POWER^3
Early Stage Development Report 2016

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The Need

Because energy storage is the limiting factor in many renewable energy applications, an effective solution to this problem would release considerable latent demand. The economic impact of improved energy storage is predicted to be $600 billion per annum by 2025 (MGI, 2013). In addition, the effect of distributed, modular battery systems will have a transformative effect on the lives of the 1200 million people who live without electrical grid connectivity (IEA, 2015).

Currently the world's energy storage accounts for just 3% of the total electrical energy generation and the majority of this is pumped hydro-electric storage (MGI, 2013). For solar power to be viable, this needs to increase to about 50% in order to be self-sufficient. A significant proportion of this need could be met by the rapidly growing Li-ion battery market, which is doubling every four years and in 2018 is expected to be worth $24 billion (MGI, 2013). Li-ion technology is improving its battery capacity by 8% pa, a trend that is predicted to continue for at least the next 20 years (Battery Bros, 2016). By 2025 the price of Li-ion storage is expected to fall from $500 MWh at present to $100 MWh over the entire battery life due to technology improvements and improved manufacturing capability (MGI, 2013).

Idea Description

Incremental innovation doesn't exist; innovation only becomes significant if it achieves an order of magnitude increase in creating value for a solution to a global problem. The POWER^3 achieves this in the minimum capital expenditure required to obtain a stand-alone electrical system. A functional POWER^3 system costs $200; this is 8 times cheaper than the lowest cost competitor Orison and 25 times cheaper than the Tesla Powerwall, even though their systems aren't self-sufficient. Furthermore, this system has a 35% lower price per kilowatt hour ($/kWh) than the best market competitor. This system is designed to meet the efficiency and safety requirements of markets in developed countries while simultaneously pricing the product to be affordable to the enormous underserved markets in developing nations.

The POWER^3 system achieves this by utilizing a modular design comprised of three modules:

1. The battery module ($20/ea)
2. The solar panel ($60/ea)
3. The power cube ($120/ea)

The solar panels produce the electrical energy, the batteries store the energy and the power cube regulates and converts the energy into the correct forms. Although the initial capacity of the system is small every component is scalable making the final capacity perfectly match the user's needs without paying for added capacity. All connections between the components use an intuitive snap on or plug in connection that doesn't require specialist knowledge. These modules have a 3D printed design which reduces material costs, labour costs and quality assurance issues. The power cube simply plugs into any power socket to electrify a house.

Potential applications include.

- Creating a low capital pathway to a fully functioning electrical system.
- Enabling off the grid applications and self-sufficiency.
- Generating income by storing and selling electricity during peaks and troughs.
- Providing backups for energy critical operations (hospitals and server farms).

The Battery Module

Li-ion 18650 battery cells are grouped together to form larger battery packs. The minimum module size contains three LGMH1 batteries in series with a capacity of 33Wh and a peak power of 240W at 12V DC (see Figure 1). They contain a fuse to isolate the module from the rest of the pack if a short occurs. These modules can be clipped together to form larger packs of any size. A battery module will cost $15.30 to make (see Table 1) and will be sold for $20 at a profit margin of 30%.

The casing and electrical connections of the battery module will be 3D printed, reducing time of construction and quality assurance issues. Unfortunately, 3D printing conductive filaments and conductive paints have resistances that are two orders of magnitude too large for this application. The electrical connections will still be printed in conductive filament; however, this is just to make it easier to apply copper to its surface through electroplating methods. It is this copper that will conduct the majority of the required current. (See appendix 1 for the calculation of the electroplating costs.)

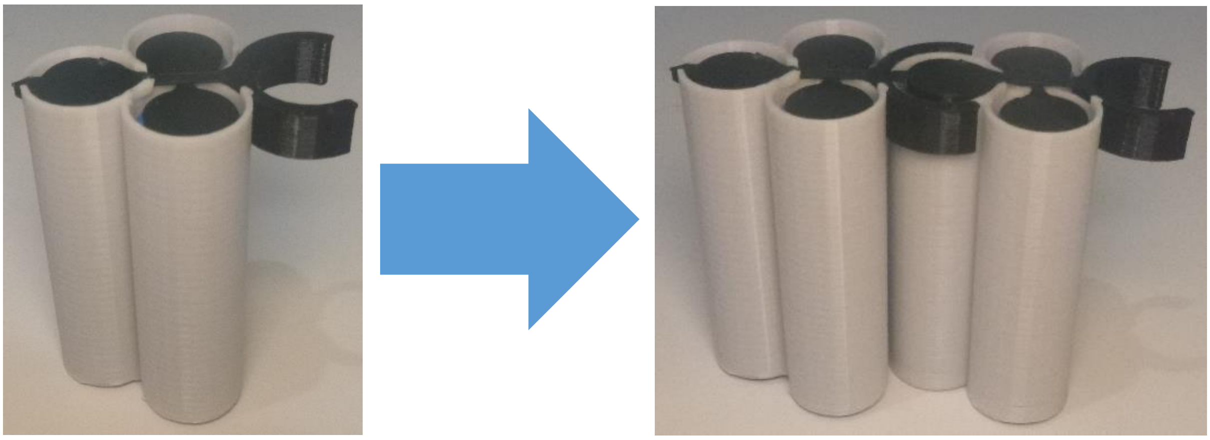


Figure 1: Prototype Battery Pack Design (black plastic is conductive, batteries inside white sleeves)

Table 1: Battery Module Cost Breakdown

Component	Cost per unit	Quantity	Cost
Battery (LGMH1)	$3.8/battery[1]	3	$11.4
Nonconductive PLA	$9/kg[2]	17g	$0.15
Conductive PLA	$550/kg[3]	4g	$2.2
Electroplated Copper	$1.56/module[4]	1	$1.56
		Total Cost	$15.3
		Cost Per kWh	$464/kWh

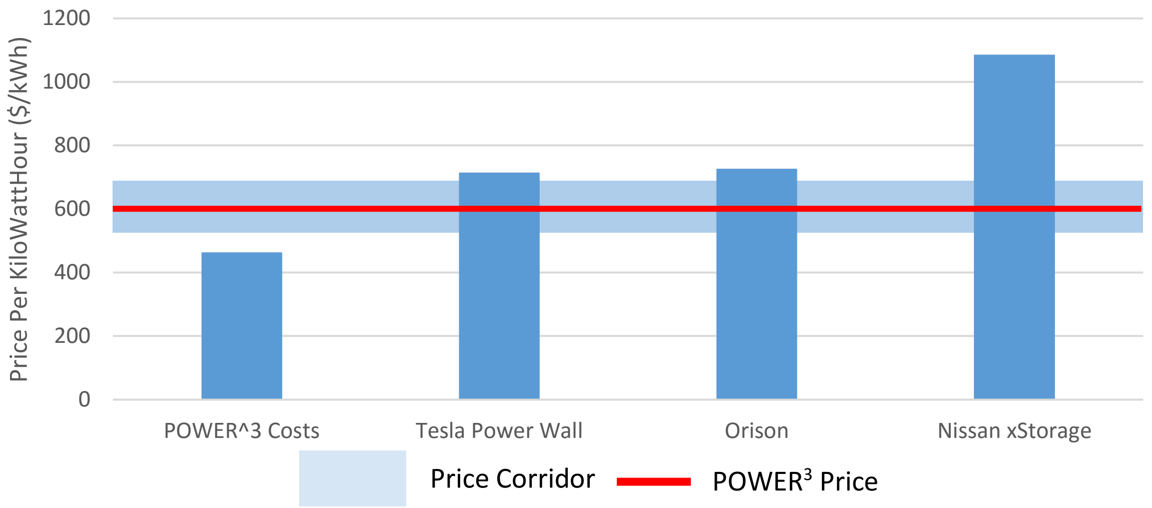
[1] Quote from Shenzhen Baishitelong Technology Company, [2] Quote from Zhuhai Sunlu Industrial Company, [3] (Black Magic 3D, 2016), [4] See Appendix 1.

To price the POWER^3 strategically it is important to set the price at its true value instead of factoring in an arbitrary profit margin. To determine this a price corridor was developed as seen in Figure 2 based on the POWER^3 cost comparison against other competitors.

The battery storage market is currently undergoing rapid growth resulting in active competition. Currently the Tesla Powerwall has the lowest price per kilowatt hour at $715/kWh and is a dominant leader. However, their high installation costs and large units outprice many customers. The POWER^3 material costs for the battery modules are $465/kWh which leaves a price corridor of $550/kWh to

$700/kWh. Due to the 3D printed design incorporating off the shelf products the POWER^3 is easy to imitate which means that it should be priced at the lower end of the spectrum at $600/kWh to dissuade competitors copying the design. This will also be within reach of impoverished customers who will only need to spend $20 per battery module.

Figure 2: Battery Module Price Corridor



(See Appendix 2 for details)

Note that 75% of the module cost comes from the cost of the batteries. As the trend of falling battery prices continues the value offering to customers or profit margins to the business will improve. These batteries can be obtained from three sources; online retailers (Battery Bros), direct from the Chinese manufacturers or from recycled laptop batteries. Table 2 compares selected batteries from each source. Battery Bros distinguishes itself on quality, ensuring every battery has the stated performance. Chinese manufacturers also assure the quality of their batteries, they typically have the same minimum order quantities as Battery Bros yet provide far better value for money. Recycling batteries can be done cheaply and locally, however the process is very labour intensive, the supply of used laptop batteries is inconsistent, there is no quality assurance on the battery performance and the battery chemistries and age is highly variable.

Table 2: Battery Source Comparison

Source	*Price*	*Capacity (mAh)*	*Max. Current (A)*	*Name*	*Reference*
Battery Bros	$7.31	3000	20	LGHG2	https://goo.gl/AQdGcs
Alibaba	$3.80	3000	20	LGHG2	Shenzhen Cylaid Technology Co. Ltd.
Recycled	$1	Variable	Variable	Variable	Substation 33

The Li-ion 18650 battery to be used in the modules is the LGHG2, which is manufactured by LG. It was developed in 2015 and is a good all round battery due to its high discharge rate (20A) and high energy storage capacity (3000mAh). The maximum and minimum voltages are 4.2V and 2.5V respectively with a nominal voltage of 3.6V. The batteries will be bought from Shenzhen Baishitelong Technology Company for $3.80/ea.

The Solar Panel

Solar cell technology cost has been exponentially decreasing (see Figure 3); however, the Australian retail price for solar panels has largely failed to reflect this achievement. For example, Jaycar sells solar panels for roughly \$3.8/Watt but the mass manufactured cost of the cells is \$0.3/Watt more than ten times less. In short, solar cells are cheap but buying solar panels in Australia is expensive. This is due to high labour and retail costs. This becomes even more apparent when this price is compared to \$1.3/W, which is the average price for solar installation in India. In order to stay competitive in both markets a strategic price must be combined with a low per unit cost. Significant cost savings has been achieved by contacting Chinese suppliers directly. Two solar panel sizes will be sold: a 50cm x 50cm solar panel delivering 40W costs \$43/ea and a 100cm x 100cm solar panel delivering 150W costs \$138/ea resulting in a cost of \$0.9/Watt.

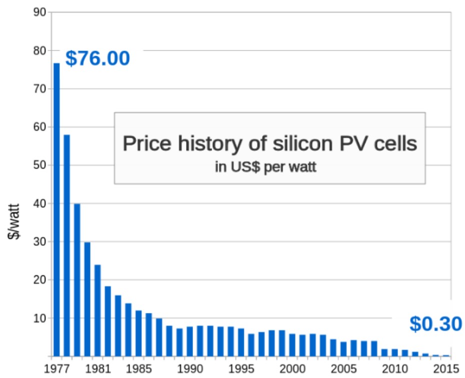
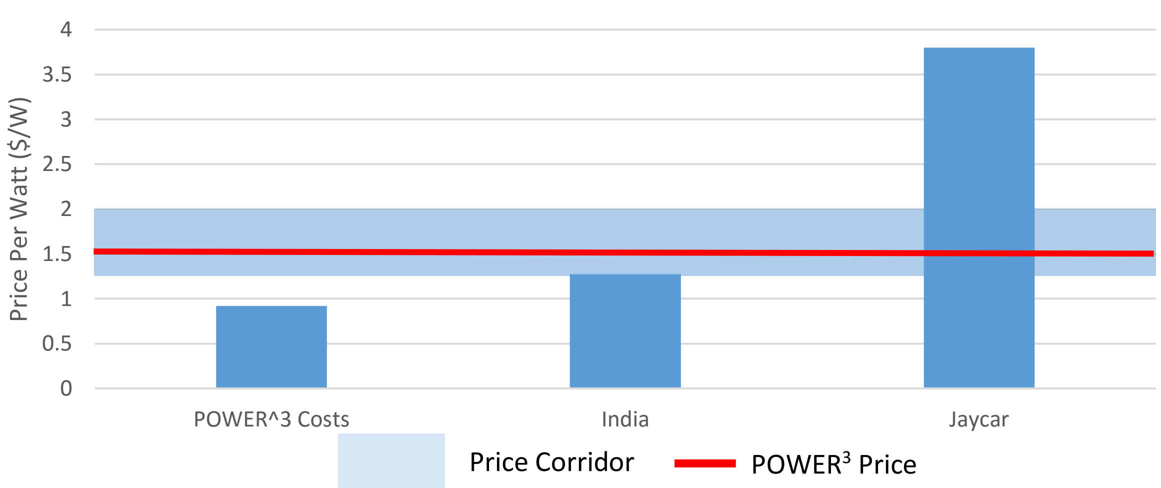


Figure 3: The exponential decline of solar cell technology (The Economist, 2012)

Figure 4 contains the price corridor for the POWER^3 solar panels which stretches from \$1.25/Watt to \$2/Watt. It shows that although it would be easier to compete in developed countries where large profit margins could be obtained, it is more strategic to price the product for the greater need and larger markets of developing countries where large volume of sales is possible. Therefore, the price of \$1.5/Watt will unlock the large demand in developing countries while also reflecting the additional value of being a modular system complete with a battery unit. As the price of solar decreases in the future it will create more value to customers or higher profit margins.

Figure 4: Solar Panel Price Corridor



Self-installation will dramatically cut labour costs and simplify the business model; however, it is important to make this installation as easy and safe as possible. Climbing up on pitched roofs is dangerous and difficult, particularly with large solar panels. So the 3D printed gutter clip system shown in Figure 5 has been developed. Each clip has a material cost of $2.5 and between two and four clips are needed per solar panel depending on size. The clip will securely attach to the gutter then the solar panel is attached to the clip and swung onto the roof. This also makes cleaning the solar panels much more efficient. All of this is performed at a safe height and is as easy as cleaning the gutters. The clips will be sold separately from the panels because they are not necessary for installation on flat roofs which is the norm in developing countries.

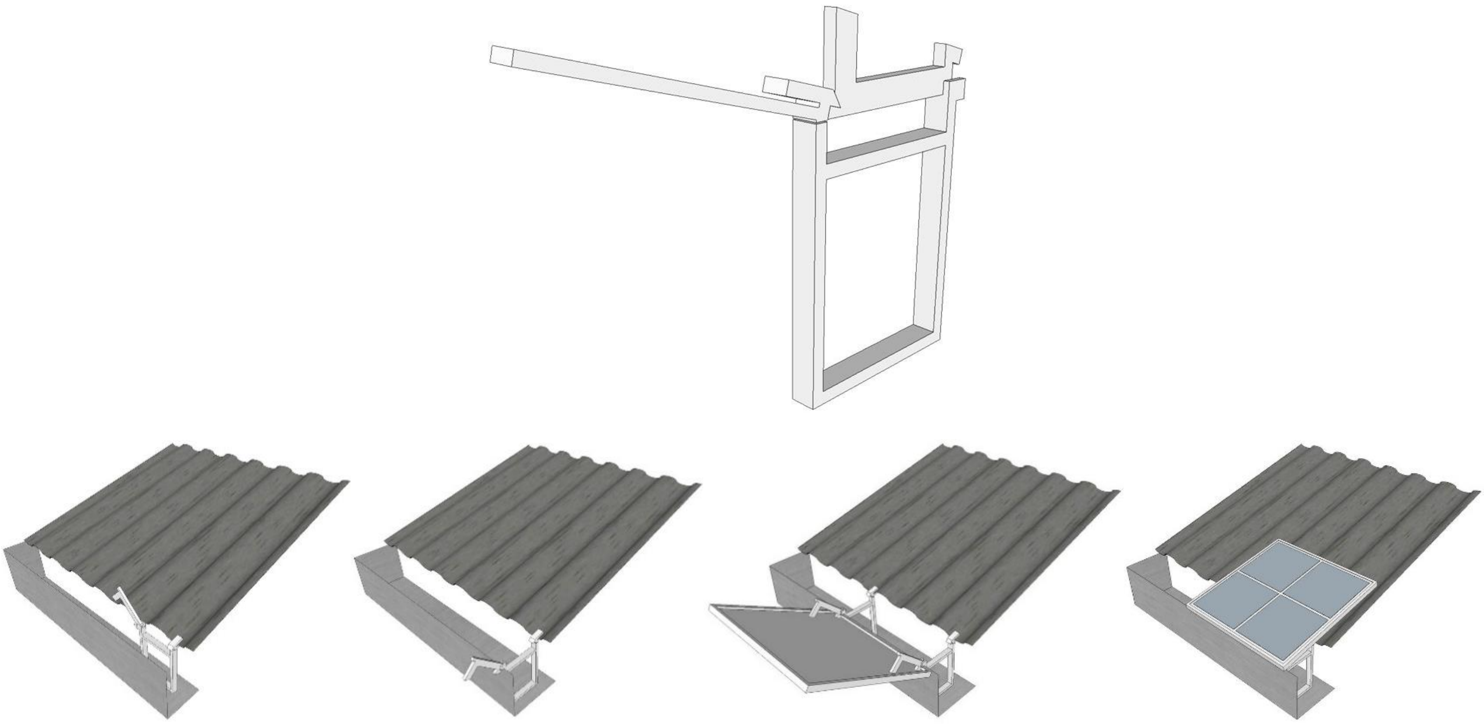


Figure 5: The 3D Printed Gutter Clip System for Solar Panels

The Power Cube

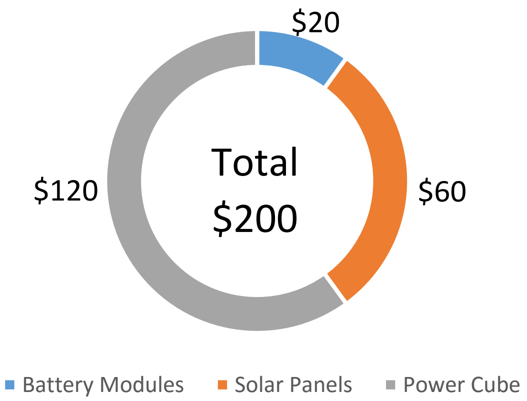
The solar panels generate the power and the batteries store it until it is needed; however there needs to be a third unit to regulate and convert the power into a useable form; this is the power cube. The power cube plugs into a standard electrical socket to electrify the house and contains the battery modules. It has 12V DC and 240V AC outlets, it contains an inverter to convert the power to the right form, it has a battery management system to correctly recharge the batteries using the solar power and it has an Arduino with a wifi shield to record and transmit power generation and usage statistics to a smartphone. The solar panels plug directly into this power cube and the batteries are stored inside.

Table 3: Power Cube Cost Breakdown

Component	Cost
Inverter (1.5kW)	$80
Arduino	$15
Case	$15
Plugs and Leads	$10
Total Cost	$120
Cost Per kW	$80/kW

The Power cube will be sold at cost ($120 see Table 3) because this represents the largest portion of the initial capital requirement (see Figure 6). The main profit margin will be generated from the solar panels and the battery modules. This results in the initial capital investment of $200 for a minimum functioning product with one battery module, one solar panel and one power cube.

Figure 6: POWER³ Total Cost Breakdown



Risk Management

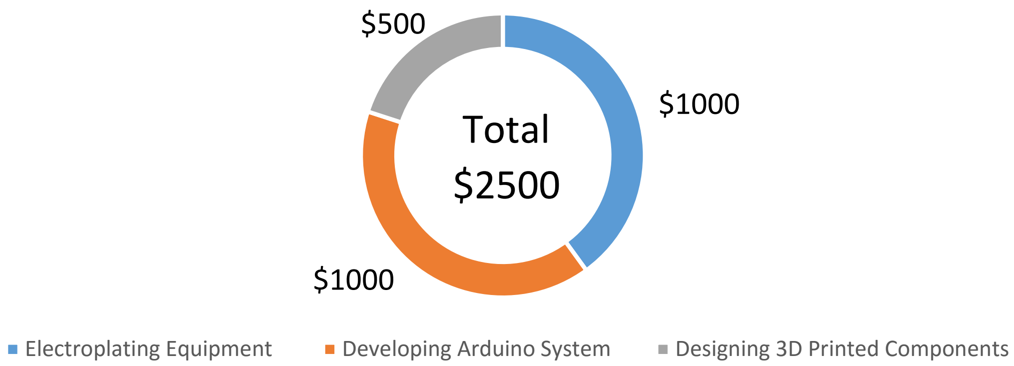
Contacts with both retailers and manufacturers have already begun. Pollinate Energy is a distributor of solar lights in India. They show significant interest in the design and would be a perfect distribution network to reach India's urban poor. Partnerships with similar social businesses and charities are also possible. Communication has begun with Chinese manufacturers; Shenzhen Baishitelong Technology Company will supply the Li-ion batteries, Zhuhai Sunlu Industrial Company will supply the PLA and Yunnan Yaochuang Energy Development Company will supply the solar panels. However, they typically require large minimum order quantities resulting in large initial costs. Covering these costs is a significant risk to the business.

Obtaining regulatory approval for use is also an important aspect. The design must protect the user from the large currents (>100A) that could potentially be generated by the system. It is important to achieve a high safety standard while not compromising the other aspects of the design.

Use of Funds

The aim is to achieve a fully functional prototype of all three module components using the $2500 prize from the DOW Early Stage Development Competition. As shown in Figure 7 the major costs involve include the electroplating equipment, development of the Arduino battery management system and the design of the 3D printed components. Once a functional prototype is obtained, more funding will be necessary to purchase the LGHG2 batteries and solar panels which have minimum order quantities of 50 and 500 units respectively.

Figure 7: Use of Funds



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Appendix 1: Estimating the Electroplating Costs

Material Costs

$$C_{material} = p \cdot \rho \cdot S \cdot t$$

Where

$$\begin{aligned}
&C_{material} = Material\ Cost \\
&p = material\ price(\$/g) = 0.0038 \\
&\rho = density\ of\ the\ material(g/dm^2 \cdot \mu m) = 8.9 \\
&S = surface\ area\ (dm^2/module) = 0.58 \\
&t = thickness(\mu m) = 50
\end{aligned}$$

Therefore

$$C_{material} = 0.0038 \times 8.9 \times 0.58 \times 50 = \$0.98/module$$

Machine Time Costs

$$C_{machine} = \frac{60t \times \rho \times S \times p_{machine}}{0.1I \times E \times Y \times b}$$

Where

$$\begin{aligned}
&t = coating's\ thickness\ (\mu m) = 50 \\
&\rho = material\ density\left(\frac{g}{cm^3}\right) = 8.9 \\
&S = surface\ area\left(\frac{dm^2}{module}\right) = 0.58 \\
&p_{machine} = cost\ of\ running\ the\ machine(\$/hr) = 5.3 \\
&I = current\ intensity\left(\frac{Amp}{dm^2}\right) = 3 \\
&E = electrostatic\ equivalence\left(\frac{g}{Amp} \cdot h\right) = 1.186 \\
&Y = current\ yield\ (\%) = 100 \\
&b = bath\ size(L) = 4000
\end{aligned}$$

Therefore

$$C_{machine} = \frac{60 \times 50 \times 8.9 \times 0.58 \times 5.3}{0.1 \times 3 \times 1.186 \times 100 \times 4000} = \$0.58/module$$

Total Electroplating Cost

The total electroplating cost is equal to the material and machine time costs combined.

$$C_{total} = C_{material} + C_{machine} = \$0.98 + \$0.58 = \$1.56/module$$

The calculation method and values obtained from http://polynet.dk/ingpro/surface/elecomk.htm.

Appendix 2: Battery System Price Comparison

Company Name	*Price ($US)*	*kWh*	*$/kWh*
POWER^3 Costs	15.3	0.033	463.6364
Tesla Power Wall	5000[1]	7[1]	714.2857
Orison	1600[2]	2.2[2]	727.2727
Nissan xStorage	4560[3]	4.2[3]	1085.714

[1] (Bounds, 2015), [2] (Metz, 2016), [3] (Vincent, 2016)