CRANFIELD UNIVERSITY

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DESIGN AND TESTING OF A NOVEL HUMAN-POWERED GENERATOR DEVICE AS A BACKUP SOLUTION TO POWER CRANFIELD´S NANO-MEMBRANE TOILET

SCHOOL OF ENGINEERING
MSc by Research

MSc THESIS
Academic Year: 2013 – 2014

Supervisor: Dr Athanasios Kolios and Prof. Feargal Brennan
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ABSTRACT

In today's world there are 2.6 billion people that lack basic sanitation (37% of world inhabitants). In August of 2012, Cranfield University was awarded by the Bill & Melinda Gates Foundation with $810,000 to produce a prototype of the Cranfield's innovative Nano-membrane Toilet (NMT). Finally, the prototype is going to be exhibited at the "Reinvent the Toilet Fair" during 21st and 22nd of March 2014 in the Taj Palace Hotel, New Delhi (India).

Cranfield's NMT demands electricity for its daily performance. Nevertheless, it is targeted to off-grid communities. Consequently, a human-powered generator (HPG) was selected as a backup solution. The current MSc by Research aimed to design and test of a prototype of the aforesaid HPG. Moreover, to promote its usage, a portable power supply unit is designed to store energy and power small-loads like charging mobile phones and electric lighting.

To select the most suitable design for our case study, a methodology using the Technique for Order of Preference by Similarity to the Ideal Solution has been developed. As a result the plugged-in bike HPG alternative was selected. Next, prototypes of this generator and the portable power supply unit were developed, tested and shipped for display.

While testing of the plugged-in generator and portable power supply unit, 26 Watt-hours (Wh) were harvested over 15 minutes, with its corresponding average charging power of 105 Watts. Nevertheless, the present study concludes 96 Wh as a more accurate energy level to be harvested during one hour of pedalling.

Considering 96 Wh of energy, a round-trip battery efficiency of 70% (lead-acid), and a NMT's demand of 283 Wh; a 10 people household needs to pedal the HPG over 4 hours and 20 minutes. Nevertheless, if considering an 85% inverter efficiency, 57.12 Wh are available to fully charge one mobile phone (5.6 Wh) and provide 4.5 hours of room and desk lighting (11 Watts bulb).

Keywords:

Human development, human power, TOPSIS Method, Multi-criteria Decision Method

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LIST OF ABBREVIATIONS

AC	Alternating current
CP	Critical Power
DC	Direct current
FEHDs	Free-Energy Harvesting Devices
HDI	Human Development Index
HP	Human Power
HPES	Human-powered energy system
HPG	Human-Powered Generator
HPGs	Human-Powered Generators
MDGs	Millennium Development Goals
MGR	Merry-Go-Round
NMT	Nano-Membrane Toilet
VOCs	Volatic Organic Compounds

1 INTRODUCTION, OBJECTIVES AND METHODOLOGY

1.1 Background and motivation

Nowadays, 1.3 billion people are estimated to lack access to reliable electricity, which accounts for one-fifth of today's world population, [1].

Having access to electricity promotes human development and boosts the accomplishment of the Millennium Development Goals (MDGs) [2] while satisfying basic human needs such as lighting, communication, irrigation...

To deal with that challenging situation, small renewable generators are donated or being subsidized to off-grid communities as a common energy policy [3]. What is more, Mechtenberg et al. [4] demand that Human-Powered Generators (HPGs)[1] should be included in the previous port-folio. These generators can be used as primary or back-up solutions. What is more, the authors explain that if that happens, it will boost human development.

1.1.1 Electricity and Human Development Index

In our current world, the link between human development and access to reliable electricity is well known. That fact is depicted in Figure 1-1, where the relationship between electricity consumption and Human Development Index[2] (HDI) is shown.

In high HDI countries, the grid availability and reliability is greater than 95%. Nevertheless, in numerous low HDI countries (HDI < 0.5) there is 5–50% of electric grid availability. What is more, the grid reliability in these countries can be lesser than 50% due to faults and over-load connections, causing an off-grid situation even when the electric infrastructure is available, [4].

[1] HPGs are generators in which the input energy is given by the human effort.
[2] The United Nations Development Programme defines the Human Development Index (HDI) with education, health, and economic indicators.

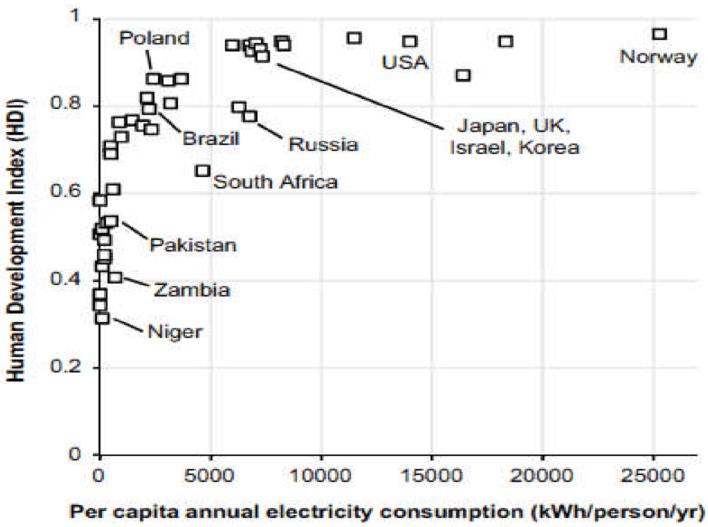

Figure 1-1 HDI versus electricity consumption [5]

1.1.2 HPGs and MDGs

Further to the relation between electricity and HDI, the contribution to electric systems to attain the Millennium Development Goals (MDGs)[3] has been acknowledged globally [2]. What is more, the G8 Task Force [6] recommends a goal of 100 Wh/day/Household as a minimum value to achieve the MDGs.

Between them, the following applications in the early stage of development are specially indicated to be powered by HPGs:

- Electric lighting. Electricity is a non-harmful way of producing light. Light allow children to study at home when there is no sunlight and allow self-employed workers to increase their productive hours while working at home. Currently, off-grid householders in developing countries light their houses using kerosene lamps and candles due to its low acquisition cost and availability. Conversely to electric bulbs, kerosene lamps and candles are dangerous since they give off harmful smoke and fumes,

[3] The eight Millennium Development Goals (MDGs) form a blueprint agreed by all the world's countries and all the world's leading development institutions. http://www.un.org/milleniumgoals/

and are a frequent cause of fires. [7]. Therefore, replacing these kerosene lamps is itself beneficial.

- Charging mobile phones and power radios, TV´s and laptops. The previous devices allow people in developing countries to communicate and have access to valuable information that can make a difference in their lives.
- Supply electricity to low-power appliances like electric water pumps, and small motors to increase the productivity of farmers and boost local economy.
- Improving health by keeping vaccines in the fridge at the proper temperature. And powering some medical equipment.

In addition, HPGs are especially useful for these applications because the power demanded by these loads is matched by the power that can be generated by HPGs (from 0 to 120 Watts [4]). Having said that, the aforementioned statement is depicted in Figure 1-2

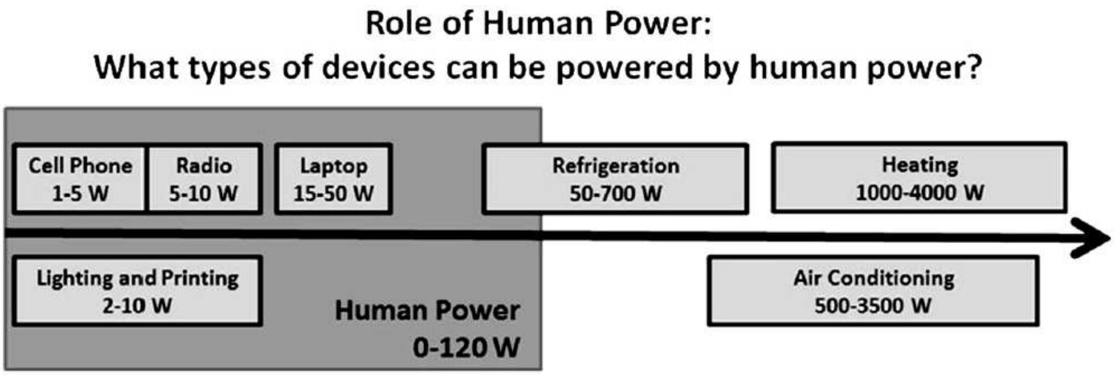

Figure 1-2 Devices powered by human power [4]

1.1.3 HPGs and renewable energy

As previously explained the relationship between electricity and human development is clear. Specifically, it has lots of applications which help people at the first stage of development. Nevertheless, in most developing countries extending the electric grid to some remote rural areas in a conventional way will be economically prohibitive and technically inappropriate. [8]

In such circumstances, local grids powered by small renewable generators have proven feasible and sustainable solutions to supply electric power to remote-rural households [9]. For instance, in Africa solar panels, wind farms, biogas and biomass reactors, small hydroelectric turbines are set up to power off-grid communities.

However, as Mechtenberg et al. [4] claims, Human Power (HP) should be included in the port-folio of renewable energy systems for certain developing countries (the ones whose average electrical power consumed is below 20 W/Capita). What is more, the authors declare that if that happens, it will boost human development directly. In favour of HPGs the following key points can be stated:

1. Generating electricity by HPGs is equally or less calorie demanding than other common labour activities in countries with HDI below 0.55. For instance, tea picking, coffee bean harvesting, tailoring, weaving are some of them. What is more, HPGs can harvest electric energy even if no extra calories are being consumed for that specific purpose. For example, the Merry-Go-Round (MGR) generator is designed to harvest energy in playgrounds while children are playing.

2. As Mechtenberg et al. [4] prove, employing people to generate electricity makes economic sense under specific situations in countries with a low income range ($1-3/day) and low energy consumption (less than 10Wh/day/household). In these countries, the high rate of unemployment and the fact of being paid for a similar calorific activity make sense. As it is the case in small business providing electricity to power household's batteries, mobile phones, etc.

3. HPGs can be donated to several householders in a domestic setting. In that way, people that cannot afford paying for electricity can harvest some power out of physical exercise. To specify that point, it is only feasible if the person is healthy and nourished enough. Thereby, with this

existing power the first stage of development applications can be addressed.

4. The high reliability and availability of HPGs make them especially useful to deal with critical energy situations (no wind, no sunlight and no diesel available plus batteries exhausted).–The term ‘availability’ refers to the possibility of being used by different users. Such back-up capability of HPGs is highlighted in [4], who claims that HPGs are specifically useful to act as a back-up systems for solar panels in cloudy days.

1.1.4 HPGs as a free-energy harvesting devices

In the present study, the term Free-Energy Harvesting Devices (FEHDs) is understood to mean devices that harvest electric energy from the mechanical motion of the human body without adding an extra calorific consumption to the main activity. This definition is based on the terms “free-energy” devices in [4] when describes the MGR generator. Other examples are shoe-equipped generators [10] …

Conversely to the FEHDs stated above, the HPG to be developed in the present study was intended to harvest energy by means of a made-on-purpose sustainable human effort. By the term “made-on-purpose” we mean that the person consumes calories and exerts mechanical power with the main purpose to generate electrical power. By “sustainable human effort”, we refer that the person exerts a physical activity that can be maintained during a limited period of time, depending on the magnitude of the effort.

Nevertheless, the HPGs referred on this thesis can be considered FEHDs when the main purpose of driving the generators is exercising instead of generating electricity. A clear example of this statement is found in the multiple retrofitted exercising machines that can be found in fitness facilities or gyms of the developing world.

1.2 Problem statement

As previously stated, HPGs can be used to satisfy the aforementioned basic electrical needs when there is no electric grid or it is unreliable. In addition, these generators can be used as primary generators in micro-grids or as back-up ones.

In the present Thesis, we develop and test a novel HPG to power a specific application. Specifically, our HPG aims to act as a back-up generator to satisfy the electric demand of Cranfield's NMT (an innovative sanitation solution) developed by Cranfield University on request of The Bill and Melinda Gates Foundation.

1.2.1 Reinvent the toilet challenge. A Gates Foundation's initiative

In our current world, electricity is not the only basic amenity that is missing and affects a nation's development. Nowadays, there are 2.6 billion people that lack basic sanitation (37% of world inhabitants) and 884 million people who don't have access to clean water [1].

Specifically, that absence of proper sanitation explains that 1.1 billion people still practise open defecation, creating a hazardous environment which triggers the occurrence of sanitation-and-unsafe-water-related diseases. As an illustrative figure, 2,000 children die every day from preventable diarrheal diseases. What is more, it is estimated that the economic losses in productivity due to sanitation related diseases are worth $260 billion. [1]

As a response of that sanitation challenging context, in the summer of 2011 the Gates Foundation launched the 'Reinvent the Toilet' challenge calling on researchers and scientists worldwide to design the toilet of the future.

The challenge was initially answered by several universities from all around the world who shared $3m in funding over 2012. Among the designs chosen were CalTech's solar-powered hydrogen and electricity generating loo and Loughborough University's toilet that produces biological charcoal, minerals, and clean water.

In August of 2012 the Gates Foundation announced a second round of grants accounting for nearly $3.4m. In that round of funding, Cranfield University was awarded with $810,000 to produce a prototype of the innovative Cranfield's NMT, which will be exhibited at the "Reinvent the Toilet (Taj Palace Hotel of New Delhi (India), during 21st and 22nd of March 2014).

Eventually, more funding will be given to the two most successful sanitation solutions, to enable final improvements and field testing. The awarded researchers will be notified after the aforesaid Delhi's Fair, and the final sanitation solution will be brought into the market by the end of 2015.

1.2.2 Cranfield's NMT Project

Cranfield's NMT is an innovative sanitation solution that will turn human waste into pathogen-free water and encapsulated briquettes which will be used respectively for irrigation and fertiliser or fuel (biomass digester).

Regarding the targeted customer, Cranfield's NMT is designed as an standalone sanitation solution for private householders in dense-populated peri-urban areas of developing countries, where there is no reliable access to clean-water, sewage and electricity utilities.

What is more, the toilet has to be affordable for these specific costumers, being not possible to charge them more than $0.05/person/day (considering a 10 people household with a toilet lifetime of 7 years). Consequently, its economic feasibility will depend on a suitable business model in which the capital, maintenance and operational costs will be covered by the customer's payments and some extra-revenue obtained by the sales of the toilet outputs. For instance, the encapsulated briquettes can be used to produce energy in a biomass digester.

To accomplish that sanitation challenge, Cranfield University proposes a reinvented toilet that integrates three nano-technologies developed by its own researchers: low glass transition temperature membranes, silica gel beads, and electro-hydro-dynamic nano-mister.

1.2.2.1 Cranfield's NMT process operation

The Nano Membrane Toilet will accept 17.5 litres of faeces and urine per day as a mixed stream (1.5Lpcpd[4] urine and 0.25Lpcpd faeces from 10 people).

The toilet bowl will have careful material's selection so no flush water will be required, and the flush mechanism will also prevent the escape of odour. Although the flush mechanism has a series of belts no maintenance is expected on these.

Volume reduction of urine and faeces will be undertaken using passive sedimentation and hollow fibre low glass transition temperature membranes that enable extraction of the water content as a vapour through the membrane wall. The treatment will be undertaken as a batch process. These membranes will be used to release the unbound water and increase the solids content to 18%. A sweep gas will be pumped through the system at 25 litres per minute, during a duty cycle of 6 hours a day.

The membrane can reject pathogens, but some volatic organic compounds (VOCs) are transported through the membrane which means the water has an odour and will promote regrowth of pathogens. Hence the water needs to be used in the home on a daily basis for washing and irrigation, not stored.

In order to try and minimise the VOCs in the water, silica gel beads are used. The beads recover 90% of the water, which is incorporated into the toilet. The toilet has a 20L storage tank for water which needs to be emptied daily (16.75l plus 20% spare capacity).

The resultant sludge will be moved through the toilet by extrusion and then sliced into 100ml disc-shaped briquettes. The sludge briquettes will enter a coating chamber, where a fibre mesh encases them. The advantage of doing so compared to an impervious coating, is that water vapour is able to escape from

[4] Lpcd. Litres per capita per day

the briquette facilitating further drying, but pathogens will remain inside the coating. The briquettes will be stored in a 18L container, which will need emptying by the household at least every 10 days (assuming an 83% packing density).

Overall the daily output from the toilet will be 15.75 l pathogen-free water, (daily washing or irrigation), 1.5L water vapour, 15g of ammonia, and 1.5L sludge briquettes (to be used in the property kitchen garden, charcoal stove, or selling). For data protection purposes, only the initial rigs of these technologies are shown in Figure 1-3.

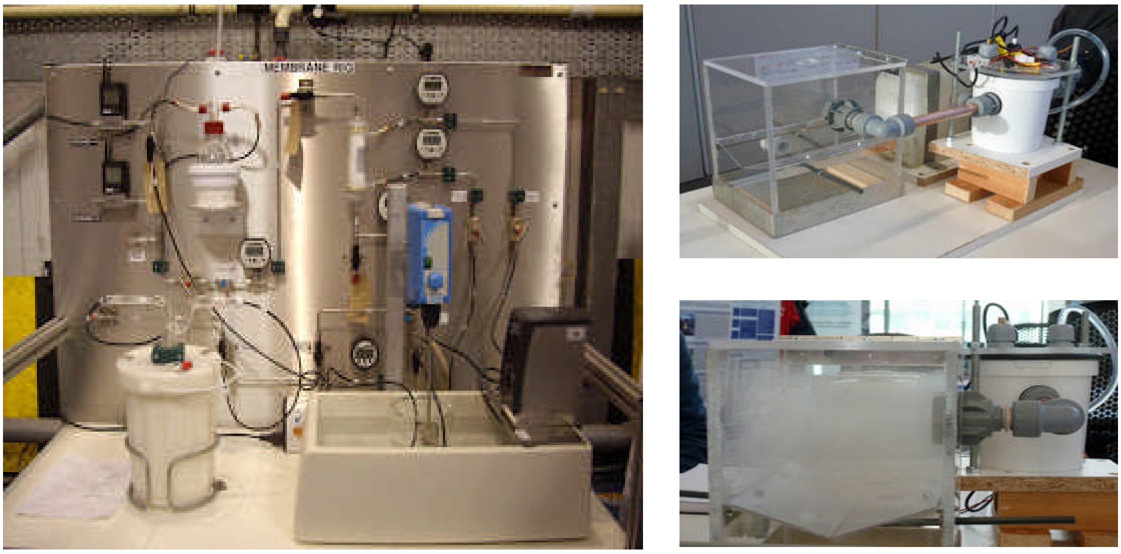

Figure 1-3 NMT membrane and beads (left) and mister rig (right)

1.2.3 Electrical demands of Cranfield's NMT Project

In the previous description of Cranfield's NMT, the toilet's input is described as a combination of faeces plus urine. Next, these inputs are transformed into useful products by means of three nano-technologies. Nevertheless, the performance of the polymeric-membranes and nano-mister requires electric power.

Regarding the dense polymeric membranes, a stream of 25 litres per minute of sweep gas is required to be pumped along the inner volume of the membrane bundle, forcing the mass transfer and water vapour extraction. The current power estimations are 30 watts of power consumption during six hours of daily performance, which accounts for a total of 180 Wh per day. To achieve that, a small power air pump, or compressor will be selected. With regards to the electric consumption of the nebuliser, an overall consumption of 103 Wh per day is currently estimated. This figure accounts for a power consumption of 82 watts during 5 minutes while treating 15 briquettes on a daily basis.

Therefore, the overall amount of energy required for the NMT on a daily basis accounts for 283 Wh, or 0.283 kWh.

1.2.4 HPGs as a backup generator to power Cranfield's NMT Project

As it is explained in next section, adult healthy people can sustain 120 Watts while pedalling for a maximum of 1 hour. While assuming an overall efficiency of 80% for a bike generator and 70% for the battery roundtrip, the amount of energy generated accounts for 67.2 Watt-hours (Wh). Therefore, a daily consumption of 283 Wh means that to power the toilet, a pedalling time of 4.3 hours is needed every day by the adults of the household.

Assuming that four adult people collaborate in the energy generation task of the household, every person will need to pedal 1 hour every day to power the toilet. Since 1 hour 7 days a week by four members requires a lot of human effort to power the toilet, another energy source needs to be allocated as a primary one.

For instance, a solar panel of 60 Watts will generate 300 Watts per day assuming 5 hours of sunlight. Nevertheless, the output wattage of solar panels depends on the sunlight available, being weather dependent. What is more, a lack of regular maintenance of the surface will mean lower power output. Consequently, it can happen that after certain days the batteries become exhausted, since the load was higher than the energy harvested.

Therefore, for critical situations a reliable and affordable source of electricity is needed. And consequently, a human-power generator makes sense as a backup solution to power the NMT in emergency situations. In these circumstances the batteries are exhausted since the primary source has failed to provide the NMT's load.

For instance, several cloudy days can triggered a situation in which the toilet's load cannot be addressed by the PV panel selected. In that situation, having a HPG, means that the user can get the toilet to work no matter the weather conditions, making the toilet reliable against weather dependence or solar irradiance.

Another emergency situation while using solar panels can be triggered due to the drop in efficiency caused when the PV surface is partially covered by dust, and there is a lack of regular maintenance. In that case the HPG will help to provide the demanded electricity until the PV surface is cleaned.

In addition, even for communities of low income countries that are connected to the electric grid, HPGs can be used to satisfy the electric demand of the toilet during a power outage in absence of backup batteries.

1.3 Objectives

The current MSc by Research aims:

- To design, build and test a novel HPG prototype to be used as a backup solution to power Cranfield's NMT.

- To design, build and test a portable power supply unit which completes the delivery of a standalone Human-Powered Energy System (HPES).

- To provide a systematic methodology for preliminary HPGs design selection using the TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) method of operational research.

1.4 Structure and methodology

To accomplish the target of the present study, a market and literature review of existing HPGs products and prototypes has been carried out. While doing so, their design capabilities and specifications are reviewed. During this process, several rated power values have been observed, with some ambiguous data.

In order to clarify that, and better understand the range of mechanical power that the human being can exert a specific study has been carried out during the present work to better understand the design of that generator typology.

Following the previous studies, a brief theoretical review of the components that comprise the prototype has been developed with the aim of examining the main properties of the different technologies to be used in HPGs systems. Doing so, helps the authors to narrow down the most accurate off-the-shelf products and technologies that will be included in a preliminary design study.

Selected six HPGs conceptual designs comprised by off-the-shelf products, the TOPSIS technique is applied to determine the best HPG for our case study. As it will be explained, TOPSIS technique uses the human judgement to rank the different designs. Thereby, to collect an accurate opinion, an online survey was carried out using Qualtrics software. As a result, the importance of ten design attributes was marked by 52 people, with 5 of them with previous experience in animal-powered and human-powered generators.

After having decided the HPG topology, two prototypes and two portable power supply units have been built. Finally, intensive testing has been developed to prove the accurate performance of the prototypes.

2 Classification of HPGs. Literature and market review

The present chapter aims to come up with a classification of the HPGs that harvest energy by means of a sustainable made-on-purpose human effort, as discussed in Section 1.1.4. Secondly, it intends to provide an overall review of the classified HPGs while describing their main design and performance characterization. To do that, an extensive market and literature review has been carried out. Thereby the HPGs presented are representative of the main HPGs developed up to now.

2.1 Classification of HPGs

The majority of HPGs harvest power out of the motion of a single person. Between them three types of HPGs can be distinguish depending on the body motion. Thereby we generally classify single's person HPGs as pedal-cranked or arm-cranked generators. Nevertheless, there are some HPGs that turn the mechanical motion of several people into electricity. A diagram depicting an overall classification for single's person can be found in Figure 2-1

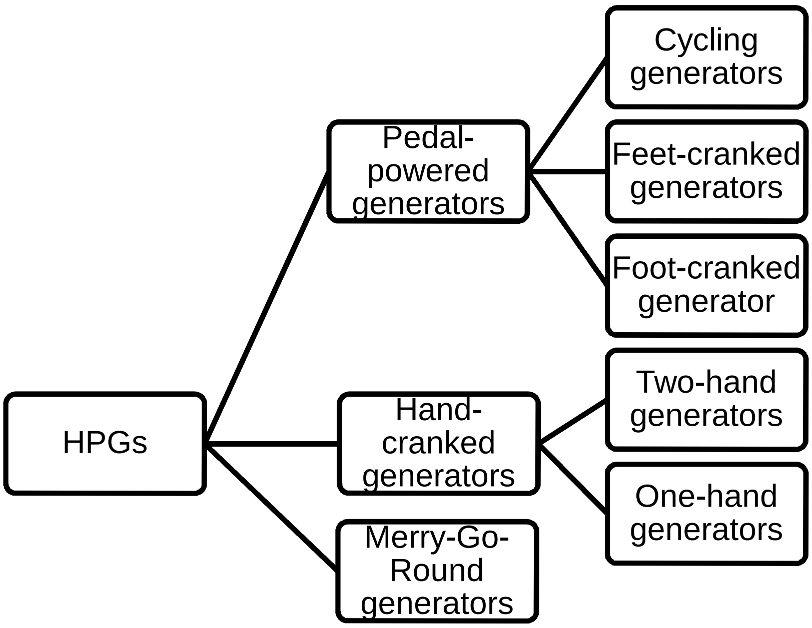

Figure 2-1 Classification of HPGs

For a better understanding, an example of a representative HPG of every category is presented below:

2.2 Pedal-powered generators

As pedal-powered generator we refer to all sorts of HPGs that harvest the motion of the lower-body while pedalling or another type of leg motion.

2.2.1 Cycling generators

Cycling generators are the ones that harvest electric energy out of a cycling motion. They can be mainly narrowed down between the ones that use a fixed structure or a conventional bike to transform the human powered into the required mechanical input power of the generator.

2.2.1.1 Fixed-cycling generators

Fixed-cycling generators use a fixed bicycle as a transmission mechanism of mechanical power. The most common ones are in the form of retrofitted spinning machines like the one shown in Figure 2-2. This specific HPG from NEERG TRADING LTD (1) is a representative one of the last HPG of this category.

Figure 2-2 Indoor bike (left) with hub motor (right) (1)

It comprises a fixed steel support structure, plus a single chain ring and sprocket. It uses a non-geared brushless in-wheel motor, Figure 2-2 (right), attached to a flywheel. The output cable is connected to the power portable box.

Moreover, its specifications are:

- Unit price: USD 415.00 USD365.00 buying 100 pcs.
- Output power: 150-200w. Max.500w
- DC output: 14.5V.
- Rated speed: from 60 to 80 rpm.
- Dimension: 1110*200*860mm.
- Weight: 38kg.
- The portable power box has a 12v/26Ah battery and 300w inverter.

On the other hand, Figure 2-3 shows a fixed-cycling generator that has been locally made by technicians in Uganda, [4]. This HPG comprises a normal bike fixed to a support structure that contains a locally made, low-rpm generator. Its drive train comprise a single chain ring and sprocket plus a flat belt fixed to the rear wheel and generator pulley.

Figure 2-3 HPG with locally made low RPM generator Mechtenberg 2012

Due to its research stage, its characteristics are not specifically mentioned. Nevertheless, in [4] an average efficiency of 80% is assumed, and a cost between 75 and 500 US dollars for bike generators.

2.2.1.2 Plugged-in bike generators

Plugged-in bike generators are the ones that use a conventional bike with any modification as a power drive train. The generator is fixed to the support structure, and the power is transmitted by friction between the wheel tire and the generator’s pulley. Figure 2-4 sets up an example of a representative generator of these type.

Figure 2-4 Plugged-in biked generators (1)

Its characteristics are like follow:

- Unit price: 540.00 US dollars per piece
- Output power: 100w, Max.120w
- Holder: for 24"/26" bicycle
- Rated speed: 50～65rpm
- Dimensions: 560*520*190mm
- Weight: ≤20kg

2.2.2 Feet-powered generators

As feet-cranked generators it is understood all the pedal-cranked generators in which the support structure is not a conventional bike. As a representative of these HPG, Figure 2-5 shows the one designed in [11].

Figure 2-5 Feet-cranked HPG device [11]

The drive train is comprised by a system of flat belt and pulleys with an attached flywheel. Its system has a gear ratio of 36, while applying two steps. They are connected to a brushless motor with a passive rectifier attached. The brushless motor is rated 200 Watts, with a rated speed of 3000 rpm and a Back EMF of 6 V/kVRPM. The DC current obtained is directly connected to a solar charge controller. Finally, the average power generated is 100 Watts while pedalling from 50 to 70 rpm.

Another example of a feet-cranked generator is the Windstream HPG (2), as shown in Figure 2-6. This generator consists of a set of two pedals, a chain drive and a brushed dc generator. It has a very compact design, with a small footprint due to the fact that the reacting torque is generated by anchoring it to the ground. In that case, the support structure is not included with the generator, allowing for a more compact design. Regarding the amount of power generated, less than 65 Watts can be sustained comfortably.


Figure 2-6 Windstream® HPG (2)

2.2.3 Foot-powered generators

As foot-cranked generator we refer the ones that are powered by the movement of one leg or while stepping one foot on them. As a representative example, Figure 2-7 shows a HPG with the following specifications:

- Unit price: 286 USD
- Output power: 14.8-37w
- DC output: 14.8V
- Current: 1.0-2.5A
- Pedal speed: 110rpm (best)
- Dimension: 385*205*201mm
- Weight: 3kg

Figure 2-7 Foot-crank generator. (1)

2.3 Hand-cranked generators

Hand-cranked generators include the HPGs that harvest the power out of the upper-body motion. In other words, the HPGs that are cranked with the hands, or using arms movement. They can be distinguished as two-hands or one-hand crank generators depending on the number of arms included to exert the movement.

2.3.1 Two-hand powered generators

Two-hand cranked generators are the ones which harvest the motion of both arms while cranking. Two representative HPGs of this type are shown correspondingly in Figure 2-8, and Figure 2-9.

Figure 2-8 Military Hand Power Generator (1)

Figure 2-9 Double handle generator. (1)

The generator shown in Figure 2-8, consist of a set of handles, a gearbox, and a generator which are assembled in a compact box. This box is welded to the support structure that allows the user to provide the motion comfortably. The power rating of the generator is either 40 Watts or 65 Watts, for 12 volts or 24 volts rating correspondingly. The unit price is 400 US dollars for one sample and 270 dollars for mass production.

Regarding the generator depicted in Figure 2-9, this has the same configuration than the previous one but its support structure is not included. Its power rating range from 12 to 30 watts, and includes a DC/DC transformer that provides a DC output voltage from 4.5 to 28 volts.

2.3.2 One-hand powered generators

One-hand powered generators are the ones that harvest electric energy out of the motion of one arm, while turning a crank mechanism.

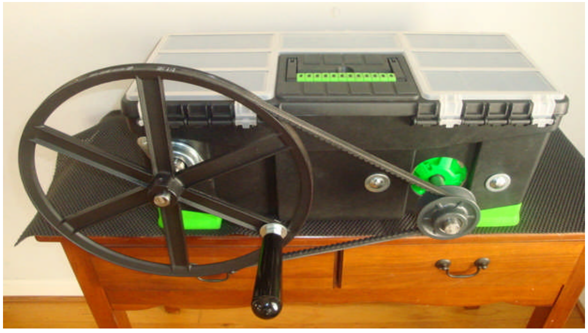

Figure 2-10 Crank-a-Watt™ generator. (3)

Crank-a-Watt ™ Deluxe generator (3) consists of a set of timing pulleys and belt, which transfer power to a low-speed high voltage customized alternator. Inside the box, lead acid batteries and a power inverter are fitted to provide DC and AC current for charging different appliances.

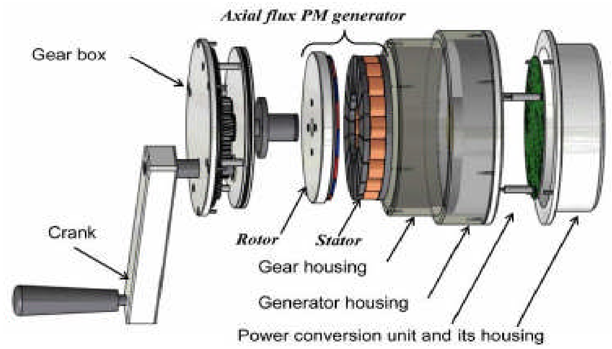

Figure 2-11 Axial flux generator [12]

Showing another type of one-hand powered generator, Figure 2-11 depicts a prototype of an axial flux generator designed in [2]. It consists of a 200 mm crank connected to a gearhead (1:20 ratio) and an axial flux generator. The design speed is 85-110 rpm, rated speed100 rpm, and the generated power results 50 ± 20 Watts.

2.4 MGR generators

The MGR generator is a mechanical device that generates electricity while children are playing.

Figure 2-12 Merry-go-round generator (4)

This type of HPG was invented by Brigham Young University faculty of Mechanical Engineers. Its development brought to the creation of Empower Playgrounds, Inc., a registered charity in USA.

This MGR generator, Figure 2-12, has a cost that ranges 5000-6000 US$. It generates an average of 100 Watts out of the mechanical power harvested when three children are playing. Approximately, 30% of the kinetic energy is used to generate electricity. The designed velocity ranges from 8-10 rpm and is turned into 200-300 using a gearbox. A 3-phase AC windmill generator is used to produce electricity, which is directly connected to a bridge rectifier to generate DC current to charge a battery bank.

Following the success of this HPG, other generators have been developed. That's the case of St. Joseph Technical Institute in Uganda [4], who has locally manufactured a MGR generator. Their MGR generator has a capital cost of 500-2000 US$, and it can a power range of 100-600 Watts.

3 HPGs and human mechanical power output

In the present Thesis, we refer to HPGs as the type of generators in which the source of mechanical power is provided by the human effort (P_{human}) while spinning a shaft, with its corresponding angular speed (ω_{human}) and torque (T_{human}). Usually, a sort of mechanical transmission system is needed to adapt these variables into the generator's required ones ($\omega_{in\ gen}$ and $T_{in\ gen}$). Then, this mechanical power is turned into electric power by the generator ($P_{out\ gen}$). Eventually, $P_{out\ gen}$ is converted with the aim of being stored ($P_{in\ storage}$), without damaging the storage system.

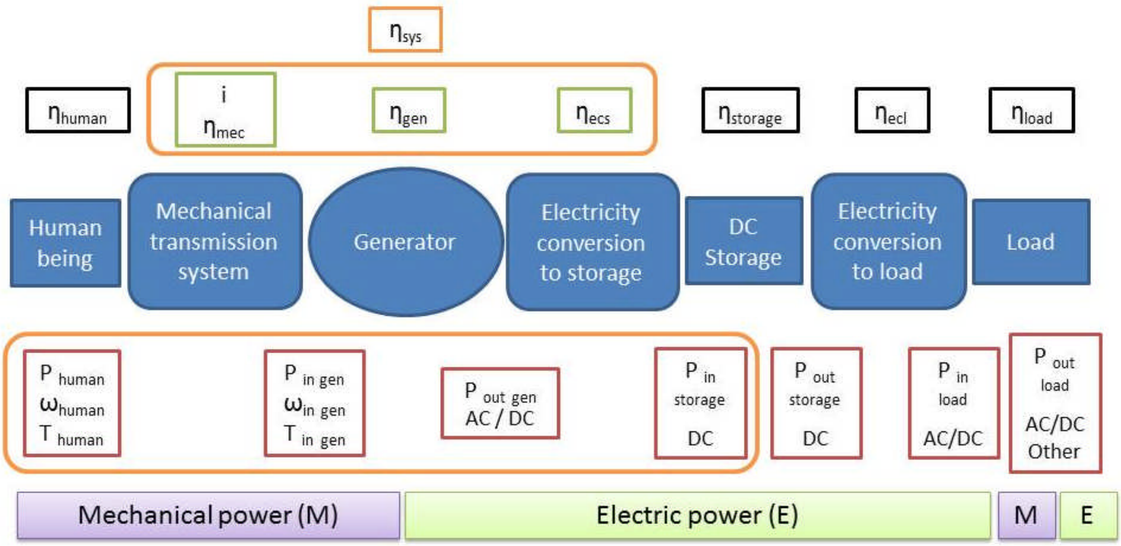

Figure 3-1 HPG electromechanical system

Over the former process, depicted in Figure 3-1, HPGs turn the human mechanical power (P_{human}) into electric power plus electromechanical losses (P_{loss}). It is shown in Equation (3-1), where η_{sys} accounts for the efficiency of the HPGs system.

$$\mathbf{P_{in\ storage} = P_{human} - P_{loss} = P_{human} * \eta_{sys}} \qquad \textbf{(3-1)}$$

Consequently, the rate in which energy is generated and stored by an HPG system depends on P_{human} and η_{sys}. What is more, a better understanding of them will establish solid arguments to predict the energy generated and stored by the HPGs to be developed in this Thesis. On the other hand, they will be used as a checking and validation arguments when comparing data with existing market products.

In the present section we focus on the study of how much human mechanical power output can be sustained during a specific period of time while hand-cranking and pedalling, studying the system efficiency later on. To determine that power, three approaches have been followed. First we review the critical power concept. Next we focus on the rated power with regards to HPGs presented on the literature review. Finally, we study this power for some products in the market.

3.1 Human mechanical power and critical power

In the field of ergonomics, it is accepted that the mechanical output power (P_{human}) is related with the time to exhaustion (Tlim) following a hyperbolic relationship defined by two constant values: the Anaerobic Work Capacity (AWC) and the Critical Power (CP), as shown in Equation (3-2).

$$\mathbf{Tlim} = \frac{\boldsymbol{AWC}}{\boldsymbol{Phuman - CP}} \quad \textbf{(3-2)}$$

Supposedly, the CP represents the asymptote of the power output against time-to-exhaustion function (Figure 3-2). Nonetheless, fatigue happens after 30 to 60 minutes of workout at CP. What is more, Oliveira et al. (2009) states that the CP fits into a transition range among intense and very intense domains of physical exercise.

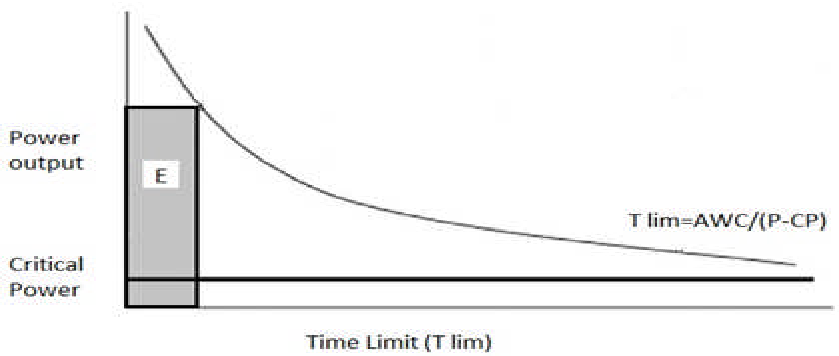

Figure 3-2 Power output vs. time to exhaustion

Furthermore, CP offers a quota of aerobic fitness for every person. Therefore, it relates to other physiological indicators of aerobic fitness such as the fatigue threshold, the ventilatory and lactate thresholds, and the maximum oxygen uptake ($\dot{V}O_{2max}$). Regarding to AWC, it provides a quota of anaerobic capacity [13].

Finally, these parameters provide an estimation of aerobic and anaerobic fitness for every person, and can be determined following the outcomes of a series of 3 to 7 or more timed all-out predicting trials [13].

3.2 Critical power while hand-cranking and pedalling

As stated before, the maximum mechanical power that can be sustained by different individuals depends on their physical-fitness (gender, age, mass, height, maximum heart rate, maximum oxygen consumption) and the muscle group that are involved in the physical exercise (one-hand cranking, two-hand cranking and pedalling).

Therefore, with the aim of achieving a rational estimation of the power output and endurance, several studies have been reviewed and summarized in Table A-1 of Appendix A. In that table, the values of CP and AWC are displayed while differentiating among body-movement and subject of study (adults with similar age, different gender, and different physiological-fitness).

Nevertheless, from now on we fixed the subject of study to the young healthy male individuals who are moderately trained and physically active aged from 19 to 32. While doing so, the different P_{human}-T_{lim} functions diverge on the different muscular mass of the targeted study's movements. Consequently we selected the studies in [14], [15] and [16]. Some of their results are presented in Table A-1, as representatives of the withstand power while one-hand cranking, two-hand cranking, and pedalling. These functions are depicted in Figure 3-3, while the main values are shown in Table 3-1 while applying Equation (3-2).

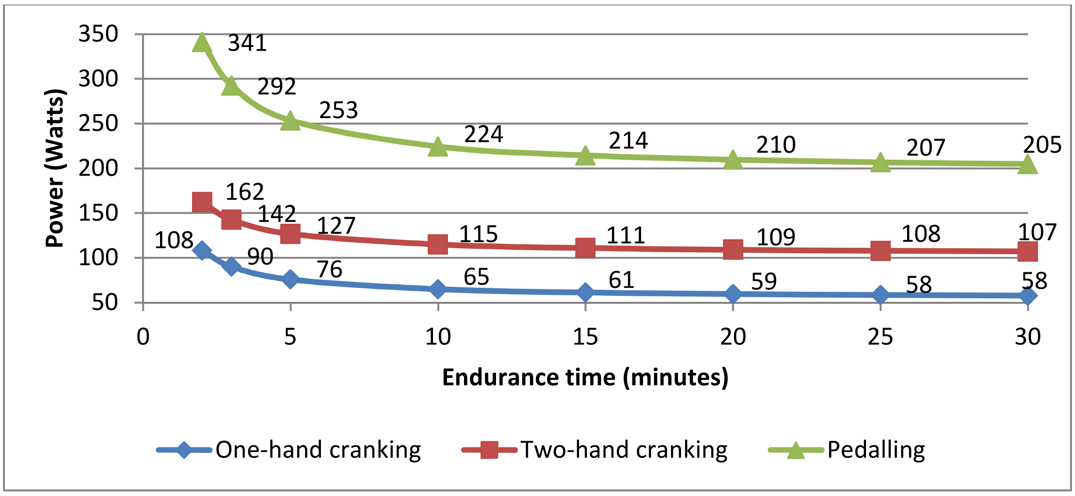

Figure 3-3 Power vs. endurance for hand-cranking and pedalling

Movement	Source	CP (Watts) (μ ± σ)	AWP (Watts) (μ ± σ)	P (15 min) Watts	P (30 min) Watts
One-hand	[14]	54 ± 14	6.48 ± 3.41	61	58
Two-hand	[15]	103 ± 26	7.08 ± 2.14	111	107
Pedalling	[16]	195 ± 46	17.53 ± 6.44	214	205

Table 3-1 P-Tlim results while hand-cranking and pedalling

As previously stated, the CP represents the level of power that theoretically can be sustained indefinitely without fatigue. Nevertheless, is worth remembering that CP is classified as the frontier between intense and very intense physiological activity, [15].

Thereby, if we assume the normal distribution of CP and AWC, statistical inference can be applied to determine a comfortable load to be withstood by 75% (μ – 0.67 σ) and 95 % (μ – 1.65 σ) of the studied population. For instance, this assumption is done in [14]. Having done that, Table 3-2 shows the values of power withstand for the studies cited in Table 3-1 for the population percentages of 50, 75 and 95 %.

Movement	Source	Time to exhaustion (minutes)	50 % (μ) Watts	75% (μ – 0.67 σ) Watts	95% (μ – 1.65 σ) Watts
One-hand	[14]	30	54	45	31
Two-hand	[15]	30	103	86	60
Pedalling	[16]		195	164	119

Table 3-2 Sustainable power inferred values

3.2.1 P_{human} and HPGs literature review

After the aforementioned discussion, the present section aims to find out which values of human power are adopted in the HPGs literature Table 3-3 point out the statements presented in HPGs articles.

Source	Subject	Movement	Power	Endurance
[17]	Regular person	One-hand	30 Watts	1 hour
[18]	Regular person	Cycling	50-150 watts	1 hour
[17]	Regular person	Cycling	100 Watts	1 hour
[4]	Regular person	Cycling	125 Watts	1 hour
[19]	Well trained cyclists	Cycling	125-200 Watts	1 hour

Table 3-3 Power and endurance. Literature review

3.3 Human powered scenarios

After the previous research of human power and exhaustion time, we assume three scenarios of mechanical human power for regular adult people (included males and females aged from 20 to 50 years), as displayed in Table 3-4.

Movement	Max. Endurance (minutes)	Medium (Watts)	High (Watts)	Very High (Watts)
One-hand	30	31	45	54
Two-hand	30	60	86	103
Cycling	60	119	164	195

Table 3-4 Human mechanical-power scenarios

These scenarios are defined by the estimations inferred in Table 3-2 for physically active adult males aged 19 to 32 and by the range of power shown in Table 3-3. Therefore the following assumptions have been made:

- Very high power scenario. Corresponding to the mechanical power level withstood for 50 % of the physically active men aged 19 to 32
- High power scenario. Corresponding to the mechanical power level withstood for 95 % of the physically active men aged 19 to 32
- Medium power scenario. Corresponding to the mechanical power level withstood for 95 % of the physically active men aged 19 to 32

Finally, the maximum endurance time corresponds with the maximum values stated in [14] for one-hand cranking and in [4] for cycling.

3.4 Human power: torque and speed values

In the previous section, three levels of human-power scenarios were considered. This power (P_{human}) results as a product of the cadence (ω_{human}) and torque (T_{human}) exerted by the human being, as stated in Equation (3-3).

$$\mathbf{P\ human} = \boldsymbol{\omega\ human\ x\ T\ human} \qquad \textbf{(3-3)}$$

As it can be deduced, the higher the angular speed exerted (cadence) the lower the torque for the same amount of power and vice versa. Nevertheless, the product of both magnitudes accounts for the same level of effort or energy consumed per time. Nevertheless, cadence and torque are principal design variables while designing electro-mechanical systems. Therefore, the variation of their values is a matter of interest.

Regarding the cadence or angular revolutions per minute, a range from 35 to 120 rpm are considered as characteristics of the human motion while exerting power while exercising the upper-body or pedalling, as they are the range of speeds of upper-body and bicycles ergometers [20]. Consequently, the resulting torque could be deduced while applying Equation (3-3) for the different range of power, as it is shown in Table 3-5.

	Medium power scenario (watts)			High power scenario (watts)			Very hight power scenario (watts)		
	One-hand	Two-hand	Pedalling	One-hand	Two-hand	Pedalling	One-hand	Two-hand	Pedalling
Cadence (rpm)	31	60	119	45	86	164	54	103	195
40	7.4	14.3	28.4	10.7	20.5	39.2	12.9	24.6	46.6
50	5.9	11.5	22.7	8.6	16.4	31.3	10.3	19.7	37.2
60	4.9	9.5	18.9	7.2	13.7	26.1	8.6	16.4	31.0
70	4.2	8.2	16.2	6.1	11.7	22.4	7.4	14.1	26.6
80	3.7	7.2	14.2	5.4	10.3	19.6	6.4	12.3	23.3
90	3.3	6.4	12.6	4.8	9.1	17.4	5.7	10.9	20.7
100	3.0	5.7	11.4	4.3	8.2	15.7	5.2	9.8	18.6
110	2.7	5.2	10.3	3.9	7.5	14.2	4.7	8.9	16.9
120	2.5	4.8	9.5	3.6	6.8	13.1	4.3	8.2	15.5

Table 3-5 Resulting torque (Nm), power and cadence

4 ELECTRO-MECHANICAL CONCEPTS OF HPGs

As previously stated, the amount of power harvested by HPGs depends on the amount of mechanical power exerted and the efficiency of the electro-mechanical system up to its storage point. In the previous chapter, the first concept is discussed. In the present chapter, a description of the technologies, concepts and components generally used to transform the mechanical human power into electric power is developed.

Depending on the adoption of these components, the electric power generated out of the mechanical human power will vary, resulting on different electro-mechanical power losses on the system. Due to the limited mechanical power output that can be achieved and sustained for a certain period of time, the correct selection of these components is crucial for the creation of an HPG.

4.1 HPGs. System components

The different components that comprise a HPG can be classified with regards to its functionality up to the storage point. Correspondingly, three sub-systems are identified as mechanical transmission, generator and electricity conversion. These ones include the process until the energy generated is delivered to the storage or transmission system, as depicted in Figure 4-1.

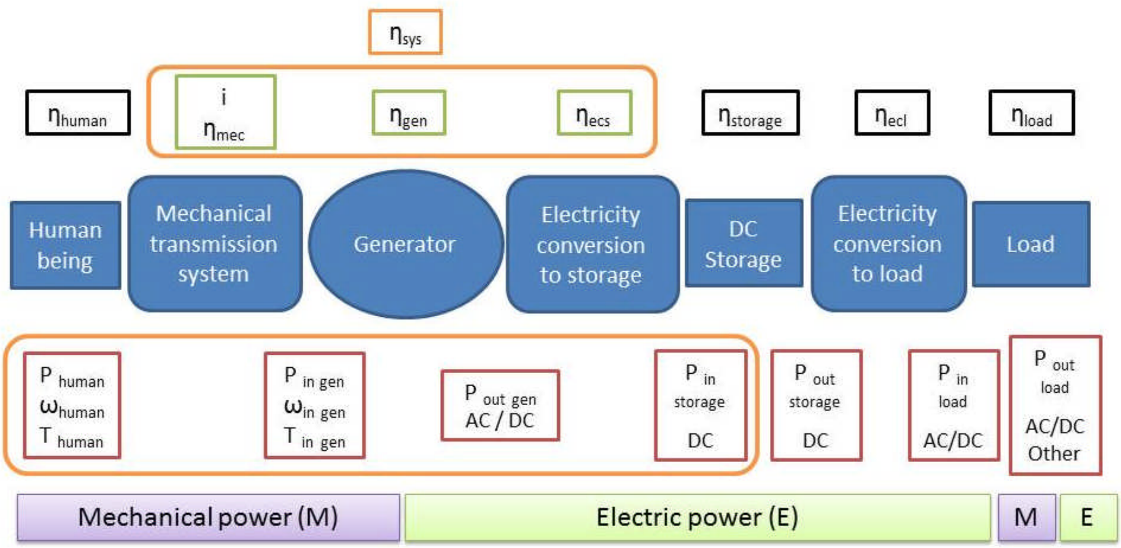

Figure 4-1 HPG electromechanical system

4.1.1 Mechanical power transmission systems

Mechanical power transmission systems are defined as the mechanical components whose functionality is to transmit mechanical power. Doing so, the values of speed and torque between the driver and driven component can be constant or being modified while experiencing certain mechanical losses, as seen in Equation (4-1),

$$\boldsymbol{\omega 1 * T1} = \boldsymbol{\omega 2 * T2 + P\ loss} = \boldsymbol{\omega 1 * i * T2 + \omega 1 * T1\ (1 - \eta)} \qquad \textbf{(4-1)}$$

where $\omega 1$ and T1, and $\omega 2$ and T2 are correspondingly the input and output angular speed and torque. P_{loss} stands for the power losses, i the ratio between the output to input speed and η, the system efficiency.

In the present study, these systems are used to transmit the human mechanical power into the required values of angular speed and torque demanded by the generator machine. As seen in Equation (4-2)

$$\boldsymbol{\omega human * Thuman} = \boldsymbol{\omega in\ gen * Tin\ gen + P\ loss} \qquad \textbf{(4-2)}$$

where, ω_{human} and T_{human} are the speed and torque exerted by the user, while $\omega_{in\ gen}$ and $T_{in\ gen}$ are the speed and torque at the generator electric machine.

Aiming to select the proper power transmission systems for the design of our HPGs, a brief description will be reviewed. Specifically, we will describe the main characteristics and range of application of the following systems: belts and pulleys, chain and sprockets, gears systems, and couplings.

4.1.1.1 Belts and pulleys

Depending on the power transmission principle, different belt and pulley systems are identified with different characteristics and applications. They can be classified as follows:

1. Flat belts and pulleys. They rely on friction and centrifugal force to transmit power as a limiting power factor, rather than the strength of the belt material.

2. V or Wedge belts and grooved pulleys. They are a variety of the previous ones, which a modified section to provide a wedging action to enhance frictional grip. Thereby, they provide higher belt power transmission in a narrower (if deeper) section, making them more compact, although less flexible.

3. Ribbed belts and pulleys. These belts are mainly flat belts with longitudinal threads to increase the contact area and thus the friction. They lack the wedge effect to increase friction but provide greater flexibility to stand higher operational speeds.

4. Toothed or timing belts and pulleys. Timings belts operate with positive engagement on toothed pulleys. They guarantee no slip thus a synchronous speed. This means that the performance limit is directly related to the strength of the belt, instead of the friction.

4.1.1.2 Chain drives

Chain drives are power transmission systems in which the power is conveyed by a roller chain, known as the drive chain, passing over a sprocket gear, with the teeth of the gear meshing with the holes in the links of the chain. The gear is turned, and this pulls the chain putting mechanical force into the system.

4.1.1.3 Gear drives

Gear drives are transmission systems comprised by gears or cogwheels. Two or more gears working in tandem are called a gear system. Geared devices can change the speed, torque, and direction of a power source assuring no slippage due to teeth or cog action. The gearbox configuration chosen for a given application is most strongly influenced by three parameters: physical arrangement of the assembly, speed ratio required, and torque loading. Other factors that must be considered when specifying a gear drive are: efficiency, space, weight limitations and physical environment.

According to these factors, different types of gears have been developed for different applications. Generally they can be classified as planetary, spur, spiral, helical, bevel, hypoid, worm, harmonic drives.

4.1.1.4 Couplings and clutches

Couplings are power transmission mechanisms that connect aligned shafts with a unity angular speed ratio. Depending on the accuracy of the alignment, they can be classified as rigid or flexible couplings. Rigid couplings are used only where accurate shaft alignment can be ensured during the whole service life of the drive train. Conversely, flexible couplings are designed to accommodate angular and axial misalignment.

By clutches it is understood the couplings that are mechanically engaged or disengaged, being able of disconnecting the driven shaft from the driver mechanism. Thereby, when they transmit power, they act as couplings.

4.1.1.5 Power systems applicability and efficiency

Regarding the application of power drives to the design of our HPG, all the mentioned power drives are able to transmit the mechanical human power (120 Watts average, 300-400 Watts peak). Having said that, their speed ratio and efficiency establish an important criterion to determine their suitability for the case study presented.

	Maximum Speed Ratio (One Stage)	Efficiencies (One Stage) %
Flat-belt	1:50	70 - 95
V-belt	1:50	85 -88
Toothed belt	1:50	85 - 95
Chain	1:6	98
Gears		
Spur	1:10	95 - 98
Helical	1:15	96 - 99
Worm	1:100	25 - 95

Table 4-1 Speed ratio and efficiencies of drive-trains [21]

4.1.2 Generator machines

Generators are machines that convert mechanical power into electrical power, while experiencing certain losses, Equation (4-3). Depending on the electricity generated, they can be differentiated into direct current (DC) or alternating current (AC) generators. On the other hand, depending on the source of magnetic excitation, they can be distinguished into permanent magnet generators or electromagnetically excited generators.

$$\mathbf{Pmech} = \boldsymbol{Pelec} + \boldsymbol{P\ loss} \qquad \textbf{(4-3)}$$

The following section aims to describe the overall characteristics of the generators that can be used for the design of HPGs.

4.1.2.1 Brushless DC permanent magnet motors.

Brushless DC (direct current) permanent magnet motors are widely available motors nowadays. Over the last 10-20 years, their demand has increased considerably due to the growth of high-precision high-performance machine and robot applications.

A brushless DC Motor is a synchronous electric motor powered by a direct current. The DC current is transformed into a specific alternating current by means of an electronic controller. The AC current is drawn into the stator, to create the magnetic field that moves the rotor. The position of the motor is registered by an optic sensor called a Hall controller. This sensor sends continuous feedback to modify the amplitude and frequency of the generated AC current and achieve the output rotor speed and torque demanded.

Nevertheless, to operate the machine as a generator neither controller nor Hall sensors are needed. And therefore, a Brushless DC Motor results in a synchronous permanent magnet three-phase alternator. Due to its brushless configuration no maintenance is required due to no brush, commutator and slip ring being present. Another advantage for their use in HPGs applications is their compact size.

Regarding the different configuration of the machine, Brushless DC motor can be differentiated into inner and outer rotor motors, as shown in Figure 4-2.

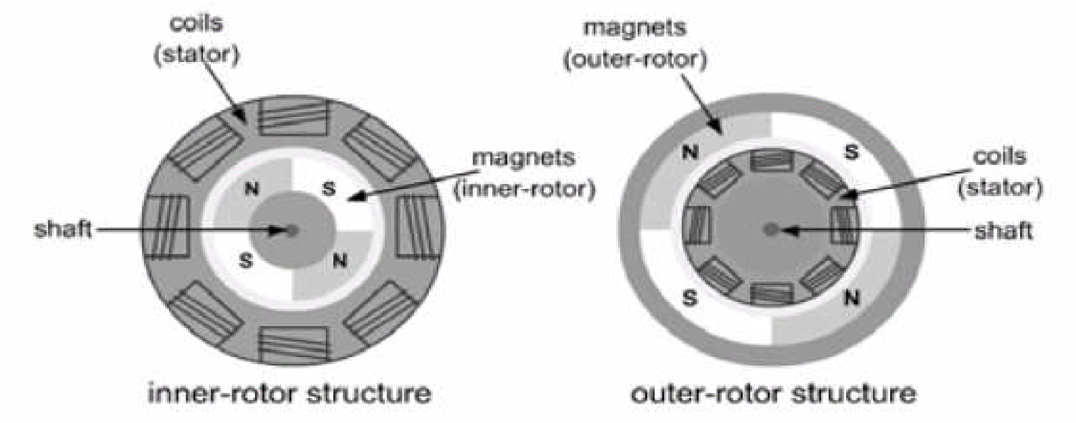

Figure 4-2 Inner (left) and outer (right) rotor assemblies [22]

The majority of the inner-rotor permanent magnet DC brushless motors available on the market are high speed rotating machines. With that design, they increase their power density while resulting in cheaper and more compact motors than low-rotating ones. As a representative example, the brushless motors commercialized by Delta Line, S. p. A. have a speed range 2600-8000 rpm, with a power range of 4-650 Watts.

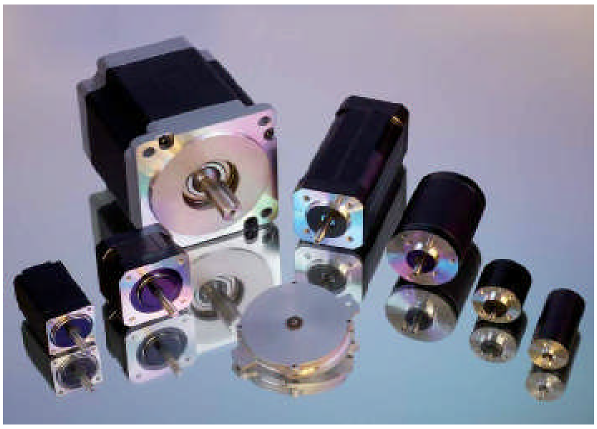

Figure 4-3 Delta Line DC Brushless Motors (Delta Line, S.p.A., 2002-2014)

Having said that, to use these small motors in a HPG, a gearbox is necessary since the human-speed range is 40-120 rpm (either arm-cranking or pedalling).

The outer-motor permanent magnet brushless motors are widely used in electric bikes. They have an array of permanent magnets on the inside surface of the hub. The stator windings are attached to the axle, and the hub is made to rotate by alternating currents through these windings. They can be classified as direct driven or internally geared machines.

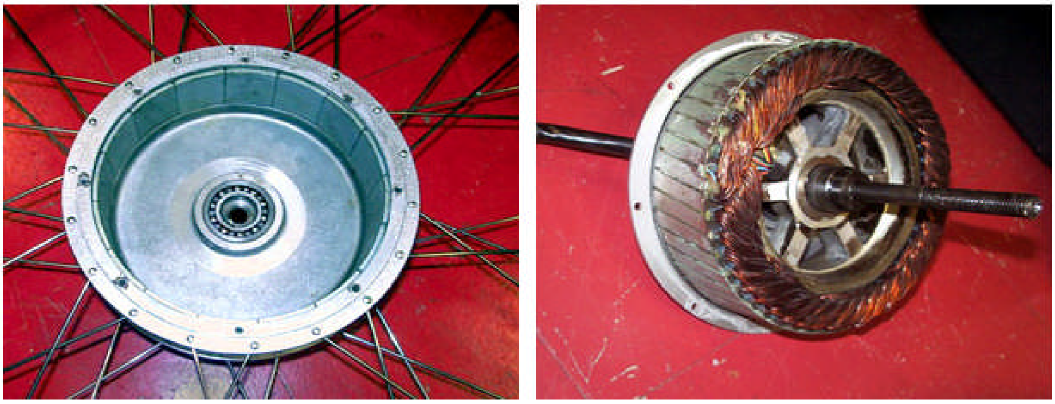

Figure 4-4 Direct-driven hub motor (5)

Direct drive motors are usually large and heavy for their power output. The reason for this is that the wheel speed is quite low, around 200 rpm. The power density available from an electric machine is directly proportional to the speed between the magnets and the winding, so in order to get adequate power and torque output the motor has to be large.

In a geared transmission the motor is often spinning over 3000 rpm, and hence a much smaller motor can deliver the same power, as seen in Figure 4-5

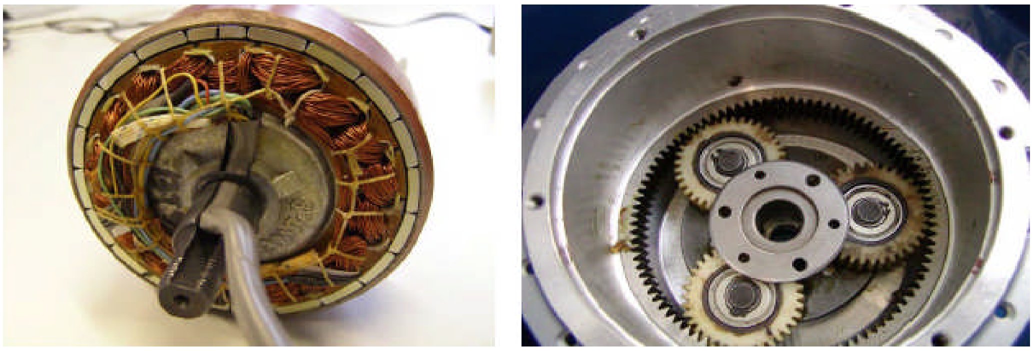

Figure 4-5 Geared-drive hub motor (5)

Geared motors typically weigh about 50% less than an equivalently powerful direct drive machine, and they often have superior torque outputs. Nevertheless, these advantages of the geared hubs have to be weighed against their disadvantages. Geared hubs are generally more expensive, there are many moving parts which are prone to wear, and they generate audible noise.

4.1.2.2 Brushed DC permanent magnet motors

Brushed DC permanent magnet motors use a set of brushes and commutator to transform the direct current into a rotating magnetic field, as seen in Figure 4-6. Thereby they use neither electronic controller nor Hall sensors. As a result they result cheaper and simpler to operate than brushless permanent magnet DC motors. Regarding their physical configuration, they usually have the permanent magnet located on the stator, and the windings on the rotor.

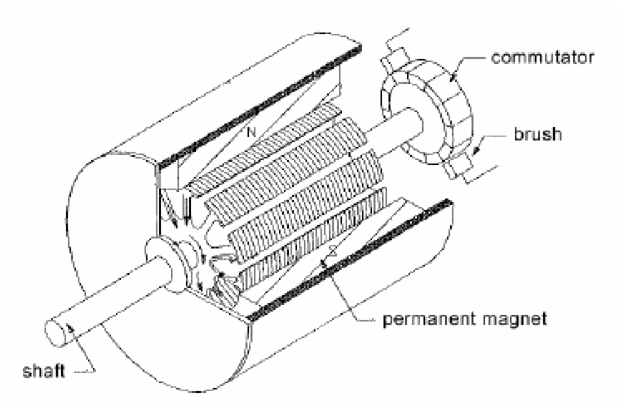

Figure 4-6 Brushed permanent magnet DC motor [22]

Nevertheless, the presence of brushes and commutator introduce different limitations to the machine, such as:

- Regular maintenance is required and have shorter lifetime, due to the friction between brushes and commutator
- Brushed dc motors have higher losses due to the voltage drop in the brush-commutator assembly

- Their output speed is limited due to the appearance of sparks in the brush-commutator assembly
- Their output power is limited due to the current density per unit area of the brushes

On the other hand, while using them as generators, brushless dc motors generate dc current, thanks to the mechanical rectification. Therefore it is not necessary to employ any AC to DC converter.

4.1.2.3 Automotive alternator

Automotive alternators are readily available generator machines. The more frequent of them is the Lundell alternator. They are mass produced for the automotive industry, with a cost of about 75 $. [23]

The Lundell alternator is an electromagnetically-excited three-phase synchronous machine that consists of an internal three-phase diode rectifier and voltage regulator. Figure 4-7 shows a Lundell alternator rotor and stator.

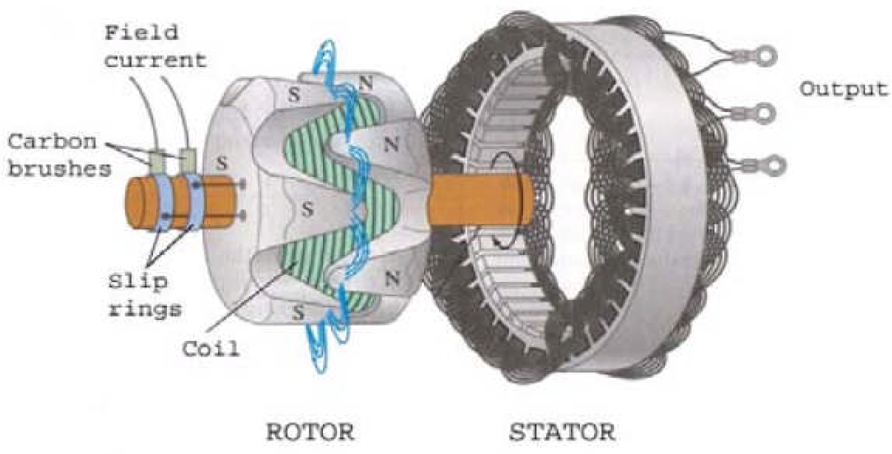

Figure 4-7 Exploded view of Lundell alternator [24]

The output voltage is set at 14 V by an internal controller that varies the field current in the range 0-1 ampere approximately. Lundell alternators are designed for a speed range of 1800-18000 rpm, while applying a typical 3:1 belt drive to a 600-6000 rpm range of engine speed, [24].

The power ranges up to a maximum of 2,100 Watts of continuous duty (14 V 150 Amps). This performance is limited by heating and magnetic saturation of the machine, having an overall efficiency of 40-55%, taking into account the regulating voltage system. Finally, they require maintenance of their brushes, depending on the level of mileage.

4.1.2.4 Wind Turbine permanent magnet alternators

Wind turbine permanent magnet alternators are generators specifically customized to be driven by a wind turbine rotor. They are synchronous permanent magnet machines, as the brushless dc motors previously stated. Conversely to these ones, wind turbine PM alternators are specifically design for higher power outputs and longer lifespan but with higher capital cost.

For instance, the GL-PMG500A generator of Ginlong Technologies, Co., Ltd can be presented as a representative machine to build up HPGs. With a cost of $785, generates 100 Watts at 250 rpm. Its main advantage versus an in-wheel direct driven motor are its more than 20 years lifespan and its specific aluminium alloy outer frame and special internal structure for heat dissipation.

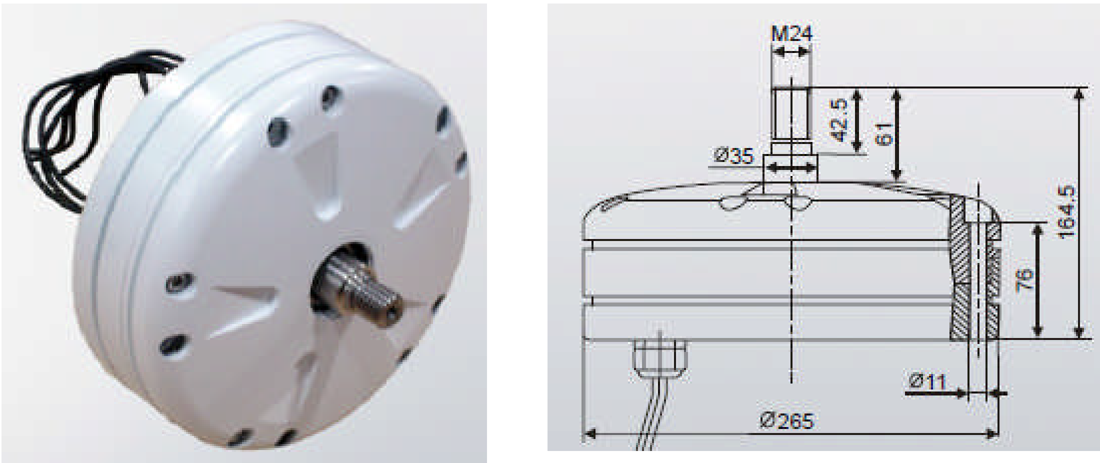

Figure 4-8. GL-PMG-500W (6)

4.1.3 AC/DC converters

The AC/DC converters are the mechanical assembly or electronic components which turn alternating current into direct current (known as rectification).

In brushed direct current generators, the assembly of brushes-commutator results in the AC/DC converter, while doing a mechanical rectification. Conversely, in three-phase brushless alternators rectification is done by means of electronic components. Depending on their ability of transmitting reactive power through them, electronic rectifiers can be differentiated into passive and active ones.

For small power applications like HPGs and small wind turbines, a diode full wave bridge rectifier is chosen versus active rectifiers due to their simplicity. [25]. In addition, depending on the power level, an array of capacitors can be installed for reactive power compensation.

4.1.4 DC/DC converters

A DC-to-DC converter is an electronic circuit which converts a source of DC from one voltage level to another. This technology has evolved from inefficient and simple linear voltage regulators to electronic switch-mode converters.

Switch-mode converters store the input energy temporarily and then release that energy to the output at a different voltage. The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors). This conversion method is more power efficient (often 75% to 98%) than linear voltage regulation (which dissipates unwanted power as heat).

In battery charging application they are mainly used to control the charging voltage and current, such as solar charge controllers.

In HPGs and small-power wind turbine applications, they are used after diode bridge rectifiers to control the output power of the generators while limiting the output voltage or current.

4.1.5 Energy storage. Batteries

Electric batteries are electro-chemical devices that transform direct current into stored chemical energy and vice versa. They consist of a positive and negative terminal (cathode and anode correspondingly) and an electrolyte solution.

Nowadays, there are three leading rechargeable battery technologies on the market: Lead acid, Nickel-metal-hydride (NiMH) and Lithium-ion (Li-ion). They characterized by the chemical composition of its cathode and electrolyte.

In the current section we will review the lead-acid and Litium-ion technologies, as current realistic batteries to be included in the design of HPGs due to their market availability in medium capacities, 4-100 Ah. NiMH batteries are the current replacement for Nickel-Cadmium ones. They are available in AA, and AAA types, with a very low capacity range 1.2-4.5 Ah to be used in HPGs.

4.1.5.1 Lead acid batteries

Lead–acid batteries have 40–45% of the battery market, since their extended use as starting, lighting, and ignition batteries in cars, trucks, and buses. [26] Nowadays, valve regulated lead acid (VRLA) battery technology have replaced the old open-vented ones. VRLA batteries are maintenance-free and the cheapest but heaviest technology, with the lowest energy density. They are highly available on the market; with an effective and implemented recycle system.

Depending on the type of application, floating or cycling, different VRLA batteries are presented on the market. Floating batteries can last up to 5-6 years if used and stored in optimal conditions. They have a range of capacities from 4-100 Ah 12 V batteries. They are use in alarm systems, medical equipment, power tools, solar power and lighting.

Deep cycle discharge batteries are specifically designed for cyclic application and their lifetime doubles the cyclic performance of float-designed batteries. They have a range of capacities from 8-100 Ah 12 Volts batteries. Their main applications are: power tools, solar power, wheelchairs, golf trolleys …

Figure 4-9 Float (left) and Deep-Cycle (right) 17 Ah-12V battery

Special attention should be given to the storage and operational temperature of the batteries. Although the increase of temperature results on an increase of instantaneous capacity, the effect of high temperatures shortens remarkably the lifespan of the batteries.

For instance, battery storage at a temperature of 30 degrees Celsius will shorten the lifespan by 50%. Thereby, it will result on a two-year lifetime instead of the estimated four-year lifespan at 20 degrees. In addition to the room temperature and with regards to cyclic applications the depth of discharge is crucial relating to the lifespan of deep-cycle batteries. They last up to 4.5 times more when discharged to 30% depth of discharge (DOD) rather than at 100% DOD.

4.1.5.2 Li-ion batteries

The lithium-ion family is divided into three major battery types, depending on the chemical compound of the cathode and electrolyte. These are:

- Lithium-ion-cobalt or lithium-cobalt ($LiCoO2$). Applications include cell phones, laptops, digital cameras and wearable products.
- Lithium-ion-manganese or lithium-manganese ($LiMn2O4$). Used for power tools, medical instruments and electric powertrains.
- Lithium-ion-phosphate or lithium-phosphate ($LiFePO4$). Applications include hybrid and electric cars, golf trolleys, solar applications…

Lithium-ion batteries can be dangerous since they contain, unlike other rechargeable batteries, a flammable electrolyte and are also kept pressurized.

Conversely to lithium-cobalt and lithium-manganese, lithium-phosphate is an intrinsically safer cathode compound with no-reported accidents. In addition, the use of phosphates avoids cobalt's cost and environmental concerns, such as cobalt entering the environment through improper disposal of the batteries.

Due to its safe and environmentally-friendly cathode, lithium-phosphate batteries where selected in the One Laptop per Child charitable project, with over 2.4 million XO laptops delivered by the end of 2011[5]

Consequently, due to their inherent safe and environmentally-friendly characteristics, their lower weight and its longer lifetime, the usage of lithium-phosphate batteries in the NMT storage-system should be investigated further in future research. On the other hand, their main drawbacks for being used are their higher capital cost and their low availability.

4.1.5.3 Battery technology comparison

Table 4-2 shows the main properties of Lead-acid, Ni-MH and Li-ion batteries.

	Pb–acid	Ni–MH	Li-ion
Theoretical			
Voltage (V)	1.93	1.35	4.1
Specific energy (Wh/kg)	166	240	410
Practical			
Specific energy (Wh/kg)	35	75	150
Energy density (Wh/L)	70	240	400
Coulometric efficiency	0.80	0.65–0.70	>0.85
Energy efficiency	0.65–0.70	0.55–0.65	~0.80
Specific power, 80% DOD (W/kg)	220	150	350
Power density (W/L)	450	>300	>800

Table 4-2 Lead-acid, Ni-MH, and Li-ion [26]

5 One Laptop per Child. Website: http://one.laptop.org/

4.1.6 DC/AC Converters. Power inverters

Power inverters are electronic devices that convert direct current into alternating current. Typical applications for power inverters include:

- Portable consumer devices that allow the user to connect a battery, or set of batteries, to the device to produce AC power to run various electrical items such as lights, televisions and power tools.
- Power generation systems such as electric utility companies or solar generating systems to convert DC power to AC power.
- Any larger electronic system where an engineering need exists for deriving an AC source from a DC source.

Inverters are rated according to the input and output voltage, output frequency, nominal power and output waveform. An inverter can produce square wave, modified sine wave, pulsed sine wave, or sine wave depending on circuit design.

5 MULTICRITERIA ANALYSIS

In Chapters 3 and 4 the state of the art and the properties of the main components that comprise HPGs have been reviewed. Next, the present chapter aims to select the HPG design that best fits the requirements established in Section 1.2 for our HPGs system (our case study). To make these decisions, the TOPSIS multi-criteria decision making (MCDM) method is used.

5.1 TOPSIS methodology

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method, which was initially developed by Hwang and Yoon in 1981 [27].

TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the Positive Ideal Solution (PIS) and the longest geometric distance from the Negative Ideal Solution.

The key advantages of TOPSIS method against other MCDM methods are its simple computation procedures and the involvement of expertise judgement. The TOPSIS methodology is represented in Figure 5-1.

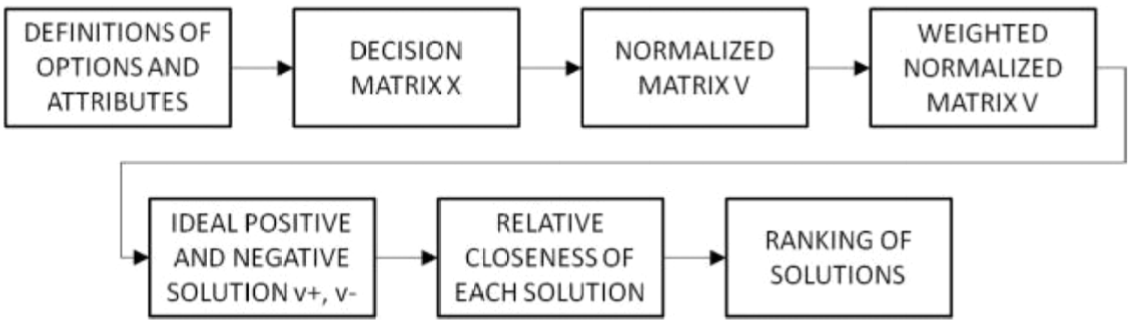

Figure 5-1 TOPSIS method diagram [28]

To begin with, different options or alternatives are selected with their corresponding attributes or criteria.

Options or alternatives are the different solutions on which the MCDM is applied to select the most suitable for the case study.

Attributes or marking criteria are the characteristics that differentiate the alternatives between them. They can be classified as quantitative or qualitative and as a positive and negative attributes. By positive attribute is understood the one that follows the rule, the higher the better. Conversely, by negative attribute is understood the criteria that follows the rule the lower the better.

After deciding the alternatives (A) and attributes (C), they are expressed in a matrix format (G) of m rows (alternatives) by n columns (attributes).

$$G = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & & x_{2n} \\ \vdots & & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

Figure 5-2 Decisional matrix [28]

From the previous matrix (G), a normalized one (I) is derived to scale the results to [0,1], by applying Equation (5-1) to every element (Xij)of the initial matrix (G)

$$r_{i,j} = \frac{x_{i,j}}{\sqrt{\sum_{i=1}^{m} x_{i,j}^{2}}} \tag{5-1}$$

By next, once the normalized matrix (I) is determined, a new matrix is developed (V) for every Weight Vector (Wj) or opinion vector, while applying Equation (5-2). The Weight Vector, characterizes the value of every attribute considered while assigning a value from 0 to 1, and it contains n elements (one per every attribute considered).

$$v_{i,j} = w_j \cdot r_{i,j} \tag{5-2}$$

This resulting matrix is called the Weighted Normalized Matrix (V), containing all the possible alternatives considered with their corresponding normalized weighted attributes.

The following step consists on the determination of the Positive Ideal Solution (A+) and Negative Ideal Solution (A-), according to their respective Equations (5-3) and (5-4).

$$A+= (v_1^+, \dots, v_n^+),$$
$$v_j^+ = \{max(v_{i,j})\ if\ j\epsilon J+; min(v_{i,j})\ if\ j\epsilon J-\} \tag{5-3}$$

$$A-= (v_1^-, \dots, v_n^-),$$
$$v_j^- = \{min(v_{i,j})\ if\ j\epsilon J+; max(v_{i,j})\ if\ j\epsilon J-\} \tag{5-4}$$

Next, once defined the reference solutions, Equation (5-5) states the distance from every i alternative to the PIS (S_i^+) and to NIS (S_i^-)

$$S_i^+ = \sqrt{\sum_{j=1}^{n}(v_j^+ - v_{i,j})^2},\ S_i^- = \sqrt{\sum_{j=1}^{n}(v_j^- - v_{i,j})^2} \tag{5-5}$$

Finally the relative proximity of each alternative to the ideal one is calculated as the one that is closest to the PIS and furthest to the NIS, while applying Equation (5-6). Thereby, the most favourable alternative is the one closest to 1.

$$C_i = \frac{S_i^-}{S_i^+ - S_i^-} \tag{5-6}$$

5.2 System attributes

As previously explained the attributes are the criteria from which the alternatives are marked. Table 5-1 shows the attributes considered for the selection of the HPG system. These attributes result from the engineering judgement of the author regarding our specific application.

HPG attributes
Capital cost
Performance time
Efficiency
Ease of control
Footprint
Portability
Maintenance
Lifetime
Components' availability
Environmentally-friendly

Table 5-1 Selected attributes for HPG and battery type selection

5.2.1 Capital cost

This marking criterion estimates the capital cost of the different options. It is a quantitative and negative criterion, and is measured in US dollars (US $)

Maintenance costs have been omitted because they account for a lower share of the total costs, and are difficult to estimate at this stage.

Operational costs have not being considered, since the intended application is to use the generator to harvest out of voluntary physical exercise.

5.2.2 Performance time

The performance time estimates the time that the user spends to harvest a specific amount of energy. In other words, this criterion values the time of the user while they are powering the generator instead of doing another activity.

This attribute is defined as quantitative and negative, and is measured in minutes. To determine it, Equation (5-7) is used

$$\mathbf{Time} = \frac{\boldsymbol{Load}}{\boldsymbol{Phuman}} \quad \textbf{(5-7)}$$

Where,

- Time is the performance time in minutes.
- Load is a fixed value of 101[6] Wh. It results from dividing the daily consumption of the toilet (283 Wh/day/household, Section 1.2.3) between four adults per household and taking into account the roundtrip efficiency of the battery, 70%.
- P_{human} accounts for the mechanical power that the user is able to exert due to the type of muscles that they use and the structural design of the generator. Considering the medium power level scenario concluded in Section 3.3, the different values of P_{human} are presented in

Movement	Medium Scenario (Watts)
One-hand	31
Two-hand	60
Cycling	119

Table 5-2 Medium mechanical-power scenario

As a final remark, is worth commenting that the actual time spent on harvesting a determined amount of energy, depends on the efficiency of the whole assembly. Nevertheless, the efficiency of the device is considered with another criterion.

5.2.3 Efficiency

Efficiency is the rate of the output energy with regards to the input one. It is positive and quantitative attribute, measured in percentage rate. In low-power

[6] 101 = 283 / (0.7 *4)

and low-exertion-time applications, efficiency is an important criterion to maximize the energy harvested per user per day.

To estimate the efficiency of the HPGs, it is quantified as the product of the partial efficiencies of the mechanical power drive (η_{mec}), generator machine (η_{gen}), and energy conversion system (η_{ecs}), as seen in Equation (5-8).

$$\eta_{sys} = \eta_{mec} \times \eta_{gen} \times \eta_{ecs} \tag{5-8}$$

The efficiency of the battery (η_{bat}) is defined in Equation (5-9), where I and V are the current and voltage for the discharging and charging process. Typical values are shown in Table 4-2

$$\eta = \frac{\int_{\text{discharge}} IV\,dt}{\int_{\text{charge}} IV\,dt} \tag{5-9}$$

5.2.4 Ease of control

Ease of control refers to the interaction between the user and the generating device. In other words, this criterion measures how easy is the operation of the system. Thereby, it is a qualitative and positive criterion. To measure it, it is transformed in a range of 1-5 depending on its control's easiness, according to the criteria shown in Table 5-3.

Mark	Category	Criteria
5	Automatic	No control is required by the user
4	Semi-Automatic	Modes of operation are selected automatically by the user. E.g. charging voltage
3	Easy Control	The control of the generator can be done while adjusting one or parameters either using analogical or digital signals
2	Controlled	The control of the generator can be done after proper training
1	Specialized control required	Specialized control required, with special equipment and software. Operate by a technician

Table 5-3 Ease of control marking criteria.

5.2.5 Footprint

This criterion estimates the volume of the HPG assembly, or in other words, its space occupied. Footprint is a quantitative and negative criterion, measured in cubic meters (m^3)

Ideally, the smaller the HPG the better since it can be used indoors while occupying the minimum living space. Another advantage of compact designs is the possibility to be kept inside the living space at nights, protecting it against robbery.

5.2.6 Difficulty of transport

As difficulty of transport it is understood how tough results to transport the generator. To simplify the analysis, it is directly related to weight of the system or components. Thereby, this criterion is defined as a quantitative and negative one. Negative since follows the rule, the lighter the weight the better.

5.2.7 Ease of maintenance

Maintenance is an important factor to maximize the operation and lifetime of the machine or component. It implies components, equipment and personnel costs and its associated downturn.

For the simplicity of the analysis, we consider maintenance as ease of maintenance, being a positive attribute. To measure it, it is established the specific scale of values and criteria shown in Table 5-4.

Mark	Ease of Maintenance
5	No need of maintenance is required during its lifetime.
4	Minor maintenance is required. No replacement of components
3	Replacement of components is needed during its lifetime. It can be fixed by the user without special training and common tools
2	Replacement of components is needed during its lifetime. It needs to be repaired by local technicians and specialized tools.
1	Replacement of components is needed during its lifetime. It needs to be fixed in a workshop with specialized machinery

Table 5-4 Marks and criteria relating to ease of maintenance

5.2.8 Lifetime

Lifetime refers to the period of time when the machine or component can be operated or used until the end of its working life. The end of the lifetime is indicated when the maintenance costs overcome the cost of replacement.

This criterion is a quantitative and positive one. Relating to the HPG system, and to simplify the analysis, the lifetime is measured in operational working hours.

5.2.9 Components' availability

The following positive criterion measures the possibility that the different systems or components can be assembled with available products on the local market, boosting local workshops and reducing delivery time.

To simplify the analysis, a numeric value is given to the options as stated in Table 5-5.

Mark	Components' availability
5	Components totally available in local market. Possibility of building the system from scratch in local workshops
3	System components partially available in local market
1	Any component is available in local market.

Table 5-5 Marks and criteria relating to components' availability

5.2.10 Environmental impact

The following criterion aims to value the influence of the difference components on the environment. It is understood as a negative criterion, following the rule the higher the impact the worse.

To simplify the analysis, this criterion focus on the existence of hazardous material in any of the components that is present in the HPG or in the batteries itself.

Mark	Environmental impact
5	Hazardous materials are contained in the component. There is a risk of direct contact.
3	Hazardous materials are contained in the component. But there is no risk of direct contact.
1	No hazardous compound exist on the component

Table 5-6 Marks and criteria relating to environmental impact

5.3 Weighted vector. Surveying process

Weighted vectors are used in MCDM to weight the importance of the marking criteria. It can be compared to “one opinion” or one “point of view”. Therefore, it reflects the human judgement of the problem. For each weighted vector, a different weighted normalized matrix is made, and a different set of Positive and Negative Ideal Solution are created.

For the followings TOPSIS analyses, the weighted vectors implemented are based on the one obtained in [29] for HPGs designs, as shown in Table 5-7.

Mean Weighted vectors	COST	TIME	SIZE	PORTABILITY	EFFICIENCY	CONTROL	MAINTENANCE	LIFETIME	COMPONENTS' AVAILABILITY	ENVIRONMENTALLY FRIENDLY
HPG	0.123	0.101	0.108	0.105	0.081	0.082	0.116	0.105	0.102	0.076

Table 5-7 HPG normalized weighted [29]

This weighted vector was obtained doing an online survey using Qualtrics Software. In this questionnaire, 52 participants with five levels of expertise took part in the survey[7]. By doing so, they marked every attribute from 1 to 9 points, from minor to major level of importance. Next, by marking their level of expertise

[7] This survey is co-authorized between C Gomez-Mu;oz, A.J Kolios and E Perez-Lopez, current author of the present MSc by Research.

from 1 to 5, increasing order of expertise, the weighted mean vector was obtained, Table 5-7

Thereby the normalized weighted vectors shown in Table 5-8, are used for the HPG TOPSIS analysis.

Mean Weighted vectors	**CAPITAL COST**	**PERFORMANCE TIME**	**EFFICIENCY**	**EASE OF CONTROL**	**FOOTPRINT**	**PORTABILITY**	**EASE OF MAINTENANCE**	**LIFETIME**	**COMPONENTS' AVAILABILITY**	**ENVIRONMENTAL IMPACT**
HPG	0.123	0.101	0.108	0.105	0.081	0.082	0.116	0.105	0.102	0.076

Table 5-8 Normalized weighted vector for HPG analysis

5.4 Alternatives description

Six designs have been selected as possible design alternatives of our HPG prototype. They are composed by different types of components, whose attributes are specified in the present chapter

5.4.1 HPGs design alternatives

Six different design alternatives have been selected as the most suitable designs for our case study, after considering the literature and market review of HPGs and components. These designs are created to be owned or shared between different householders in off-grid communities of developing countries.

5.4.1.1 Option 1: Indoor-bike with in-wheel brushless hub motor

Figure 5-3 Indoor-bike (left) (7) and in-wheel brushless hub motor (right) (8)

Support structure	Indoor-bike
Mechanical power drive	Chain ring and sprocket. Single gear ratio
Generator	In-wheel brushless
Electric system	Three phase bridge rectifier plus boost chopper converter.

Table 5-9 Option 1. System characterization

5.4.1.2 Option 2: Plugged-in bike with in-wheel brushless motor

Figure 5-4 Bike (left) (9), bike stand (centre) (10) hub motor (right) (11)

Support structure	Bike-stand
Mechanical power drive	Chain ring and sprocket. 21 gear ratios.
Generator	In-wheel brushless. Rear wheel.
Electric system	Three phase bridge rectifier plus boost chopper converter.

Table 5-10 Option 2. System characterization

5.4.1.3 Option 3: Fixed-bike plus car-alternator

Figure 5-5 Bike fixed to car alternator [23]

Support structure	Bike-support structure
Mechanical power drive	Single chain ratio plus timing belt.
Generator	Car alternator
Electric system	Already included in the car alternator.

Table 5-11 Option 3. System characterization

5.4.1.4 Option 4: Plugged-in bike with brushless dc motor

Figure 5-6 Plugged-in biked generators (1)

Support structure	Bike-stand
Mechanical power drive	Chain ring and sprocket. 21 gear ratios. Friction between tyre and shaft or pulley
Generator	DC Brushless motor
Electric system	Three phase bridge rectifier plus boost chopper converter.

Table 5-12 Option 4. System characterization

5.4.1.5 Option 5: Two-hand-cranked generator

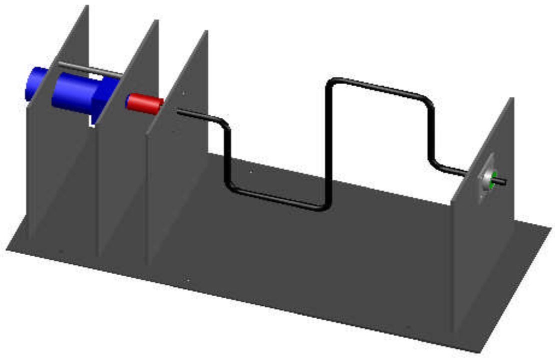

Figure 5-7 Two-hand-cranked generator Conceptual design

Support structure	Other. Specific steel structure.
Mechanical power drive	Two-hand crank directly coupled to a planetary gearbox
Generator	DC Brushless motor
Electric system	Three phase bridge rectifier plus boost chopper converter.

Table 5-13 Option 5. System characterization

5.4.1.6 Option 6: Two-hand-cranked generator

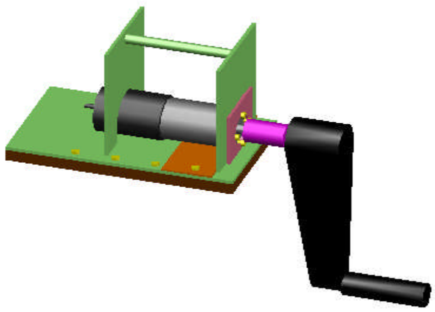

Figure 5-8 One-hand-cranked generator Conceptual design

Support structure	Other. Specific steel structure.
Mechanical power drive	Two-hand crank directly coupled to a planetary gearbox
Generator	DC Brushless motor
Electric system	Three phase bridge rectifier plus boost chopper converter.

Table 5-14 Option 6. System characterization

5.4.2 Components comparison

Once the main components of the design have been identified, the following step is to select the ones that fit our application. Knowing their specifications enable us to create the decisional matrix.

5.4.2.1 Support structure

Options #	Support structure	Power likely to develop	Cost	Weight	Size
		Watts	£	kg	m*m*m
1	Indoor bike	119	274	21	1.10*0.47*0.90
2 &4	Plugged-in bike plus bike stand	119	195	22	1.72*0.85*1.10
3	Fixed-bike support structure plus car alternator holder	119	233	24	2.00*0.85*1.10
5	Two-hand-cranked generator support	60	75	10	0.75*0.30*0.30
6	One-hand-cranked generator enclosure	31	50	2	0.30*0.20*0.20

Table 5-15 Support structure. Attributes description

5.4.2.2 Power drives

Options #	Power drive	Efficiency (0-1)
1,2,3 & 4	Chain	0.98
3	Belt	0.95
4	Friction	0.75
5 & 6	Rigid coupling	1
5 & 6	Planetary gearhead (2 Stages)	0.81

Table 5-16 Power drive. Attributes description

5.4.2.3 Generators

Options #	Generator	Cost	Rated power	Rated speed	Rated voltage	η	Lifetime	Weight
		£	Watts	rpm	Volts	0-1	years	kg
1 & 2	In-wheel brushless motor	69	500	235	24	0.9	10	6.2
4	Brushless motor	72	168	4000	36	0.8	7	1.25
5 & 6	Geared brushless motor	150	88	74	36	0.8	7	1.5
3	Car alternator	47	1000	1800	14	0.55	7	2.5

Table 5-17 Generators. Attributes description

5.4.2.4 Electric conversion system

Options	Electric components	Cost	Efficiency
		£	0-1
1, 2, 4, 5 & 6	Three-phase bridge rectifier	12	0.96
1, 2, 4, 5 & 6	Boost DC/DC Chopper	6	0.95
3	None	0	1

Table 5-18 Electric components. Attributes description

5.4.3 Decision and Normalized matrix

Option	CC (-)	PT (-)	E (+)	EC (+)	F (-)	DT (-)	EM (+)	L (+)	MA (+)	EI (-)
#	(£)	(min)	(%)	(1-5)	(m3)	(kg)	(1-5)	(years)	(1-5)	(1-5)
1	360	36	80.4	5	0.47	29.0	4	10.0	1	1
2	282	36	80.4	5	1.61	30.1	4	10.0	3	1
3	305	36	51.2	5	1.87	27.8	2	7.0	5	1
4	285	36	53.6	5	1.61	23.3	4	7.0	3	1
5	273	71	59.1	5	0.07	11.5	5	7.0	1	1
6	248	137	59.1	5	0.01	3.5	5	7.0	1	1

Table 5-19 Decisional Matrix. HPG

Option #	CC (-)	PT (-)	E (+)	EC (+)	F (-)	DT (-)	EM (+)	L (+)	MA (+)	EI (-)
1	0.50	0.21	0.50	0.41	0.16	0.51	0.40	0.50	0.15	0.41
2	0.39	0.21	0.50	0.41	0.54	0.53	0.40	0.50	0.44	0.41
3	0.42	0.21	0.32	0.41	0.63	0.49	0.20	0.35	0.74	0.41
4	0.40	0.21	0.34	0.41	0.54	0.41	0.40	0.35	0.44	0.41
5	0.38	0.42	0.37	0.41	0.02	0.20	0.50	0.35	0.15	0.41
6	0.34	0.81	0.37	0.41	0.00	0.06	0.50	0.35	0.15	0.41

Table 5-20 Normalized Decision Matrix. HPG

5.5 TOPSIS results

Option #	CC (-)	PT (-)	E (+)	EC (+)	F (-)	DT (-)	EM (+)	L (+)	MA (+)	EI (-)
PIS	0.042	0.021	0.054	0.043	0.000	0.005	0.057	0.053	0.075	0.031
NIS	0.061	0.081	0.035	0.043	0.051	0.044	0.023	0.037	0.015	0.031

Table 5-21 Positive and negative ideal solution

Option #	d to PIS	d to NIS
1	0.075	0.079
2	0.067	0.077
3	0.076	0.086
4	0.066	0.073
5	0.068	0.078
6	0.088	0.075

Table 5-22 Distance to PIS and NIS.

Option #	Relative closeness
1	0.512
2	**0.536**
3	0.531
4	0.526
5	**0.533**
6	0.461

Table 5-23 Relative closeness of each solution

5.6 Discussion of results

Table 5-23 lists the final comparison results of the TOPSIS analysis for the HPG design. For each alternative, these numbers express the proximity of the suggested design to the ideal solution. Specifically, the closer the number is to the unity, the nearer the design is to the ideal design. Thereby, according to the weighted vector considered, the best solutions are the plugged-in bike generator and two-hand-cranked machine.

6 HPG. TESTING AND RESULTS

Following the results of TOPSIS method a HPES was developed. It comprises a plugged-in bike generator and a portable power supply unit. In addition, this system will allow the NMT customer to harvest energy to power small loads like charging mobile phones and lighting. The prototypes will be displayed in the Reinvent the Toilet Project showcase that celebrates in Delhi (India) on 21st of March of 2014.

The current chapter is structured as follows. Firstly, an overall system description of the bike and portable power supply unit is addressed. Secondly, the results of characterization and performance experiments are presented. Finally, a discussion of these results is followed.

6.1 Plugged-in bike generator

As seen in Figure 6-1, the plugged-in bike generator consists of a bike-stand, a men style 26-inches wheel and a rear-wheel hub motor. In addition, replacing the bike's rear wheel by the one with hub motor implemented, allows the final customer to use the bike as an electricity generator and means of transport, while unplugging it from the bike stand.

Figure 6-1 Plugged-in HPG

Overall, the bike plus rear-wheel motor weights 26 kg (17 bike plus 8 of the in-wheel motor) and measures 172 cm x 85 cm x 110 cm (length x width x height). Regarding the power drivetrain of the bike, it uses a 3 chain rings and 7 sprockets, allowing for 21 speed gear ratio with a range 0.79-3.14

On the other hand, the bike-stand weights 5 kg and can be easily folded for transportation, with a folded dimensions of 60 cm x 25cm x 60 cm (length x width x height)

6.2 Portable power supply unit

The portable power supply unit is conceived to provide the customer of the HPGs with an energy system that allows him to store the energy generated and discharge this energy either to power the toilet or another low power consumption loads, like charging mobile phones, CFL lamps, radios, laptops…

Figure 6-2 Portable power supply units

The box weights 11 kg with exterior dimensions of 58cm x 29cm x 29cm (length x width x height). It has the following components:

1. Two input AC sockets.
2. Switch and power meter to measure the input AC power
3. Two three-phase bridge rectifiers mounted on heat sinks
4. Two step-up DC/DC boost chopper converter to regulate the charging current and voltage. One per every kind of generator (12)
5. Two 12 V 12 Ah Deep Cycle Lead Acid batteries, connected in series to 24 V voltage (13)
6. One step-up DC/DC boost chopper converter for DC discharge (12)
7. One 24 V 300 W power inverter (14)
8. Two AC sockets to supply energy to low-power loads
9. Switch and power meter for output power
10. Diode battery level indicator and general switch
11. Cooling fan with its respective switch
12. Power meter circuit with PC interface
13. One Stanley® toolbox (15)

6.3 Prototype testing

After an overall description of the prototypes, the electro-mechanical performance of the system is tested and presented in the current section. The results discussion follows next.

6.3.1 Tuning the boost chopper converter

Once all the components in the electric circuitry are fitted inside the power supply unit, the next step consists on tuning the DC-DC step-up boost chopper converter. While doing so, we are setting the charging voltage up to a maximum of 29 Volts, and the maximum current in relation with the rotational speed. By tuning of the boost chopper converter, we refer to these two procedures.

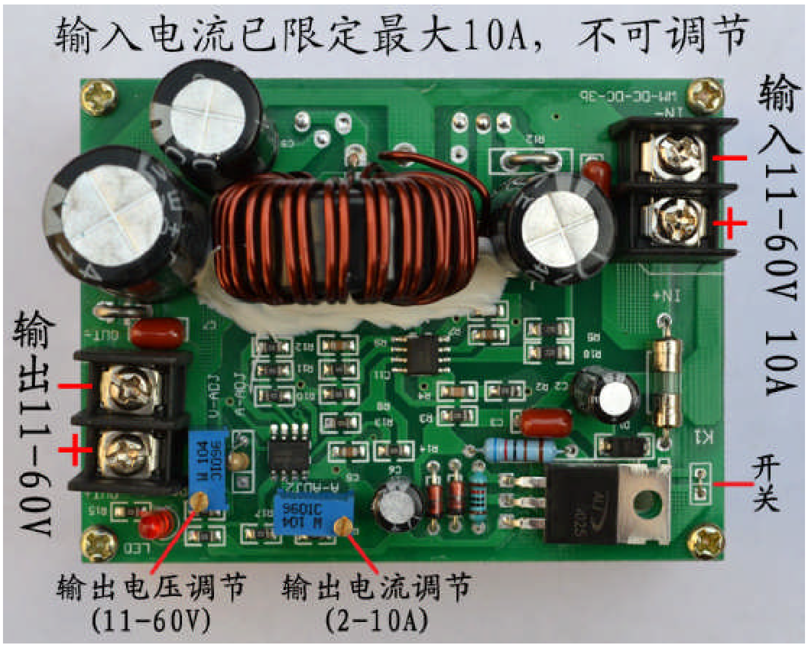

Figure 6-3 Step-up boost chopper converter (12)

To do the first tuning procedure, the output voltage is regulated to 29 Volts when the circuit is open. To achieve that, two people are needed; the first will be pedalling the bike generator at a normal speed of 80 rpm and a gear ratio of 3.14, the maximum one. The second regulates the output voltage while turning a bolt in the output voltage controller (Figure 6-3, blue component with voltage units, left bottom side).

Next, the maximum current with respect to rotational speed of the motor or driver cadence is fixed while using the current regulator component (Figure 6-3, blue component with current units, centre bottom side). To do that, the rider is continuously communicating its "sense of comfort" of the physical exercise to the person that is operating the current controller. In that procedure, the gear ratio is fixed on the maximum value of 3.14 while using the largest chain ring and smallest sprocket. Doing so means that the rider pedals at a comfortable cadence and maximum rotor speed.

6.3.2 Experiment set-up

To analyse the generator's performance, two main experiments have been developed. Firstly a variable speed test has been carried out to determine the relationship between electric power stored in the batteries and rotor speed. Secondly, and endurance test followed. This experiment consists on measuring the power generated during 15 min of pedalling.

Both testing were realized by the author with a gear ratio of 3.14 (44/14 chain-teeth ratio) and the rotor angular speed charging current and battery voltage were measured. For that, a tachometer UNI-T UT372 was used to measure the speed, and two UNI-T UT60F multimeters for both voltage and current. These three variables were collected in its respective software. The whole setup is shown in Figure 6-4

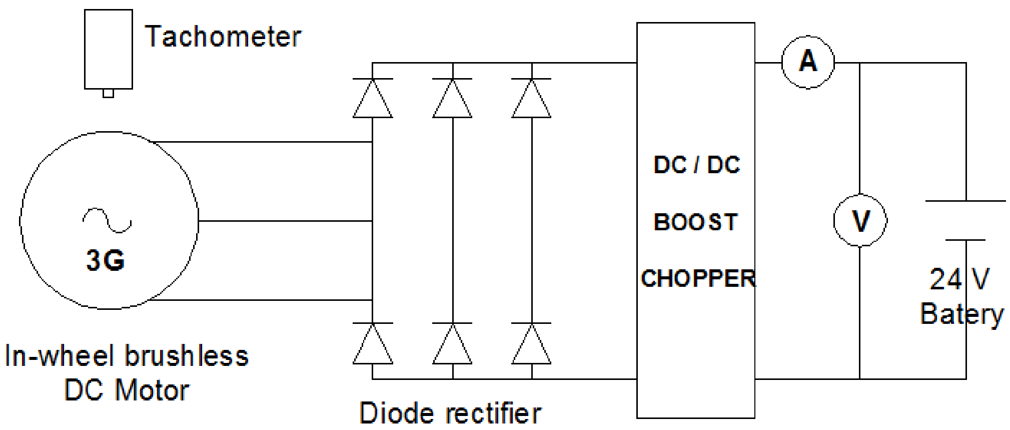

Figure 6-4 Testing setup for variable speed and endurance test

6.3.3 Variable speed test

Once the step-up boost chopper converter is tuned, no further setting is needed and unique performance behaviour is shown from now on by the generator. Thereby, while pedalling at different constant rotor speeds the corresponding electric power at battery level are generated. Table 6-1 shows the three measured average values of rotor speed, charging current and voltage plus the two calculated ones of crank speed and power. During every stage, the rider pedalled during two and a half minutes keeping the speed constant while focusing on the rotor speed value displayed in the monitor screen.

Gear ratio 3.14	Crank speed	Rotor speed	Charging current	Charging Voltage	Power
	rpm	rpm	Amp	Volts	Watts
Stage 1	96.33	302.46	2.91	24.83	72.36
Stage 2	102.83	322.89	5.07	25.45	129.07
Stage 3	104.96	329.58	5.89	25.61	150.94

Table 6-1 Main variables of variable speed test

Figure 6-5 depicts the power sent to the battery against the rider's cadence. All the experimental data gathered is depicted in their respective figures on Appendix B.

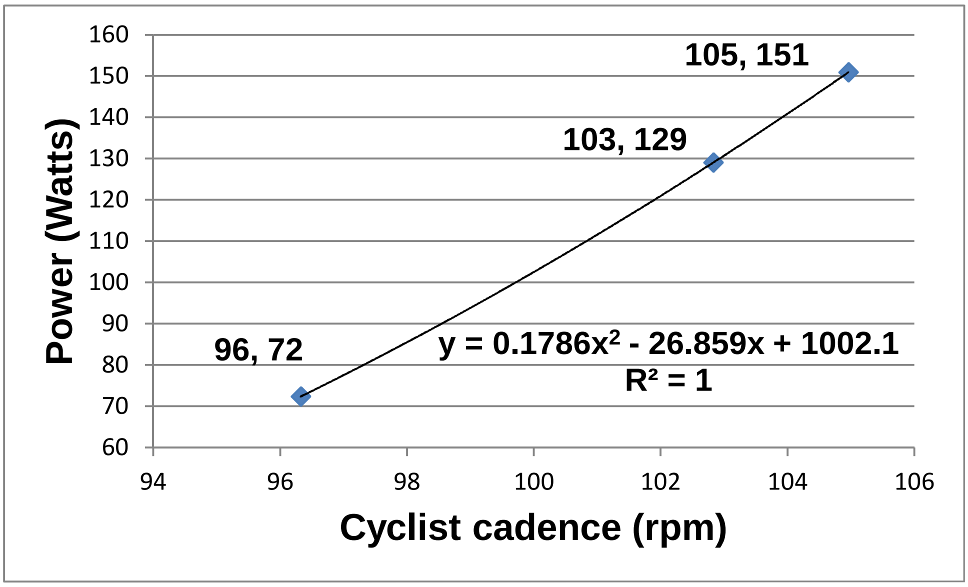

Figure 6-5 Charged power against cyclist cadence in plugged-in generator

6.3.4 Endurance test

The endurance test measures the power generated during 15 minutes of pedalling at any rotational speed. The result of this test is an average power of 105.6 Watts at an average cadence of 100.5 rpm. Table 6-2 shows the average values of the remaining variables involved. For their instantaneous values refer to Appendix B.

Time	Average cadence	Average rotor speed	Current	Voltage	DC Power	Charged energy
min	rpm	rpm	Amps	Volts	Watts	Watt-hours
15	100.5	315.4	4.1	25.5	105.6	26.0

Table 6-2 Plugged-in bike generator endurance test

6.3.5 Peak power

By peak power is meant the maximum power that human beings are able to exert. Figure 6-6 shows an instantaneous power of 450 Watts power level. It is exerted over a second.

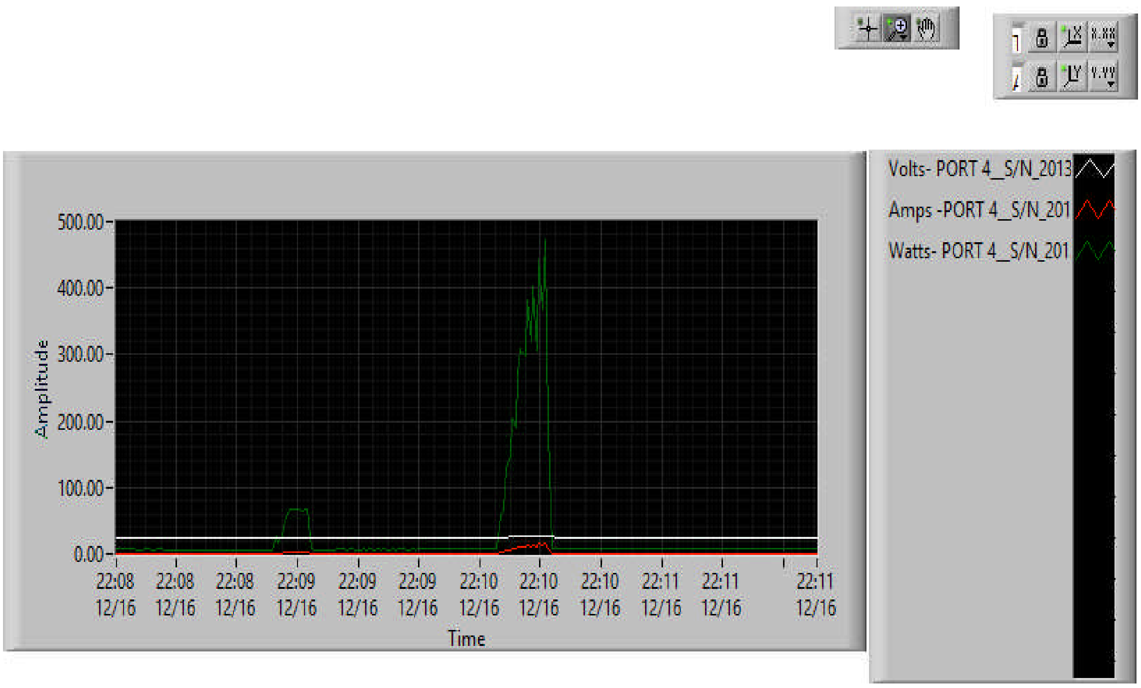

Figure 6-6 Experimental screen shot

6.4 Results discussion

In the present chapter, we initially discuss the performance of the plugged-in generator to end up commenting the different loads that can be addressed with our HPES.

6.4.1 Plugged-in generator performance

The plugged-in generator is designed to accommodate from 60-160 Watts in the cadence range from 96 to 105 rpm, as seen in Figure 6-7, while using the maximum gear ratio available in the bike (3.14 or 44/14).

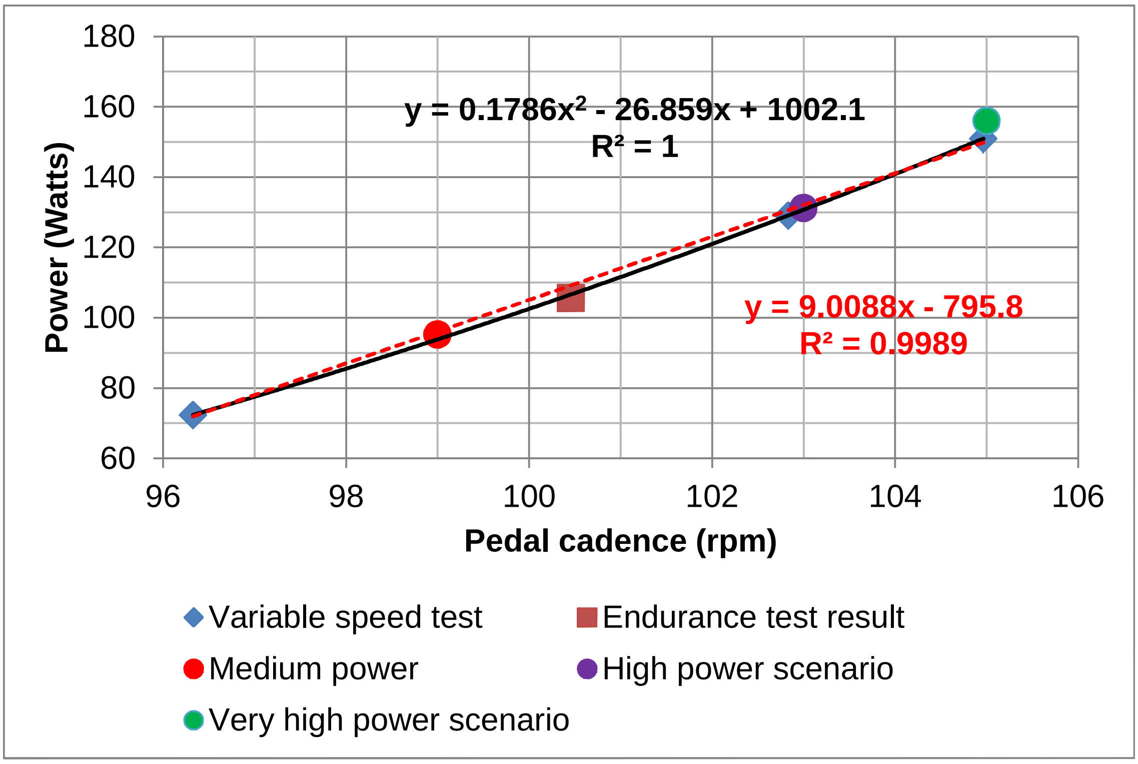

Figure 6-7 Charged power against cyclist cadence

According to [30] usual pedalling rates used by cyclists are the ones in the range from 70-110 rpm. Thereby our generator's range of cadence corresponds with the half upper division of it, being a high-cadence demanding generator.

Nevertheless, lower and more frequent pedalling power levels (60 to 120 Watts of P_{human}, Section 3.3) are addressed within 96 to 100 rpm, with can be considered in the middle range of cyclist speed as mentioned before. This high speed characteristic correspondent to the highest output powers has the advantage that increases the power density in the generator machine.

Considering the relationship shown in Figure 6-7, the human powered scenarios defined in Section 3.3, and an overall electric efficiency of 80%[8], the main mechanical and electric characteristics of our HPG are shown in Table 6-3.

	P_{human}	Losses	P stored	Cadence	Torque	V ref	I amp
	Watts	Watts	Watts	Rpm	Nm	Volts	Amps
Medium	119.0	23.8	95.2	99.2	11.5	25.5	3.7
High	164.0	32.8	131.2	103.1	15.2	25.5	5.1
Very high	195.0	39.0	156.0	105.5	17.7	25.5	6.1

Table 6-3 Mechanical and electric variables of the plugged-in generator

Regarding to the endurance power test, it accounts for an average stored power of 105.6 Watts, considering an overall efficiency of 80%, it results on a mechanical power of 132 Watts. That figure is closer to the medium power scenario than to the high power one.

After performing that experiment over 15 minutes, the author ended up with the feeling that a higher level of exercise would not have been able to maintain, and with the feeling that it would have been difficult to sustain that power level during one hour. The physiological characteristics of the author are the ones of a healthy male aged 27 with a height of 1.73 m and 80 kg of weight. In the same way, if we apply an 80% of overall efficiency, the electric power stored in the battery with the power levels of the high and very high scenarios matches the ones sustained during the highest levels of the variable speed test.

These coincidences make us feel more confident about the accuracy of the different scenarios hypothesized to work out energy harvested by HPGs.

[8] Efficiency = 0.95 (Chain) * 0.9 (Generator) * 0.96 (Rectifier) * 0.95 (Boost chopper) = 0.8 (80%)

6.4.2 HPES electric capabilities

After discussing the electric capabilities of our plugged-in generator, we assume 95 Watts-hour of electric energy as a sensible value to be harvested by regular adult people (Section 3.3) during one hour, as explained in Table 6-3.

Secondly, with the creation of the portable power supply unit, we deliver to the NMT customer an energy system that enables them to supply electricity for their electrical demand like charging mobile phones, electric lighting… as shown in Figure 1-2. If we set up a limit of half an hour per person per day of pedalling, and considered that every person harvest half of the 96Wh already discussed, 28 Wh[9] are available for consumption with our HPES.

Number of people pedalling 30 minutes each	Total time	Available energy	Cell phone	Lighting (11 Watts bulb)	Radio (10 Watts)	Laptop (50 Watts)	Used energy
	hours	Wh	# Fully charged phones (5 Wh)	working hours	working hours	working hours	Wh
1	0.5	28	1	2	0	0	27
1	0.5	28	2	1	0.5	0	26
1	0.5	28	0	0	0	0.5	25
2	1	57	2	3	1.5	0	58
2	1	57	2	2	0	0.5	57
2	1	57	2	1.5	0.5	0.5	56.5
3	1.5	85	2	3.5	1	0.5	83.5
3	1.5	85	2	2	0	1	82
3	1.5	85	2	3	0	0.75	80.5
4	2	113	2	3.5	1	1	108.5
4	2	113	2	4	1	1	114
4	2	113	1	3	0	1.5	113

Table 6-4 AC load capabilities of our HPES

[9] Considering efficiencies of 70% for lead-acid batteries round-trip (Figure 4-9) and 85% for the power inverter selected (Section 6.2)

6.4.3 Powering the NMT

To power the toilet, the NMT customer has two options:

1. Direct connection. This option connects the generator with the batteries allocated inside the toilet.

2. Indirect connecting. Using the generator to charge the batteries in the power supply unit, and later on to transfer this energy to the batteries inside the toilet.

Depending on the electrical characteristics of the electric system of the toilet, AC or DC and the type of connection; the pedalling time needed to fully power the load varies from 4.3 hours to 7.5 hours per household per day, as expressed in Table 6-5. These time values are the ones that result after solving the equations shown in Appendix C.

		Type of load	
		AC	DC
		hour	hour
Type of charging	Direct	5.0	4.3
	Indirect	7.2	6.1

Table 6-5 Hours required to charge the NMT

Thereby, is highly recommended to charge the toilet directly when the emergency situation happens. Therefore the indirect charging method should be applied when the NMT customer wants to exercise and the batteries inside the power supply unit are already full.

6.5 HPES specifications and justification

After discussing the capabilities of the plugged-in generator and power supply unit, a set of specifications is established for each of them to summarize their capabilities and compare them with the ones of existing market products. Next, justification for these specifications is provided.

6.5.1 Plugged-in generator specifications

Table 6-6 shows the specifications of the plugged-in generator discussed. The following characteristics are described as follows:

Specifications	Value	Units
Rated power	290	Watts
Expected power	95	Watts
Maximum expected power	156	Watts
Rated current	10	Amperes
Max DC Voltage	29	Volts
DC Voltage range	23 - 29	Volts
Expected current	3.8	Amperes
Maximum expected current	6.8	Amperes
Expected cadence	99	Rounds per minute
Expected rider's torque	11.48	Newton x meter
Expected rotor speed	311	Rounds per minute
Expected rotor torque	3.47	Newton x meter
Dimensions	1.72 x 0.85 x 1.1	m x m x m (length x width x height)
Weight	30	kg
Cost	282	GBP (£)

Table 6-6 Plugged-in generator specifications

6.5.1.1 Rated power

The power rating of the plugged-in generator is based on the minimum rated power of its components, taking into account their power and current rating, Table 6-7.

Component	Power rating	Current rating	Source
Hub motor	500 Watts	21 Amperes	(8)
Passive Rectifier	28 kVA	35 Amperes	(16)
DC - DC Boost Chopper	Up to 600 Watts	10 Amperes	(12)

Table 6-7 Component's power rating

Therefore, the rated power in the plugged-in generator is limited by the current rating of the DC-DC boost chopper converter. Since, the battery system is 24 Volts rated, the charging voltage is set to 29 Volts, and therefore, the power rate of the plugged-in generator accounts for 290 Watts (29 Volts, 10 Amperes). It is a continuous duty range of power, since the maximum withstand current is 16 Amperes and therefore 464 Watts (16 Amps x 29 Volts).

6.5.1.2 Expected power

Although the plugged-in generator is ranged up to 290 Watts in continuous duty, the expected continuous power output produced by human power accounts for 95.2 Watts. This figure results while considering the medium human power scenario (119 Watts of mechanical power sustained by physically active adults, Section 3.3) and an overall average efficiency of 80%[10] for the plugged-in generator. These overall average efficiencies are based on the ones obtained for similar applications, as shown in Table 6-8.

[10] Efficiency = 0.95 (Chain) * 0.9 (Generator) * 0.96 (Rectifier) * 0.95 (Boost chopper) = 0.8 (80%)

Component	Average efficiency adopted (%)	Source
Chain	95	Table 4-1
Brushless hub generator	90	[25] (Table IV, 350 rpm and diode application)
Three phase bridge rectifier	95	[12] (Table V, Measured results)
DC-DC Boost chopper	96	(12)

Table 6-8 Component's efficiency

6.5.1.3 Maximum expected power

The maximum expected power for the plugged-in generator accounts for 156 Watts. This figure corresponds with the very high power scenario, defined in Section 3.3, and the overall average efficiency of 80%.

6.5.1.4 Rated current

This parameter is already exposed in Section 6.5.1.1.

6.5.1.5 Maximum DC voltage

For cycle use charging while controlling the voltage, the charging voltage ranges from 29 to 29.8 Volts (13). For the present study, the boost chopper is set at 29 Volts to keep on the safety side.

6.5.1.6 DC voltage range

The minimum voltage operating value of the power inverter is 21 volts or 10.5 volts per battery (14). For that voltage level, the batteries are completely discharged. More exactly, that voltage allows to power loads up to 2.4 amperes during a minimum of 3 hours {Cut off Voltage and Discharge characteristics tables (13)}.

6.5.1.7 Expected current

The expected sustained current for a physically active adult is 3.8 amperes. It is calculated while dividing the expected power, 95 Watts (Section 6.5.1.2), between the average charging voltage level, 25 Volts[11].

6.5.1.8 Maximum expected current

The maximum expected current is calculated as the previous section but using the maximum expected power instead.

6.5.1.9 Expected cadence

The rated cadence of the driver is 99 rounds per minute. This value results for the positive solution of Equation (6-1), for y being 95 Watts. This equation is determined in section 6.4.1, while correlating the obtained experimental power output (y, variable) with the rider's cadence (x, variable)

$$\mathbf{y} = \mathbf{0.1786}\,\boldsymbol{x}^{2} - \mathbf{26.859}\,\boldsymbol{x} + \mathbf{1002.1}\,(\boldsymbol{rpm}) \qquad \textbf{(6-1)}$$

6.5.1.10 Expected rider's torque

The rated torque is 11.5 Newton x meters. This value is the torque needed to output 119 Watts, Section 3.3, with a rated speed of 99 rpm.

6.5.1.11 Expected rotor speed and torque

The rated rotor speed and torque relates with the rated cadence and rider's torque while applying the transmission relationship shown in Equation (6-2) and Equation (6-3).

$$\boldsymbol{\omega}\ \textbf{rotor} = \boldsymbol{\omega}\ \textbf{human x i} \qquad \textbf{(6-2)}$$

$$\textbf{T rotor} = \textbf{T human} / (\textbf{i x}\ \boldsymbol{\eta}) \qquad \textbf{(6-3)}$$

Where i equals to 3.143, which stands for the ratio between the two speeds and the ratio between the smallest sprocket (14 teeth) and largest chain ring (44

[11] 25 = (21 + 29) / 2 Volts

teeth). To determine the torque an overall efficiency of 95% in the chain power drive train has been considered as reasonable as shown in Table 4-1.

6.5.1.12 Dimensions

The dimensions of the plugged-in generator are determined according to the overall dimensions of the mountain bike and its bike stand. It is shown in Table 6-9

6.5.1.13 Weight

The weight of the plugged-in generator results while adding up the weight of the individual components, as shown in Table 6-9.

6.5.1.14 Capital cost

The capital cost of the plugged-in generator results from the addition of the off-the-shelf products that integrates the device, as seen in Table 6-9.

Option 2	Dimensions (length x width x height) (m)	Weight (kg)	Capital Cost[12] (£)	Source
Mountain bike	1.72 x 0.85 x 1.1	17.00	158.33	(9)
Bike stand	0.9 x 0.6 x 0.25	5	37.2	(10)
Hub motor		8.00	69.00	(11)
Rectifier			11.90	(16)
Converter			5.70	(12)
Total	1.72 x 0.85 x 1.1	30.00	282.13	

Table 6-9 Dimensions, weight and capital cost of plugged-in generator

[12] VAT excluded

6.5.2 Power supply unit

The electrical specifications of the power supply unit are briefed in Table 6-10.

Specifications / Description	Source
288 Wh battery bank. 2 x 12 V 12 Ah batteries. Series connection.	(13)
24 Volts 3 Amps battery charging capabilities. (Using DC/DC step up boost chopper converter and cigarrete lighter socket).	(12)
300 Watts power inverter. Quasi sine wave. 21-30 to 230 V 50 Hz	(14)
2 x DC BS1363 Sockets. 230 Volts 13 Amps 50 Hz	(17)
2 x USB socket. 5 Volts DC 1.3 Amps maximum	(17)
Dimensions (58,4 cm x 29,3 cm x 29,5 cm)	(15)
Weight 12 kg	
Capital cost. £283.72 (VAT excluded)	

Table 6-10 Power supply unit specifications

6.5.2.1 Capital cost

Table 6-11 includes the main costs of the power supply unit made of off-the-shelf products.

Item	Number	Cost (£)	Total cost[13] (£)	Source
Battery	2	48.37	96.74	(13)
Toolbox	1	25	25	(15)
AC Socket. Output	1	26.82	26.82	(18)
AC Socket. Input	2	4.83	9.66	(19)
LED battery monitor	1	13.33	13.33	(20)
DC Socket	1	3.56	3.56	(21)
Power meter	2	6.80	13.60	(22)
Boost chopper converter	3	5.60	16.80	(12)
Power inverter	1	38.25	38.25	(14)
Rectifier	2	11.9	23.8	(16)
Total			267.56	

Table 6-11 Capital cost break down

[13] Cost exclude VAT

7 CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

In the present MSc Thesis a novel Human-Powered Generator prototype has been made to provide a backup solution to the NMT's electrical demand. In addition, a portable power supply unit prototype has been built to provide the NMT customer with a human-powered energy system that allows them to charge mobile phones and lighting.

The TOPSIS method has proven to be an effective methodology for the preliminary design stage of HPGs. Later the plugged-in bike generator and corresponding portable power pack has been developed with off-the-shelf components that include newest technologies such as in-wheel brushless dc motors and boost chopper converters.

While testing of the plugged-in generator and portable power supply unit, 26 Watt-hours were harvested during 15 minutes, with its corresponding average charging power of 105 Watts. Regarding one hour of pedalling, 96 Watt-hours are selected as an energy cap. This is supported by a literature review study (119 Watts, for the medium power scenario) and the strong perception of the author (while testing) that 105 Watts of charging power cannot be sustained during one hour. Nevertheless, it should be confirmed by a forthcoming statistical study using the current HPES.

To charge the toilet, charging directly the batteries inside the toilet is more efficient than charging it using the power supply unit, taking 4 hours and 20 minutes instead of 6 hours for a DC load case. Hence, the amount of time involved highlights the usage of our HPG as a backup solution for the NMT.

Finally, the power supply unit developed allows the NMT off-grid household to satisfy their basic electrical demands, improving their quality of life. For instance, the 100 Wh/day/household of energy consumption to satisfy the achievement of the MDGs can be supplied by 1 hour and 45 minutes of pedalling by the members of the household. What is more, while pedalling the

HPES designed, the household can charge one mobile phone; have three hours of room lighting and power one laptop over one hour and a half.

7.2 Future work

The current MSc Thesis is the result of the SoE participation into Cranfield's NMT project phase I. As explained in Section 1.2.2, the winners of the Reinvent the Toilet Fair in New Delhi's will enter in the second round of grants, called the NMT Project Phase II. For this purpose, the following studies or tasks are suggested as a continuation of the current study.

1. Customizing the in-wheel hub motor for our application. The one that we actually have is oversized (500 Watts of nominal power). Thereby, using cheaper permanent magnet, motor configurations… It can lead us to reduce the cost of the motor down to less than $50 while achieving mass production

2. Adopting an optimized gear ratio of the power-drive train to improve the efficiency

3. Customizing the power electronics and developing software that correlates the generator output power with the heart rate of the driver. In addition, design this system to charge 12 Volts or 24 Volts batteries

4. Integration of power electronics in the stator of the in-wheel hub motor. Thereby the size of the portable power supply unit will be reduced

5. Test and compare the advantages or disadvantages of using $LiFePO_4$ batteries against lead acid batteries

6. Developed intensive testing of the generator while doing a statistical study between Cranfield's students.

The suggestions will be investigated in the forthcoming year. In 2015, intensive testing of the HPES in off-grid communities is planned.

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Appendix A Human mechanical output power

Source	Body-exercise	Subjects	Experiment set-up	CP (Watts) (mean ± SD)	AWC (kJ) (mean ± SD)	Endurance at CP (minutes)
[14]	One-hand cranking	8 males Age 19 to 26 Healthy males	60 rpm 175 mm crank arm length	54 ± 14	6.48 ± 3.41	30
[15]	Two-hand cranking	10 males Age 22 to 32 Physically active	80 rpm 2 x 172 mm crank arm	103 ± 26	7.08 ± 2.14	42.9 ± 12.9
[20]	Two-hand cranking	16 males Age 20-34 Physically active	35-120 rpm	96 ± 16	7.46 ± 2.11	
[31]	Pedalling	7 males / 1 female Age 22 to 28 5 out of 8 competitive sportsmen	90 rpm 2 x 170 mm crank length	242 ± 25	19 ± 1.0	
[16]	Pedalling	6 males / 6 females Age 20 to 26 Moderated trained	70 rpm 2 x 170 mm crank length	178 ± 47 (all) 195 ± 46 (males) 161 ± 45 (females)	13.41 ± 6.25 (all) 17.53 ± 6.44 (males) 9.29 ± 1.87 (females)	

Table A-1 Upper and lower limb physiological studies

Appendix B Experimental data

B.1 Variable speed test

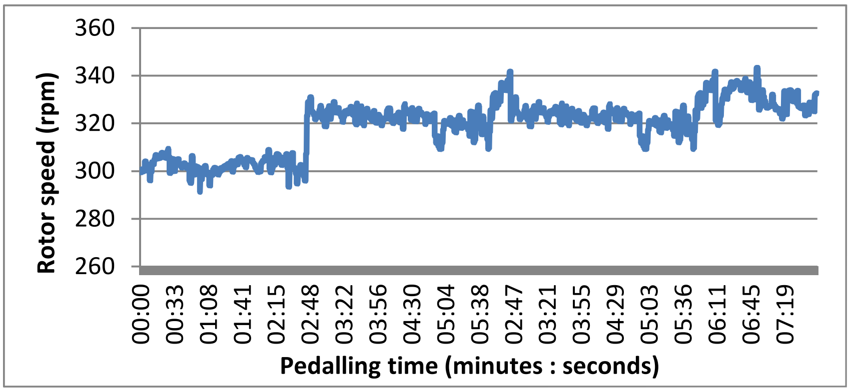

Figure B-1 Variable speed test. Rotor speed[14]

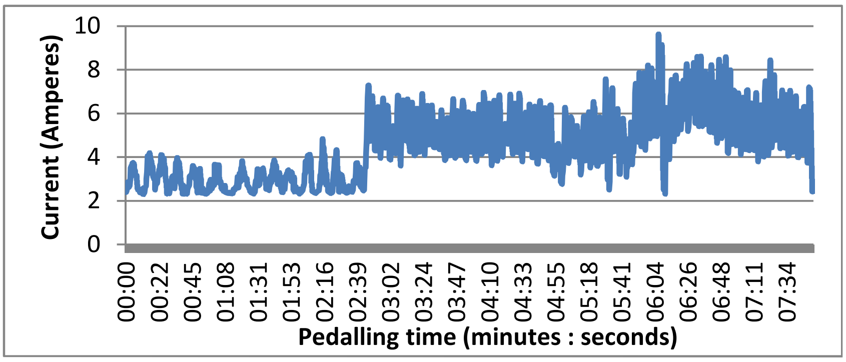

Figure B-2 Variable speed test. Charging current

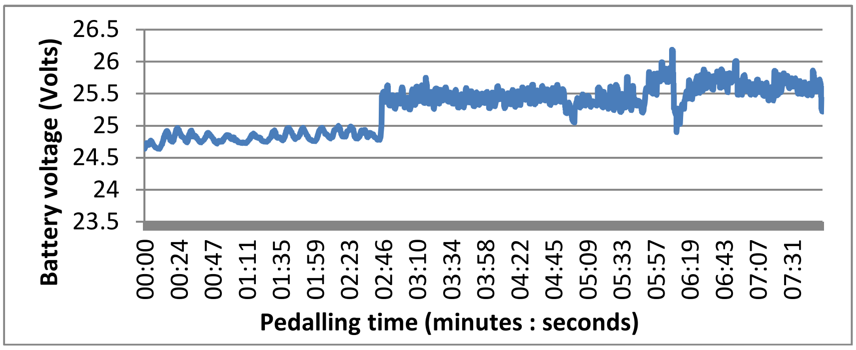

Figure B-3 Variable speed test. Battery voltage

[14] (3.14 speed ratio, rotor to rider speed)

B.2 Performance test. 15 minutes.

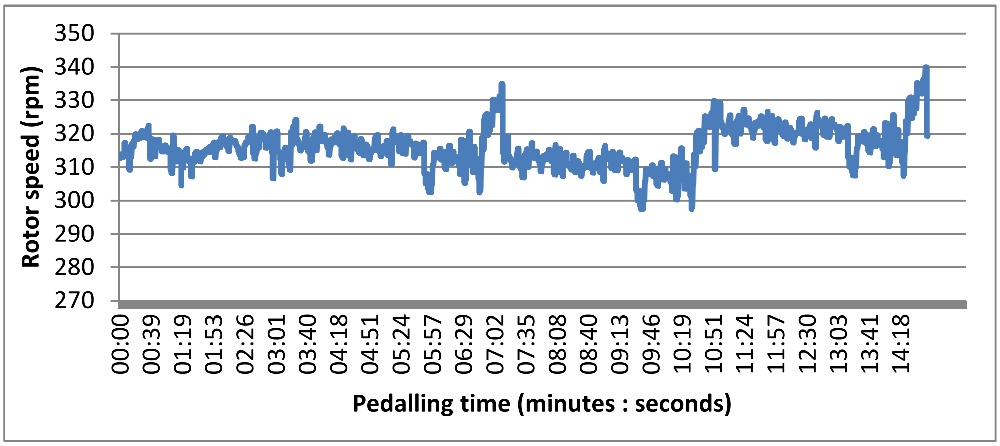

Figure B-4 Performance test. Rotor speed[15]

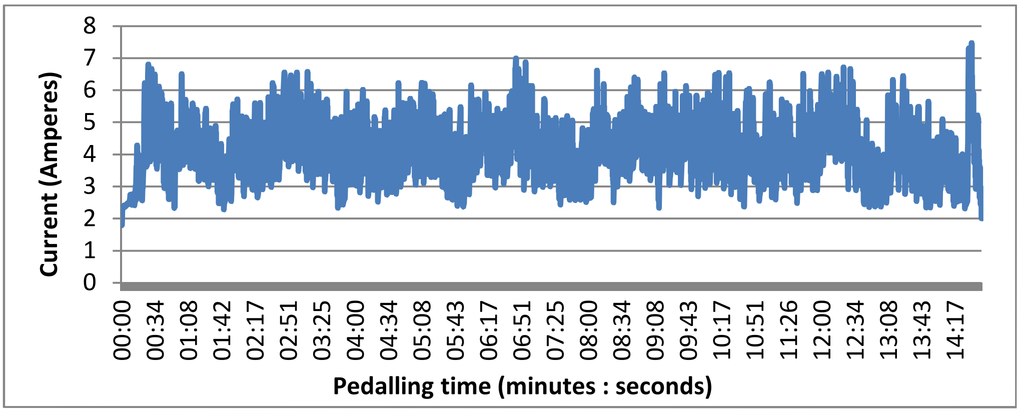

Figure B-5 Performance test. Charging current

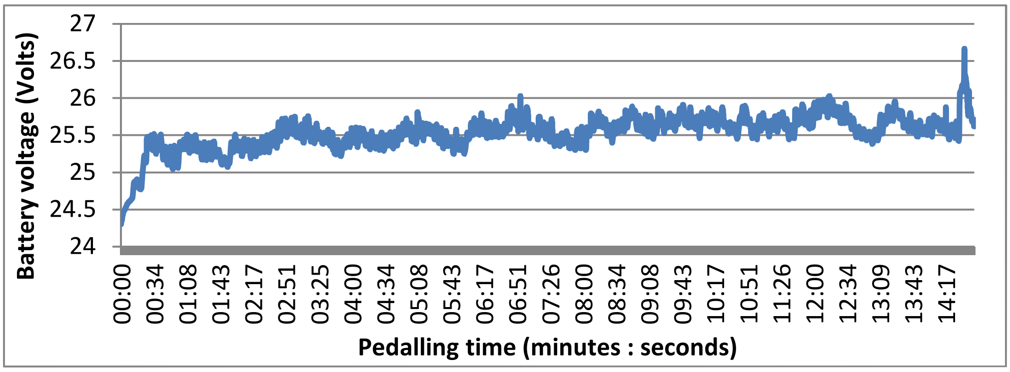

Figure B-6 Performance test. Battery voltage

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[15] (3.14 speed ratio, rotor to rider speed)

Appendix C NMT charging time calculations

		Type of load	
		AC	DC
		hour	hour
Type of charging	Direct	5.0	4.3
	Indirect	7.2	6.1

Table C-1 Hours required to charge the NMT (T human)

For direct charging and AC load:

119 Wh[16] x 0.8[17] x 0.7[18] x 0.85[19] x T_{human} = 283 Wh **(C-1)**

For direct charging and DC load:

119 Wh x 0.8 x 0.7 x T_{human} = 283 Wh **(C-2)**

For indirect charging and AC load:

119 Wh x 0.8 x 0.7 x 0.7 x 0.85 x T_{human} = 283 Wh **(C-3)**

For indirect charging and DC load:

119 Wh x 0.8 x 0.7 x 0.7 x T_{human} = 283 Wh **(C-4)**

[16] Medium power scenario power level. (Section 3.3)
[17] Overall efficiency of the plug-in bike generator up to the storage point (Footnote #1)
[18] Lead-acid round-trip battery efficiency (Figure 4-9)
[19] Selected power inverter efficiency