Rack-level Power for an Off-Grid Medium-Sized Data Center: Final Design

Group B3

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Abstract

Data storage is an important cause in today's world due to high energy requirements, which led to the advent of data centers. While on-grid data centers requiring electricity grid connections are often considered the go-to data center energy source, we have chosen to go with an off-grid, natural gas source used to power Solid Oxide Fuel Cells, which efficiently produce electricity. In our development of our data center, we have considered many components including the technical specifications, mass/energy balances, Process Flow Diagram (PFD) development, economics, and optimization processes. In doing so, we were able to design a 3000 SOFC, 150-MW data center that has been proven to break even with traditional on-grid power sources in 10 years of implementation while additionally developing a plan to make 10% profit over 10 years. In our optimization process, we have maximized the possible profit to be made upon reducing the cost of manufacturing SOFC cells. Through this diverse analysis, we have determined the feasibility of SOFCs and make the recommendation that SOFCs are both an economically and technically viable and should be implemented.

Motivation & Background

Effective and efficient energy consumption is crucial for industrial processes and even more important for modern data centers due to an increased need for data storage, as a result of the advent of cloud services, which requires a large amount of data [1]. By creating large data storage areas, the transfer of information into the cloud allows for individuals and companies to store more data than they would through using their own storage devices. This requires large amounts of energy to power the many racks of servers and corresponding cooling systems needed [2]. For that reason, fuel cells are an attractive source of energy to utilize in data centers.

Basic fuel cells are those that take in energy and produce electricity through chemical reactions based at internal electrodes, one positive and one negative. Fuel cells contain electrolyte(s), which allow electrons to move from one electrode to another. The input fuel sources, which can be quite diverse, include natural gas, coal, or biomass, which are added alongside air and provide the necessary elements of hydrogen and oxygen to undergo the following chemical reactions to produce mainly Carbon Dioxide (CO_2) and Water along with electricity [38].

$$H_2+O^{2-} \rightarrow H_2O + 2e^-$$
$$CO+ O^{2-} \rightarrow CO_2+2e^-$$
$$0.5O_2+2e^- \rightarrow O^{2-}$$

Fuel cells are appealing due to their low emissions and high electrical output - producing water as a primary byproduct, and the output being values up to 100 kW of direct current (DC) electricity [39]. While there are many kinds of fuel cells, including Alkali, Phosphoric Acid, and

Proton Exchange Membrane (PEM) fuel cells, of great interest for this project are Solid Oxide Fuel Cells.

SOFCs are unique in the type of electrode that is utilized; mainly a ceramic oxide such as Calcium/Zirconium Oxides. Efficiency is around 60% and operating temperatures tend to be extremely high, some even over 1000℃ [39]. Figure 1 is a depiction of the chemical process that occurs within an SOFC:

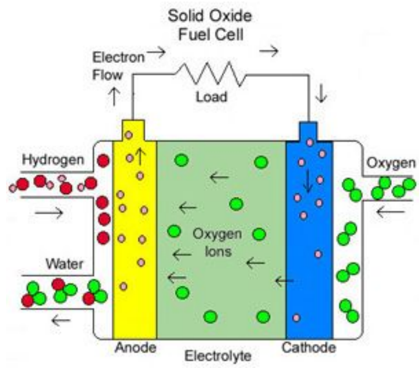

Figure 1. Chemical Reactions within an SOFC

Our theoretical data center is located outside of Salt Lake City, Utah as electricity and natural gas is extremely affordable in Utah. While our data center had previously been running on on-grid electricity, we are proposing to improve our mid-sized data center of 250,000 ft^2 by changing the energy source from an on-grid electrical source to an in-house Solid Oxide Fuel Cell (SOFC) based energy source. We believe this will be both an economically viable and environmentally sustainable energy source that will provide many benefits, some of which are the following:

- **Energy source reliability**: Natural gas, the primary feed for SOFCs, is highly reliable as outages due to weather are very rare due to the fact that Natural gas reserves are stored underground [3]. In the United States, between 2006 and 2015 there were six or less natural gas outages per year from severe weather across the whole United States [4]

Figure 2. Lack of failure points as seen in an SOFC-powered data center [33]

- **High efficiency**: Due to the fact that there is no longer any reliance on the electric grid, which requires substations and other infrastructure demands, there are fewer points of failure to consider. Moreover, in having the SOFCs in-house, there will be a minimization of lost energy. The Energy Information Administration (EIA) estimates an average of 5% of the energy created in the United States is lost just in transmission and distribution [5].

- **Lower greenhouse gas emissions**. Carbon dioxide emissions are reduced 49%, Nitrogen Oxides (NOx) reduced by 91%, and Volatile Organics reduced by 93% [3].

- **Lower operation costs [3].** The cost of electricity is $0.0787/kWh for Utah, on average for industrial customers in 2016 [5]. As a comparison, the cost of natural gas in Utah is $0.0210/kWh, which is significantly lower than the cost of electricity, which suggest that it is cheaper to use natural gas than electricity [40]

- **Ease of reproducibility**: Because of the ease of using SOFCs, data centers can be easily be brought online anywhere in the world. Relying on the grid means that the SOFCs are dependent upon the voltages and power outputs of the specific grid, whereas natural gas is fairly constant throughout the world [3].

- **Parallel Utilization:** The SOFCs can be set up in parallel, so that if one or two racks go offline, there are several more to take up the slack. This is done to increase redundancy and reliability of the power to the stacks.

We will consider our SOFC system implementable if we are able to breakeven with costs associated with the on- and off-grid data centers upon 10 years of operation, or alternatively, 10% profit to be made within ten years of implementation, the emissions of our system are less than using an on-grid power source, and the number of outages decrease significantly.

Technical Specifications

Power needs for our system will be based on our available floor space in our data center and how many server racks we will be able to put into it. Based on current layouts used in data centers, cooling is optimized when the racks are arranged back to back, so that there are hot aisles behind server racks and cold aisles in front of them, as seen in Section A2, Figure 12 in the appendix. With hot aisles that are 3 feet wide and cold aisles that are 4 feet wide about half of the floor space available is needed for an efficient cooling setup [8]. This leads to a design in which there will be 9000 server racks in our data center that will need to be powered [6,8]. The space is oriented so that the racks are arranged in many long rows, with spaces at intervals between the aisles for ease of movement through the facility. With a rack power of 16.67 kW, which is based on power densities of current servers and racks, our plant will need 150 MW of power to run [10, 14]. This is an important number for estimating the viability of switching from an on-grid power source to an off-grid, SOFC-based system.

In order to satisfy reliability requirements, smaller SOFCs to be used locally situated above the racks. With 1 SOFC powering 3 racks, there will be redundancy within each row, increasing the reliability of our power source. This leads to a requirement for each SOFC to be able to produce 50 kW of power. The fuel cells were assumed to produce 50 kW so that it could power 3 racks. It is adequate to have as many fuel cell stacks as possible for reliability purposes, but the cost and the sizing will be the compromising aspects of having one SOFC system per each rack. Hence, we have decided to allocate 3 racks to one SOFC system. It will be later discussed if this is the optimal configuration, and if we further need to optimize the number of racks per a fuel cell system.

Another assumption of importance is the ideal location for the data center. The location in the United States to use as a basis is one where cooling and electricity is cheaply available, and this is used as an estimate because data centers would already be established. By locating in a dry area of the United States, such as Utah, the viability of using evaporative cooling increases as air humidity will not restrict the ability to cool as much as humid air might [7].

One of the assumptions made for technical specification is the lifetime of the SOFC. Today, SOFCs are likely to have a lifetime around 10 years [13]. In our evaluation of using SOFC generated power, the total time to evaluate possible economic advantage will be 10 years, as many components of data centers are being constantly replaced, and longer evaluations generally lose accuracy with time.

To summarize, the main assumptions that we have developed are:

- **Location:** Data center is located outside of Salt Lake City, Utah, and because of the climate, swamp cooling is used [7]
- **Layout:** Hot and cold aisle design for system cooling [8]
- **Total Data Center Area:** 250,000 ft^2
- **SOFC Life Cycle:** 10 years [9]
- **Rack Type**: APC 42U Universal Rack (78.39” x 23.62” x 42.13”) [6]
- **Number of Racks:** 9000
- **Number of SOFCs:** 1 SOFC/3 racks; 3000 SOFCs
- **Peak Rack Power**: 16.67 kW [10, 14]
- **Power Rating**: 50 kW per SOFC
- **Total Plant Power Requirement:** 150 MW

Optimized Flow Sheet and Stream Table [51, 52]

Description of the Process

As seen in Figure 3, the PFD for this process, the primary fuel, natural gas, is fed from the pipeline into the system entering H-101 at a pressure of 1 atm and 25℃. The stream is brought up to 400℃, allowing the reforming of methane. Air, another feedstock, enters the process at 25℃ and 1 atm which is then raised to a temperature of 400℃ through H-102. Two streams then are inputted into the fuel cell, R-101, and the temperature rises to 600℃. The operating temperature of R-101 is validated via 1-D stack model, which will be discussed later. The exit streams from R-101 then goes through tail gas burner, R-102. The streams are already hot at 600℃ so the combustion reaction occurs spontaneously. The temperature rises to 624℃. At the exit of R-102, the exhaust streams split to provide heat demand for H-101 and H-102.

We made the decision to split the streams so that the two streams are at comparable temperatures of 266℃ when later combined after passing two heat exchangers, and 9% of the exhaust stream goes to H-101 and 91% to H-102. The exhaust streams then combine to power H-103 and exit the system at 193℃. Water is also added as a feedstock for gas reforming, and is inputted through H-103 for phase change. It then mixes with natural gas before entering H-101 altogether. To prevent water condensation, H-103 has to supply enough heat to the steam so that the steam/gas mixture maintains its temperature at 140℃. Also, excess water is inputted to prevent coking during reforming, and the steam to carbon ratio is at 2.5.

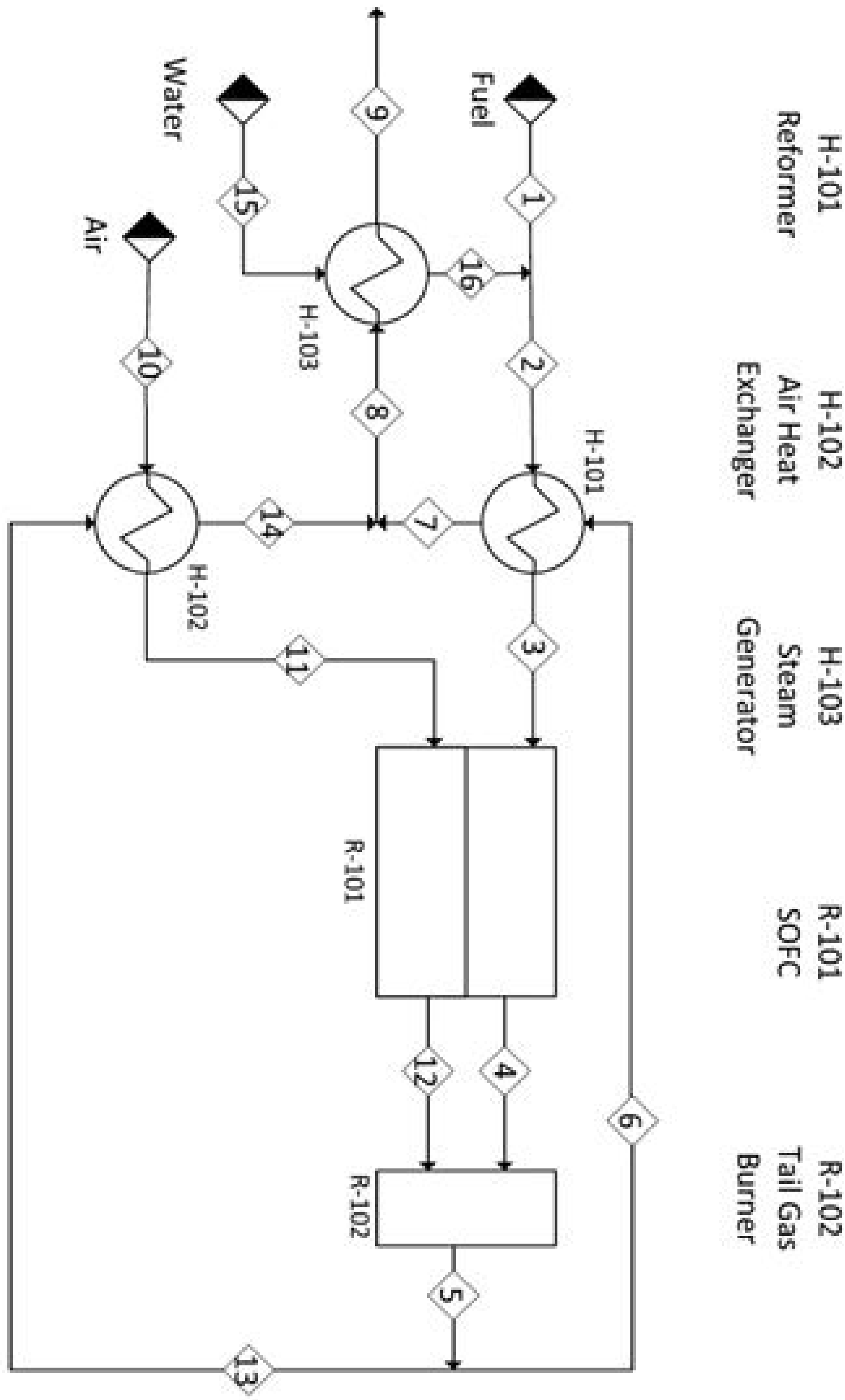

Figure 3. PFD of SOFC Design

Table 1. Equipment Table for SOFC Design

Equipment	Operating conditions	Material
R-101	400-600℃	Details in SOFC design section
R-102	600-624℃	N/A
H-101	140-624℃	Stainless Steel
H-102	25-624℃	Stainless Steel
H-103	25-256℃	Stainless Steel

Table 2. Stream Table

Stream:		1	2	3	4	5	6	7	8
T (°C)		25	140	400	600	624	624	386	256
P (atm)		1	1	1	1	1	1	1	1
ntot (mol/s)		0.136	0.48	0.53	8.77	8.77	1.21	1.21	8.77
nN2 (mol/s)		0	0	0	6.55	6.55	0.90	0.90	6.55
nO2 (mol/s)		0	0	0	1.47	1.47	0.20	0.20	1.47
nCO (mol/s)		0	0	0.001	0.002	0	0	0	0
nH2 (mol/s)		0	0	0.095	0.025	0	0	0	0
nCH4 (mol/s)		0.13636961	0.136	0.112	0	0	0	0	0
nCO2 (mol/s)		0	0	0.023	0.134	0.136	0.019	0.019	0.136
nH2Og (mol/s)		0	0.34	0.29	0.59	0.61	0.085	0.085	0.61
nH2Ol (mol/s)		0	0	0	0	0	0	0	0
xN2		0	0	0	0.75	0.75	0.75	0.75	0.75
xO2		0	0	0	0.17	0.17	0.17	0.17	0.17
xCO		0	0	0.001	0.000	0	0	0	0
xH2		0	0	0.181	0.003	0	0	0	0
xCH4		1	0.286	0.214	0	0	0	0	0
xCO2		0	0	0.044	0.015	0.016	0.016	0.016	0.016
xH2Og		0	0.714	0.560	0.067	0.070	0.070	0.070	0.070
xH2Ol		0	0	0	0	0	0	0	0
total		1	1	1	1	1	1	1	1

Stream:	9	10	11	12	13	14	15	16
T (°C)	193	25	400	600	624	256	25	191
P (atm)	1	1	1	1	1	1	1	1
ntot (mol/s)	8.77	8.30	8.30	8.04	7.98	7.98	0.34	0.34
nN2 (mol/s)	6.55	6.55	6.55	6.55	5.96	5.96	0	0
nO2 (mol/s)	1.47	1.74	1.74	1.48	1.34	1.34	0	0
nCO (mol/s)	0	0	0	0	0	0	0	0
nH2 (mol/s)	0	0	0	0	0	0	0	0
nCH4 (mol/s)	0	0	0	0	0	0	0	0
nCO2 (mol/s)	0.136	0	0	0	0.124	0.124	0	0
nH2Og (mol/s)	0.61	0	0	0	0.56	0.56	0	0.34
nH2Ol (mol/s)	0	0	0	0	0	0	0.34	
xN2	0.75	0.79	0.79	0.82	0.75	0.75	0	0
xO2	0.17	0.21	0.21	0.18	0.17	0.17	0	0
xCO	0	0	0	0	0	0	0	0
xH2	0	0	0	0	0	0	0	0
xCH4	0	0	0	0	0	0	0	0
xCO2	0.016	0	0	0	0.016	0.016	0	0
xH2Og	0.070	0	0	0	0.070	0.070	0	1
xH2Ol	0	0	0	0	0	0	1	0
total	1	1	1	1	1	1	1	1

Table 3. Energy Balance

Energy Balance - Overall Balance Check							
		in (1,10,15)			out (9)		
species	n	h	nh	n	h	nh	
N2 (ex)			0	6.5535	4942	32391	
O2 (ex)			0	1.4693	5129	7537	
CO2 (ex)			0	0.1364	-386487	-52705	
H2O (ex)			0	0.6137	-236073	-144869	
N2 (air)	6.5535	0	0			0	
O2 (air)	1.7421	0	0			0	
CH4 (feed)	0.1364	-74810	-10202			0	
H2O (liq)	0.3409	-285830	-97446			0	
We						49999	
total			-107648			-107648	J/S

Unit Design Specifications

hot box

Figure 4 shows a SolidWorks 3D model layout. The hot box has dimensions of 100x150x200 cm, which can just fit on top of each 3 racks. A 1’’ thick Ceramic Insulation is used inside the hot box shell to ensure a reduction of heat losses [43]. The total volume of the hot box is 3m^3.

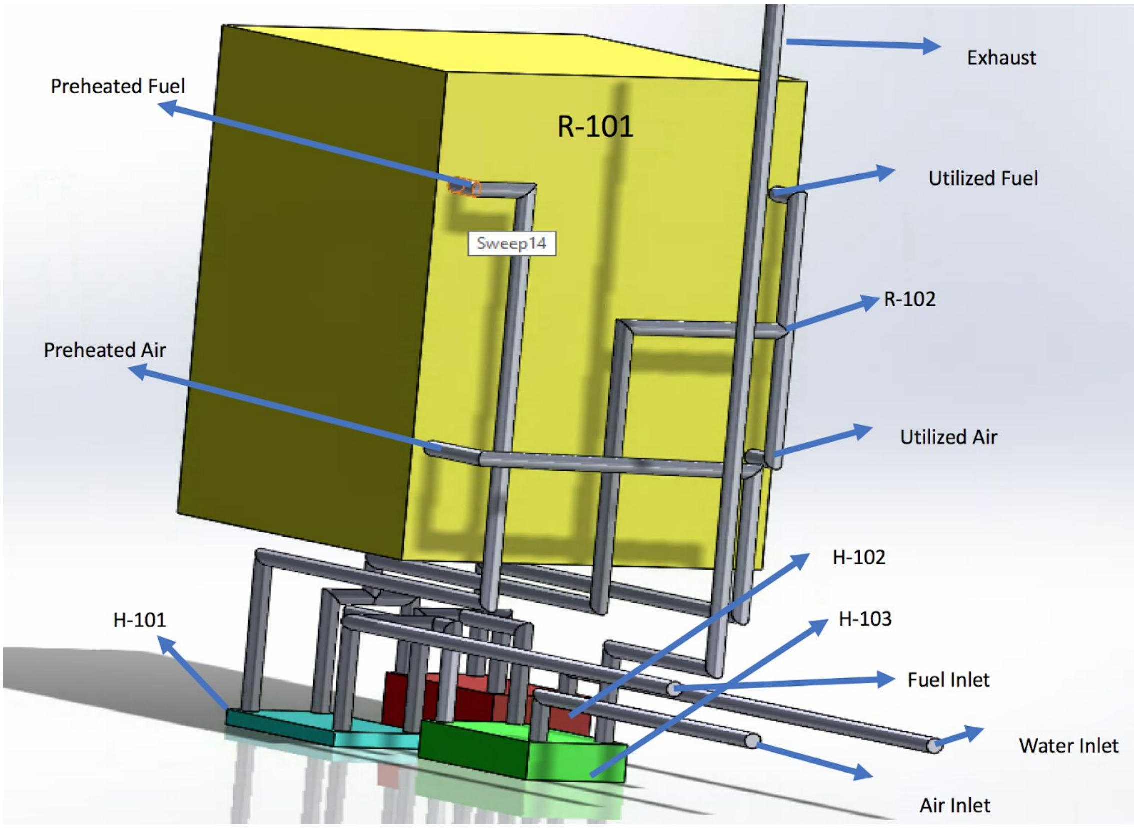

Figure 4: 3D model inside the hot box.

As seen in Table 4, the Equipment Table for the SOFC design, there are several key features to be discussed. Each SOFC has 3 heat exchangers associated with it - reformer, air heat exchanger, and a steam generator - and they together compose a module. All the components of our design are operating at high temperature. This presents design problems with regards to materials that can be used without negatively affecting the system. Carbon steel is not usable in these high temperature unit operations, increasing cost of materials in the SOFC design [11, 36]. High temperature heat exchangers in our system are still within the limits of stainless steel being usable as piping and materials of construction for our processing equipment. [36, 37] This is an important factor for costing as higher temperature operations would require more expensive materials such as stainless steel, or ceramics [11].

Table 4. Equipment Design Specifications

Equipment	Dimension (L*W*H)	Operating Pressure	Operating Temperature	Material	Notes:
hot box	100x150x140 cm	1 atm	N/A	Ceramic (Insulation)[43]	Includes all the units below
R-101	90x110x70 cm	1 atm	400-600℃	Details in Table 9	Yellow in Figure 4, many different materials
R-102	N/A	1 atm	600-624℃	Stainless Steel [36, 37]	High Temperature, but within stainless steel range.
H-101	52.8x24.6x4.03 cm	1 atm	140-624℃	Stainless Steel [36, 37]	High Temperature, but within stainless steel range.
H-102	52.8x24.6x32.7 cm	1 atm	25-624℃	Stainless Steel [12]	High Temperature, but within stainless steel range.
H-103	52.8x24.6x12.5 cm	1 atm	25-256℃	Stainless Steel [36]	High Temperature, but within stainless steel range.

R-101

Fuel cell specification is discussed later in detail in “SOFC Stacks Specifications and Layout”. It’s optimal operating temperature was determined by the 1-D stack model, and is 400°C to 600°C [45]. The upper limit was based on material constraints for the system. At 600°C, stainless steel is close to its maximum usable temperature, and to keep costs down overall in the system it is ideal to get as close to the maximum allowable temperature to take advantage of higher fuel utilizations at high temperatures. The fuel cell produces 50 KW to power 3 racks at the utilization of 0.95 with 0.5 volts per stack. The total flow in for this unit operation is 8.83 mol/s.

R-102

The tail burner is shown on the process flow diagram as a unit operation, but is not specified in size and cost analysis. It raises the temperature of the exhaust by less than 30°C, which indicates that we are not extracting a significant amount of thermal energy. As the streams are already hot at 600℃, we are assuming that the combustion reaction occurs spontaneously as well. So the implementation of the tail burner as a physical unit operation is not necessary. While the tail burner will not be modeled as an actual equipment cost, it will be modeled as a T-junction pipe, which will function as an intermediate holding area where the mixture may remain until moving on to the next stage. The exit streams from the cathode and anode in fuel cell are combined before splitting to support heat exchangers. The total flow in is 1.36 mol/s.

H-101

We will be utilizing flat plate heat exchangers for all the heat exchanger units, as they are generally known to have low costs, flexibility and have low maintenance [41]. H-101 takes the natural gas and the steam and allows for gas reforming. The fuel cell itself cannot oxidize the natural gas directly, so the conversion of methane to carbon monoxide and hydrogen gas is necessary before entering the fuel cell. This process is endothermic requiring some energy input; we are using 9% of the R-102 exhaust stream to support the heat demand for the reaction. The temperature of the exhaust stream drops from 624°C to 256°C. The fuel and steam mixture is brought from 140°C up to 400°C. The required heat transfer area is 1.3 m^2, calculated with heat transfer principles. The dimension of the unit shown in Table 1 is further calculated based on a commercially available brazed plate heat exchanger model. The sample calculation is shown in Appendix. Flow through this heat exchanger is 1.74 mol/s.

H-102

Air also enters the fuel cell to supply oxygen, and H-102 needs to heat the air from the ambient condition of 25°C up to 400°C. There is excess air, at 60 to 1 molar ratio with respect to the carbon feed, to cool down the SOFC stack. Due to its huge molar flow, 91% of the R-102 exhaust stream needs to divert to supply enough heat. The exhaust stream exits at 256°C. It has a larger heat transfer area of 14.4 m^2, as a result of a larger flow of 16.28 mol/s. hence more plates are required in the heat exchanger. It is the largest heat exchanger we need in the process.

H-103

Exhaust streams after powering H-101 and H-102 combine and supports steam generation of the water inlet at 25°C. Water is vaporized and brought up to 191.4°C before being injected into the fuel inlet stream to enter the reformer. H-103 needs to be able to support both latent heat of vaporization and sensible heat, and this duty is met by the combined exhaust streams. The exhaust streams entering the unit at 256°C exits the entire system at 193°C. The heat exchanger area is 5.2 m^2, based on the total flow of 9.11 mol/s. Hot steam joining the fuel after this heat exchanger unit brings the temperature to 140°C, which imposes less stress on the following reformer unit, and prevent the water condensation.

Economic Analysis

This analysis also determines the ΔTCO, or the change in the total cost of ownership, which is defined as the TCO_{final} - $TCO_{initial.}$ The TCO_{final} includes all the costs associated with an off-grid data center run entirely on natural gas, and the $TCO_{initial}$ includes all the costs associated with an on-grid data center run with no SOFCs and with electricity as the main fuel source. Both situations and associated costs are summarized in Table 5. There are several costs that we are not considering as they are present in both the on-grid and off-grid scenarios: (1) servers/racks, (2) swamp cooling, and (3) land/building costs, as well as (4) battery systems as this will be present in both on- and off-grid systems to ensure functioning for a limited amount of time if there is an outage [17].

Table 5. Overall Costs for On-Grid and Off-Grid Data Center for Break Even Cost Analysis

Equipment/Input	On-Grid	Off-Grid
		Operational Inputs
Electricity	$923,100,000.	N/A
NG Feedstock	N/A	$433,600,000.
		Conditional Inputs
UPS	$1,320,000.	N/A
Generators	$26,500,000.	N/A
NG Piping	N/A	$150,000.
LNG Storage Tanks	N/A	$378,000.
H-101	N/A	$861,000.
H-102	N/A	$9,200,000.
H-103	N/A	$2,810,00.
R-101	N/A	$628,020,000.
Hot Box Insulation	N/A	$1,100,000.
Total Cost	$950,900,000.	$950,900,000.

*Cost for ten-year data center lifetime, for operation 24 hours a day, 365 days a year

$TCO_{initial}$

In order to determine the $TCO_{initial}$ we determined the cost an on-grid data center would accrue on a yearly basis and then brought it forward to the total cost accrued over 10 years. First to consider is **electricity**. Wholesale electricity costs $0.0787/kWh in Utah; this equals $923,100,000 over the course of 10 years [18]. This value was determined by making an adjustment in the cost over the 10 years, which was done by considering the Rate of Return (ROR), and then determining the present value of the annuity. In determining the ROR of the electricity utilities for the on-grid data center, the Rate of Equity was determined, which was then was converted into the ROR, which was 2.12% [49]. This calculation can be seen in Section A5 of the Appendix. Moreover, though maintenance is an important component to ensure the smooth operation of a data center, we have made the assumption that maintenance will be significantly less than other costs, so have chosen to not include them here. However, these costs are important, and they are shown below in Table 4.

Table 6. Breakdown of Electricity Costs in an On-Grid Data Center [19]

Parameter	MV Switchgear	Transformers	LV Switchboard	Panelboard	PDU/RPPs
Location	Electrical Space	Electrical space, IT room	Electrical Space	Electrical space, mech space, IT room	IT room
CB type	Vacuum CB	N/A	Air CB; MCCBs;	MCCBs; General CBs	MCCBs; General CBs
Rated voltage	MV	LV and MV	LV	LV	LV
Power rating	4-50MVA	50kVA-50MVA	100kVA-6MVA	1.5kVA-75kVA	50kW-500kW
Equipment cost per kW of data center capacity	$8 - $92	$35 - $90	$80 - $200	$20 - $40	$100 - $400

There are essentially two courses of action to be considered in calculating the total costs for the electrical system, the first being to calculate each cost on its own and to add them all up, as we have been doing. However, another way would be by following the general estimation that the electrical system takes up 40-50% of the total costs associated with a data center of which 50-60% represents equipment costs, installation about 25-35%, and design takes 15-20% [20]. Here, we chosen to do the former, and for future considerations, it may be of use to do the latter procedure.

Next to consider are the **Uninterruptible Power Supplies** (UPS) which are crucial for backup power in the case of an electricity outage. We are using the Eaton 93PM 50 kW UPS, which then means that in order to produce 150 kW, we will need three of these [21]. Moreover, because we have assumed a 2N reliability, as recommended by reliability standards, we have doubled our UPS's to satisfy reliability requirements, which then leads to 6 UPS', equaling a total of $1,320,000 over the course of 10 years [22]. Maintenance will also be needed to be considered for the UPS, but due to the longer lifetime of these machines, maintenance will generally be less.

Third to consider are **backup generators**. Based off of preliminary research, we have chosen the most cost-effective solution of the 2 MW Cummins Diesel Generator, priced at $349,000/unit. In order to support the data center, we will need a total of 76 units (75 units to support base load and 1 per N+1 reliability standards). This is priced at a total of $26,500,000 [23, 24]. In consideration of these generators, maintenance will also have to be considered, but as mentioned previously, we are not including it in our analysis. Another type of generator to be considered is a 30 kW Diesel generator, priced at $14,000/unit, of which we would need 5000 units, equaling upwards of $50,000,000 [25]. In order to satisfy economies of scale, we have chosen to go with the 2 MW generator.

$\underline{TCO_{final}}$

There are several considerations that must be considered when calculating the TCO_{final}. First and foremost are the costs associated with steady operation of the natural gas feedstocks.

Because we are choosing to turn off some of the SOFCs when not at peak power, it is important that we consider that when developing the total cost of the SOFCs.

To be considered is the cost of wholesale **natural gas**, which will fuel the system. In Utah, natural gas is priced at $6.33/MCF, this equals $433,600,000 for 10 years at our maximum power load [27]. This cost is variable and thus must be adjusted to account for inflation, etc. which can be done by the ROR. In determining the ROR of the natural gas, the average rate of return was 10%, which was then used to calculate the ROR for the 10-year period [50]. Piping will also be required, and this require a capital cost of $150,000 to ensure the piping is correct [28]. The materials of construction needed here are PVC piping, which should also significantly reduce prices.

Also of importance are the **LNG storage tanks**, which will be used to store the liquefied natural gas. In order to cost these tanks, we have made the assumption that the LNG tanks are costed at $1500/tonne [31]. Using the assumption that each tank can hold 1500 gallons, and the fact that we need 14 tanks to satisfy our peak usage requirements for 12 hours, we calculated the total cost that will be required for the tanks, to be $378,000 [32]. The maintenance will also be considered, but due to the fact that it will be a considerably lower number, we have chosen to not include it for the purposes of this report.

Next, are the costing of the SOFCs. First to mention are the costs associated with the SOFC hot box insulation. All the components of the SOFC, including the three heat exchangers, (H101-H103), and the fuel cell components (R101-R102) are included within the hot box. In order to reduce heat losses, **hot box insulation** is also important to considered. Priced at $385/hot box, the total costs associated with this is $1,100,000 over the 10 years.

Next, the heat exchangers were sized according to heat transfer principles as seen in the Appendix. These researched units can do perform at slightly higher levels than that of our required heat transfer areas, but are within our researched temperature ranges. Duda Energy, a biodiesel supply company, offers various sizes of 304 stainless steel copper brazed plate heat exchangers [46]. In Section A4, Table 11, there is a brief description of heat exchangers from Duda Energy that we used to determine the estimated prices of the heat exchangers. Our calculated costs are based off of products of various sizes they sell, then adjusted for 316 Stainless Steel, as this type of steel is more durable for our temperature ranges [36]. The Duda Energy heat exchangers we are comparing to have a much lower maximum temperature than our system requires, and although material of construction is not the only factor in maximum temperature of a unit, it is what we will base our conversion on, as it is believed to be a major factor. Thus, the estimation of prices will be based on readily available heat exchangers and a percent increase in price based on differences in material prices. In May 2017, the average price of 316 stainless steel was 40% higher than 304 Stainless Steel. [48] Prices for heat exchangers, summarized in Table 5 have been adjusted in this way, and then has led to the determination of **H-101** to be priced at $861,000, **H-102** to be priced at $9,00,000 and **H-103** to be priced at $2,810,000.

The prices reflected in Table 3 are the total costs associated for a 10-year period. Also to be considered is the determination of R-101 and R-102, as seen in Table 5**. R-102** is not a unit operation and is represented as T-junction piping, so it will be assumed to be included in R-101, which is the actual SOFC. In order to do the pricing for the SOFC, we are back-calculating the cost. The important assumption made here is that we are to **simply trying to break even**. This means that we want the on-grid and off-grid prices to be the same. With this assumption, we can back-calculate the cost of R-101, the actual SOFC. This calculation can be seen in the Appendix, but the final result is that **R-101** will cost $628 million over 10 years for 3000 SOFC hot boxes, which equals $209,000 for each SOFC. This number qualitatively means that each of the SOFCs must cost $209,000 at most in order for the off-grid data center to break even with the on-grid data center.

Not considered in the TCO, but still part of our system is the use of batteries. We are assuming batteries were present as backup power for the electrical on grid set up, and part of our design relies on these still being a part of the data center and backup power. By having an electrical backup for any SOFCs that go out of commission, our system gains reliability. As this is done by using the batteries that will be present in both systems, the cost is not considered for the TCO, and does not need to be further specified in the design as they are assumed to have already existed for the same power load.

While the previous results are only for a breakeven price, we have also analyzed the effect of making the goal of achieving 10% profit over 10 years, shown in table 7. Following the same process as previously, we determined the cost for all components except that of R-101, which is the cost of all 3000 required SOFCs. Then, with the assumption of 10% profit, we determined that R-101 must be $532,900,000, which then suggests that each SOFC costs around $177,000. This puts tighter restrictions on the allowable manufacturing costs of the SOFC's, but a motivation factor to be able to sell or implement an SOFC system is to have it be cheaper than an on grid connection. With this change, the price of the SOFC's must drop 15% in order for a ten percent profit to be made.

Table 7. SOFC Prices for 10% Profit

Equipment/Input	On-Grid	Off-Grid
Operational Inputs		
Electricity	$923,100,000.	N/A
NG Feedstock	N/A	$308,396,000.
UPS	$1,320,000.	N/A
Conditional Inputs		
Generators	$26,524,000.	N/A
LNG Storage Tanks	N/A	$270,000.
H-101	N/A	$861,000.
H-102	N/A	$9,282,000.
H-103	N/A	$2,810,000.
R-101	N/A	$532,926,000.
Hot Box Insulation	N/A	$1,155,000.
NG Piping	N/A	$150,000.
Total Cost	$951,000,000.	$856,000,000.

SOFC Stack Specifications and Layout

A vital part of our design are the SOFC requirements. This includes such decisions as the arrangement of parts in the SOFC hot box, assumed cell and stack characteristics and total number of fuel cells needed for our energy producing process.

First, cell characteristics were determined by comparing and adjusting the provided cell model to match SOFC voltage and current density data. In a patent by Steele Fuel Cells for lower temperature fuel cell voltage and current density data, it was observed that high utilization of fuel could be achieved within a fuel cell that has a maximum operating temperature only around 600°C [45]. This is ideal for the ultimate goal of keeping costs of the system low by using cost-effective materials. Based on the graph and data available in the report our model was adjusted to give a similar voltage-current density curve, shown in Figure 5. These characteristics may be achievable by using materials such as ferritic stainless steel interconnectors, yttria-stabilized zirconia anodes and electrolytes, and a compound that is called LSCF for the cathodes, which are materials that would be ideal for the design. This is summarized with corresponding material thicknesses in Section A3 in the appendix. Fuel utilization, current density, and temperature distribution are used to determine fuel flow per cell and required cell amount per hot box, which are shown in appendix Figure 15.

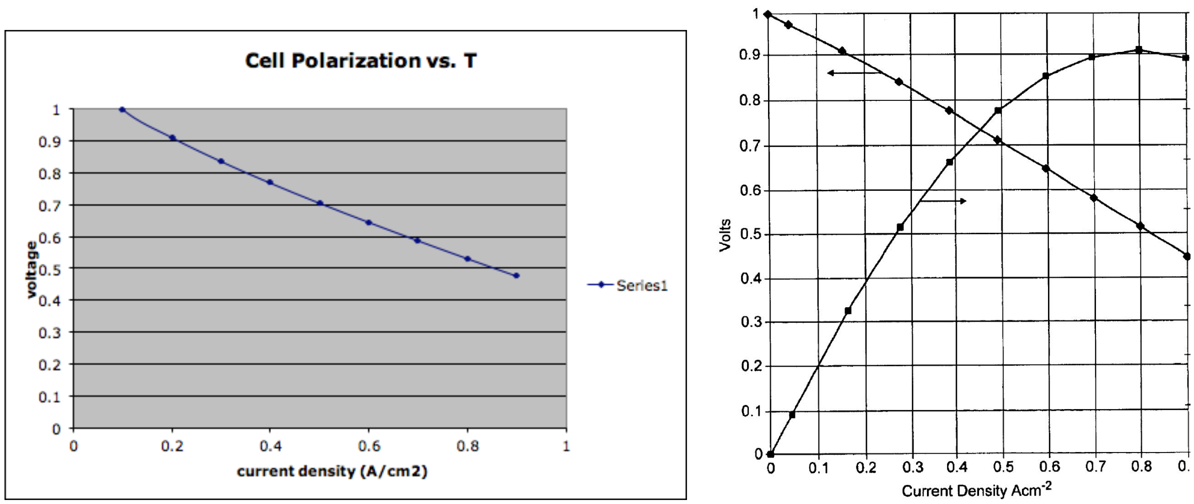

Figure 5. designed i-V curve (left) imitating the literature i-V curve (right) under 500°C [44, 45].

Using modeling and the comparisons to literature values to make i-V curves results in several important specifications. These include the possible work recovery, ideal cell length, number of cells per hot box, and fuel flow which was also modelled with mass and energy balances to give the necessary electrical work for our system. These results are summarized below, in Table 7.

Table 8. SOFC specification [44, 45]

Electrical Work	50	kW
Cell Voltage	0.5	volt
Total Current	21.3	amps/cell
Cell power	10.7	watts/cell
Work Recovery	49	%
Number of Stacks	30	stacks
Number of Rows	3	rows
Stacks per row	10	stacks
Cells per Stack	157	cells
Total Cell Number	4687	cells
Cell Thickness	4	mm
Cell length	10	cm
Fuel flow	2.74e-5	mol/s
Fuel Utilization	99.6	%

Figure 6 shows a layout of the fuel cell box in each unit. Inside the fuel cell box, 4687 cells are needed and divided into 30 stacks with each having 157 cells. 30 stacks are evenly distributed in 3 rows with each one containing 10 stacks. The yellow area represents the stacks, and the gray area represents rooms for piping and wiring. Thus, with each cell having an area of 100 cm^2, there is 468,700 cm^2 of cell area total in each SOFC. For our entire total of 3000 hot boxes, there will be 14.06 million cells required at minimum for our whole data center to operate. In Section A1 of the Appendix, Figure 12 in the unit design specification section has the hot box arrangement, which shows the SOFC requiring the most space, while the fuel pre-reformer, air preheater, and steam generator heat exchangers are much smaller.

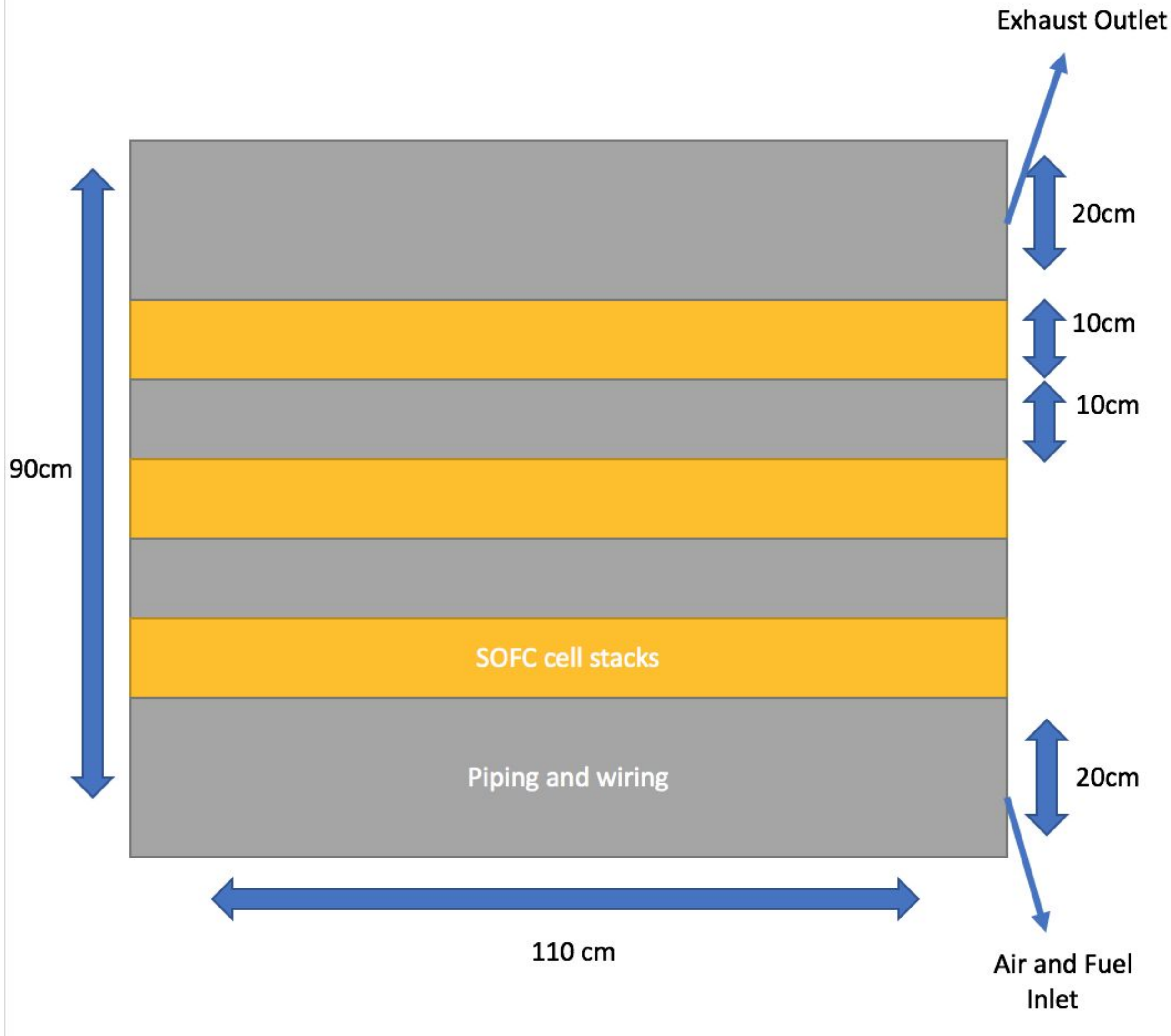

Figure 6. Fuel Cell Box Layout.

In every process, minimization of heat loss is a vital part of optimization. Our hot box will be enclosed overall by an outer layer of stainless steel, and just inside of it there will be insulation. This will be a 1” ceramic fiber material, as specified in the overall unit design, based on available high temperature insulation materials [42].

Each hot box will have a modular cost dependent mainly on the heat exchanger prices and the price of all of the cells. Based on comparison with readily available heat exchangers close to our required sizes, these will cost almost $13,000,000 total for our data center. With a breakeven price compared to the on-grid electrical power system, the cost of the fuel cell within a module must be $209,000 or less, using the design that has been presented. This price was calculated based on the totals of calculated prices excluding the SOFC cost, then comparing the total and solving for a price per SOFC that would result in the breakeven price at the end of our ten-year comparison period.

Based on this back calculation price analysis, and optimization presented in the next section, the resulting cell cost is a maximum of 30 cents per cm^2, to make the breakeven price. This was calculated based on the total cost of the SOFC and the total area of cells in each SOFC. Additionally, the whole hot box, which has a footprint of 9900 cm^2 by the design, will only be a viable design if the module costs less than \$21.15 per cm^2.

Process Optimization Analysis

In order to be a viable option to compete with the grid, the current model must meet strict cell fabrication cost constraints, limited by things like:

- **The use of a Perovskite precursor solution**. This makes up the electrolyte solutions in the electrodes and is highly costly.

- **Each cell is extremely delicate with a thickness of 4 mm and with a complicated sandwich structure**. The more cells are in one stack, the higher the cost of techniques, like annealing, to create these structures.

In order to offset these costly fabrication limitations, our cells must be optimized in their performance such that the number of cells and fuel flow rates required are balanced to give the best return on investment.

Thus, to find optimized fuel flow rate per cell, the highest allowable price per area of SOFC is what we desire. Voltage is very closely tied with the fuel flow rate, and Figure 7 shows how the maximum allowable price per area of a cell changes with the voltage varying. As the voltage rises, the total fuel flow rate decreases, but the required number of cells per hot box increases. Purchasing more cells is costly, as is increasing the fuel flow rate, and optimization must occur to find the best cell characteristics. From Figure 7, we can observe that at 0.5 volts, it reaches a maximum allowable price per area of SOFC at \$0.3/cm^2. As the voltage deviates positively or negatively from 0.5 volts, the cells need to be less expensive to meet the breakeven point that we analyzed in the TCO section. If we choose to operate at 0.5 volts and be able to purchase the cells at any price lower than \$0.3/cm^2, it will be easier to make profit than picking any other voltages. As a result, 0.5 volts is chosen as our operating voltage. Table 13 in Section A5 of the Appendix shows the data we need to plot Figure 7. Many prices are considered in the calculation of the price per area, such as heat exchangers, which have changing duties, and therefore different heat exchangers must be used depending on those requirements.

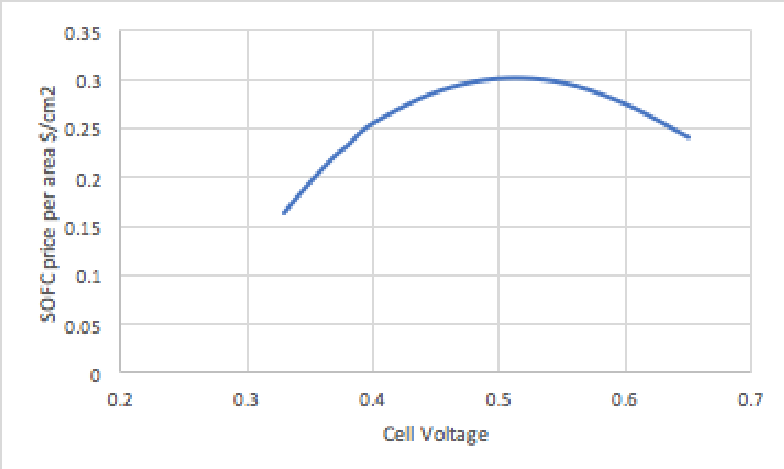

Figure 7. Process Optimization

Discussion/Recommendations

Through our analysis we have concluded that the use of Solid Oxide Fuel Cells is viable. Reliability and environmental motivations are easily realized with the use of SOFCs, and this analysis makes suggestions on the economic requirements to make SOFCs competitive with an on-grid electricity set up. Optimization of economics and fuel cell characteristics provide guidelines of the requirements for process viability. Our design uses lower temperatures than other SOFCs to reduce material costs throughout, but still has a fuel utilization of 99.6%. Economic struggles in each design are centered around the utility needed. Electricity in the on-grid situation is just under a billion dollars for the 10-year period, when adjusted to present value, making up 97% of the calculated costs in the $TCO_{initial}$. In the SOFC set up, natural gas is a third of the price of the electricity, reducing the utilities impact on the overall price. Instead, the dominant price is the cost of the SOFCs, and to break even, each SOFC must cost $177,000, which leads to a maximum of 30 cents per square centimeter price for the fuel cells.

There are also several design considerations included in our current design that may pose as constraints for efficient operation of our data center. For this reason, these constraints also represent future recommendations to further improve this design. The following constraints are what we must consider:

- **Thorough insulation**. Insulation between pipes and units are not used. In this report we only considered the insulation for the hot box itself. Practically, thorough insulation around all pipes and units should be used to achieve optimal operating temperatures for each unit, and for future designs we recommend this course of action.

- **1D Coflow**. The model we are using right now is 1D coflow. For both air and fuel entering the cells alternatively from the same side with only millimeter separation distance, the complexity of piping is extremely high. We also recommend analyzing this further, and perhaps even considering 1D Crossflow, as discussed further in the next bullet point.

- **1D Crossflow**. However, for cross flow, air and fuel enter the cells from two sides which could be easily achieved without piping or separator installed at the entrances or exits of cells. This may be an optimization option that may be considered, as costs will be significantly less using crossflow.

Appendix
Section A1

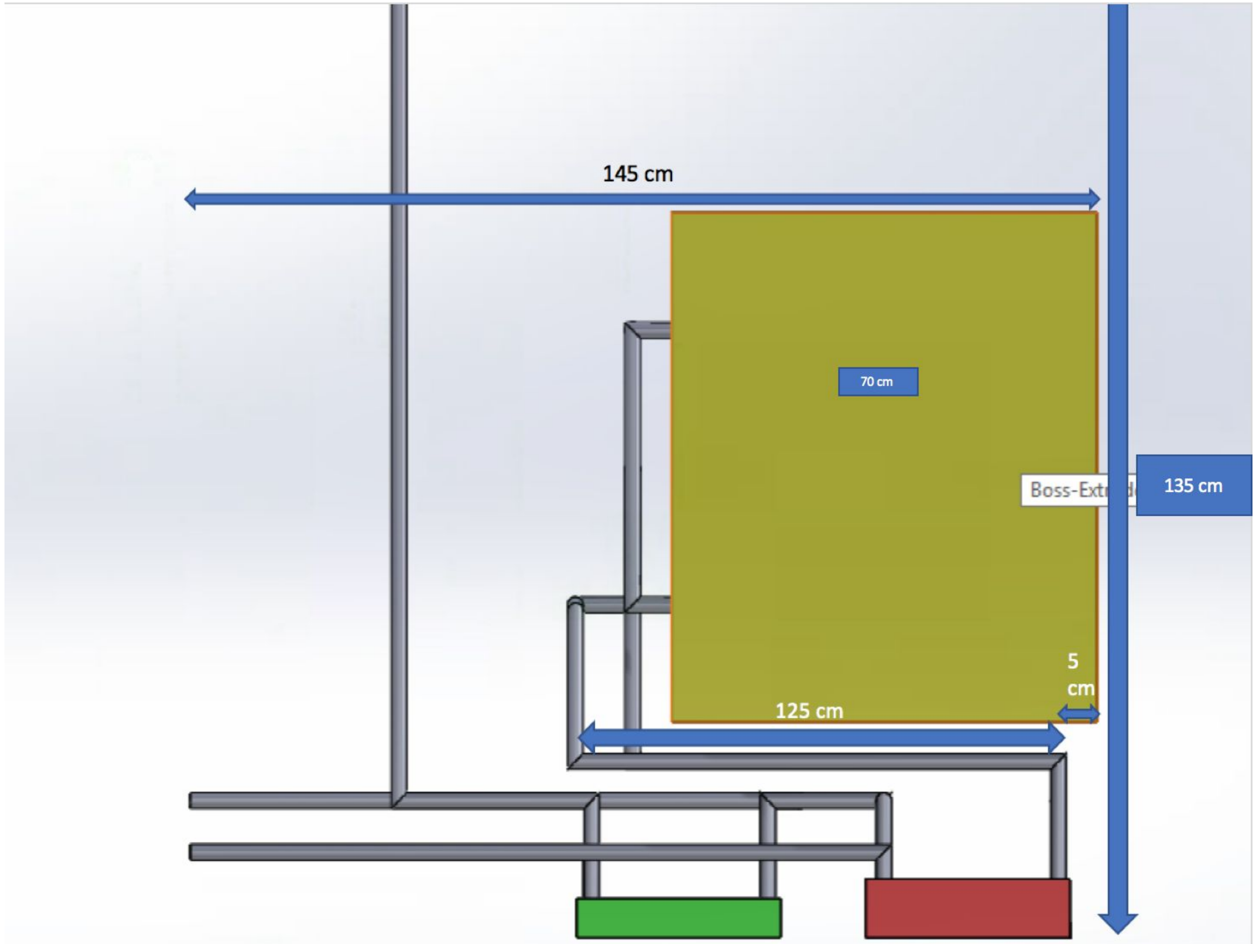

Figure 8. hot box Layout

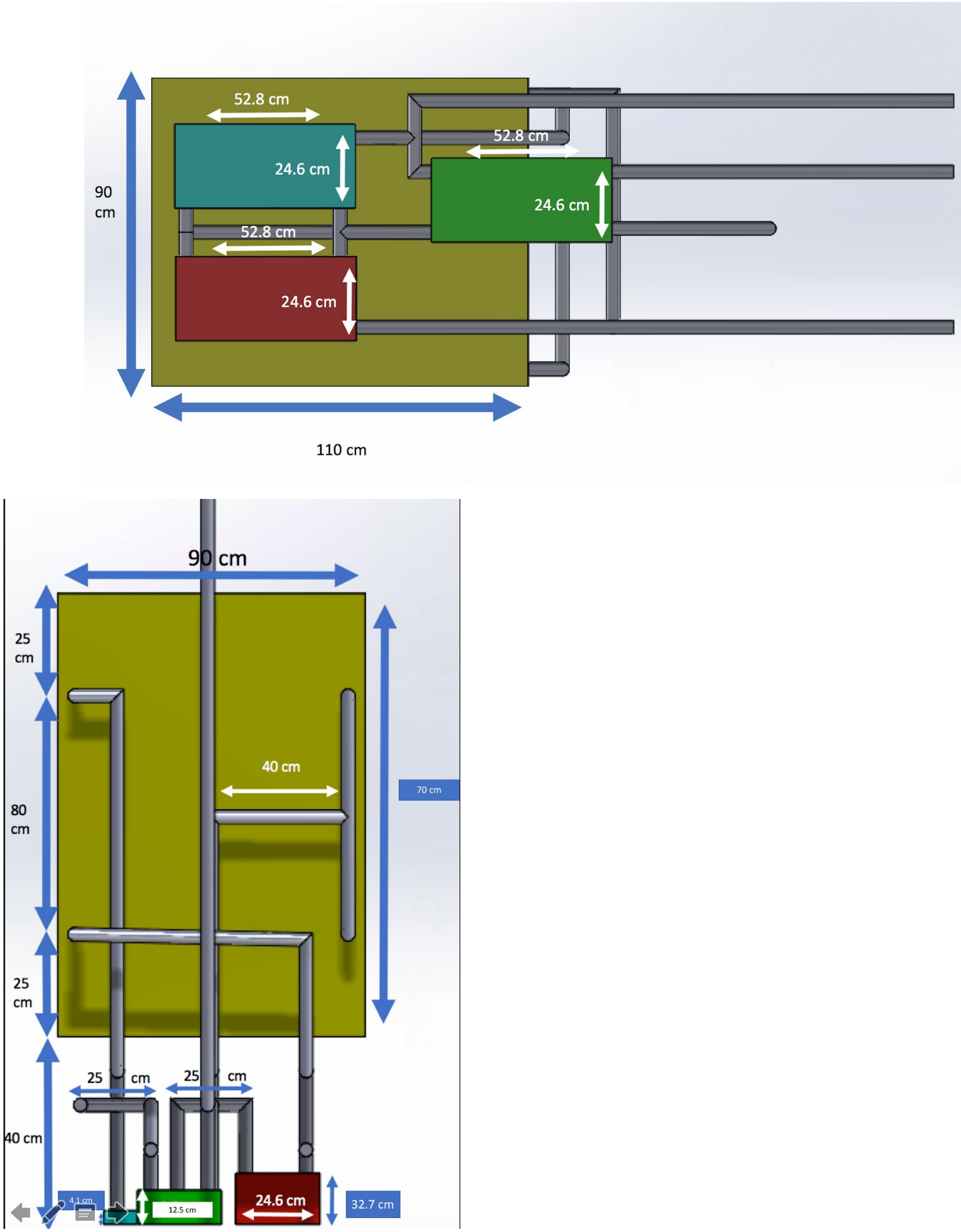

Figure 9. Alternate views of the hot box

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Section A2. Layout of the Data Center

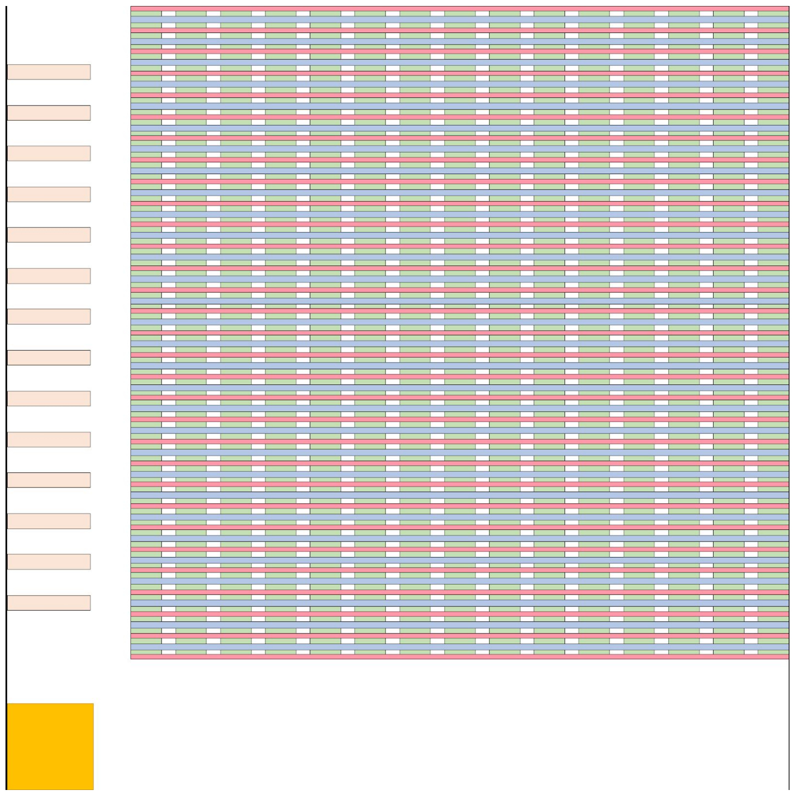

Figure 10. Layout of Data Center (Scale of 1:200 scale map)

Table 9. Key for Data Center Components

Notation	UO	Specification	Quantity
	LNG Storage Tank	2.89 x 2.89 x 16.15 m [30]	14
	Racks and SOFCs	1.99 x 5.99 x 1.07 m,10 racks per, with SOFCs for every 3 racks.	900
	Cold Aisle	1.22 x 1.07 m	30
	Hot Aisle	0.914 x 1.07 m	31
	Space between rows	2.74 x 1.07 m	840
	Regulatory and Registration	16.764 x 16.764 m	1

Section A3. Layout of SOFC

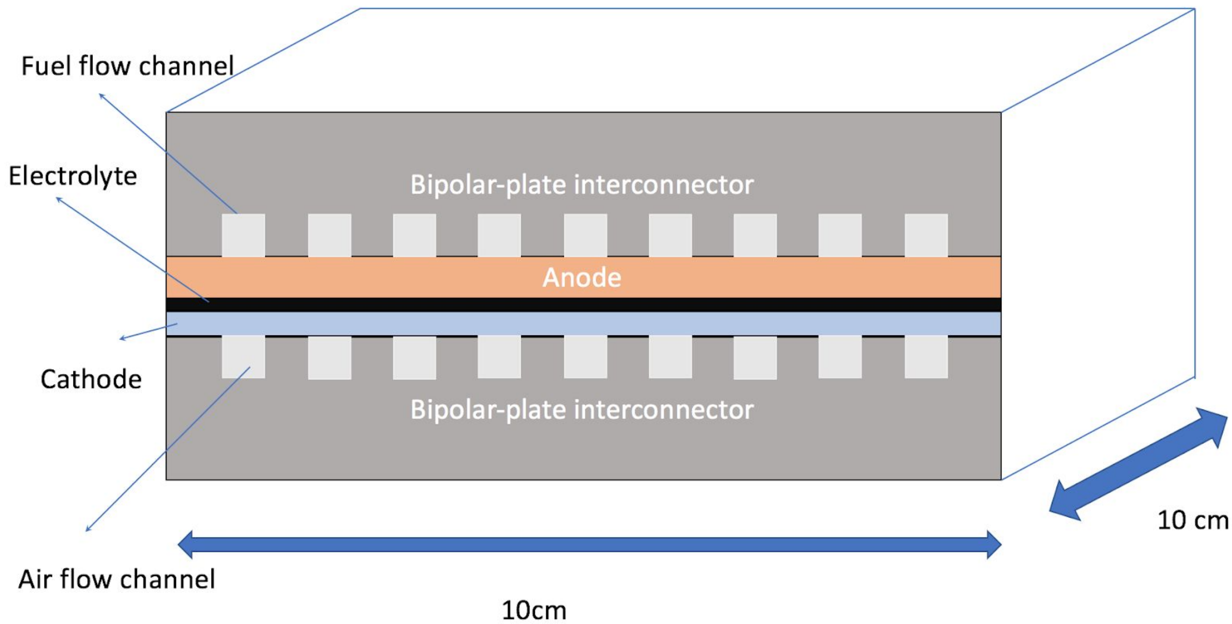

Figure 11. Layout of fuel cell [44, 45]

Table 10. SOFC unit cell design specifications [44, 45]

Component	Thickness (mm)	Material
Bipolar-plate interconnector	1.72	Ferritic Stainless steel
Fuel flow channel	0.5	N/A
Anode	0.5	NiO-YSZ (Yttria-stabilized zirconia)
Electrolyte	0.01	YSZ
Cathode	0.05	LSCF ($La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$)
Total	4	N/A

Section A4. Heat Exchanger Sizing

Heat Exchanger Sizing

Heat flow calculation

$dH = C_p dT$

$\Delta H = \Delta U + \Delta(pV)$

$\Delta U = q + w = q - p\Delta V + w_{shaft}$

$\Delta H = q - p\Delta V + w_{shaft} + \Delta(pV)$

$assume\ constant\ pressue, and\ no\ shaft\ work$

$\Delta H = Q = \int C_p dT$

$\Delta H\ for\ each\ stream\ is\ calculated\ in\ the\ supplementary\ excel\ file$

Heat transfer area calculation

$Q = UA\Delta T_{lm}$

$$\Delta T_{lm} = \frac{(T_{hot,in} - T_{cold,out}) - (T_{hot,out} - T_{cold,in})}{\ln\left(\frac{(T_{hot,in} - T_{cold,out})}{(T_{hot,out} - T_{cold,in})}\right)}$$

$assume\ U = 30 \frac{W}{m^2 * K}$

$A = \frac{Q}{U\Delta T_{lm}} = Heat\ transfer\ area$

$Below\ is\ the\ calculated\ heat\ transfer\ area\ of\ 1)\ reformer\ 2)\ air\ heat\ exchanger\ 3)\ steam\ generator$

Reformer					
Heat Transfer Area Calculation					
Input			**Output**		
Q	9290	J/s	T_lm	234.68952	
T_hin	897	K	**A**	1.3194342	m^2
T_cin	413	K			
T_hout	528	K			
T_cout	673	K			
U_est.	30	W/m^2*K			

Air HX					
Input			**Output**		
Q	93792	J/s	T_lm	216.62151	
T_hin	897	K	**A**	14.432582	m^2
T_cin	298	K			
T_hout	529	K			
T_cout	673	K			
U_est.	30	W/m^2*K			

Steam gen					
Input			Output		
Q	16942	J/s	T_lm	108.21447	
T_hin	529	K	A	5.2186611	m^2
T_cin	298	K			
T_hout	466	K			
T_cout	464	K			
U_est.	30	W/m^2*K			

Plate heat exchanger

$$N = \frac{Heat\ transfer\ area}{Heat\ transfer\ area\ per\ plate} = Number\ of\ plates$$

$Heat\ transfer\ area\ for\ each\ unit\ operation\ is\ previously\ calculated,$

$and\ the\ heat\ transfer\ area\ per\ plae\ is\ given\ as\ 0.1099m^2$

$Length\ and\ width\ of\ the\ heat\ exchanger\ is\ given\ as\ 52.8cm\ and\ 24.6cm$

$H = 11.5 + 2.40 * N = Thickness$

$Below\ is\ the\ calculated\ dimension\ of\ 1)\ reformer\ 2)\ air\ heat\ exchanger\ 3)\ steam\ generator$

Plate heat exchanger: [3]					
A required	1.31943418		# plates	12.0057705	
L	52.8	cm	H	4.03138492	cm
W	24.6	cm			
A per plate	0.1099	m^2			

A	14.4325815		# plates	131.324672	
L	52.2	cm	H	32.6679213	cm
W	24.6	cm			
A per plate	0.1099	m^2			

A	5.21866114		# plates	47.4855427	
L	52.2	cm	H	12.5465302	cm
W	24.6	cm			
A per plate	0.1099	m^2			

We have used plate heat exchangers as they allow for the maximum heat transfer for a given area. Figure 13 shows how the orientation of the plates yields maximum heat transfer [41]. In calculating the dimensions of the heat exchangers, a commercially available heat exchanger was referenced. KAORI is a Taiwanese manufacturer of brazed plate heat exchangers, and the model H series targets the fuel cell industry with its resistance to high temperatures up to

900°C. The pricing of the units was not available, which led us seek alternatives for pricing purposes only.

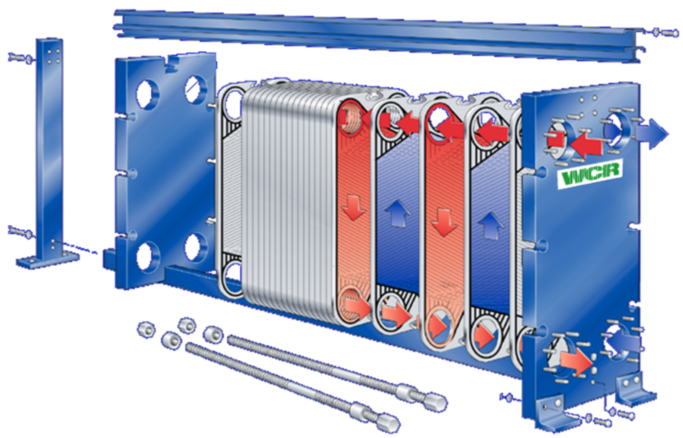

Figure 12. Structure of The Plate Heat Exchanger [47]

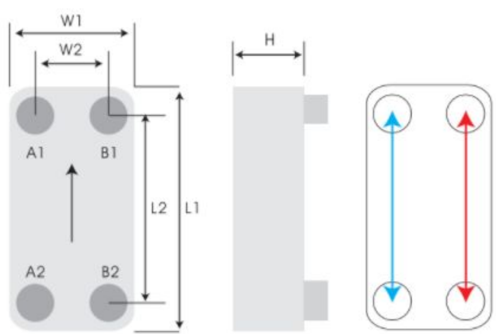

Figure 13. Heat Exchanger Dimensions [47]

Table 11. Heat Exchanger Dimensions [47]

Model	L1, length (mm)	W1, width (mm)	H, thickness (mm)	Heat Transfer Area per Plate (m^2)
H205	528	246	11.5+2.40*N	0.1099

The parameter N in heat exchanger thickness is the number of flat plates required. It is easily calculated with previously determined heat exchanger area, and gives the total dimension of all the heat exchangers units presented in Table 1.

Section A5. Pricing Calculations

Table 12. Industry Models for Heat Exchangers [46]

HX	Industry Model	HT Area (m^2)	Price
H-101	B3-36A 40 Plate Heat Exchanger with M8-1.25 Mounting Studs	1.37 m^2	$205/unit
H-102	B3-95A 160 Plate Heat Exchanger with M8 Mounting Studs	15.2 m^2	$2210/unit
H-103	B3-95A 40 Plate Heat Exchanger with M8-1.25 Mounting Studs	3.8 m^2	$669/unit

For **H-101:**
Base price: $205/unit
Material change factor: 1.4 ($ 316 stainless steel/$ 304 stainless steel)
Total number of H-101s needed: 3000

Total cost of H-101 heat exchangers:

$$\frac{\$205}{Unit}\frac{3000\ Units}{Whole\ data\ center}\frac{1.4\ (316\ stainless\ steel)}{(304\ stainless\ steel)} = \$861000$$

Present value pricing for utilities:

Electricity:

Annuity to Present Value:

$P = A * \frac{(1-(1+r)^{-n})}{r}$ [54]

Where P is the present value, A is the annuity value, r is the interest rate/ rate of return, and n is the number of periods

For Electricity, A=$103411800 per year, r = 2.12%, and n is 10 years

$P = \$103411800 * \frac{(1-(1+0.0212)^{-10})}{0.0212} = \$923,100,000.00$ (rounded)

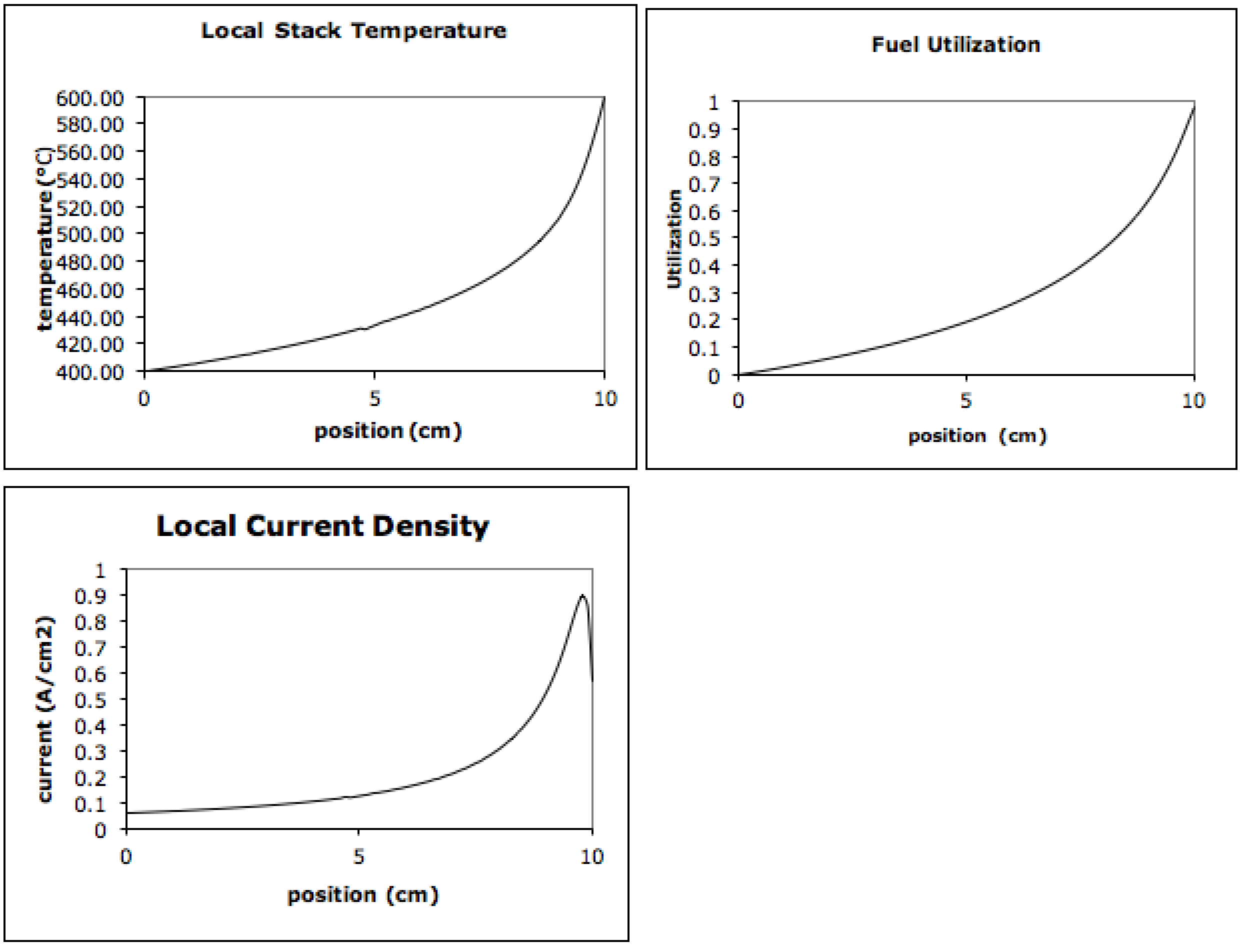

Figure 14. Cell characteristics: temperature, fuel utilization, and local current density along length.

voltage	total flow rate	cells	fuel cost	sofc cost	cost per area
0.33	0.206	4128	652254373.7	203595226	0.16440183
0.35	0.195	4079	617425256.7	238424343	0.194838885
0.37	0.184	4097	582596139.6	273253460	0.222319958
0.38	0.18	4094	569931006.2	285918594	0.232794817
0.4	0.17	4142	538268172.5	317581428	0.255578165
0.45	0.1515	4358	479691930.2	376157670	0.287714295
0.5	0.13637	4687	431786062.8	424063537	0.301588463
0.55	0.124	5192	392619137.6	463230462	0.297400143
0.6	0.1136	6000	359689790.6	496159809	0.275644339
0.65	0.105	7223	332459753.6	523389846	0.241538533

Table 13. Data required to plot Price per cell area vs Voltage.

Molar flow per hotbox (mol/sec)	sec/min	min/hour	12 hour	hotbox	total mol
0.13637	60	60	12	3000	17673552
Methane denstity (mol/gallon)	gallon	tank size (gallon)	# of Tanks		
99.66	177338.471	13000	13.6414208		

Table 14. LNG tank sample calculation.

SOFC Pricing:

Using the 10% desired profit margin, the following relation was created:

$TCO_{Final} = 0.9*TCO_{Initial}$

Then, the difference between those values is set to zero by changing the price of the SOFCs. This was done using excel solver, and yields the result of each SOFC needing to cost $209,000 or less to get the desired profit.

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