 'Plastics Materials and Resins', 'Other Basic Organic Materials', and 'Fabricated Metal Products' subindustries appear to be attractive for integration due to their large amount of energy usage and the large fraction of natural gas usage (for thermal energy input) with respect to other energy sources. It is important to note that even though these manufacturing plants may be simpler than some to integrate with heat from nuclear power plants, significant modification of the plant itself may be required.
- With a few exceptions, the selected subindustries use a small amount of energy relative to the total electricity sold on the grid. The exceptions are in the states of South Dakota, Iowa, and Nebraska, which all use a large amount of energy to distill corn into ethyl alcohol while also having a relatively low usage of electricity. None of the other states use a large amount of energy relative to their electricity usage for the selected subindustries. Further integration with other industries is possible, but will likely require more complex changes to the system to accept steam or high temperature heat from a nuclear power plant.
- An alternative option for integrating manufacturing plants in HESs is to incentivize the creation of an alternative energy market, where hydrogen or methanol is used to provide energy to manufacturing plants and as transportation fuels. Further research will be required to develop low economic risk options, recognizing that the integrated manufacturing plant that uses the alternative hydrogen or methanol energy source may need to be constructed in parallel with the other integrated plants in the HES. If this is successful, very large plants may

be able to be economically built to absorb large amounts of excess capacity from the electric grid.

4. References

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