Imperial College London

EE2-PRJ E2 Project

Final Report

Second year group project

GUHUNGIZA – Freshen your Fire!

A Domestic Ventilation System for Underdeveloped Areas

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Year: 2nd Year

Course: EEE

Submission Date: 15.03.2015

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ABSTRACT

Meaning 'to fan a fire' or 'oxygenate' in Kinyarwanda, the Rwandan language, Guhungiza is our system to extract smoke from the homes of people cooking over open fires. There have been many different approaches to reduce the harmful effects of incomplete combustion of wood-burning stoves. A non-intruding, easily implementable system that can adapt well to established cooking traditions, as well as low cost and maintenance requirements are desired characteristics for a truly effective solution. This is what Project Guhungiza intends to provide. We have constructed a ventilation system that makes use of two strategically placed fans, to both reduce the amount of dangerous Carbon Monoxide produced, as well as bring fresh air into the room. A key focus of Project Guhungiza is to provide an efficient electrical energy generation system. We have spent a lot of time designing and testing thermoelectric technology that will utilise the thermal energy from a fire to generate enough power to drive the chosen fans, providing an optimum airflow.

INTRODUCTION

This Final Project Report provides in-depth detail about the procedures we have gone through in the design and testing stages of Project Guhungiza, leading to a more detailed and specific solution to the problem that we are tackling. We will detail the steps that have followed on from our previous Project Report [1], including collated information from a survey we ran in Rwanda and the challenges that we have overcome.

Project Guhungiza has two primary focus areas: firstly, providing a solution that reduces air-pollution, that is adaptable and can be easily integrated into the Rwandan culture of cooking using a wood-fire stove; and secondly, generating electricity for regions not connected to 'the grid'. To allow for easy integration we could not change the way in which people cook, so with this in mind, our choice of system design had to be as compact and unimposing to the cooking environment as possible.

Our main competitors come in the form of eco-stoves, including solar cookers and the 'Canamake' stove. The principal downfall of most of these approaches came from ineffective integration into the culture involved; higher costs often prohibited their prevalence also [1]. This spurred our key focus to create a system that does not impose or seek to change any cooking habits, but to develop a simple low cost ventilation system to clean up the fatal cooking environments.

With regard to our second focus, generating power off-grid, we considered several different technologies of this nature and compared them with respect to our key design criteria in order to make a well-judged decision towards the most feasible option. Another consideration that backed up our decision was the cost. Our target audience are people with extremely low incomes so we will have to develop a very low-cost solution.

CASE STUDIES FROM RWANDA

Thanks to our collaboration with E.quinox, we were able to forward a questionnaire to their team travelling to rural Rwanda in January 2015. This allowed us to receive first-hand information from locals on their cooking habits as well as their opinions regarding our idea. The questionnaire consisted of questions relating to their awareness of the pollution problem they undergo on a daily basis, their cooking habits, their living conditions and also how they perceive changes in their daily habits. The E.quinox team members carried out the questionnaires in two different areas of Rwanda: Rugogwe and Minazi. We asked them to note further observations such as the size of fires, the fire's location in the house, the sizes of houses and any current ventilation means, no matter how rudimentary.

After analysing the questionnaire responses and observations noted by the E.quinox team, several conclusions were made that helped us base our decisions on how to carry out our product's investigation and design. A surprising 90% of people told us they have their cooking fires in separate buildings from the main house in order to stop smoke from filling the whole house. In the kitchen building, two to three people (most commonly mothers and girls) spend about two hours of cooking for each meal. Cooking takes place for each of the two to three meals a day consisting mainly of rice, beans and potatoes. 70% of the people who are frequently exposed to cooking fires mentioned that they had suffered or were suffering from coughing and eye diseases.

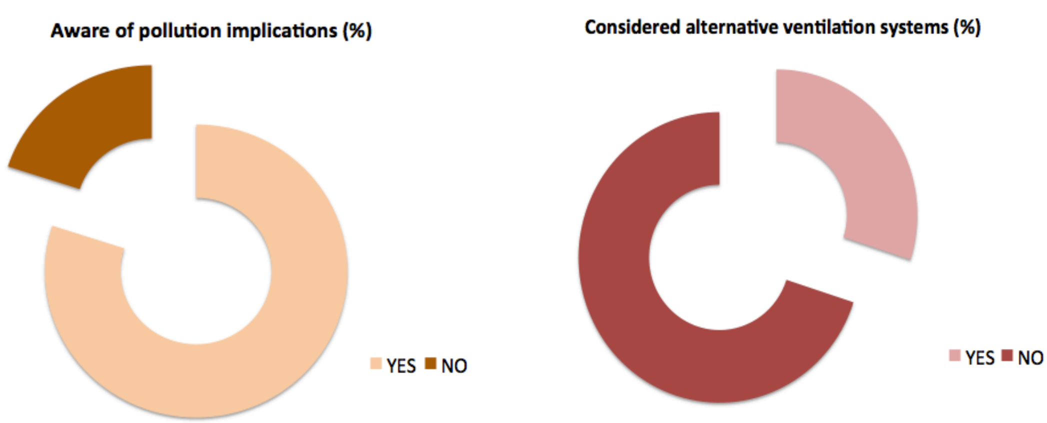

Figure 1: Survey results from Rwanda

An important observation made is that only 20% are unaware of the implications smoke pollution can cause. However, a mere 30% of these have ever considered including ventilation systems in their kitchens or homes, the extent of which only including very basic measures such as holes in the roofs and walls as well as windows. They would like to place the fires near the door of the building to allow the smoke to escape, but usually have to place them further inside the room as the wind and rain would prevent the wood from burning.

Questions relating to the affordability of the product and willingness to install a ventilation system into the house were also asked. Rwandan citizens are commonly split in 4 income categories. People in category 1, the richest people, earn over £50 per month and tend to live in urban areas. Category 2 citizens earn between £30 and £50 per month, those in category 3 earn between £10 and £30 each month, and those in category 4 have an income of less than £10 per month.

The people completing our questionnaire fell within categories 2, 3 and 4, with categories 3 and 4 being the most common. There was much uncertainty when asked their thoughts on the pricing of our product due to their lack of knowledge of anything comparable. Based on the few figures that we did receive, we came up with an initial estimate value of £10-12. All of the people asked said they would only be able to pay with the help of a micro-loan, which are vastly popular in their country. 400 Rwandan Francs (RWF) per month (equivalent to £0.40 per month) was an acceptable amount for the majority of those interviewed.

With all this information, we were able to create a strategy to design a very simple device to keep it accessible to our targeted clients. Therefore, we have attempted to create our device with the most vital functionalities and a clear focus on the main objective to remove the smoke from the houses or kitchens. Specifications and pricing are discussed further on.

Design Criteria

Similarly to the interim report, we will describe the 8 most important aspects defined in our Product Design Specification (PDS). This analysis formed the basis of our decision towards a final design concept, which will be evaluated in the following sections. The complete PDS can be found in appendix 2 of our interim report.

PERFORMANCE

The product must:

- Reduce smoke and fumes created by open-fires in homes.
- Be powered by renewable sources.
- Provide an air exchange rate between 10 and 20 cubic metres per hour.

The product could:

- Manage any surplus power for other domestic uses.

ENVIRONMENT

The product must:

- Withstand temperatures in its close environment - outdoors as well as e.g. close to the fire, which can be up to 300°C.
- Be resilient to dirt, smoke and insects.
- Ensure any components placed outdoors are weather-proof.

MAINTENANCE

- Fans pumping smoke will get dirty and will need periodic cleaning, no more than once weekly.
- All parts should be replaceable and relatively easy to source or make. Local materials and techniques should be employable.

ERGONOMICS

- The ventilation system should automatically switch on and off when necessary.
- The system should run quietly.
- It should not interfere with the user's cooking habits, so any casing should be small and implementable into the kitchen environment.
- If possible, the system could be integrated into an existing stove.

The product could:

- Encourage healthier posture or enhance cooking experience

TARGET PRODUCT COST

- The product should cost between £10-12. With creative finance models, a cost up to £15 may be justifiable.
- The product could be funded through the application of a micro-finance system.

SAFETY

- There should be no access to parts that get hot, ie. heat sinks. This is to protect the user from burns.

SOCIAL IMPLICATIONS

- The product should improve users' well-being by reducing smoke in homes.
- The product could raise awareness about the importance of clean air

MATERIALS

- Materials should be accessible locally and inexpensive

Concept Designs Considered

In order to solve the problem of domestic air pollution, we had to make several decisions regarding the design of our system. Once we had decided to use the fan for the purpose of ventilation, we had to think of different ways to generate the required power, considering that our target users do not have mains electricity available to them.

As mentioned in our interim report, our team was divided into 3 sub-groups each focusing on a different electricity generation method: Solar panels, thermoelectric modules and the battery and standalone boxes sold by the student-led project E.quinox. In the following paragraphs, we outline the most important data from each method, further details can be found in our interim report [1].

Solar Panels

One option is to use solar panels, which utilise the photoelectric effect to generate electricity and is a widely known method for this purpose. The advantages of this method are that the energy is renewable and that it has already found wide application, where it has proven to work reliably. However, solar panels have an efficiency in the range of 15-19% [2], which is not constant as it is affected by many parameters. Moreover, generation is only possible in daylight hours, with good weather conditions.

This leads to further components being required for energy storage for night-time usage. As well as this, during the daytime, they may generate more energy than necessary, which would either go to waste, or require the extra components for energy storage. The panels would also require cleaning periodically as dust and debris on the panel can reduce its effectiveness significantly. A 5W solar panel has a price of approximately £12 [3], which makes them difficult to incorporate while meeting the price point specified in the PDS.

Thermoelectric Modules

This solution involves the use of thermoelectric generators (TEGs), which generate a voltage proportional to the temperature difference across its faces, known as the Seebeck effect [4]. In our case, the hot side would be connected to a heat probe reaching into the cooking fire and the cold side could be connected to a heat ,sink at ambient temperature.

The benefits of using TEGs are that they are relatively cheap and they can generate a range of voltage between about 1 to 5 volts [5]. This method is also independent of weather conditions, unlike solar panels, and will only generate power when the fire is burning. As it is kept indoors, it should require cleaning less often than solar panels, which are exposed to the elements. On the other hand, TEGs have a very low efficiency of only a few per cent [5].

E.quinox Solutions

Another option is to make use of the products that the project E.quinox has started to introduce in Rwanda: Providing ‘Battery boxes’ for charging phones, powering light bulbs etc. which can be recharged with solar power at their energy kiosks. There are two solutions that we have considered: The standard battery box and the standalone solution [10].

The battery box requires the user to regularly visit the kiosk to recharge the box, which would become more frequent if the box is also used for ventilation, as more power would be needed to drive the fans. Therefore the standalone solution, a small solar panel that one mounts on the roof, seems more reasonable. The advantages of this solution are that the local adaptability has already been proven through the project's success and locals have been trained to maintain and look after the system. However, this method would limit our product to E.quinox's target area so it could not be sold in other places.

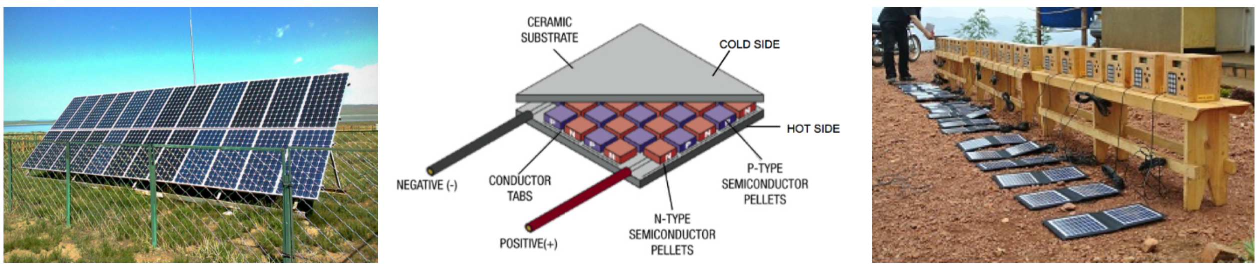

Figure 2 a: Solar array in Mongolia [8] b: Structure of a TEG [9] c: E.quinox standalone solution [10]

Concept Selection

Each of the aforementioned power generation methods has got advantages and disadvantages in terms of its feasibility for our purpose. In order to compare the methods and decide for the most promising technology, we have used a weighted matrix to compare our concepts. We have used the PDS as a basis for important criteria and evaluated these with weights and ratings ranging from 1-10.

The matrix below (figure 3) suggests that TEGs form the most promising concept to be developed. All solutions have been developed with the main aim of improving health conditions in a way that is adaptable to local culture, but they do have differences in their overall performance and suitability to this purpose.

We chose TEGs over solar panels and the E.quinox solutions because they provide an overall higher reliability, lower cost and are more adaptable to different environments and locations. Even if the efficiency of the TEG is considerably lower than any of the other solutions, this is not a major concern for us as long as a good ventilation of the house is provided. The effectiveness of the solution is more important than efficiency in this case and the TEGs may still be effective at providing energy while being inefficient. On top of that, the TEGs offer a great advantage, as power generation is independent of weather conditions and functions exactly when needed, automatically switching on and off. This means that no interaction with the user is required i.e. there is no intrusion or need for the user to change their habits.

A strength of the E.quinox system is the technical expertise that is already available, and our project would have to train local people in a similar way. We are also aiming to use locally available materials, for example the system's casing. The thermoelectric solution offers good possibilities for such adjustments. Furthermore, thermoelectric technology has not yet found much application in our field of interest and therefore turns this project into a very interesting piece of engineering work.

FEATURE / ATTRIBUTE		OPTION 1: Equinox Standalone		OPTION 2: TEC's		OPTION 3: Solar panels	
	WEIGHT (0-10)	Score	Total	Score	Total	Score	Total
PERFORMANCE							
Reliabilityof power generation method	7	8	56	6	42	8	56
Availability of power when required	9	4	36	9	81	5	45
Efficiency at smoke reduction	8	8	64	9	72	8	64
Surplus power production	2	8	16	1	2	5	10
ENVIRONMENT							
Little visual impact	3	6	18	4	12	8	24
Resilience to weather conditions	6	4	24	10	60	4	24
Resilience to dirt	6	5	30	2	12	5	30
INNOVATION							
Originality of design	6	7	42	8	48	3	18
MAINTENANCE							
Easy replacing of system parts	6	7	42	4	24	4	24
Low frequency of maintenance	4	3	12	2	8	3	12
Possibility to use locally available materials	5	2	10	7	35	2	10
ERGONOMICS							
Automatic swtiching ON/OFF	7	3	21	9	63	5	35
Little interference with user's cooking habits	8	8	64	7	56	8	64
PRICE							
Low cost of generation method	8	7	56	6	48	3	24
SAFETY							
Low possibility of burning	4	10	40	3	12	10	40
SOCIAL IMPLICATIONS							
Improvement of clients health	8	8	64	8	64	8	64
Adaptability to Rwandan culture	8	8	64	8	64	7	56
LIFE IN SERVICE							
Life span	6	8	48	4	24	7	42
Adaptability to other locations	7	3	21	10	70	6	42
TOTAL SCORE			707		727		642

Figure 3: Concept selection matrix

CONCEPT DEVELOPMENT

As previously discussed, we decided to develop the design concept based on thermoelectric technology. The core of the design is a TEG, which generates a DC voltage depending on the temperature difference between the hot and the cold side. The hot side of the TEG is connected to a heat probe that reaches into the cooking fire, while the cold side is connected to a heat sink. Testing results have also shown that it is necessary to connect a small fan to cool down the heat sink. The generated power is used to power both the cooling fan and the extractor fan mounted at the wall. See figure 4 for some of our design ideas.

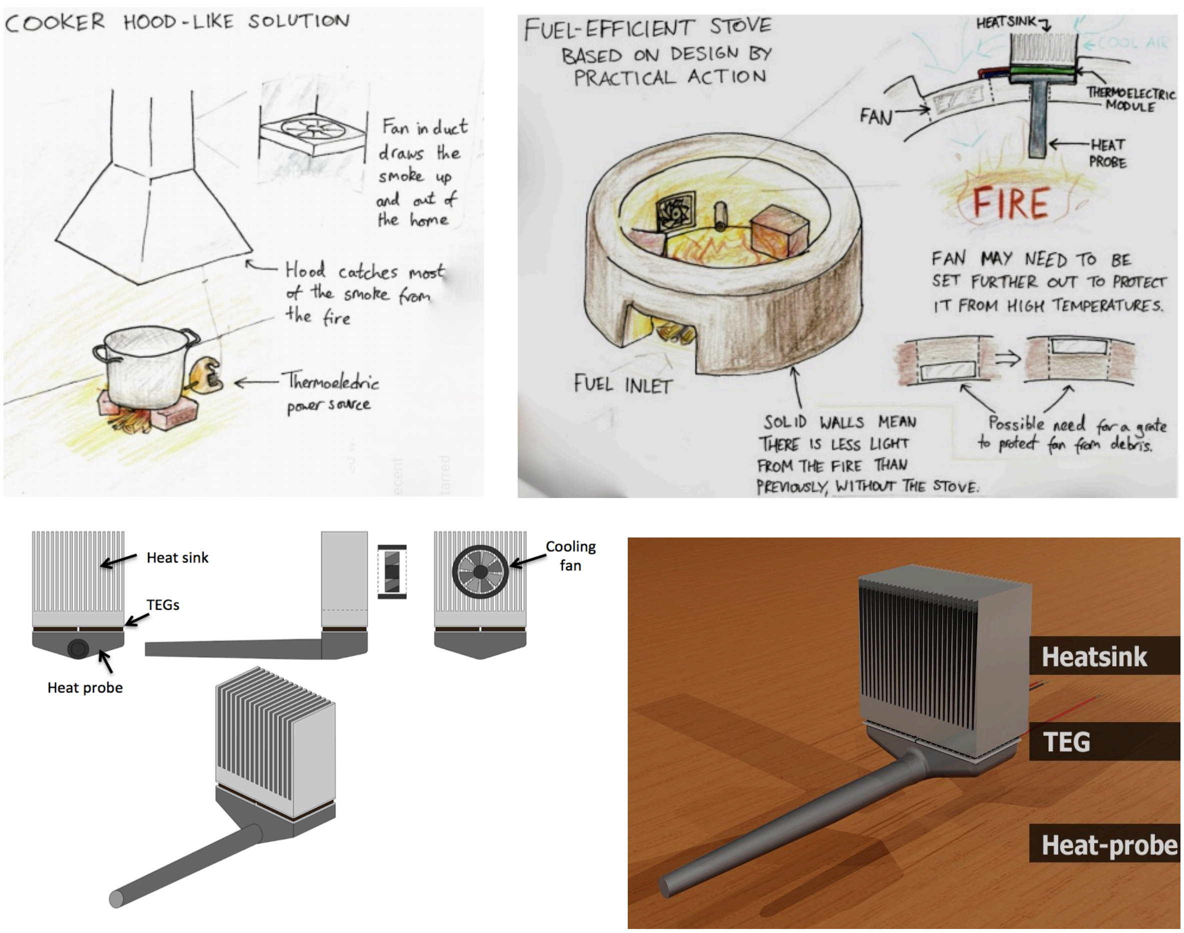

Figure 4: System design sketches. Top: placement of generator and fan; Bottom: generator module design.

As there are great differences between our testing environment and the environment of application, we had to make various assumptions and approximations to test the feasibility of our idea. Firstly, it is impossible for us to test our technology with a real fire, due to safety restrictions, so we used a hot plate to model the fire. We worked with temperatures of 200°C (in the following referred to as level 5) or 250°C (level 6). Heating the hot plate up to this temperature made sure that we did not exceed the ratings of the TEG [5], while allowing a high temperature gradient. This temperature is much lower than typical combustion temperatures of 500°C - 800°C [6], which will allow us to place the heat probe further from the centre of the fire, simplifying the design constraints.

The following sections aim to summarise the most important outcomes of our different experimental setups and to outline the consequences of these for our project. For more detailed information on experimental results, please refer to appendix 2.

TESTING THE FANS

Taking the average OF the estimated air exchange required to only extract the smoke created by a fire and the air exchange rate required to ventilate the entire kitchen, we have estimated a required air flow of between 20 to 30m^3/hour (appendix 3). During our testing, we measured the electrical characteristics of different fans as well as the airflow in order to ensure the usefulness of the tested fans for the purposes of this project.

We first tested three readily available fans from old computers to ascertain their impedance, power consumption and airflow with varying input voltage. Computer fans are known to be very efficient, due to the spatial limitations in PCs. These fans were all rated at 12V, but started running at 4V with no current-limiting from the power supply. One fan had too low an airflow, so we disregarded it, while the two others had good, but similar results. From here on, we took only one of them into account, the fan mounted to a *Quadratic* brand heat-sink (fan 1). In the range of voltages achievable by the TEGs (4V-8V), the resistance of the fan was 25 - 45Ω, the power consumed was 0.4 - 2.4W and the airflow was 27 - 51m^3/hour. We then ordered two fans that were more optimal for our use. One was a 5V fan intended for cooling the heat sink (fan 2), and the other one was a 12V fan with a high air flow to be used as extractor fan (fan 3). We then carried out the same tests for these two.

Fan 2 turned on at very low voltages and currents as it had less inertia due to its small blades. This was useful in the starting phase when the hot side of the TEGs was still heating up and the voltage was low. Despite its small size, this fan provided an airflow of 15 - 34m^3/hour in the voltage range of concern, which was sufficient to cool down the heat sink. The resistance of fan 2 was fairly stable at 35 - 37Ω, but its power consumption varied from 0.5 - 1.7W. Fan 3 had a greater impedance (49 - 69Ω) than the old computer fans, and consumed less power (0.2 - 1.3W), as $P = V^2 R$. Nevertheless, it gave a higher airflow of 33 - 70m^3/hour in our voltage range. Similar to the computer fans, it turned on at around 4V no current limiting on the power supply. This voltage increased for limited current.

The airflow from all the larger fans when run at about 5V was sufficient to provide the estimated air exchange rate necessary. At this voltage they all ran very quietly as well - the noise was less than 30 dB (quiet whisper [11]). Two of the computer fans we tested were already mounted on heat sinks, so that the direction of airflow was optimal for cooling. For the other cooling fans, a difficulty was to mount them on a heat sink in an efficient and secure way, so we could keep the temperature of the heat-sink as stable as possible.

TESTING THE TEGS

The main object of this testing phase was to determine the circumstances in which the TEG(s) give an optimal power output. This included testing varying electrical loads as well as finding creative ways to overcome practical issues such as designing a mechanical layout that assures a steady temperature difference and allows good airflow. We used TEGs and PC cooling heat-sinks, some with fanS mounted on top, that were available to us in order to test different mechanical designs and their effectiveness (see figure 5).

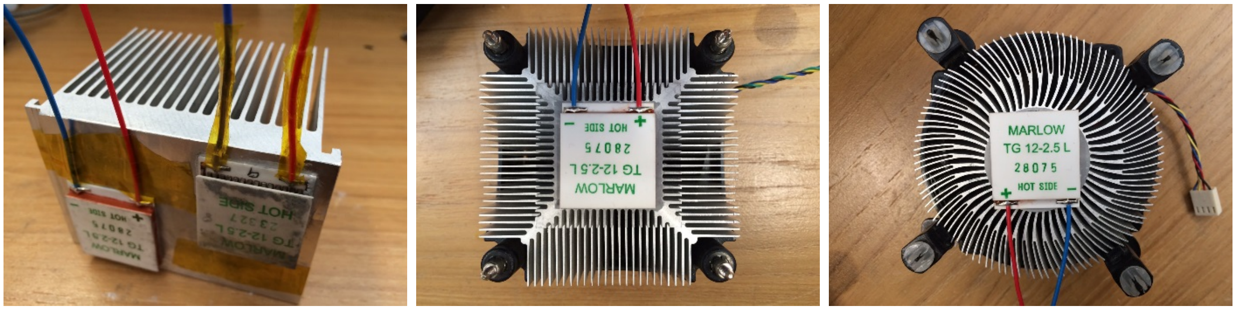

Figure 5: Heat sink 1: without fan 2: square heat sink with fan 3: round heat sink with fan

Attaching the TEG's cold side to heat sink 1 (using heat-conducting thermal paste), we firstly put the hot side directly onto the hot plate. With this setup, we recorded an unexpectedly high power output of up to 790mW with the plate on level 6. However, the heat sink heated up rapidly, causing a quick drop in output voltage. This was mainly due to the fact that a lot of the heat from the hot plate was transferred directly to the heat sink because of the proximity of the two surfaces. We therefore introduced an aluminium block and an aluminium foil taped around it to reduce the impact of the hot plate on the heat sink while keeping the bottom side of the TEG hot [6]. The aluminium block heats up to about 160°C with the plate on level 6, which shows its good heat conduction properties. See figure 6 for testing setup.

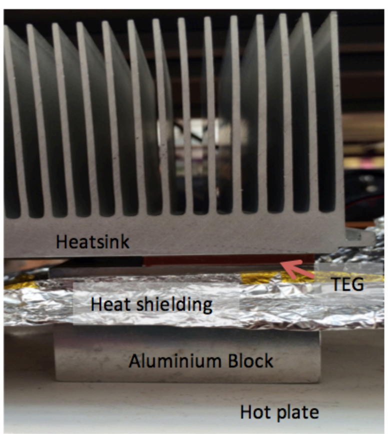

Figure 6: Experimental setup

Using this new setup, we tested the performance of the TEG when connected to different heat sinks. We still observed that having no fan connected caused a steady increase in the heat sink's temperature, even if it was not as quick. From this we concluded that it will be necessary to include a cooling fan into our design to make sure the temperature difference across the TEG was constant so that it would give a reliable output. We therefore powered a fan mounted to each heat sink at 5V, which we approximated as an achievable voltage from the first testing setup.

From our collected data we observed that all setups showed a similar behaviour of power against load, but with different total power outputs. Heat sinks 2 & 3 gave higher power outputs due to their optimised designs for good airflow. However, the round bottom of heat sink 3 meant that the entire TEG was not directly attached to the heat sink. As the different semiconductor elements are electrically connected in series [7], an unsteady temperature gradient across the module prevented a steady current from being generated and hence an unsteady output was produced. Furthermore, we observed that the maximum power output occurred at about 7Ω (see figure 7), which is approximately equal to the optimal load indicated in the datasheet.

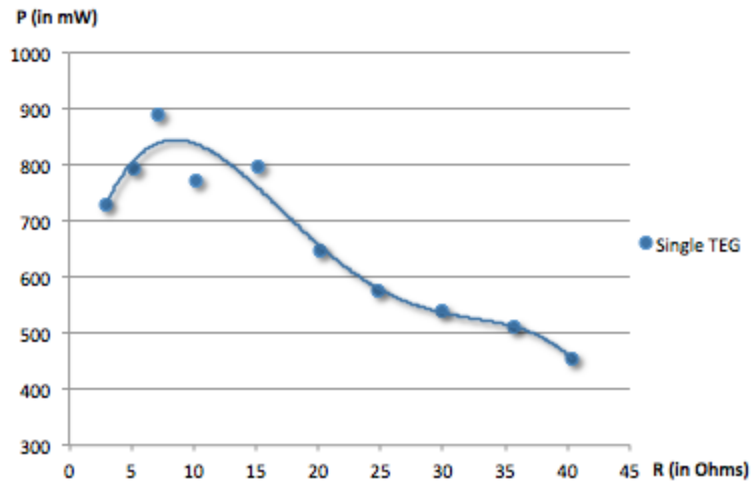

Figure 7: Power output characteristic for a single TEG

The TEG generated maximum and average power outputs of approximately 900 and 700mW respectively, for voltages ranging from 1.5V for a load of 3Ω up to 4.3V at 40Ω. This setup could drive a single fan, but as two fans are required for our system, the power output might not suffice, so we tested the output power from 2 TEGs. However, the faces of heat sinks 2 & 3 were too small to accommodate 2 TEGs, so we could not use them for further testing. Heat sink 1's face was large enough for both TEGs, so we proceeded testing using this heat sink.

Mounting the two TEGs thermally in parallel (whilst electrically in series) on heat sink 1 and using a larger aluminium block with similar heat shielding as before, we obtained a disappointingly low voltage. In order to find a solution to this problem, we moved the TEGs further apart from each other, reducing the temperature impact on each other. We also moved the aluminium foil to the top of the aluminium block, just leaving cutouts for the modules. As the reflective surface is facing the aluminium block, a large amount of the heat is reflected. This turned out to allow a very stable temperature of the heat sink and resulted in useful testing results. We obtained a peak and average power of 1.8W and 1.4W respectively, with voltages from 1.6V up to 7.5V. As the TEGs were in series, the peak power shifted to a load of about 15Ω (their combined impedance). All these results looked very promising for the system assembly.

Assembly

In order to test the performance of our complete system, we connected our 2-TEG generator to the small cooling fan and a larger extractor fan. The two fans were connected in parallel, while the two TEGs were in series. This means that the total load seen by the generator is reduced to the parallel combination of the fans, while the internal impedance of the TEGs was doubled. This meant that the operating point of the system moved considerably closer to the peak generation of the TEGs, which can be observed in figure 8. Even though the combination of fans 1 & 2 gave a higher total power output, we found that the combination of fans 2 & 3 gave a higher airflow when running, which is more suitable for our purpose, even if it does not provide maximum total power output.

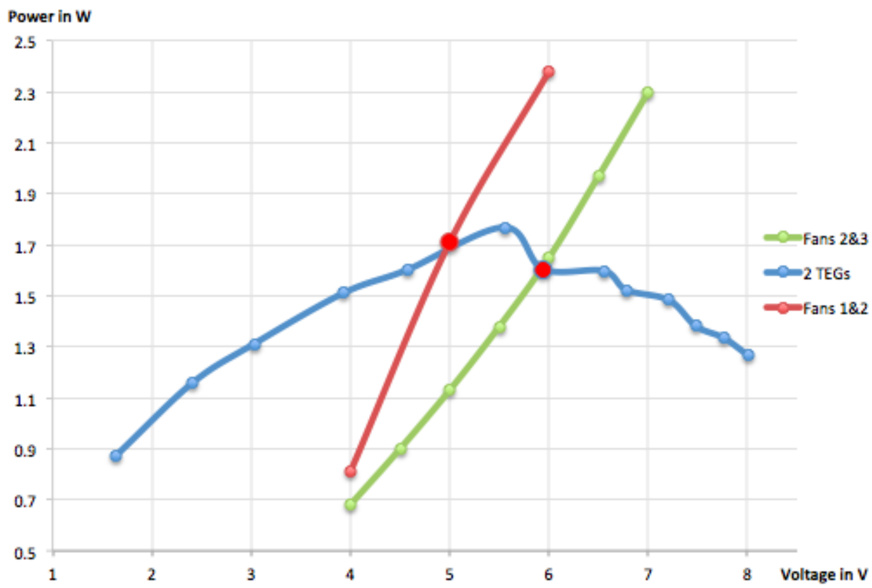

Figure 8: Compared performance curves of TEGs and parallel fan combinations

Furthermore, we tested the effects of removing single elements of our circuit in order to make sure that all components put are necessary for the design. Removing one TEG caused a voltage drop as we observed in previous testing. This allowed us to keep the cooling fan running, however it was not possible to power the extractor fan. This proved that it is essential to include a second TEG. Disconnecting the cooling fan did not have an immediate impact on the performance, but we observed a constant temperature increase which gradually reduced the output voltage. This means that system stability is only provided if the cooling fan is included.

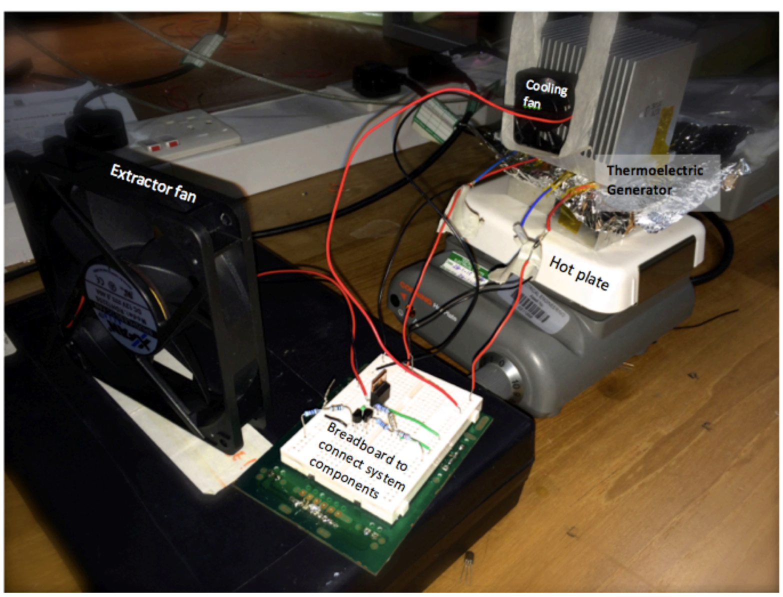

Figure 9: Assembled testing set-up

Finally, we tested the system's performance having the TEGs mounted to the aluminium block. While the small fan started as expected at around 3V, the larger fans did not start to run. The problem that we found is that as the voltage increases very slowly, the fan cannot generate enough torque to overcome its inertia. The fact that the fan starts running if the connection to the TEGs is broken and then reconnected proves this theory. The simplest solution to this problem would be to include a switch that needs to manually be connected every time the user desired the fan to run, and including a control LED that shows that the voltage suffices. However, this requires frequent interaction with the user and is therefore undesirable.

In order to provide an automatic switching, we had to design a voltage sensing circuit that switches on at about 5-6V. Initially we considered the use of zener diodes connected to a BJT, this caused problems, however, as zener diodes require high currents to flow in order for them to provide a stable output. Furthermore, we did not have a constant reference voltage, as the voltage itself was increasing, so our circuit needed to be independent of any reference.

We decided to test a thyristor, which is a PNPN-transistor that can be used as a very rapid switch. It is formed of a PNP- and an NPN-transistor with each's collector connected to the other's base (see figure 10). This connection means that as soon as a very small base current into the NPN-transistor is supplied from the biasing circuit, the collector current provides base current to the PNP-transistor, which is then again fed back to the NPN. In this way, the currents keep reinforcing each other, causing a quick increase in the current through the applied load, in our case the fan.

Testing showed that this circuit required a base voltage of 350 mV to switch on, using readily available BJTs. However, the voltage drop across the thyristor was about 0.8V, which is a considerable drop that might not allow the large fan to continue running. Therefore we will connect the output of the thyristor to a p-channel MOSFET, which uses the signal from the thyristor to turn on when it is triggered. Testing will have to prove if this allows a stable running of the fan. Another enhancement could be to include some capacitors that can store charge and therefore increase the current boost when needed.

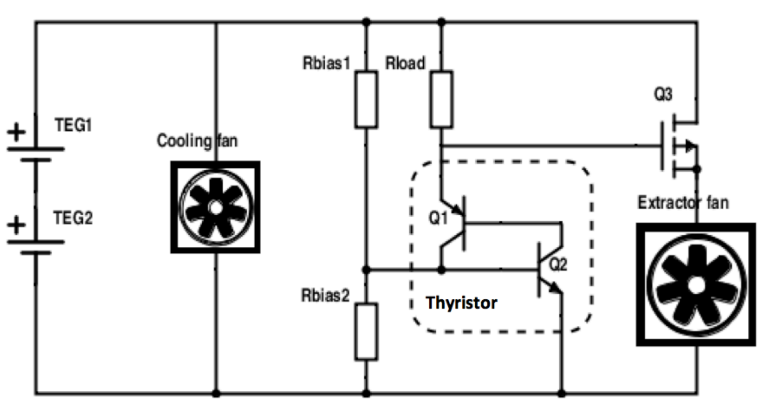

Figure 10: final circuit design

Discussion

As seen above, it seems very feasible to apply thermoelectric generation technology to tackle the problem of indoor air pollution in underdeveloped areas without mains electricity. TEGs have been used to generate power before and extractor fans are well known, but these two aspects, applied to this environment, have never been combined in this way, utilizing the heat from the cooking fire to ventilate the kitchen. We have several competitors that also try to solve this problem, but our solution is different, as it does not intrude the cooking habits of the user group and thereby threaten their traditions. This is very important, because the users might not want a product that affects their way of living, even though it fulfils their needs.

One of our main considerations in the design development was to keep it simple, so that it would be affordable for the user group and easily maintained. This is why we did not want to include complicated control circuitry. However, the large inertia of the extractor fan proved to be a serious issue, so we needed to include a circuit to make it kick off without user interference. We did not want to use a switch, because the system should be as unobtrusive as possible and therefore automatically switch on when needed. The solution we found was to include three transistors and a few resistors, forming a thyristor, to make the fan connect to the circuit only when the voltage is high enough. This is not very complex, it does not take up much space, and it is not expensive. Therefore it does not decrease the simplicity of the design.

Another key design criteria was the performance of the system in terms of power generation and smoke reduction. Our experimental results show that the power produced is more than enough to run both a fan to cool the heat sink and a fan to extract the smoke. The airflow achieved is higher than the estimated value needed for ventilating a kitchen, which leaves us some headroom. We saw that the cooling fan actually consumed slightly more power than the extractor fan, so most of the power generated is not directly used for ventilation. However, the power gained from introducing the cooling fan is greater than the power it consumes, so in the end we obtain a higher airflow.

The reliability of power production is high and the power will always be available when required. The only problem is that it takes some time (approximately fifteen minutes) from starting to heat the hot plate until this heat is converted into sufficient energy. On the other hand, the fan also keeps running for around ten minutes after the hot side of the TEG starts to cool down again. This means that all in all the fan will run for about the same amount of time as the fire is on, only slightly delayed. Since the need for ventilation is higher when the fire is dying out compared to when it has just started, this is not a problem.

The product cost is also an important design consideration. As the user group has very low income, it is vital to keep the price as low as possible and preferably at around £10-12, which our field research showed as the target product cost. The total cost of our prototype is higher than this and there will be additional costs for the casing and cables. However, bulk prices of the components are much lower, which lead to an estimated a total product cost of less than £15 when buying large quantities and using local materials where possible, especially for the casing (see appendix 4 for a breakdown). As we have not tested them, we cannot know for sure if these components and materials will match our optimal criteria. A more thorough analysis is therefore required to prove that the system is financially feasible.

Future Work

Even if the technical feasibility of our idea has been shown, there are multiple issues that we have not met yet during our testing. We have summarised below the further considerations that we anticipate to be important in getting our design ready for market, as well as some enhancements that we imagine could be added in the future.

To test our system further, we would have to test it with a real fire in a room of a similar size to the houses in Rwanda, rather than simply using the hotplate in the labs. With the full setup we would be able to test the temperatures more accurately and be able to establish the necessary layout and dimensions of the electrical system. With a full environment setup we would also be able to test how efficiently smoke is removed, and thus be able to adapt appropriately to ensure maximum efficiency from our system.

With the testing environment set-up, we will be able to follow through with our design concepts to design the casing and systems mechanical features; including cabling and mounting of the extractor fan to a wall/roof. Ideally the electrical system would have an all-encompassing casing with only the probe and the wiring to the fan being on the exterior. In our tests so far, the heat sink has been fully open to the air around it, and so the cooling due to convection current in the surrounding air has been possible. However in our complete product the cooling fan and heat sink will need to be somewhat enclosed, for durability and safety reasons. We will need to test the mechanical design of fitting different fan-heat sink combinations, as well as casing materials and structures, to keep the cold side of the TEG as cool as possible to maximize efficiency. With intense testing in the proper environments, we will be able to optimise the temperature gradients that we can achieve, and thus will achieve an optimal electricity generation system.

With a fully functioning final product in mind, we have thought up some enhancements that could improve our simple system. The first would be to implement a control system, in order to protect the electrical components from overheating and getting damaged. A simple system could use a temperature sensor to light up an LED to signal that the components are getting critically hot and indicate to the user that the probe (and therefore the encased electrical system) must be moved away from the fire. This would not consume much power but add important value to the durability of our product.

The second enhancement we have envisaged is to utilise any excess electrical energy that is generated, and have the functionality of charging a battery or run a 5V USB port additional to the ventilation system. This idea arose from the observation that it is even possible to connect 3 fans while still obtaining sufficient air flow, so there much be some excess power available. Despite the fact that the excess energy may not be huge in this case, we believe it still may be enough to put to use. All enhancements would require a further analysis in terms of functionality and cost.

CONCLUSION

Air pollution related diseases cause 4.3 million deaths each year. These daunting figures classify incomplete combustion as a worldwide issue. An issue which our solution of a ventilation system aims to reduce. We decided Rwanda to be the starting territory of our feasibility study, as it is widely affected by the problem of incomplete combustion and we observed that our peers in the E.quinox team are already successfully operating there.

As mentioned in the interim report, one of the main focuses of our project is to avoid a clash with Rwanda's cultural background and cooking traditions when implementing our product. In order to obtain hand information from locals, we conducted case studies in two different areas of Rwanda. The results confirmed our hypothesis, proving that most people suffer from health problems due to indoor air pollution. Even if only 30% of the interviewed people however have considered making changes to improve their health conditions, many gave positive feedback towards our idea and would be interested in investing into a micro-financed solution.

The second most important focus of our project was to create a design capable of off-grid electricity generation. There was no question that an extractor fan would necessary to remove the polluted air, but there remained the question: Which method should we use to power it?

To make this decision we thoroughly evaluated our concepts based on their performance and suitability. The three main options were solar panels, TEGs and E.quinox solutions, which were all viable and renewable. After a thorough analysis and with the aid of a decision matrix we concluded that TEG's are the most suitable power generation method as they are low-cost, weather-independent, small and therefore very adaptable.

Once we were sure that our design would fit in with the Rwandan culture and how we were going to power it, we had to develop the detailed technical design. Through rigorous testing of TEG's and fans, we concluded that by using two TEG's in series we can generate enough power output to drive two fans: an extractor fan and a cooling fan in order to keep the heat sink at a constant temperature and therefore provide a stable power output. Some extra circuitry was added to make the extractor fan overcome its inertia and start.

Even if the technical feasibility of the design has been proven, there is still a lot of work to do in order to bring our design past the finish line. These tasks include testing the system in a real cooking environment to prove effectiveness in smoke reduction, define a proper placement of the generator around the fire and designing a safe casing for the generator.

Project Guhungiza is defined as a ventilation system for underdeveloped areas. Underneath this name lies a group of engineers and designers that have been working hard to show that our solution is viable. But the real reason that attracted each member of our group was the opportunity to explore a whole new culture, and the challenge to meet our engineering specifications while respecting traditions. The gratification of building a working prototype, proving the feasibility of our idea, is truly unmatchable.

ACKNOWLEDGEMENTS

We would like to give a huge thanks to the team from E.quinox, who greatly supported us with their knowledge and experience. We got very helpful results from the interviews carried out during their January expedition. Furthermore our meetings with their members gave us a lot of information about the environment and the people living in local areas in Rwanda.

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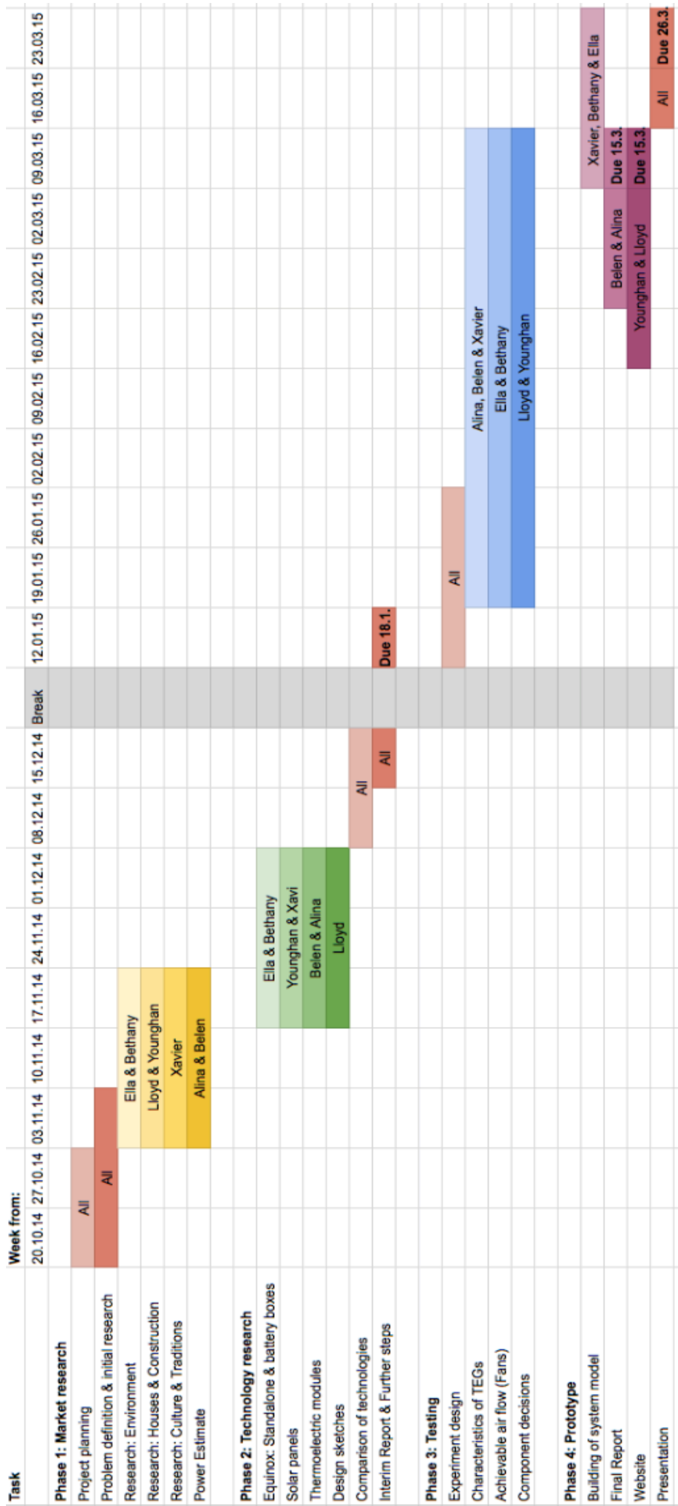
APPENDIX

1 REVISED GANTT CHART



2 Detailed experimental results

Testing the fans

Testing setup: Fan connected to power supply (PSU), use digital multimeter (DMM) to measure current as voltage across 1Ω Resistor. Airflow is measured using an anemometer.

Rated: 12V, desired air flow: 20-30 m3/h

Fan 1

V(V)	I(A)	R(Ω)	P(W)	Airflow (m3/h)
4	0.09	44.44	0.36	27.5
5	0.2	25.00	1	27
6	0.23	26.09	1.38	37.5
7	0.28	25.00	1.96	40.5
8	0.3	26.67	2.4	51
9	0.33	27.27	2.97	56
10	0.39	25.64	3.9	62
11	0.43	25.58	4.73	71
12	0.48	25.00	5.76	74

<turn-on: 3.89V

Fan 2

V(V)	I(A)	R(Ω)	P(W)	Airflow (m3/h)
3	77	38.96	0.23	8
3.5	97	36.08	0.34	12
4	112	35.71	0.45	14.8
4.5	128	35.16	0.58	17
5	142	35.21	0.71	22
5.5	156	35.26	0.86	24
6	167	35.93	1.00	27.2
6.5	180	36.11	1.17	29
7	193	36.27	1.35	30.5
7.5	205	36.59	1.54	31
8	218	36.70	1.74	34

Fan 3

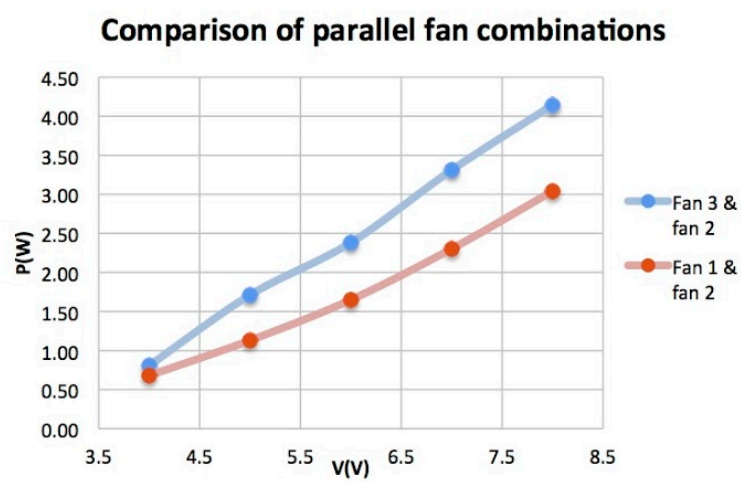
V(V)	I(A)	R(Ω)	P(W)	Airflow (m3/h)
3.5	12	291.67	0.04	/ off
4	58	68.97	0.23	33
4.5	73	61.64	0.33	33
5	84	59.52	0.42	40
5.5	95	57.89	0.52	46
6	108	55.56	0.65	48
6.5	123	52.85	0.80	58
7	136	51.47	0.95	59
7.5	150	50.00	1.13	60
8	162	49.38	1.30	70
9	192	46.88	1.73	75
10	222	45.05	2.22	76
11	250	44.00	2.75	80
12	280	42.86	3.36	90

Fan 1 & fan 2

V(V)	R(Ω)	P(W)
4	19.80	0.81
5	14.62	1.71
6	15.11	2.38
7	14.80	3.31
8	15.44	4.14

Fan 3 & fan 2

V(V)	R(Ω)	P(W)
4	23.53	0.68
4.5	22.39	0.90
5	22.12	1.13
5.5	21.91	1.38
6	21.82	1.65
6.5	21.45	1.97
7	21.28	2.30
7.5	21.13	2.66
8	21.05	3.04



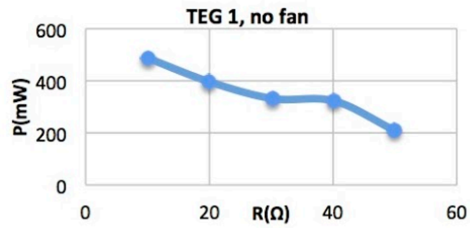
Testing the TEGs

Testing setup: TEG(s) connected to a load bank, use DMM to measure voltage across TEG

Heat of hot plate on level 6 (250°C) if not indicated differently. Temperature at aluminium block reaches 160-180°C, temperature of heat sink is around 50-70°C (if fan is connected).

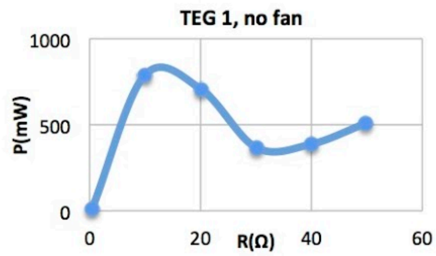
TEG1 max O/P on level 5 (no fan or aluminium block)

R(Ω)	V(V)	I(mA)	P(mW)
10.1	2.22	220	487
19.93	2.81	141	397
30.25	3.17	105	332
40.14	3.60	90	323
49.92	3.24	65	210



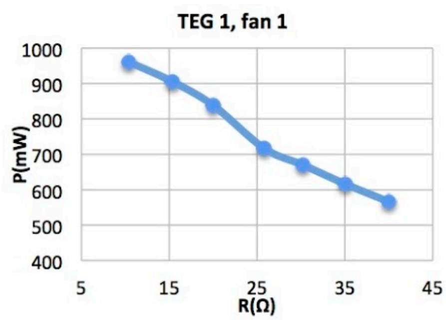
TEG1 max O/P on level 6 (no fan or alu > high inaccuracy for measurements!

R(Ω)	V(V)	I(mA)	P(mW)
0.44	0.07	166	12
9.94	2.80	282	788
20.14	3.77	187	705
30.12	3.32	110	366
40	3.94	98	388
49.77	5.03	101	508



TEG1 with fan 1

R(Ω)	V(V)	I(mA)	P(mW)
10.39	3.16	304	961
15.37	3.73	243	905
20.01	4.10	205	838
25.8	4.30	167	717
30.22	4.50	149	670
35.04	4.65	133	616
40	4.76	119	566



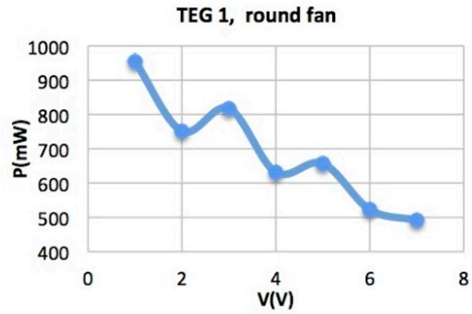
TEG1 with fan (normal heatsink)

R(Ω)	V(V)	I(mA)	P(mW)
10.39	3.10	298	925
15.48	2.86	185	528
20.58	3.40	165	560
25.55	3.34	131	436
30.99	3.72	120	447
34.9	3.59	103	370
40.46	3.70	91	337

TEG1 with fan (round)

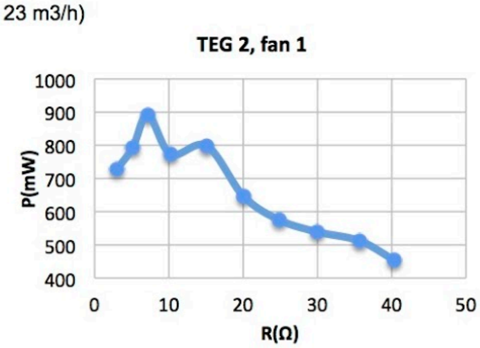
R(Ω)	V(V)	I(mA)	P(mW)
9.87	3.07	311	955
15.38	3.40	221	752
20.06	4.05	202	818
25.09	3.98	159	631
30.27	4.46	147	657
35.38	4.30	122	523
40.09	4.44	111	492

>measurements were not taken in the same order,
so taking .5 values later shows drop in time (less reliable)



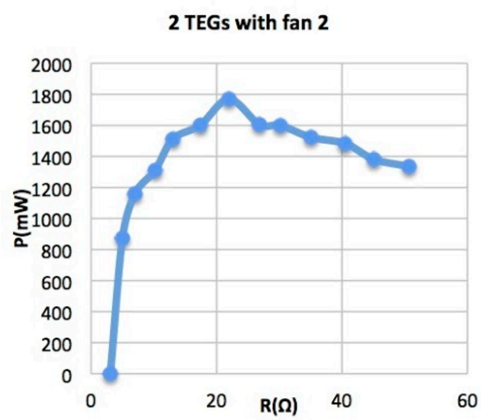
TEG2 (with heatsink 2 at 180degrees/level 6, fan power 23 m3/h)

R(Ω)	V(V)	I(mA)	P(mW)
3.01	1.48	492	728
5.13	2.02	393	793
7.18	2.53	352	891
10.25	2.80	276	773
15.1	3.47	230	798
20.07	3.60	179	646
24.86	3.78	152	575
29.97	4.02	134	539
35.68	4.22	122	512
40.34	4.28	106	454



2 TEGs with fan 2

R(Ω)	V(V)	I(mA)	P(mW)
3.08	1.64	532	873
5.01	2.41	481	1,159
7	3.03	433	1,312
10.22	3.93	385	1,511
13.04	4.57	350	1,602
17.41	5.55	319	1,769
21.98	5.94	270	1,605
26.84	6.55	244	1,598
30.19	6.78	225	1,523
35.06	7.21	206	1,483
40.5	7.48	185	1,381
45.1	7.76	172	1,335
50.7	8.01	158	1,265
		Average P:	1,416.73



3 Revised Watt Estimate

	lower boundary	mid-range / avg	upper boundary	unit	comment
WOOD					
Overall wood consumption per day		5,000,000.00		kg	Data from: http://solarcooking.org/regional/rwanda/rotary-rwanda-report-jan2005.htm
Population (Total)		11,780,000.00			Data from: http://www.rema.gov.rw/soe/chap2.php
Population (rural)		8,700,000.00		people	
Number of Households (rural)		2,023,255.81		households	
Number of households (cities)		508,681.82			
--> wood consumption per household (rural)	1.83	2.20	2.47	Kg/day	
--> on-time of fire	4.00	6.00	12.00	hours	
HOUSES					
average kitchen size (floor space)	5.00	10.00	12.00	sq m	Estimation according to information from Equinox
average kitchen height	2.00	3.00	4.00	m	
--> kitchen volume	10.00	30.00	48.00	cubic m	
CONCLUSIONS					
Air exchange rate (current)		0.67		per hour	estimate for room with door/window on only 1 side
Air exchange rate (optimal)	15.00	25.00	60.00	per hour	Data from: http://www.engineeringtoolbox.com/air-change-rate-room-d_867.html
Typical ventilator power (per air exchange)	1.00	3.00	6.00	W	
Wooduse per hour	0.46	0.37	0.21	kg/hr	Assuming pure charcoal; for wood we usually assume 0.5kg of C for 1KG of wood
moles of CO_2 per hour of wood/charcoal	38.02	30.49	17.16	mol/hr	
Mass of CO_2 per hour	1.67	1.34	0.76	kg/hr	Assumption: 12g carbon give 44g of CO_2
Volume of CO_2 gas (all combustion)	851.73	682.98	384.42	l/hr	Assumption: CO_2 extends to 22.4l/mol
--> Volume of combustion gases in hosue		0.68		m3/hr	
CO_2 Concentration		0.003 m3/m3			necessary data: CO_2 supplied to the room
Air exchange rate:		1.00			get same amount out as its coming in freshly (only for volume of smoke)
Good fan characteristic		40.27		m3/h	--> 23.7 cubic feet/min
Required fan characteristic (whole house)		60.00		m3/h	--> air exchange rate 2h-1; volume 30m3 (ventilate all the air in the room twice per hour)
Required fan characteristic (fire)		0.68		m3/h	--> very low estimate!!!
		17.07		m3/h	--> exchange 25 times the CO_2 volume (considering desired air exchange rate of 25)
ESTIMATES					
Ventilation for entire house		3W/60m3/h			possible values from ventilator datasheets
Centred ventilation of woodfire gases		1W/20m3/h			

* comparing with typical air exchange values: for room w only 1 window: 0.67 --> for a kitchen of 30m3 this gives a natural air exchange of about 20 m3/h

4 Cost breakdown

	Estimated bulk price	Quantity	Total cost
Fans	£2.00	2	£4.00
Thermoelectric modules	£3.00	2	£6.00
Heat sink	£0.50	1	£0.50
Electronic components	£0.40	1	£0.40
Heat probe	£1.50	1	£1.50
Casing	£1.00	1	£1.00
Cables	£0.30	1	£0.30
TOTAL			£13.70