UBC Social Ecological Economic Development Studies (SEEDS) Student Report

An Investigation intoTriple Bottom Line Value of Pavegen Tiles: Installation at UBC

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APSC 261

November 24, 2011

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ABSTRACT

It has been proposed to install eight Pavegen tiles in the new Student Union Building (SUB) at UBC. Each tile produces 3J of energy when stepped on and the combined purchase, shipping, and installation cost of eight tiles is $30 800 minimum. The main goal of the proponent is to use the tiles as a tool to increase students' awareness of sustainability. The energy produced would help to power display screens used for way-finding and for displaying sustainability related information.

To determine if this project should be done, a triple bottom line investigation has been performed that considers economic, environmental, and social indicators. Economic indicators found the net present value to be -$30 244.27, the internal rate of return to be -66.18% and the payback period to be 303 149 years. Environmental indicators found that the energy required to produce and to ship the device to be 142.88MJ while it would only generate 6MJ over its lifetime. Needless to say the economic and environmental analysis both show significant loss. Moreover, the device cannot be called "sustainable" because it produces net negative energy over its cradle-to-grave life. The social indicators show the potential to reach 40 000 students over the life of the device which can be either very positive or very negative depending on people's reaction. Unfortunately anyone who discovers the economic and especially the environmental indicators, will likely develop a negative reaction. Hence, it is not recommended to purchase the Pavegen tiles.

Both primary and secondary research was performed. Secondary research included books, internet sources, Pavegen customer information sheets, and AMS information sheets. Primary research included a student survey and a faculty survey. Many details about the product were not available due to intellectual property limitations and so numerous assumptions and estimates were made. A sensitivity analysis was performed where possible to asses the effect of variations in the assumptions. It was determined that the overall conclusion would not be affected by such variations. Assumptions made included: no maintenance costs, all tiles reach their full lifetime, constant inflation rate of 2%, quantity of the materials used in fabrication, and that only 30% of students use the stairs in the SUB.

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GLOSSARY AND ABBREVIATIONS

NPV – The Net Present Value of an investment is the sum of all cash flows with their values converted to their present value.

IRR – The Internal Rate of Return is the interest rate or inflation rate that results in zero net present value

PBP – The Payback Period is the amount of time required to recover start-up costs.

TBL – A Triple Bottom Line is decision analysis that includes economic, environmental, and social factors as opposed to the conventional bottom line which only looks at economic factors.

SUB – The Student Union Building

1.0 INTRODUCTION

Pavegen is UK based company that produces floor tiles which generate electricity when stepped on. It has been proposed to the AMS to include eight of these tiles in the new Student Union Building (SUB). The tiles would be installed on the stairs and would help to power interactive display screens to be used for way finding on campus and to display a range of sustainability information. Refer to Figure 1.

The purpose of this investigation is to determine if the Pavegen tiles are a good investment. The proponent has requested that we perform a triple bottom assessment focusing on economic, environmental, and social indicators. The proponent stated that their main goal was to increase students' awareness of energy and sustainability. Economic factors were least important of the three categories but were still important enough to investigate. The proponent also stated that they had requested this study because of their limited technical knowledge. They wanted groups of engineers to estimate the energy production and overall technical feasibility of the project.

The triple bottom line model takes the point of view that an investment should take the interest of its stakeholders as its primary concern. Returns to shareholders should be of secondary concern. The indentified stakeholders include:

- **Students**: are concerned about how their fees are used and the educational benefits associated with the device.
- **Faculty**: are concerned with opportunities to showcase research and the educational benefits of the device.
- **AMS and UBC**: are concerned with their reputation as a leader for sustainability among Educational organisations.
- **SUB users**: are concerned with their ability to use the stairs without impediment and to easily use the display screens.
- **Greater community**: are concerned with the energy payback and sustainable values of the device.

Figure 1: A Pavegen tile and an example of a display screen

2.0 METHOD

A triple bottom line approach is a structured evaluation method where economic, environmental, and social indicators are studied independently at first and then the results are combined to reach a decision. Indicators chosen for each category will be further discussed in their appropriate sections of the report. To combine the results, we identified the net costs and benefits of each section. This alone made the decision obvious as will be seen in the discussion section.

Both primary and secondary research was conducted. Secondary research included using textbooks, online sources, and information packages from both the AMS and the Pavegen company. Primary research included a meeting with the proponent, a student survey, and a faculty survey. The proponent meeting helped our group to fully understand the goals of the proponent and AMS as well as to further our background knowledge of the new SUB project and the Pavegen tiles. The student survey address the social indicators and helped our group to understand students needs and goals for the new SUB. The faculty survey assessed the interest of faculty in using Pavegen to somehow showcase their research or to integrate their research with the product. There was only one favourable response out of fifteen inquiries.

A major challenge of the investigation was obtaining specific details about the tiles. As Pavegen would like to protect their intellectual property, we had to make some assumptions. Even with the assumptions made, it will be clear that the decision reached would not be significantly affected by changes in the assumptions. The effects of changes in the assumptions were verified by a sensitivity analysis where possible.

3.0 ANALYSIS

The analysis was broken into three categories as is traditionally done in a TBL study. The categories include: economic, environmental, and social evaluation. This suits the needs and goals of the proponent and allows for capturing the interests of all stakeholders. A set of indicators was selected for each category as will be discussed below. Finally, the results of each category are combined to reach a decision as outlined at the end of this section.

3.1 ECONOMIC

The economic evaluation was divided into three steps including data reduction, data sensitivity analysis, and economic indicator evaluation. The data reduction step collects raw data from a variety of sources to estimate the annual energy generation and the associated annual energy value. The sensitivity analysis determines how much each input has to change to move to the break-even point. The indicator evaluation uses the results of the data reduction to evaluate net present value (NPV), internal rate of return (IRR), and payback period (PBP).

Data reduction uses a variety of input data to estimate annual energy production and its associated economic value based on BC Hydro rates. The total potential lifetime energy production, based on a lifetime of 20 million steps (Pavegen Systems PG006) is also found. The data is given in Table 1 with details and equations in Appendix A. Note the insignificantly small economic value that these tiles produce over their lifetime.

Table 1: Summary of energy generation and economic calculations

INPUTS	VALUE (one tile)	RESULTS	VALUE (eight tiles)
Unit steps/day (winter)	500	Total steps/year	1.2 million
Unit steps/day (summer)	winter/2 = 250	Unit lifetime in years	13.12 yr
Total unit lifetime in number steps	2 000 000	Total energy/year	1.016 KWh or 3.7 million J
Energy/step	3W * 1s = 3 J	Total energy value/year	+0.1016 $/yr
BC Hydro energy rate	0.10 $/KWh	**Potential lifetime energy**	**13.33 KWh**
		Potential lifetime energy value	**+1.33 $ total**

The sensitivity analysis checks the buffer zone for variations in input data. This is important because many of the inputs are based on rough estimates which can also change with time. To test sensitivity, we perform a "goal seek" operation and set the economic value of lifetime energy equal to the full cost of purchase and installation, which is $30 800 (Chris Karu, personal communication, October 2011). This would be the break-even point if inflation was at zero percent. It is critical because it separates the profit domain from the loss domain. We then determine the required value for each input while all other inputs are held constant. Table 2 shows that the changes required are impossibly large and so it is unlikely that variations in the inputs will affect the conclusion of the economic analysis.

Table 2: Sensitivity analysis

Item	Estimate	Break even value	Percent change
Unit steps/day	500	12 657 534	25 315%
Energy/step	3 J	69 300 J	23 100%
Energy cost	0.10 $/KWh	$2 310 $/KWh	23 100%
Product life (# steps)	2 000 000	46 200 000 000	23 100%

The economic indicators used include: net present value (NPV), internal rate of return (IRR), and payback period (PBP). The NPV indicates how much economic value is gained or lost over the lifetime of the project in terms of today's dollar value. The IRR indicates the interest rate required to breakeven, or to turn an NPV of zero. Most organizations have a minimum acceptable rate of return (MARR) that they use to determine if an investment if acceptable. Project with an IRR below the MARR are usually screened out, while anything above the MARR is ranked based on the current goals of the organization. The MARRs for UBC and for the AMS were not available for good reasons; however, we include it here so that executives from both organizations can refer to it if interested. Negative NPV and IRR indicate an economic loss whereas positive values indicate an economic profit. It is desired to maximize both indicators. The PBP shows how long it takes to recover all costs incurred in a project with all future cash flows converted to their present values. An economic lose occurs if PBP is greater than the project lifetime. Appendix A contains the details of the economic analysis, but the results are summarized in Table 3. The inflation rate used is 2.0% (Bank of Canada).

Table 3: Economic indicators

Factor:	NPV	IRR	PBP
Estimate:	-$30 225.47	-66.25%	303 149 years

To summarize the economic analysis, installing Pavegen tiles has negligible economic return on the investment. The project is estimated to result in an economic loss of $30 244.27. The IRR is negative therefore well below any organization's MARR. All eight tiles will have to be operational for 303 149 years just to break even. This is impossible as the device will have to be replaced after about 13 years as indicated in Table 1.

The economic loss alone does not mean that the project should be rejected. The proponent stated that the main goal of the project was to obtain positive social benefits and to create awareness for sustainability. Since the project has been found to result in a net expense, the question is whether the social and environmental factors justify this expense.

3.2 ENVIRONMENTAL

The Pavegen tile is made of different types of recycled materials which are assumed to be sustainable and helps reducing the carbon emissions of production. An analysis of the environmental impacts caused by the materials used to produce Pavegen tiles, especially carbon emission and energy consumption is carried out and the approximate values are calculated where possible. In addition, the approximate amount of carbon dioxide emission produced and energy used for different methods of transportation was analysed.

The top surface of a Pavegen tile is made up of recycled rubber car tyres. (Pavegen) Rubber car tyres are considered to be a potentially risky factor due to heavy metals and other pollutants within the material. It has potential to introduce toxins in groundwater, and therefore the use of this material has been restricted. However, research shows that only using a small amount of shredded tires as a light fill material is harmless. (George, 2009) Even though it has a potential risk factor, recycling rubber car tyres is considered to have an effect on making a contribution to decrease carbon emissions. It was found that 124 kilograms of carbon dioxide are produced per metric ton of rubber recycled on average in 2007. The electricity used for the recycling process and the fuel for transportation of material was a big factor in this carbon emission. (IERE, 2007) With the data given for average carbon dioxide emission in 2007, a rough estimate of the carbon dioxide emission for recycled rubber used to produce a Pavegen tile is calculated. Assuming that the recycled rubber used to create one Pavegen tile weighs 2 kilograms, the carbon dioxide generated is calculated to be as 0.248 kilograms. Also, less than 2.3 mega joules of energy is used to produce one kilogram of recycled rubber tyre, therefore roughly 4.6 mega joules of energy is used to produce a Pavegen tile. (EWC)

Table 4 shows the summary of the energy and carbon emission calculations for one Pavegen tile. Full details are in Appendix B.

The internal component of the tile is made up of recycled aluminum. There is a huge advantage in recycling aluminum, in which it only requires about 5 percent of the energy to produce it in comparison with primary production. (AA, 2007) About 1.6 tonnes of carbon dioxide is produced per tonne of recycled aluminium.(IAI) If the aluminum used to produce one Pavegen tile is assumed to be 2 Kg, the total carbon dioxide emission for using recycled aluminum in making a Pavegen tile comes out to be 3.2 kilograms. In 2007, energy required for primary aluminum production was 50 MJ/Kg. Recycled aluminum would require 5% of this energy which is 2.5 MJ/Kg. The Pavegen tile would use 5MJ of energy for its constituent aluminum. (Wikipedia, 2011)

The exterior housing of the Pavegen tile is made up of marine grade 316 stainless steel. Marine grade 316 stainless steel is specially designed for use near water, and thus it has high resistance to corrosion and rust. This material was used because the Pavegen tile needs to be able to withstand wet environments such as rainy days and snow when it is installed outside. Although in our case, this would not be too much of a concern, the tiles will still be produced with this material. This alloy is specialised and is more resistant than normal household stainless steels, thus they are more expensive. (MGS, 2010) The data for carbon emission of marine grade 316 stainless steel production could not be found, therefore carbon dioxide emissions for producing generic steel was used as an approximation. The steel produced in an electric arc furnace produces 2345.8 Kg of carbon dioxide emission per ton of steel produced. (Beskow, Rick & Engholm) If the amount of marine grade 316 stainless steel is assumed to be around 0.8 Kg, the carbon dioxide emission can be estimated to be around 1.877 Kg. As for the energy used to produce stainless steel, at least 77.2 MJ is used per Kg of steel produced, thus 61.76 MJ of energy is consumed in producing one Pavegen tile. (Ashby, 2005)

Toughened clear glass with an optical film is used to maximise the slip resistance on the walking surface. (Pavegen) This type of glass is used for safety reasons. With this type of material, even when glass is impacted, it does not shatter like normal glass; however, it crumbles and stays together like when a car window breaks. For 1 square meter of 4mm thick toughened glass, 46.06 Kg of carbon dioxide are produced. An estimate of a circular glass piece with assumed radius of 70 mm produces 0.709 Kg of carbon dioxide. (Oloke, 2010) Assuming that the glass piece is 0.5 Kg, and also that about 30 MJ of energy is consumed to produce 1 Kg of glass, approximately 15 MJ of energy is consumed to produce one Pavegen tile. (Ashby, 2005)

Table 4: Summary of energy and carbon emissions in production of a single Pavegen tile

Material	**Mass (kg)**	**Energy consumed (MJ)**	**CO_2 produced (kg)**
Recycled rubber car tyre	2	4.6	0.248
Recycled aluminum	3.2	0.66	3.2
Marine grade 316 stainless steel	0.8	61.76	1.877
toughened clear glass	0.5	15	0.709
Total	**6.5 kg**	**82.02 MJ**	**6.034 kg**

As calculated in the economic part of this report, one tile produces 6 MJ of energy in its lifetime. However, it takes 82.02 MJ of energy to produce one tile. This shows that from an environmental and energy perspective, it is not sustainable for use anywhere in the world. Next we look at transportation costs.

Pavegen produces their tiles in London, England. In order to receive the products, they have to be transported to Vancouver by some means of transport. However, the carbon dioxide emission and energy consumption of different types of transportation can only be roughly estimated as we cannot access the information on which transportation the Pavegen company will use to send the products over.

The distance between Vancouver, BC and London, England is 7608 kilometres. This distance was used in calculations to estimate the carbon emission and energy consumption. (Time and date, 2011)

The carbon dioxide emission and transport energy are calculated by multiplying the weight by the distance traveled and the fuel-vehicle coefficients listed in the table in Ashby's book. Once again, it should be noted that this is only a rough estimate. Following Table 5 shows the results. (Ashby, 2009)

Table 5: Energy and carbon emissions for transporting a single Pavegen tile

Transportation	CO_2 emission (kilograms)	Energy (MJ)
Plane	209.22	31573.2
Shipping	5.706	60.864

If the tiles are transported by plane, the total energy required to produce and to transport 8 tiles would be 32229.36 MJ. Therefore, the energy payback period would be 8813 years.

If the tiles are transported by ship, the total energy required to produce and transport 8 tiles would be 717.024 MJ. Therefore, the energy payback period would be 196 years.

The energy payback period calculation clearly shows that the Pavegen tiles will not be able to produce more energy than are spent producing them. Therefore the tiles are not sustainable in environmental aspect.

3.3 SOCIAL

To determine the social impact of installing Pavegen tiles, the three criteria chosen were number of students impacted, media coverage/reputation impact, and personal reactions. Each criterion was given a traffic light rating, green (positive), yellow (neutral) and red (negative) in order to evaluate the three indicators side by side in the end.

The number of potential students it could impact is massive. In 2010/2011 there were 47,883 registered at UBC including distance education (UBC, 2011). If out of these 47,833 students, only about 30% walk the stairs in the new SUB, about 14,500 students will be impacted by the stairs every four years. Assuming a life time of thirteen years as found in the calculations of Appendix C, 40,137 students will have walked the stairs over the lifetime. This estimate assumes about 40,000 students will leave the university and 40,000 new ones will replace them every four years. [See Appendix C] This is a significant amount of students in this fairly conservative estimate that does not account for university growth or outside visitors. Being able to potentially reach 40,000 or more students and conveying a message is very positive and will be given a green rating.

Media coverage was one of the criteria considered as millions of people in Canada and the United States would hear about the project since it would be one of the first ones in North America. It is likely that there would be a fair amount of newspaper and television coverage. This could help UBC's reputation as a leader in sustainability. However, due to the economic and especially the environmental costs, the project could likely receive negative media coverage which could hurt the AMS's and UBC's reputation. It is difficult to evaluate this since millions of people could be influenced positively or negatively, so the corresponding rating is yellow.

The UBC student newspaper "Ubyssey" published an article against the Pavegen project (Schwenneker, 2011). All the corresponding public comments online were negative, mainly due to the economic cost of the project. We assume that the students posting did not even know about the environmental costs. Objective evaluation was difficult as the author of the comment is unknown. One of the more notable comments is posted here:

> Anything that's "green" (as in, environmentally friendly) but not economically viable (that is, it doesn't turn a profit, or at the bare minimum, pay for its own construction and operating costs), isn't sustainable. ("M" anonymous, 2011)

Since the comments are not an objective source, a small survey was conducted to gather pre-project feedback from students at UBC. The value of the survey is limited since only sixteen people were interviewed, but it gave a good indication of the public opinion about the project. Since the cost is the most controversial aspect of the whole project the first question of the survey did not mention the costs to evaluate peoples' initial opinion. [See Appendix] There was strong support of the idea with 87.5% of people being in favour of it. However, once the price and the energy output were revealed, the number in favour decreased significantly to 31.3% with 25% of the respondents noted that it was too high of a price simply for creating awareness. None of the respondents asked had previously heard about Pavegen. Our group also received an email from Dr. Dunford, an Electrical and Computer Engineering Professor who remarked that the project "[seemed] to be just the sort of project which gets sustainability a bad name" since it produces very little energy and probably makes it harder to walk up the stairs. (Dunford, 2011) This criterion is given a yellow light since the majority of respondents were resilient about paying the price and possible negative media coverage could affect students' opinions.

It is difficult to evaluate personal impact as there are very few projects using Pavegen and there was no research data available on this. Pavegen is a "fun" feature and such will definitely catch peoples' attention. An example of this is the musical stairs project in a subway station in Stockholm, Sweden constructed by Volkswagen which increased the use of the stairs compared to the escalator by 66% by making the stairs look and sound like a piano every time someone walked on them (Volkswagen, 2009). Pavegen could have a similar effect as it would let people think about sustainability. In the survey, 62.5% of the respondents thought that the project would raise awareness while four respondents noted that a display board would be needed to achieve the full awareness effect.

In conclusion, Pavegen could, combined with a display board, raise awareness for sustainability since it would have a very large outreach. Summarizing a green rating and two yellow rating were given. The yellow ratings however have the potential to go to red due to significant potential for controversy in the purchasing and construction phase. If these ratings go red, then the green rating would also go red as large numbers of people would be negatively impacted. The overall social rating is neutral.

3.4 ASSIMILATION OF RESULTS

At this point, the economic, environmental, and social aspects have been evaluated individually. The economic and environmental aspects were found to be a net cost, while the social aspects have potential for positive benefits. Unfortunately, the positive social benefits could easily become negative if people's reactions and the media's reactions are poor. Due to the fact that the device requires more energy to produce and ship than it can generate in its lifetime, it cannot be called a sustainable product under any definition. If people find out about this, they may well develop a negative reaction to the Pavegen tiles. In this way, the negative outcomes of the economic and especially the environmental aspects draw the social aspect into the negative region as well.

In the opinion of the group, the Pavegen project will detract from the truly positive green features that are already planned. Just as a bad mark on a test, brings down a student's average, the Pavegen tiles could bring down the perceived average value of the other green features of the SUB. Negative reactions towards the Pavegen tiles will take positive attention away from the sustainable features that are actually significant and which will earn our new SUB the honour of a LEED Platinum certification.

It is valuable for people to learn about energy and sustainability; however, sustainability is still a vague subject for a large number of people. Hence a learning tool should also be strong example or role model of a sustainable device. Pavegen is far away from being such a device. The economic cost and especially the environmental cost could very likely produce negative media and personal reactions. For this reason, we conclude that Pavegen is a seriously poor investment decision.

4.0 CONCLUSION AND RECCOMENDATIONS

The triple bottom line analysis has led our group to determine that Pavegen tiles are not worth the investment. Our economic indicators show a loss with an NPV of -$30 244.27. The economic return on investment in negligible. The environmental analysis shows that the device is unquestionably a net user of energy rather than a net producer over its full lifetime. This carries an associated carbon footprint. Both the economic and environmental indicator evaluations showed a negative impact by orders of magnitude. We can safely be assured that there is no chance that a realistic variation of input data could cause any of these indicators to become positive. As a result, the social indicators are trumped by the fact that negative media and negative personal reactions caused by the economic and environmental losses are likely to be formed. It is our recommendation that the AMS does not purchase the Pavegen tiles because they will detract from the features that are actually sustainable.

Our group would like to make a further recommendation that is outside the scope of this study. The proposal for the Pavegen tiles indicated that they would be used to help power way finding displays and displays with sustainability information. As discussed in a CIVL 405 class, electronic-waste has become a huge global sustainability problem. For more information see (BBC, 2011). It is suggested that a triple bottom line study be carried out on the use of computer screens for way-finding and displaying sustainability information. We feel that it is prudent to avoid unnecessary electronic devices and to abstain from the rampant electronic consumerism that our modern society has quietly slipped into.

APPENDIX A: ENERGY GENERATION AND ECONOMIC ANALYSIS

The data reduction calculations done in Excel can be seen in Figure 2. The data in the black box on the left are the inputs that were obtained from research while the other data on the right are calculated based on the inputs as follows. Inputs are given for one tile and outputs are given for all eight. We assumed that winter counted for 67% of a year and summer for 33% of a year. The number of steps per day in summer is half the number of steps per day in winter because there are much fewer students on campus. Price of energy was difficult to find; however, Manitoba Hydro had some data for major Canadian cities (Manitoba Hydro, 2011). The "num year" calculation finds the lifetime in years assuming that the device lasts for 20 million steps (Pavegen Systems, PG006). Pavegen claims that the device produces 4-8W of electricity per step however, numerous other sources say it produces 2W. It is likely that body weight influences generation capacity.

*Steps/year = (C6*365*0.67+C7*365*0.33) *8*

*Num year = C8/H6 *8*

*Energy/year (J) = H6*C9*

Energy/year (KWh) = H8/3600000

*$ generated/year =H9*C11 = $0.1016 (rounded to 2 decimal places in figure)*

Figure 2: Data reduction table

	A	B	C	D	E	F	G	H	I
1	life is 2 million steps and carries 4tonnes					1kWh is 3600000 J			
2	product spec doc pG 006								
3	3 W for about 1sec give 3Joules or								
4									
5			ONE TILE					EIGHT TILES	
6	step/day (winter):		500			steps/year:		1219100	
7	step/day (summer):		250			num year:		13.12444	
8	lifetime steps:		2000000			energy /year:		3657300	J
9	energy per step:		3	J		energy /year:		1.015917	KWh
10						$ generated/year:		$0.10	$ CAD
11	cost of energy:		$0.10	$/KWh					
12	http://www.hydro.mb.ca/regulatory_affairs/energy_rates/electricity/utility_rate_comp.shtml								
13									
14				ONE TILE		EIGHT TILES			
15	lifetime energy			6000000	J	48000000	J		
16	liftime energy			1.666667	KWh	13.33333	KWh		
17	lifetime savings potential:			$0.17	$ CAD	$1.33	$ CAD		

In the above figure, the values below the black line give the maximum potential outputs of the device. The column for eight tiles takes the results for one tile and multiplies by eight. The single tile calculations are completed as follows:

*Lifetime energy (J) = C8*C9 (lifetime base on 20 million steps)*

Lifetime energy (KWh) = D15/3600000

*Lifetime saving potential =D16*C11 (upper bound on revenue generated since no inflation)*

Table 6 contains the cash flows for calculating NPV. The proponent said that about half the cost was expected to be paid out at the beginning with the remaining payments made equally over a three year period. We made the approximation as recommended by (Newnan, Eschenbach, Whittaker, & Lavelle, 2010) to lump all continuous cash flows into yearly groups with the flow occurring at the end of each year. The NPV is the sum of all entries in the "PV cash flow column" which is the final row of the "Net PV" column. A 2% inflation rate was assumed as that is in the middle of the target range set by the Canadian government (Bank of Canada, 2011). It is very close to the current inflation rate.

Table 6: Data for NPV calculation

Year	Expense	Revenue	Cash Flow	PV cash flow	Net PV
0	-$15,800.00	$0.00	-$15,800.00	-$15,800.00	*-$15,800.00*
1	-$5,000.00	$0.10	-$4,999.90	-$4,901.86	*-$20,701.86*
2	-$5,000.00	$0.10	-$4,999.90	-$4,807.59	*-$25,509.46*
3	-$5,000.00	$0.10	-$4,999.90	-$4,716.89	*-$30,226.34*
4	$0.00	$0.10	$0.10	$0.09	*-$30,226.25*
5	$0.00	$0.10	$0.10	$0.09	*-$30,226.15*
6	$0.00	$0.10	$0.10	$0.09	*-$30,226.06*
7	$0.00	$0.10	$0.10	$0.09	*-$30,225.97*
8	$0.00	$0.10	$0.10	$0.09	*-$30,225.89*
9	$0.00	$0.10	$0.10	$0.09	*-$30,225.80*
10	$0.00	$0.10	$0.10	$0.08	*-$30,225.72*
11	$0.00	$0.10	$0.10	$0.08	*-$30,225.63*
12	$0.00	$0.10	$0.10	$0.08	*-$30,225.55*
13	$0.00	$0.10	$0.10	$0.08	***-$30,225.47***

The IRR was found by using the IRR financial application that is built into the Texas Instruments TI-83 Plus calculator. The entry was:

irr(-15800,{-4999.90,0.1},{3,10}) = -66.2469

The result is expressed as a percent, -66.25%.

The PBP was approximated by dividing the total cost by the annual revenue. This is not the most correct way to calculate PBP; however, the numbers in Table 6 make it fairly obvious by inspection that the PBP period is impractically large. The correct method would account for inflation and would increase the result obtained for PBP since $0.1 in the future is worth less than it is worth today.

$$PBP_{approx} = total\ cost/annual\ revenue = 30800/0.1016 = 303\ 149\ years$$

APPENDIX B: ENVIRONMENTAL ANALYSIS

The following calculation were used in the environmental analysis to find energy and CO2 emissions required for production and shipping of the eight tiles.

- Total carbon dioxide generated to produce top surface with recycled rubber car tyres.

$$\frac{124\ kg\ \mathbf{CO2\ generated}}{\mathbf{1000}\ kg\ recycled\ rubber} * \mathbf{2}kg\ recycled\ rubber\ used = \mathbf{0,248}\ kg\ \mathbf{CO2\ generated}$$

- Total energy took to produce top surface with recycled rubber car tyres.

$$\frac{2.3\ MJ\ energy}{1\ kg\ recycled\ rubber} * 2kg\ recycled\ rubber\ used = 4.6MJ\ energy\ consumed$$

- Total carbon dioxide generated to produce internal components with recycled aluminum.

$$\frac{1600\ kg\ \mathbf{CO2\ generated}}{\mathbf{1000}\ kg\ recycled\ aluminium} * \mathbf{2}\ kg\ recycled\ aluminium\ used = \mathbf{3.2}\ kg\ \mathbf{CO2\ generated}$$

- Total energy took to produce internal components with recycled aluminum.

$$50\ MJ\ of\ primary\ aluminium * 0.05 = \frac{2.5\ MJ}{1\ kg\ of\ recycled\ Aluminium}$$

$$\frac{2.5\ MJ}{kg\ recycled\ aluminium} * 2 = 5\ MJ\ energy\ consumed$$

- Total carbon dioxide generated to produce exterior housing with steel (assume just steel).

$$\frac{2345.8\ kg\ \mathbf{CO2\ generated}}{\mathbf{1000}\ kg\ steel} * \mathbf{0.8}\ kg\ steel\ used = \mathbf{1.87664}\ kg\ \mathbf{CO2\ generated}$$

- Total energy took to produce exterior housing with stainless steel.

$$\frac{77.2\ MJ}{1kg\ stainless\ steel} * 0.8\ kg\ stainless\ steel = 61.76\ MJ\ of\ energy\ consumed$$

- Total carbon dioxide generated when using toughened clear glass with an optical film.

Area = $\pi * (0.07m)^2$ = 0.01539 m^2

$$\frac{46.06\ kg\ \mathbf{CO2\ generated}}{\mathbf{1}\ m^2} * \mathbf{0.01539}\ m^2 = \mathbf{0.7088634}\ kg\ \mathbf{CO2\ generated}$$

- Total energy took to produce toughened clear glass

$$\frac{30\ MJ}{1\ kg\ of\ glass} * 0.5\ kg\ of\ glass\ per\ tile = 15\ MJ\ energy\ consumed$$

- Carbon emission for transporting 8 tiles by plane

$$50\ kg\ tiles * \frac{1\ tonne}{1000\ kg\ tiles} * 7608\ km * \frac{0.55\ kg\ CO2}{1\ tonne\ km} = 209.22\ kg\ CO2\ generated$$

- Energy took to transport 8 tiles by plane

$$50\ kg\ tiles * \frac{1\ tonne}{1000\ kg\ tiles} * 7608\ km * \frac{8.30\ MJ}{1\ tonne\ km} = 31573.2\ MJ\ energy\ consumed$$

- Carbon emission for transporting 8 tiles by shipping

$$50\ kg\ tiles * \frac{1\ tonne}{1000\ kg\ tiles} * 7608\ km * \frac{0.015\ kg\ CO2}{1\ tonne\ km} = 5.706\ kg\ CO2\ generated$$

- Energy took to transport 8 tiles by shipping

$$50\ kg\ tiles * \frac{1\ tonne}{1000\ kg\ tiles} * 7608\ km * \frac{0.16\ MJ}{1\ tonne\ km} = 60.864\ MJ\ energy\ consumed$$

- Payback period for 8 tiles when transported by plan

$$86.36\ MJ * 8\ tiles\ +\ 31573.2 = 32264.08\ MJ\ energy\ consumed\ to\ produce\ \&\ transport$$

$$\frac{32264.08\ MJ\ energy\ consumed}{3.6573\ MJ\ energy\ produced\ \frac{}{year}} = 8822\ years\ (rounded\ up)$$

- Payback period for 8 tiles when transported by shipping

$$86.36\ MJ * 8\ tiles\ +\ 60.864 = 751.744\ MJ\ energy\ consumed\ to\ produce\ \&\ transport$$

$$\frac{751.744\ MJ\ energy\ consumed}{3.6573\ MJ\ energy\ produced\ \frac{}{year}} = 206\ years\ (rounded\ up)$$

APPENDIX C: SOCIAL ANALYSIS AND STUDENT SURVEY

Table 7 gives a summary of the student survey results. Students were asked if they had already heard about the Pavegen proposal. None had. Their original opinion was noted before informing them of the costs. Their reactions to the cost were noted. Finally they were asked if the device could be beneficial for increasing student awareness of sustainability.

Table 7: Student survey results

Answer	Heard of Pavegen	Original Opinion	Opinion re Costs	Awareness
Yes or in favour	0	14	5	10
Yes (Percent)	0%	87.5%	31.3%	62.5%
No or not in favour	16	2	11	2
No (Percent)	100%	12.5%	68.7%	12.5%
Indecisive	0	0	0	4
Indecisive (Percent)	0%	0%	0%	25%

Calculation steps:

Number of students affected = 47,833 students * 30% + 2.25(40,000 students * 30%)   = 41350 students

40,000 students replace 40,000 old ones every four years. A rough estimate since potential growth is difficult to predict.

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