Hydrogen Powered Micro-Grid

Team ASU : Design Report

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Executive Summary

In this design proposal, a hydrogen powered micro-grid system is outlined and analyzed to perform the task of backing up electrical power to a portion of a college campus, ASU Polytechnic campus. If the electrical grid power is lost, then this micro-grid system will act as a backup power system to keep the buildings running for up to two days. The design goal is to have the micro-grid power a group of buildings up to 90% of peak power for up to 2 days of typical usage. A group of 16 building on ASU Polytechnic campus have been selected for the design. The typical power profile for an average building starts the design and analysis. Instead of creating one large mega-watt power generation plant, our design team has elected to create a distributed power system where each building receives its own backup power plant. This approach is analogous to an uninterrupted power supply (UPS) system on a per-building basis. Each micro-grid system is powered by a photovoltaic array located on the roof of the building. The photovoltaic array then powers a water electrolyzer to generate hydrogen to be stored. The generated hydrogen is then compressed to around 200 bar and stored in a group of 15 hydrogen storage cylinders. When backup power is needed, the stored hydrogen is delivered to two groups of proton exchange membrane fuel cells. Combining the power of the fuel cell groups and the photovoltaic array, up to 90% peak power can be delivered during typical peak power periods. Each micro-grid system can deliver up to 84 kW during mid-day sunny conditions and can deliver 750 kWhr of energy per day for two days. Economic analysis of the system show that each micro-grid system costs near $500,000 and has a lifespan of 21 years. When taking lifetime power generation, initial cost, and maintenance costs into account, the electricity cost works out to be 15.5 cents per kWhr. The ASU micro-grid system demonstrates that backup power for public buildings using hydrogen as an energy storage medium can be feasable.

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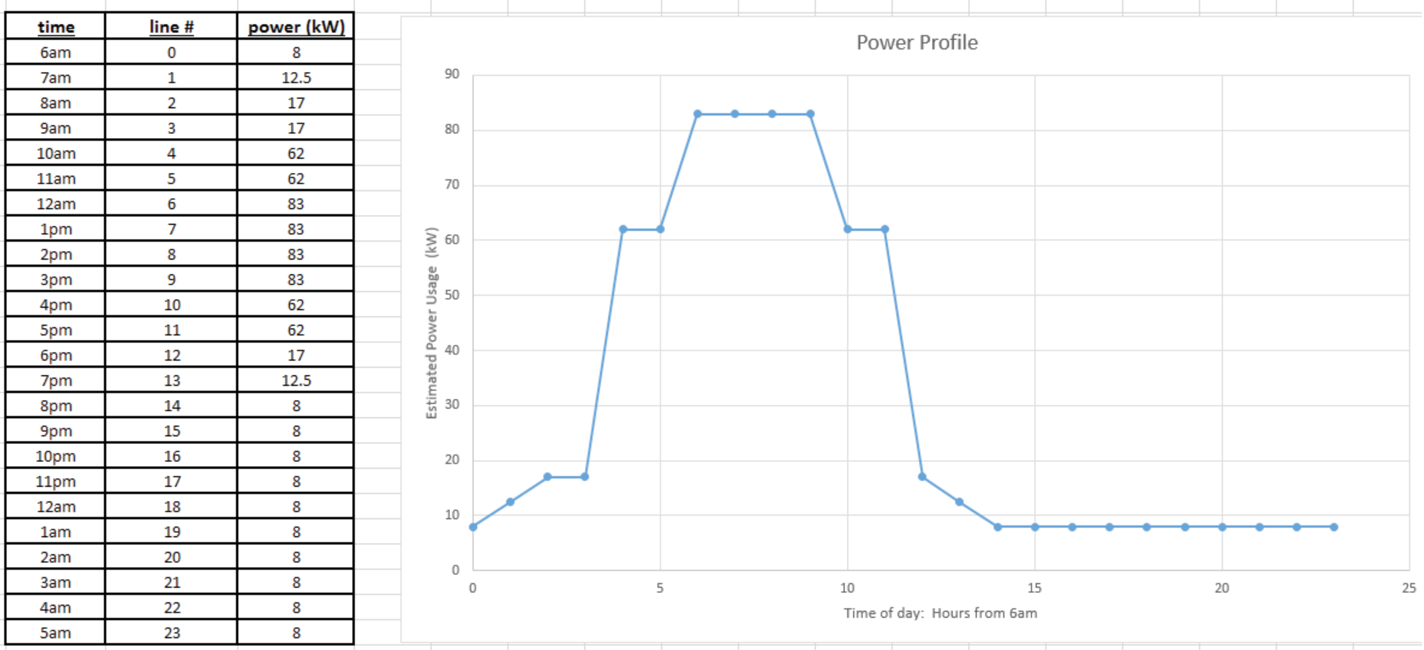
I. Design Approach

The proposed micro-grid design is implemented on a per-building basis. At Arizona State University, we propose a incremental approach to realize a hydrogen powered electric backup utility system. The goal of the electric power backup system is to supply power to on-campus buildings during a macro-grid power outage. The micro-grid acts as a uninterrupted power supply to a building which can supply up to 90% of typical peak power usage for a period of two days. To start the design process, an average electric power usage profile for one building is presented below in figure 1.



time	line #	power (kW)
6am	0	8
7am	1	12.5
8am	2	17
9am	3	17
10am	4	62
11am	5	62
12am	6	83
1pm	7	83
2pm	8	83
3pm	9	83
4pm	10	62
5pm	11	62
6pm	12	17
7pm	13	12.5
8pm	14	8
9pm	15	8
10pm	16	8
11pm	17	8
12am	18	8
1am	19	8
2am	20	8
3am	21	8
4am	22	8
5am	23	8

figure 1 : typical building power profile

Two key parameters are extracted from the power profile, the peak power usage of 82kW and the total energy used during one day, 750kWhr. The peak power will determine the required power generation capacity and the total energy will specify the required hydrogen storage capacity. Converting the total energy to mega-Joules, 750kWhr is equivalent to 2700MJ. Noting that hydrogen has a specific energy of 141.86MJ/kg, the mass of hydrogen needed for one "building-day" is 19.033 kg. Taking into account the typical efficiency of a proton exchange membrane fuel cell (PEMFC) which is 40%, 47.6 kg of hydrogen is used in one building-day.

As a consequence of being located in Arizona, solar power is an abundant renewable energy source. To take advantage of the solar resource available, the choice for a clean energy source is a photovoltaic system. For our system, an array of photovoltaic modules will power a water electrolyzer to produce hydrogen, or be used to augment the micro-grid. Note that the power profile from figure 1 shows peak power usage only during times where the sun is high in the sky, around 10am to 6pm. This feature allows for the photovoltaic system to reliably augment the micro-grid during peak usage. In other words, when the macro-grid is available, the photovoltaic system may power the water electrolyzer to produce hydrogen. When the macro-grid is not available, the photovoltaic system may augement the power capacity of the micro-grid. This dual-role feature of the photovoltaic system is a key attribute of our design approach which significantly reduces the overall cost of the micro-grid system.

To outline the overall structure of the proposed micro-grid system, each major component of the system is briefly discussed. We start with the photovoltaic system; a 24kW photovoltaic system is implemented using 96 photovoltaic modules (250 Watts each). The inverter for the photovoltaic system is a 24kW, 3 phase, 480V industrial power inverter. The 480 volt, 3 phase output allows the photovoltaic system to directly interface to either the water electrolyzer or the building power directly without the need for further power conditioning. The water electrolyzer then produces hydrogen with a rate capacity of 10 Nm^3/hr. The output of the water electrolyzer is then fed to a compressor unit which raises the pressure from 30 bar to 248 bar. The high pressure hydrogen is then stored in a 9000 Liter storage tank with a maximum pressure of 248 bar. A system controller unit will monitor the storage tank pressure to determine how full it is. While the macro-grid is online, if the hydrogen storage tank is full, the photovoltaic power will be diverted to power the building. When the macro-grid goes offline, the UPS feature of the micro-grid is activated. Hydrogen from the storage tank is fed to a two stage pressure regulator which reduces the hydrogen pressure to a level compatible for the PEM fuel cell arrays. The fuel cell system consists of two groups of PEM fuel cells. Each fuel cell group consists of six 5kW PEMFCs with a combined power output of 30kW. In total, both fuel cell groups have a 60kW power capacity. The output power from the fuel cells is again 480V, 3 phase to be compatible with both the building power and the output of the photovoltaic system. When the macro-grid is offline, peak power available from the entire micro-grid system is a combination of the two fuel cell groups and the photovoltaic system, resulting in a total power capacity of 84kW during ideal conditions. Photovoltaic power contribution may derate to13.8kW and still meet the 90% peak power requirement. An overall system diagram is shown below in figure 2.

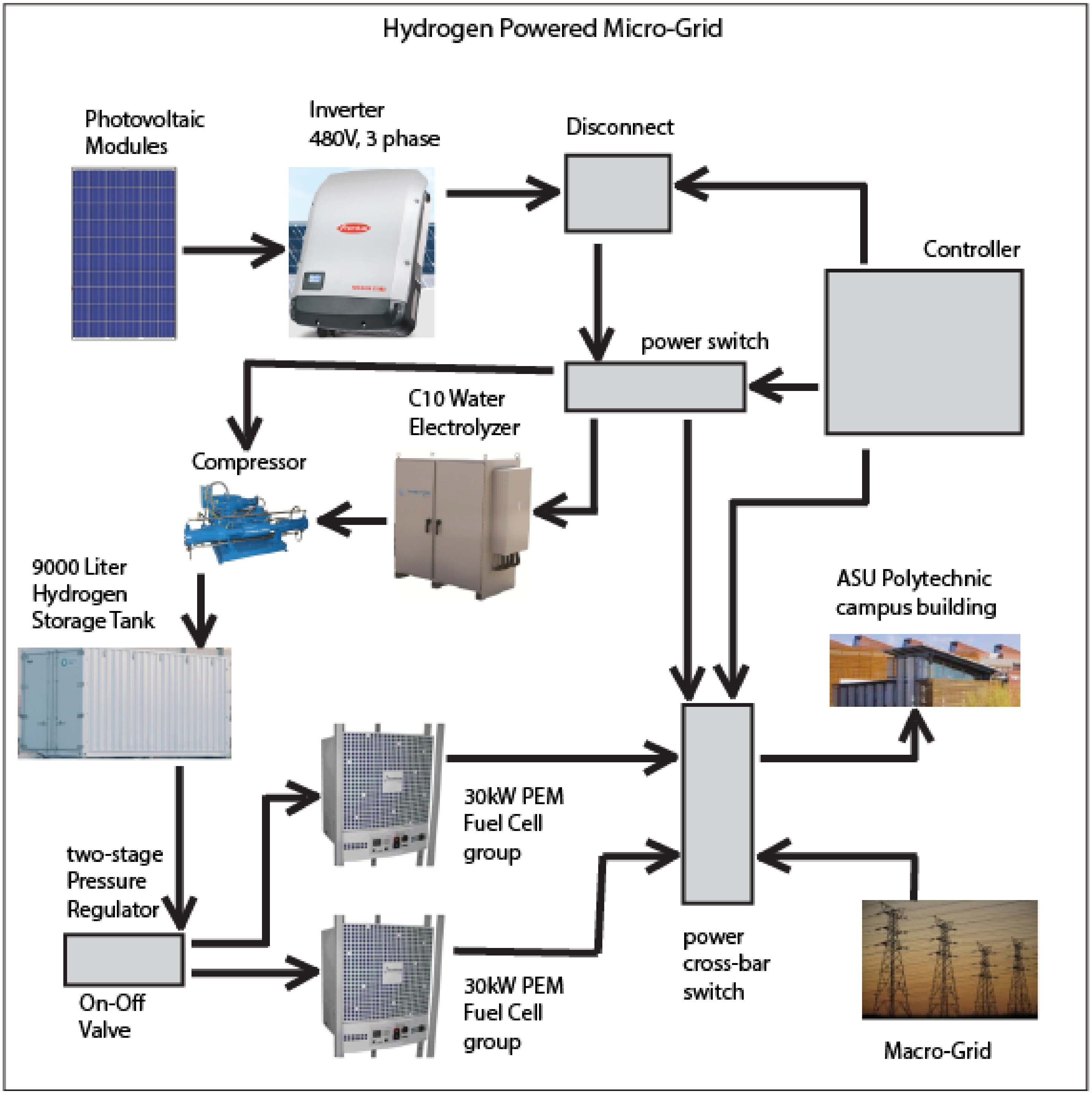


figure 2 : Hydrogen Powered Micro-Grid Simplified Block Diagram

The controller unit receives input from various sensors in the system. For example, the controller monitors the status of the macro-grid and the pressure of the hydrogen storage tank. Additionally, the controller monitors the power output of the photovoltaic system and both fuel cell groups. Last, the controller monitors the load power delivered to the building. With these information sources, the controller can set the proper system state for the power switch, cross-bar switch, disconnect and hydrogen on-off valves.

II. Photovoltaic System

The photovoltaic system consists of 96 photovoltaic modules connected in four strings of 24 modules. The selected solar panels are the Trina Solar TSM-25_PA05.08 modules which are rated at 250 W. The number of modules connected in series is determined by the input voltage range of the inverter, and the number of strings connected in parallel is determined by the inverter power capacity and the system requirements. With 4 strings of 24 modules, the DC output of the photovoltaic array is 726V at 33A at the maximum power point. To minimize the real estate taken up by the PV array, we propose to mount all 4 strings on the roof of the building. The PV array should be mounted to be south facing with a 5:12 pitch to maximize fixed performance. The actual area taken up by each string is shown below in figure 3, and the building roof can fit all 4 strings.

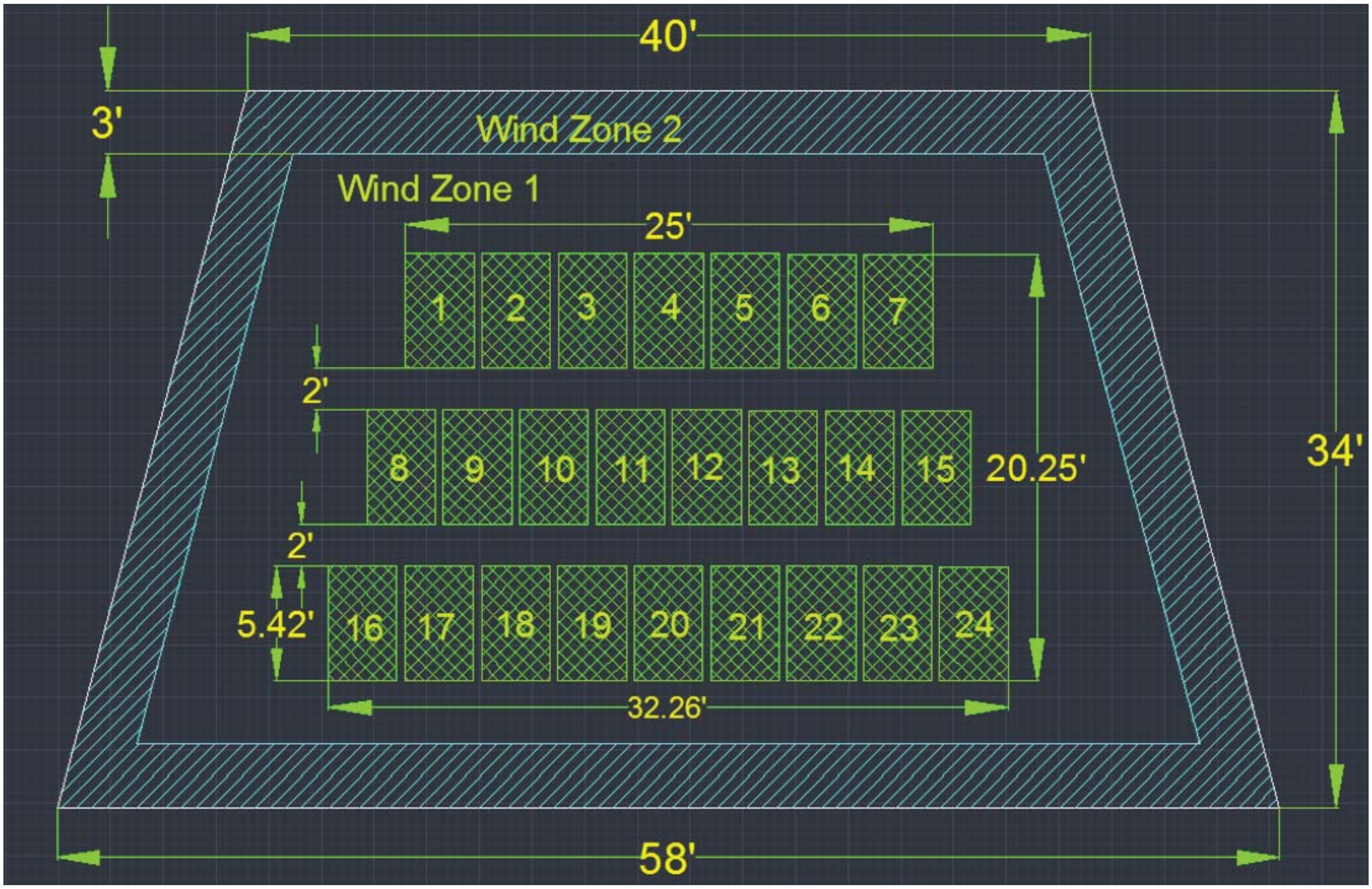


figure 3 : PV module string layout

The PV array feeds into a Fronius Symo Lite 24.0-3 inverter. The inverter is rated at 24kW, the same input power that is received from the PV array. The output of the inverter is 480V, 3 phase power which is then sent to the disconnect. The disconnect device is a mandatory safety device to disconnect the PV array under hazardous conditions. The output power is then delivered to the power switch which is in turn managed by the controller.

III. Water Electrolyzer and Compressor

The choice of hydrogen generation is electrolysis of water. The design requires that the storage system must recharge completely from an empty state within 2 weeks. In other words, for two building-days, 95.2 kg of hydrogen must be generated in 336 hours. Therefore, the minimum hydrogen generation rate is 283.3 g of hydrogen per hour. For our design, we chose the Proton C10 hydrogen generation system which has an adjustable generation rate between 0 and 900 g of hydrogen per hour. To meet the minimum generation rate, the Proton C10 system would be operating at 31.5% capacity. One reason for operating below maximum H_2 generation capacity is the limited power available from the PV array. From the C10 data sheet, the power consumed by the C10 system is rated at 68.9 kWhr/kg of H_2. If the C10 system were operating at maximum capacity (900 g/hr), it would require 62kW of power. If operated at 32% capacity, the C10 system consumes 19.84kW of power which is within the power range of the PV array. If a faster H_2 generation rate is required, power to the C10 system may be augmented by the macro-grid. Also note that the PV array may commonly operate below ideal operating conditions and so power available from the PV array may often be less than 24kW. In addition, the PV array must also deliver power to the compressor. The bottom line is that the 24kW PV array combined with the C10 system is a nice balance between required H_2 generation rate and available power from the PV array. Of course the PV array only delivers power during daylight hours; if we assume that the equivalent hours available for PV power per day is 8 hours, then it would take 42 days to completely recharge the H_2 storage tanks. To meet the system requirement of a 2 week recharge period, macro-grid power must be used to power the C10 system and the compressor during non-daylight hours. The upside to this requirement is that off-peak macro-grid power is cheaper. If macro-grid power is not to be used, then the system will take 42 days of good sunlight conditions to fully recharge.

The Proton C10 hydrogen generation system has other inputs besides electrical power. First, a source of de-ionized (DI) water must be provided. This water source serves as the water that is electrolysed to create the hydrogen. The C10 data sheet states that DI water is consumed at a rate of 2.4 gallons per hour at maximum capacity. Running at 31.5% capacity, 0.756 gallons per hour of DI water is consumed. Second, the C10 system requires a second source of water for cooling. The C10 system must be cooled during operation and the amount of coolant water required is significant. At maximum capacity, the C10 system required 24 gallons per minute of coolant water flow. Taking into account operation at 31.5% capacity, 7.56 gallons per minute of coolant water flow is required. To reduce operational costs, the coolant system may consist of a closed system where the same coolant water is recycled. Using a water resevior and a heat radiator system, the system may operate using a closed loop water supply. At maximum capacity, the C10 system generates 33.5kW (114307 BTU/hr) of heat; at 31.5% capcity, the C10 system generates 10.55kW (36006 BTU/hr) of heat. With a 20% safety factor, the coolant system for the C10 must be able to dissapate 12.67kW of heat during the hottest day-time conditions.

The hydrogen output from the C10 system is nominally at 30 bar of pressure (435 psi). The hydrogen compressor must be able to compress the hydrogen from 30 bar (435 psi) to 284 bar (3596 psi) of pressure while flowing 3.15 Nm^3/hr (1.853 scfm). For our design, we chose the Hydro-Pac C03-03-300/600LX two-stage hydrogen compressor. This compressor is designed to operate with an input pressure between 300 and 600 psi and outputs a maximum discharge pressure of 3000 psi. The flow capacity under these conditions is rated at a maximum rate of 5.3 scfm. Taking into account the actual flow rate of 1.853 scfm, the compressor would be operating at 35% capacity. This compressor matches up well with the C10 hydrogen generation rate. If the C10 hydrogen generation rate is increased above 31.5%, the compressor will be able to keep up with the flow. In other words, the compressor can keep up with the C10 hydrogen generation rate up to 90% H_2 generation capacity. The downside of the compressor selection is the lower output pressure, 3000 psi instead of 3596 psi. The limited output pressure results in a lower storage capacity of hydrogen within the storage tank. Taking the ratio of 3000psi over 3596 psi, we find that only 83.43% of the hydrogen storage capacity is utilized. The electrical power used by the compressor is 2.3kW at maximum capacity. Running the compressor at 35% capacity results in a lower power requirement, about 1kW. The design compromise is that we trade lower output pressure for keeping the compressor within the PV array power budget. The added benefit is that the operational pressure of the storage tank is lower than expected, thus increasing the safety factor of the storage tank.

IV. Hydrogen Storage Tank

The hydrogen storage tanks must contain enough diatomic hydrogen to generate energy for two building-days. From part I, we found that this value of stored hydrogen is 95.2 kg of H_2 which is 47,225 moles H_2. Using the ideal gas law, we may calculate the required volume to accomodate 47,225 moles of H_2 compressed to 3000 psi. Also, the outside temperature of the Phoenix Arizona weather must be taken into account. In the summer time, afternoon temperatures typically reach 108 degress Fahrenheit (42.2 degrees Celsius). Adding a 20% safety factor, we calculate required volume at a temperature of 130 F (54.4 C or 327.5 K). For gas at high temperature and pressure, the ideal gas law is slightly modified due to strong inter-molecular forces. The result is the introduction of a "compressibility factor", Z. Using standard tables, we find hydrogen at 330K and 3000 psi (206.84 bar) has a compressibility factor of 1.08.

$$V = \frac{n \cdot Z \cdot R \cdot T}{P} = \frac{(47225 \cdot mol) \cdot (1.08) \cdot \left(8.314 \cdot {}^{J}\!/\!_{mol \cdot K}\right) \cdot (327.5 \cdot K)}{(20684280 \cdot Pa)} = 6.714 \cdot m^3 = 6714 \cdot Liters \qquad (1)$$

For our design, we chose Hexagon Composites TUFFSHELL MAGNUM Tanks™. These hydrogen storage tanks are made of high-strength carbon fiber / glass hybrid material with a polymer liner. Each tank is equipped with a safety pressure release valve. Choosing the 450 liter tank size, we find that 15 tanks yield 6750 liters of storage capacity. Each tank has a physical shape of a cylinder of 10 feet long and 2.1 feet diameter. To protect the cylinders from the weather and curious spectators, our design houses all 15 cylinders in a small outdoor shed located at the ground floor at the back of the building. The shed structure should provide ventillation to help keep the cylinders at a reasonably cool temperature. Figure 4 below shows an image of the cylinders.

figure 4 : Tuffshell hydrogen storage cylinders (450 liters)

V. Fuel Cells

For the fuel cells, our design features two groups of Ballard Electragen H2 fuel cells. These PEM fuel cells have the capability to be grouped together in banks of 6 fuel cells at 5kW each. Each group then generates 30kW of power yielding a total power generation capacity of 60kW. A key feature of the Electragen is the built in power management option where the output can be specified as 480V, 3 phase. The expected operating lifetime of the fuel cells is 4000 hours. The fuel cells can be located outside the building next to the shed where the hydrogen storage cylinders are located. This will minimize the length of H_2 feed lines to the fuel cells.

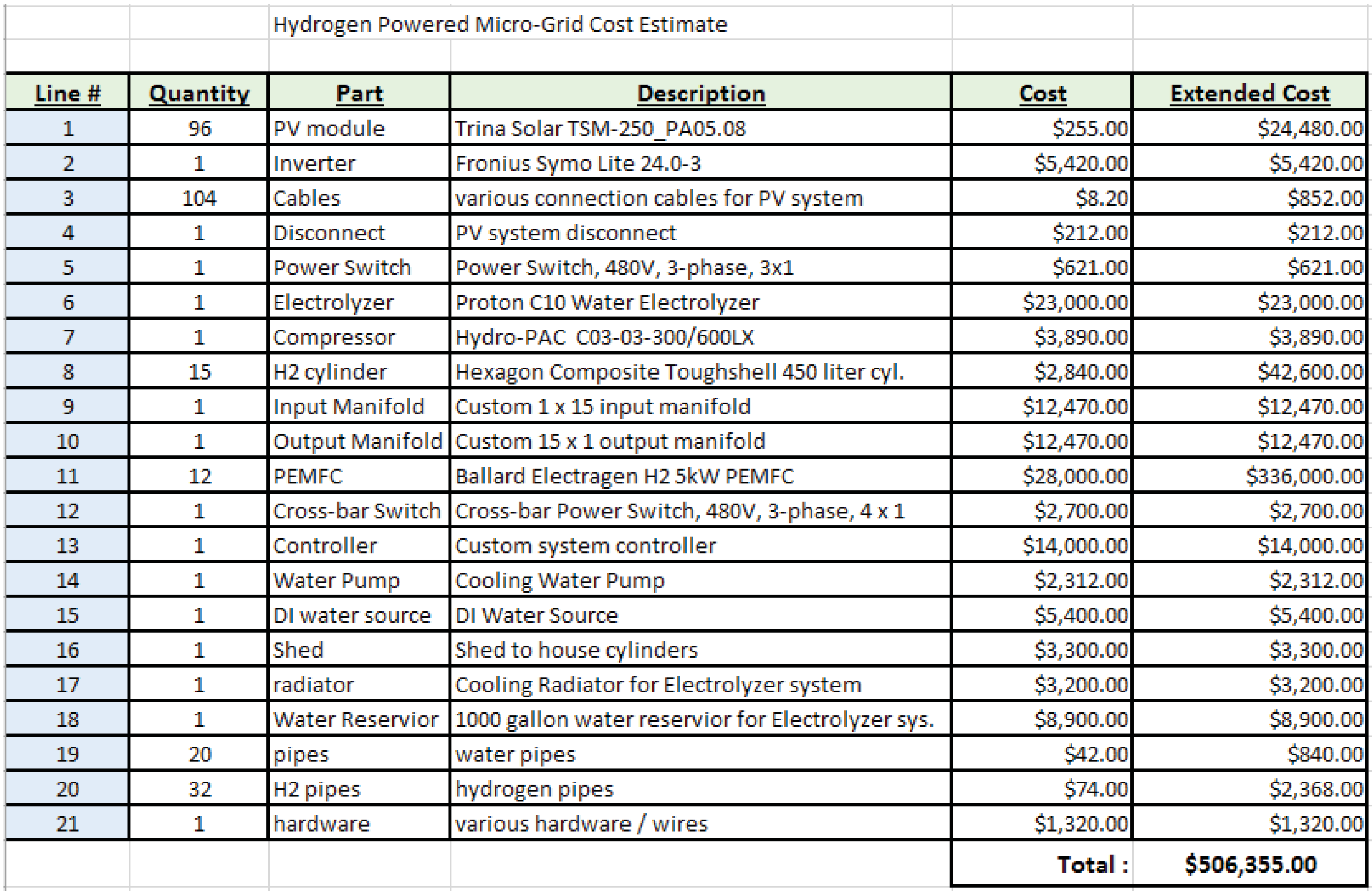
VI. Controller, Power Switches, BOP

The controller is to be located inside a utility room of the building. Since no such controller with the specific operating specifications is available, a custom solution is necessary. The controller can be a simple personal computer with a custom program that controls the micro-grid through IO such as ethernet and expansion cards. The controller senses the status of the micro-grid and macro-grid to make decisions on the state of the micro-grid system. The state of the disconnect, power switches, cross-bar power switch and H_2 control valves is managed by the controller. The power switch and cross-bar power switch are similar in that they control the flow of 480, 3 phase power. The cross-bar switch has a rating of the full power of the building load (96 kW) while the power switch only needs to be rated for the PV array power (24kW).

For the balance of plant items such as the pressure regulators, hydrogen manifolds, and hydrogen control valves, standard off the shelf components may be used. For example, the pressure regulators must reduce the storage tank pressures (~200 bar) down to the input pressure required by the fuel cells. The hydrogen control valves turn on or off the H_2 supply to either fuel cell group. Last are the hydrogen manifolds. As the storage cylinders are filled, the generated H_2 must be routed to the next cylinder. When all cylinders are full, some signal must be sent back to the controller. Similarly, for using the stored hydrogen, as cylinders are drained, a separate manifold must select the next cylinder to keep the hydrogen flowing. In total, there is an input manifold for hydrogen entering the storage cylinders and there is an output manifold for hydrogen leaving the storage cylinders. Both manifolds interface to the controller to send status data and receive commands.

VII. Cost and Economics

For each building, an estimated cost for the micro-grid is listed in table 1 below.



Hydrogen Powered Micro-Grid Cost Estimate

Line #	Quantity	Part	Description	Cost	Extended Cost
1	96	PV module	Trina Solar TSM-250_PA05.08	$255.00	$24,480.00
2	1	Inverter	Fronius Symo Lite 24.0-3	$5,420.00	$5,420.00
3	104	Cables	various connection cables for PV system	$8.20	$852.00
4	1	Disconnect	PV system disconnect	$212.00	$212.00
5	1	Power Switch	Power Switch, 480V, 3-phase, 3x1	$621.00	$621.00
6	1	Electrolyzer	Proton C10 Water Electrolyzer	$23,000.00	$23,000.00
7	1	Compressor	Hydro-PAC C03-03-300/600LX	$3,890.00	$3,890.00
8	15	H2 cylinder	Hexagon Composite Toughshell 450 liter cyl.	$2,840.00	$42,600.00
9	1	Input Manifold	Custom 1 x 15 input manifold	$12,470.00	$12,470.00
10	1	Output Manifold	Custom 15 x 1 output manifold	$12,470.00	$12,470.00
11	12	PEMFC	Ballard Electragen H2 5kW PEMFC	$28,000.00	$336,000.00
12	1	Cross-bar Switch	Cross-bar Power Switch, 480V, 3-phase, 4 x 1	$2,700.00	$2,700.00
13	1	Controller	Custom system controller	$14,000.00	$14,000.00
14	1	Water Pump	Cooling Water Pump	$2,312.00	$2,312.00
15	1	DI water source	DI Water Source	$5,400.00	$5,400.00
16	1	Shed	Shed to house cylinders	$3,300.00	$3,300.00
17	1	radiator	Cooling Radiator for Electrolyzer system	$3,200.00	$3,200.00
18	1	Water Reservior	1000 gallon water reservior for Electrolyzer sys.	$8,900.00	$8,900.00
19	20	pipes	water pipes	$42.00	$840.00
20	32	H2 pipes	hydrogen pipes	$74.00	$2,368.00
21	1	hardware	various hardware / wires	$1,320.00	$1,320.00
				Total :	**$506,355.00**

table 1 : Cost estmiate for Micro-Grid per Building

If the micro-grid system is installed on 16 buildings on ASU Polytechnic campus, the estimated cost would be :
16 x $506,355.00 = $8,101,680.00 (US dollars)

Each micro-grid is an 84kW system, then the total aggregate power capacity over 16 buildings is 1.344 MW.

Operational Cost Analysis (per building-month) :

Water Usage :	5000 gallons per month	$ 18.72	
Maintenance :	Clean photovoltaics	$370.00	(campus job created)
	Monitor system	$720.00	(campus job created)
	General Maintenance	$ 350.00	(campus job created)

	Total:	$1458.72 per building per month	

Over all 16 campus buildings, operational costs : $ 23,339.52 per month

Estimated electricity cost : Solar + backup power, 8 peak-days per month (96,000 kWhr), 24 cents / kWhr

Over 4,000 hour lifetime, system will last 83 months or about 7 years.
With 2 system overhauls at 7 year intervals, system lifetime estimated at 21 years. (overhaul ~$510,000.00)
Total System electrical power cost : $15,003,239 / 96,768,000 kWhr = 15.5 cents per kWhr.
-> benefit : Campus will have backup power for 21 year period at only 3.5 cents over standard rate.

VIII. Safety Analysis

For the safe and continued operation of the micro-grid system, proper safe guards are designed into the system and operational procedures. Over the lifetime of the system, regular maintenance is necessary to maintain high safety levels during operation. Starting with the safe design of the system, the micro-grid design will conform to the National Electric Code NFPA 70. Although the operating voltage of the micro-grid is 480V, 3-phase which is under 600V, all micro-grid power transmission lines are to be placed at a safe distance from normal pathways. All high power access points are to be sectioned off using a fence or other barrier. Only trained authorized personel are permitted access to high power access points. The photovoltaic system operates at 726V and is thus a high voltage system (over 600V). All NEC NFPA70 requirements are to be put in place. Again, only trained authorized personel are allowed access to the photovoltaic system. Electrical conduit is to be used for all applicable power cables in accordance with NEC NFPA 70. Circuit breakers and disconnects shall be placed at appropriate locations in the system to prevent any fire hazard. In areas where maintenance should be performed, proper safeguards and distances shall be included in the design.

Operational procedures are of equal importance as the design safeguards. All personel operating or maintaining the micro-grid system shall be trained in applicable emergency procedures and scenarios. In addition, basic safety training shall be completed by all personel working with the system. Literature outlining the micro-grid safety procedures shall be published and available to the public. The same safety bulletins and publications shall be posted in common areas for the university community to review. Unforseen events such as lightning strikes and impact damage to the micro-grid shall have set safety procedures to be included in published documentation.

Maintenance personel shall receive proper training before performing any function. Maintenance personel must also pass a written examination demonstrating proper awarenes of hazards and emergency procedures before authorized to work at various locations. For example, the PV array cleaning does not need a specialist to perform the task, however the person carrying out the cleaning must be aware of the hazards and safeguards when cleaning the PV array. All lockout-tagout procedures are to be followed at all times.

The Ballard Electragen H2 fuel cells meet applicable safety standards such as CE, ANSI/CSA FC1:2012. The storage tanks and hydrogen delivery lines must pass testing before the system is certified for use. Hydrogen can be dangerous if a leak is not detected and fixed. Proper leak testing equipment must be used at all hydrogen pipe junctions to ensure there are no leaks in the system. All pathways where hydrogen lines are present shall have a upward vent or a direct atmosphere vent path. Proper labels shall be posted in all areas of the system that store, use, or transport hydrogen such as the NFPA 704 fire diamond. Installation of the micro-grid shall conform to ANSI/NFPA 853, Installation of Stationary Fuel Cell Power Plants. The micro-grid system shall conform to NFPA 110, Standard for Standby Power Systems. Each micro-grid PV array and PEMFC group shall conform to IEEE 1547, Interconnecting Distributed Resources with Electrical Power Systems. After installation, micro-grid qualification testing shall conform to IEEE 1547.1a, Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electrical Power Systems.

X. Operation and Maintenance

Operation of the micro-grid will be on a per-building basis. Each micro-grid will have the controller located in the building where the micro-grid is installed. The controller shall consist of a computer program connected to all micro-grid resources. The controller program shall include operational tests to verify all portions of the micro-grid are operating as defined. For all areas where hydrogen is stored, used, or transported, regular leak checks are to be performed and recorded in a system safety log. For PV array maintenance, PV modules top surfaces shall be cleaned at regular intervals using proper safety procedures. Hydrogen storage tanks shall be inspected at regular intervals to check for material fatigue or hydrogen leakage. The hydrogen compressor should be maintained regularaly according to the manufacturers recommendations.

X. Environmental Analysis

The environmental impact of the micro-grid system is minimal. The photovoltaic power generation is clean and does not produce any waste. Since the PV array is located on the building roof, no land is taken up by the PV array. The electrolyzer may have the largest environmental impact due to the cooling system. The cooling system has a large water reservior which may displace some land in the back of the building. Also, the heat radiator may present a hot object hazard. The cooling system should be fenced off to prevent injury. The hydrogen storage shed placed near the same location again displaces some land but does not produce any waste. The hydrogen storage shed should also be fenced off to prevent any injury. Most of the micro-grid system does not produce any noise. The C10 water electrolyzer system does generate some noise but is not at problematic levels. Overall the micro-grid system has zero carbon footprint and does not impact the environment except for occupying a small amount of land at the back of the building.

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