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Prototype Combined Heater/Thermoelectric Power Generator for Remote Applications

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This study presents a prototype thermoelectric generator (TEG) developed for remote applications in villages that are not connected to the electrical power grid. For ecological and economic reasons, there is growing interest in harvesting waste heat from biomass stoves to produce some electricity. Because regular maintenance is not required, TEGs are an attractive choice for small-scale power generation in inaccessible areas. The prototype developed in our laboratory is especially designed to be implemented in stoves that are also used for domestic hot water heating. The aim of this system is to provide a few watts to householders, so they have the ability to charge cellular phones and radios, and to get some light at night. A complete prototype TEG using commercial (bismuth telluride) thermoelectric modules has been built, including system integration with an electric DC/DC converter. The DC/DC converter has a maximum power point tracker (MPPT) driven by an MC9S08 microcontroller, which optimizes the electrical energy stored in a valve-regulated lead-acid battery. Physical models were used to study the behavior of the thermoelectric system and to optimize the performance of the MPPT. Experiments using a hot gas generator to simulate the exhaust of the combustion chamber of a stove are used to evaluate the system. Additionally, potential uses of such generators are presented.

Key words: Thermoelectric generator, maximum power point, MPPT, power generation, biomass stove

INTRODUCTION

According to the International Energy Agency,^{1,2} 1.4 billion people live without electricity, most of them in developing countries. They rely on biomass such as wood, charcoal, agricultural waste, and animal dung to meet their energy needs for cooking. Biomass is burned in an open fire, making an important contribution to household air pollution. According to the World Health Organization, use of wood fuel and dung for cooking and heating causes over 400,000 premature deaths in India annually,

mostly women and children; For example, the concentration of airborne particulate matter in Indian household air using biomass is over 2000 μg per cubic meter, compared with the US limit of 150.³⁻⁶

To avoid this air pollution, the first thing to do is to use a stove instead of an open fire. To be efficient, stoves need tall flues to generate adequate draw. These flues are expensive and time-consuming to build. In some countries, with flat roofs, people do not have the technology to build chimneys going through the roof.

The possibility of adding an electric fan dramatically increases the widespread use of stoves. Addition of a fan greatly improves the overall performance of cooking stoves: it improves the air-to-fuel ratio,

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61 allowing far better combustion, and the total heat
62 recovery can be improved because the combustion
63 gases do not need to be at a high temperature.

64 Improving the efficiency and quality of combus-
65 tion contributes to reducing outside air pollution
66 and to reducing the quantity of wood used, which is
67 especially important in areas where wood is scarce.

68 When a household gains access to electricity, the
69 normal first use is as a kerosene or biomass sub-
70 stitute for lighting, extending working hours in the
71 evening or night. The other basic needs are mainly
72 radio and cellular phone charging (overall telephone
73 ownership in India reached 74% at the end of June
74 2011⁷).

75 Connecting these households previously without
76 electricity to the power grid would mean two
77 important costs for remote villages: the cost of
78 building new landlines and the cost of electricity
79 distribution.

80 A study conducted by the International Bank for
81 Reconstruction and Development⁸ shows that the
82 cost of connecting houses to the grid in Bahia
83 (Brazil) depends considerably on the distance of the
84 village from the grid and on the number of utility
85 poles per consumer, and also on the terrain (flat or
86 hilly). The average cost of connecting households is
87 more than US \$300, assuming one utility pole per
88 consumer. The more scattered the households are
89 (villages with more than two utility poles per con-
90 sumer), the more the costs increase (more than
91 US \$1000 for a distance of less than 1 km to the
92 grid). For four poles per consumer the cost explodes
93 to more than US \$4000, justifying the search for
94 alternative methods of generating electricity.

95 The cost of transmission and distribution of elec-
96 tricity in India has been studied by Nouni et al.⁹ It
97 varies from US \$0.07 to US \$5.1 per kWh depend-
98 ing on the peak electrical load and the load factor.
99 The worst case was for a distance of 20 km between
100 the village and an existing 11-kV line, a peak load of
101 5 kW, and a load factor of 0.1 (where electricity
102 would be mainly required for lighting in the evening
103 for a few hours). These villages built on hilly ground
104 have a relatively lower number of households.
105 Moreover, most of them have no industrial or com-
106 mercial load.

107 This result clearly indicates that providing elec-
108 tricity through grid connectivity to small remote
109 villages in hilly and other inaccessible areas where
110 people have very low income is financially unviable.
111 Renewable energy technologies such as solar, wind,
112 and thermoelectric generators (TEGs) are cost-
113 effective options for these specific off-grid house-
114 holds.

115 Small TEG prototypes with optimized DC/
116 DC convertors (Fig. 1) have been studied in our
117 laboratory. These TEGs are one of the solutions for
118 these households far from the power grid. Coupled
119 with clean and efficient cooking stoves developed by
120 Planète Bois (Fig. 2), TEGs can provide electricity
121 in order to improve the combustion and to respond

122 to basic household needs [light-emitting diodes
123 (LEDs), cell phone and radio charging devices].
124 Planète Bois, a nongovernmental organization, aims
125 to transfer recent knowhow in biomass combustion
126 and in use of traditional materials (lime, hay, sand,
127 and straw) to promote the use of low-cost and highly
128 efficient stoves for household and small-scale
129 industries, mainly in rural areas.

130 Figure 2 shows a schematic drawing of the
131 energy-efficient, multifunction, mud stove devel-
132 oped by Planète Bois. The wood in the pyrolysis
133 chamber rests on a bed of embers fed by the entry of
134 primary air at this level. Combustible gases are
135 given off as a result of decomposition by heat (pyro-
136 lysis) in the absence of flames and sucked towards a
137 nozzle. Then, these gases are mixed with the oxygen
138 from the secondary air. The flame then breaks out
139 downstream of the injection of secondary air. The
140 smoke extractor fan allows control of the air-to-fuel
141 ratio and therefore optimizes the combustion. The
142 fan also permits the use of a horizontal pipe,
143 avoiding the necessity for long metal flue pipes and
144 building of chimneys. The idea is to put the TEG in
145 a cogeneration system which simultaneously pro-
146 vides electric power and useful heat for hot water.¹⁰
147 Measurements made with a 10-kW wood-burning
148 cooking stove developed by Planète Bois showed
149 that about 2.4 kW is used to heat up domestic hot
150 water. This heat flux from the hot gases to the water
151 will provide the temperature difference through the
152 TE modules.

153 A prototype TEG (consisting of one or two com-
154 mercial bismuth telluride modules) has been
155 designed and tested with a gas heater providing a
156 flux similar to the one of the cooking stove. The
157 mechanical and thermal parts of this prototype have
158 already been described.¹¹

159 During combustion, the temperature of the com-
160 bustion gases varies significantly (fire ignition,
161 wood loading, presence or absence of pans on the
162 hotplate, and quality of wood). Furthermore, the
163 water temperature increases slowly but can vary
164 quickly when the user takes hot water and adds cold
165 water to the tank. For these reasons, the tempera-
166 ture difference fluctuates a lot during use of the
167 stove.

168 Thermoelectric modules are made of n couples of
169 p -type and n -type semiconductor pellets connected
170 with metal solder. They can be represented by a
171 voltage source with an internal resistance. The
172 voltage source is approximately proportional to
173 the temperature difference between the two sides of
174 the thermoelectric elements: $E_{oc} = n\alpha_{pn}(T_{hot} - T_{cold})$,
175 and the internal resistance $R_i = n[(\rho_n \times L_n/S_n)$
176 $+ [\rho_p \times L_p/S_p]] + R_c$ is also correlated with temper-
177 ature. T_{cold} and T_{hot} are, respectively, the cold- and
178 hot-side temperatures of the TE modules, and n is
179 the number of semiconductor couples.

180 L_n , L_p and S_n , S_p are, respectively, the leg length
181 and cross-sectional area of the pellets. ρ_p and ρ_n
182 are the resistivity of each material, and α_{pn} is the



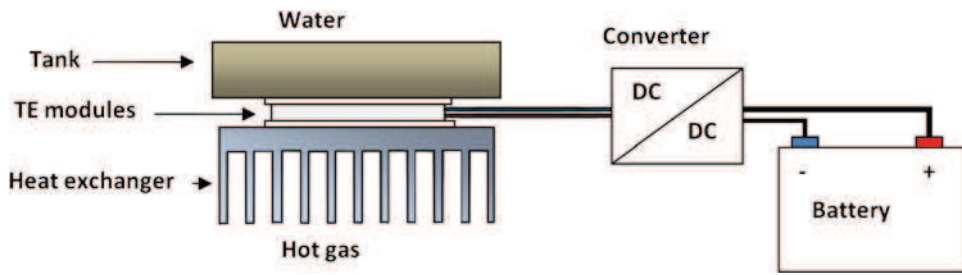


Fig. 1. Prototype TEG with optimized DC/DC converter, for use with hot gas source and cold water sink.

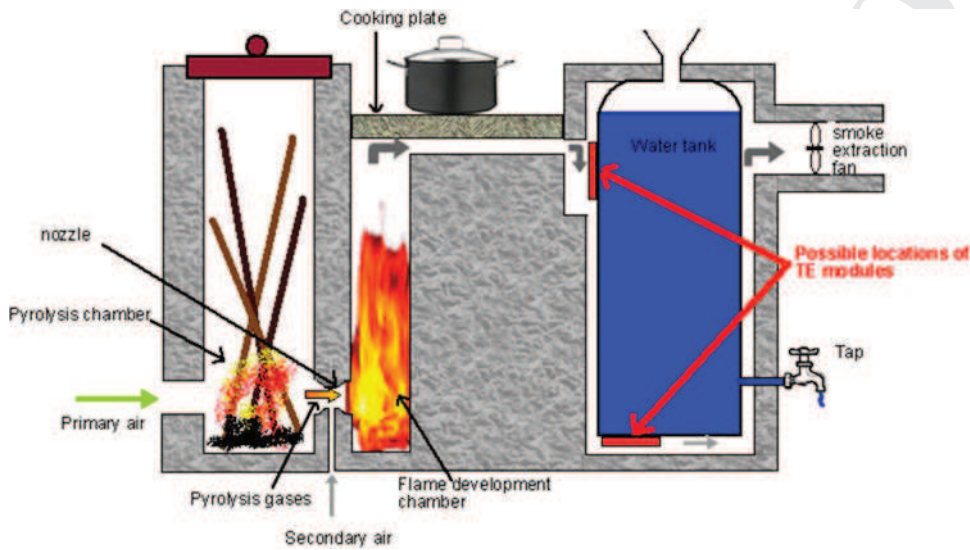


Fig. 2. Planète Bois cooking/water heating stove design.

183 Seebeck coefficient of the couple; these parameters
184 are temperature dependent. R_c represents all the
185 electrical contact resistances.

186 Figure 3 shows the variations of the output volt-
187 age and of the temperatures for a 1-h experiment
188 based on typical use of the cooking stove.

189 Because of this huge variation, a DC/DC con-
190 verter (Fig. 4) is necessary to regulate the voltage
191 and to store electricity in a battery in order to have
192 electricity available all day long, as the TEG only
193 produces when the stove is working. To get the
194 maximum power from the TE modules, the load
195 should be adapted, which means that the impedance
196 seen by the TEG is equal to its internal resistance.
197 As the current in the battery depends on the battery
198 charging but also on the variation of the load, the
199 output current and thus the input current of the
200 DC/DC converter will fluctuate a lot. With a fixed
201 output voltage the load would not be adapted and
202 the efficiency would be low. To be always adapted,
203 the solution is to control a DC/DC converter with a
204 maximum power point tracker (MPPT). This can be
205 done by adding a microcontroller which controls the
206 output power of the converter.

207 The next section describes the DC/DC controller
208 and the use of the MPPT algorithm. Special attention

209 has been paid to the choice of electronic components
210 in order to increase the internal efficiency of the DC/
211 DC controller. The MPPT algorithm efficiency has
212 also been studied using a Matlab–Simulink model
213 including measurement noise in order to determine
214 the best tracking increment value (or rather range).
215 The overall electrical efficiency between the output
216 power of the TE module and the power at the battery
217 terminals is presented. The test of the DC/DC con-
218 troller is presented in the following section. In the last
219 section, the first experimental results obtained with a
220 hot gas generator simulating the exhaust of the
221 combustion chamber of a cooking stove are shown.
222 The final stored electrical power results are pre-
223 sented, and the energy efficiency between the elec-
224 trical energy given by the TE modules and the energy
225 storage in the battery is measured. Based on these
226 results, the daily electrical production of the multi-
227 function cooking stove and its possible uses are
228 evaluated.

DC/DC CONVERTER

229
230 The study that was done to maximize the perfor-
231 mance of the DC/DC converter is presented in this

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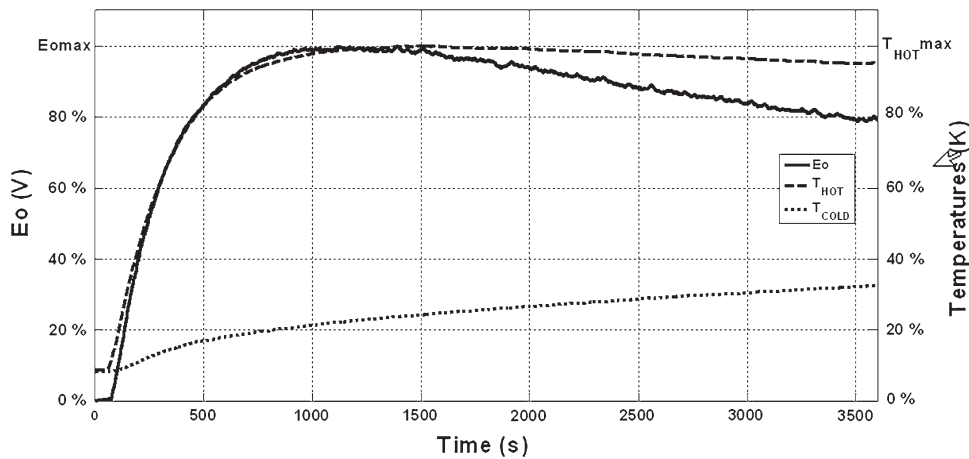


Fig. 3. Typical variations of the output voltage and temperatures of the TEG.

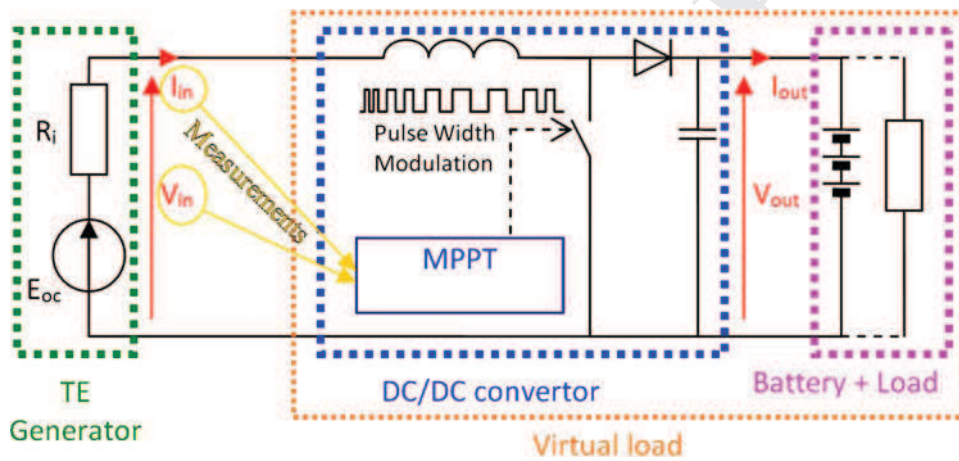


Fig. 4. Global electric circuit of the TEG with its storage battery and load.

232 section. The power efficiency can be defined as the
 233 ratio of the power stored in the battery to the
 234 maximum power that the thermoelectric module
 235 can provide for a specific operating point. The
 236 energy efficiency can be defined as the ratio of the
 237 energy stored in the battery to the maximum energy
 238 that the thermoelectric module can provide during
 239 typical use of the stove. The goal is to optimize
 240 energy efficiency.

241 The design of the converter can be separated into
 242 two stages: first the electrical components part which
 243 gives us the DC/DC efficiency, then the algorithmic
 244 part which represents the MPPT efficiency. This
 245 study is divided into two stages, because the total
 246 efficiency is the result of the following product: Effi-
 247 ciency = MPPT efficiency ×
 248 electronic efficiency, which can be studied separately.

249 For this application, a boost converter has been
 250 used (Fig. 4). V_{in} and I_{in} are, respectively, the input
 251 voltage and current of the DC/DC converter. V_{out}

and I_{out} are, respectively, the output voltage and
 252 current of the DC/DC converter. 253

Principle of the MPPT 254

Description of the MPPT Algorithm 255

256 The TE module with the DC/DC converter and the
 257 load is illustrated by Fig. 5. The electrical power (P_{in})
 258 characteristic of the TE modules as a function of
 259 the voltage is plotted in Fig. 6 for several values of the
 260 temperature difference between the two sides of
 261 the TE modules. These curves, typical of TE modules,
 262 show that the voltage V_{in} must be adapted in order to
 263 get the maximum power. The maximum power point
 264 (MPP) changes with the temperature difference,
 265 which is why a management algorithm is necessary.

266 The parameter driven by the microcontroller is
 267 the duty cycle (Dc) of the pulse width modulation,
 268 which is the fraction of the commutation period
 269 T during which the switch is on. Assuming an ideal

Author Proof

270 converter (without losses) the relations governing
 271 the system are:

$$I_{in} = \frac{I_{out}}{(1 - Dc)} \dots V_{in} = V_{out} \times (1 - Dc) \dots P_{in}$$

$$= V_{in} \times I_{in} = V_{out} \times I_{out} = P_{out}.$$

273 P_{out} is the electrical power output of the DC/DC
 274 converter.

275 It is reasonable to consider that V_{out} is fixed by
 276 the battery voltage, therefore the choice of Dc im-
 277 poses the voltage V_{in} and as a consequence the
 278 currents.

279 A simple MPPT algorithm strategy making V_{in}
 280 equal to $E_{oc}/2$ could not be used in this study be-
 281 cause E_{oc} fluctuates a lot with temperature. Another
 282 strategy based on tracking the internal resistance is
 283 not possible since this internal resistance is also a
 284 function of the temperature.

285 The solution is to measure both V_{in} and I_{in} in
 286 order to determine the electrical power and to

adjust Dc in order to maximize this value. The
 perturb and observe (P&O) method which maxi-
 mizes the input power (P_{in} , the power generated by
 the TEG) without any knowledge of the source is
 chosen for the MPPT. The principle (Fig. 7) is to
 alter the voltage V_{in} by a small amplitude (obtained
 by changing Dc slightly) around its initial value and
 analyze the behavior of the P_{in} power variation that
 results. If a positive increment of the voltage V_{in}
 causes an increased power P_{in} , this means that the
 operating point is on the left of the MPP. If the
 power decreases, this implies that the system has
 exceeded the MPP. A similar analysis can be done
 when the voltage decreases. From these various
 analyses of the consequences of changing voltage on
 the characteristic $P_{in} = f(V_{in})$, it is easy to locate the
 operating point from the MPP. Then, appropriate
 control will allow convergence to the maximum power.

The algorithm is described in Fig. 7. The fre-
 quency of the algorithm was fixed at 1 Hz for all the
 analyses.

V_{in} and I_{in} are measured using the analog-
 to-digital converter inputs of the microcontroller.
 Measurement of V_{out} is also necessary to incorpo-
 rate battery protection in order to increase its life
 expectancy. Moreover, to avoid problems due to
 noise at low measurement values, we decided that,
 for input power less than 1 W, the algorithm does
 not start and the Dc is fixed.

Efficiency Analysis and Optimization

The principal limitation of the P&O method¹³ is
 the oscillations around the maximum power which
 decrease the MPPT efficiency. The amplitude of
 these oscillations, which depends on the noise
 measurements (ΔI_{in} and ΔV_{in}) and on the input
 voltage values, can be minimized by choosing an
 optimized Dc increment ΔDc .

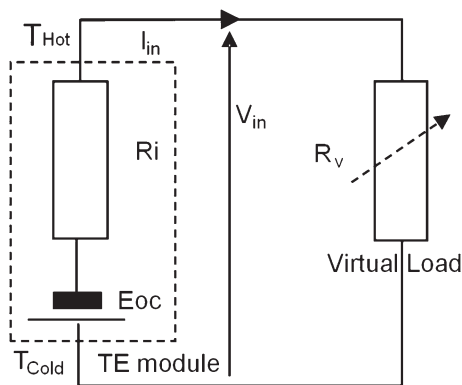


Fig. 5. Electrical model of the TE module and the DC/DC virtual load.

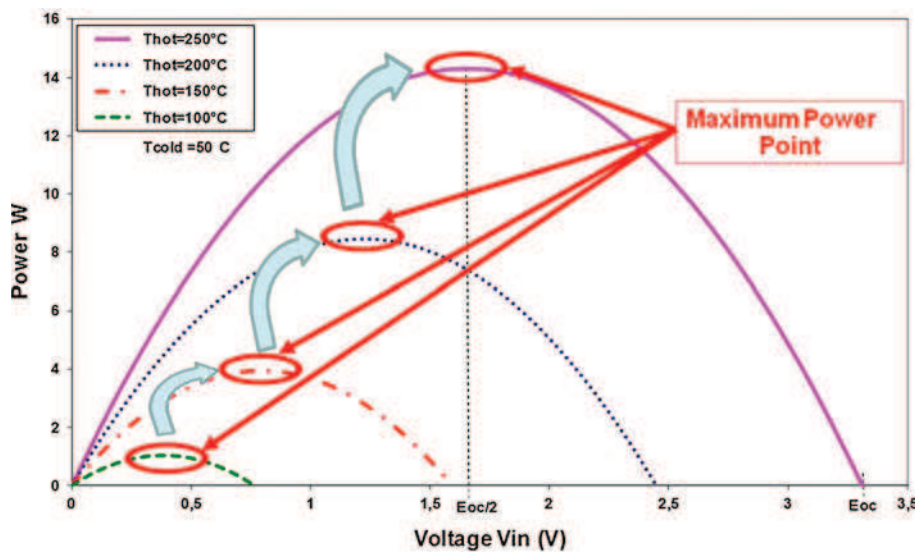


Fig. 6. TE module output power as a function of the TE voltage for different temperatures.

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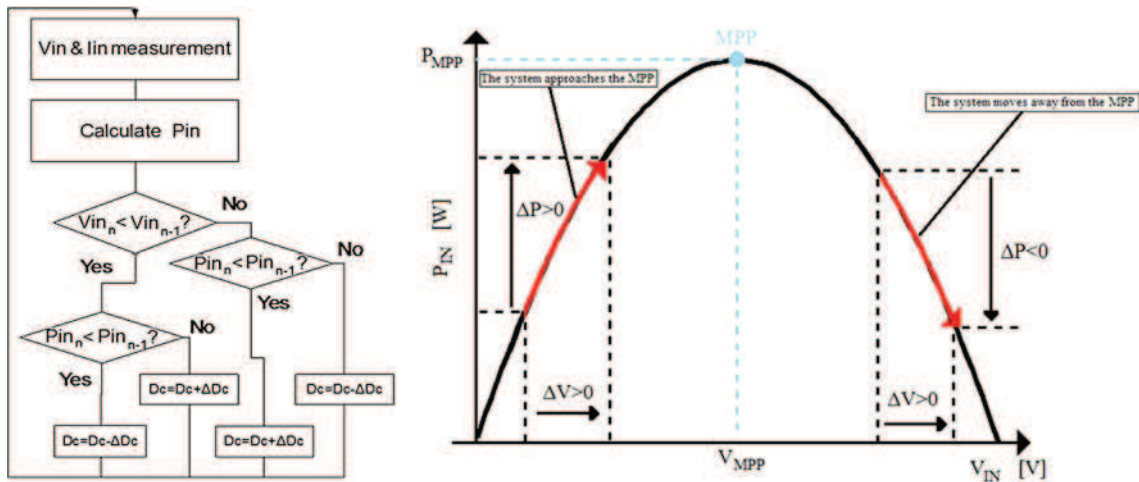


Fig. 7. Principle of MPPT with its algorithm.

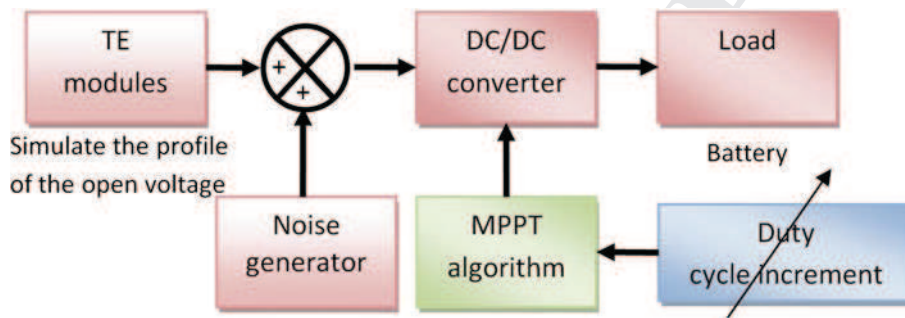


Fig. 8. Simulink model of the TE generator with its load.

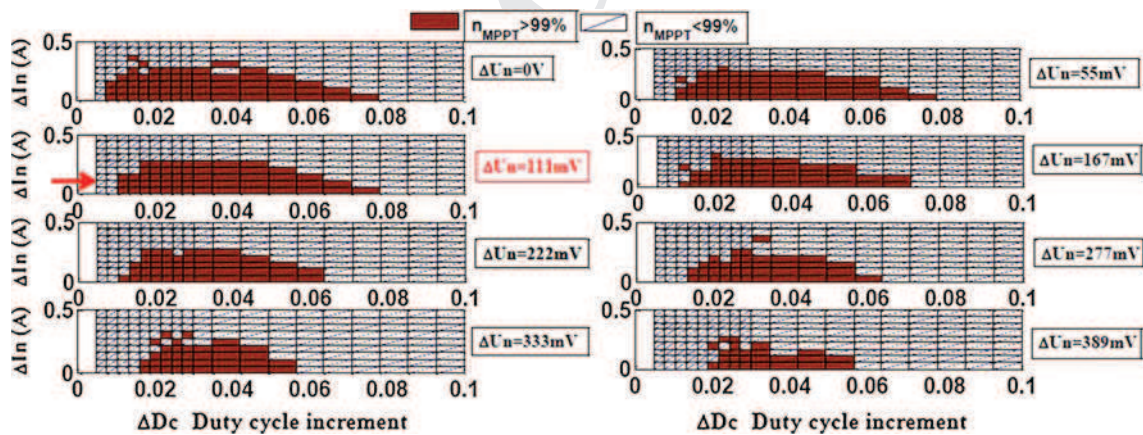


Fig. 9. Influence of noise (ΔI_n and ΔV_n) on the energy efficiency of the P&O algorithm.

Two analyses were carried out using a Simulink model (Fig. 8), the first one taking into account the impact of the noise on the current and voltage measurements, and a second analysis taking into account the influence of the maximum open-circuit voltage.

To carry out a realistic analysis, the cycle of Fig. 3 based on typical use of the cooking stove was used for the TE modules block. A noise generator added

random noise (white noise) on V_{in} and I_{in} . A heat cycle of 1 h is considered. The typical value of the open-circuit voltage reached during the typical cycle E_{omax} is 9.2 V (corresponding to 10 W), but it was used as a parameter in our study.

The first analysis presents the influence of the Dc increment choice for different noise values on the efficiency. Noise can originate in the environment of the system, but it mainly comes from the DC/DC

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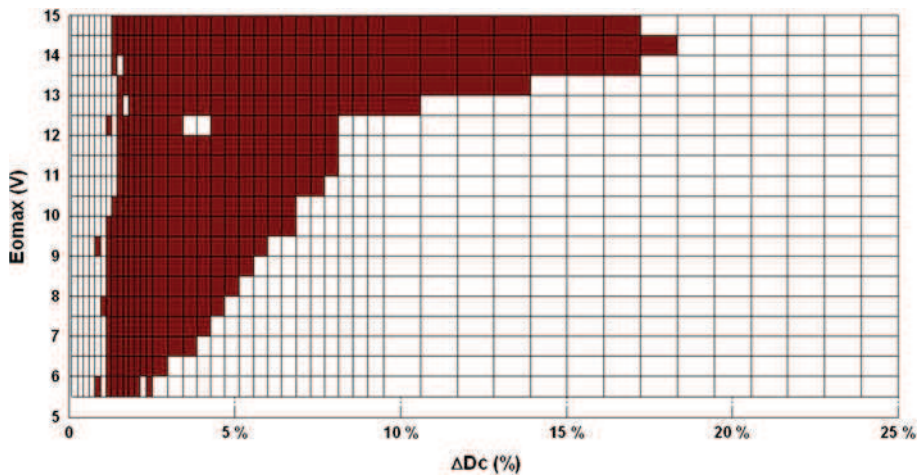


Fig. 10. Influence of the maximum open-circuit voltage on the energy efficiency of the P&O algorithm for different increments of Dc.

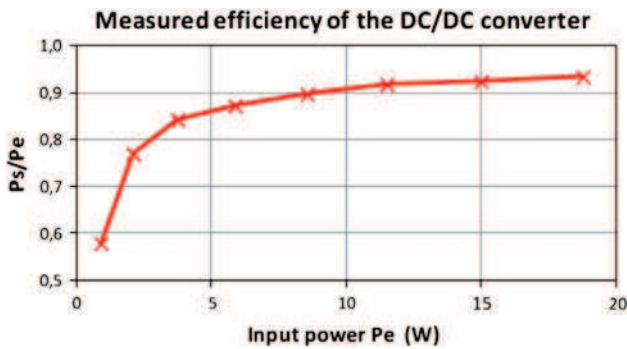


Fig. 11. Electronic power efficiency of the DC/DC converter.

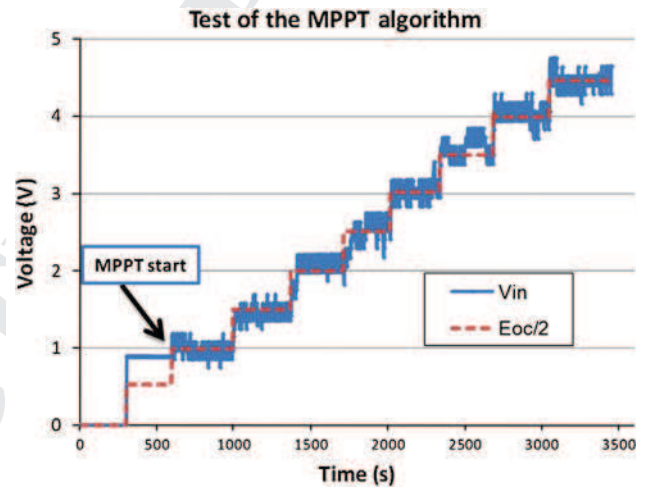


Fig. 12. Test of the P&O algorithm.

342 converter. The DC/DC converter works at about
 343 100 kHz, and the maximum commuted voltage and
 344 current are, respectively, 7 V and 3 A, so the noise
 345 cannot be avoided. The Simulink model was run ten
 346 times for each point, and the energy efficiency over
 347 the entire cycle was calculated.

348 ΔDc is a crucial parameter in choosing a trade-off
 349 between speed and oscillations. If ΔDc is too small,
 350 in case of quick variations of the variables (mainly
 351 input voltage and output current), the algorithm is
 352 slow to reach the MPP. If ΔDc is too big, the algo-
 353 rithm oscillates too much around the MPP at
 354 steady-state operation.

355 The results presented in Fig. 9 (MPPT efficiency
 356 over 99% is in brown and below 99% in white) show
 357 that the brown area decreases when the noise vol-
 358 tage increases. In the case of unknown noise sources,
 359 the Dc increment has to be chosen between 2% and
 360 5% in order to maximize efficiency.

361 The second analysis was performed to evaluate
 362 the effects of variation of the maximum open-circuit
 363 voltage.

364 In winter, according to Planète Bois, the hot
 365 water needs are more important (2.5 kW instead of
 366 1.75 kW), so the heat flux increases, and the voltage
 367 of the TE modules increases. Moreover, the ageing

of various materials and the installation of the
 system may also change the operating point. To
 study this influence, we chose to keep the same
 curve shape (Fig. 3) and to vary the maximum value
 of the open-circuit voltage E_{omax} . This is why an
 analysis on the impact of the maximum open-volt-
 age was carried out.

In our prototype, the noise is the result of the
 voltage and current commutations at 100 kHz of
 the DC/DC convertor. Measurements show that the
 voltage noise is around 110 mV and that the current
 noise is around 110 mA (represented by a red arrow
 in Fig. 9). It will be the same in isolated houses. The
 criterion is also to keep the energy efficiency over
 99%.

The result of the simulation is presented in
 Fig. 10, where the MPPT efficiency over 99% is in
 brown and below 99% is in white. E_{omax} was
 chosen between 5.5 V and 14 V, because when
 $E_{omax} < 5.5$ V, the electrical power output is not

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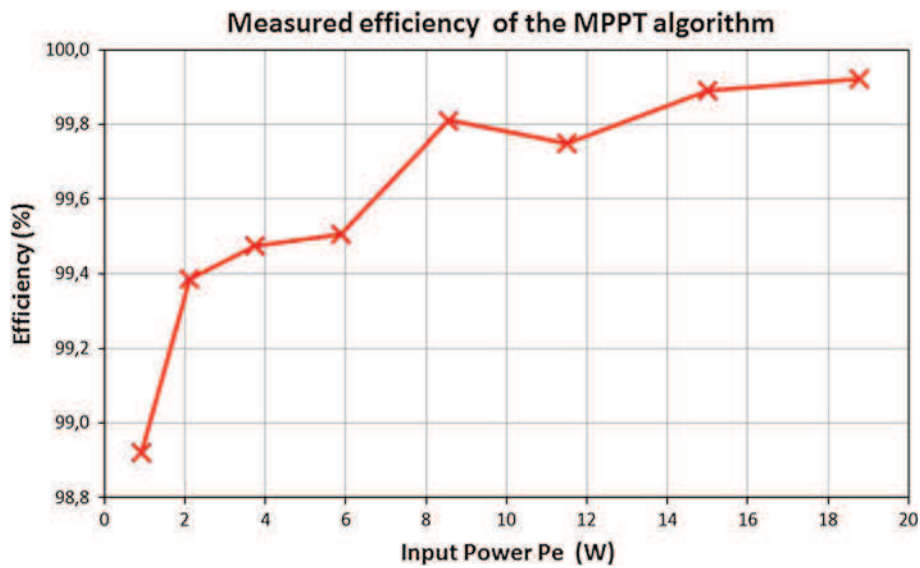


Fig. 13. Measured power efficiency of the P&O algorithm.

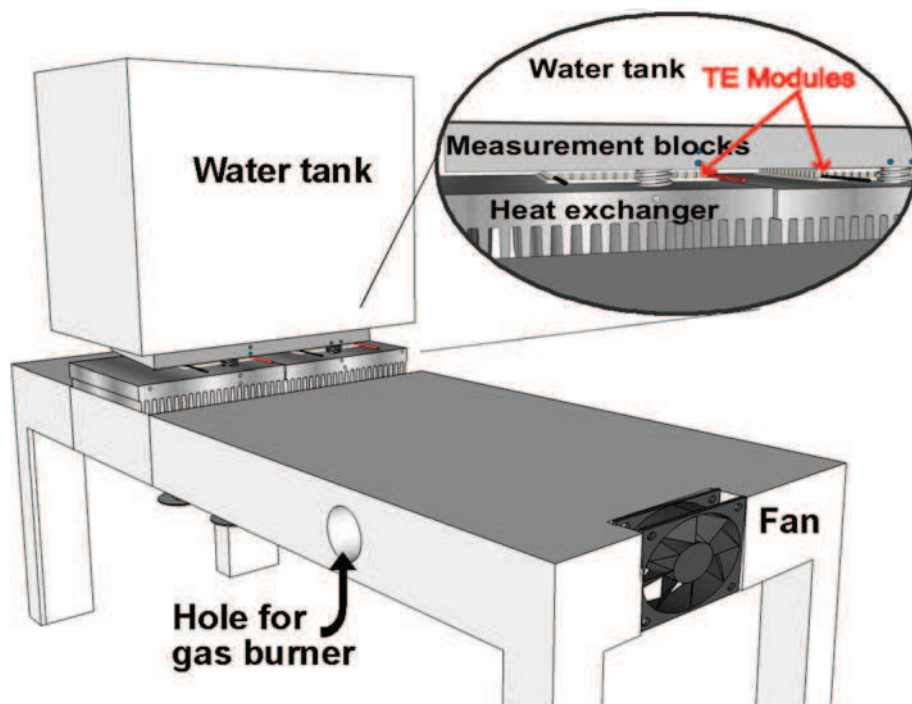


Fig. 14. Test bench for simulating the stove.

388 significant and because 14 V is the maximum value
 389 for the boost converter.

390 The figure shows that, when the open-circuit
 391 voltage increases, the area of efficiency up to 99%
 392 increases. This is due to the oscillation phenome-
 393 non: at low open-circuit voltage, if the D_c incre-
 394 ment is too high, oscillations cause significant losses,
 395 whereas at high open-circuit voltage, even if
 396 increasing the D_c increment increases the oscilla-
 397 tion losses, 99% is maintained.

Figure 10 clearly demonstrates that the optimal 398
 value for the increment of D_c is around 2%, and the 399
 large area of the graph with acceptable values 400
 shows that this value is not critical. 401

MPPT Conclusion 402

A MPP boost converter dedicated to the TEG has 403
 been developed. The model-based design of the DC/ 404
 DC converter, including modeling of noise and using 405

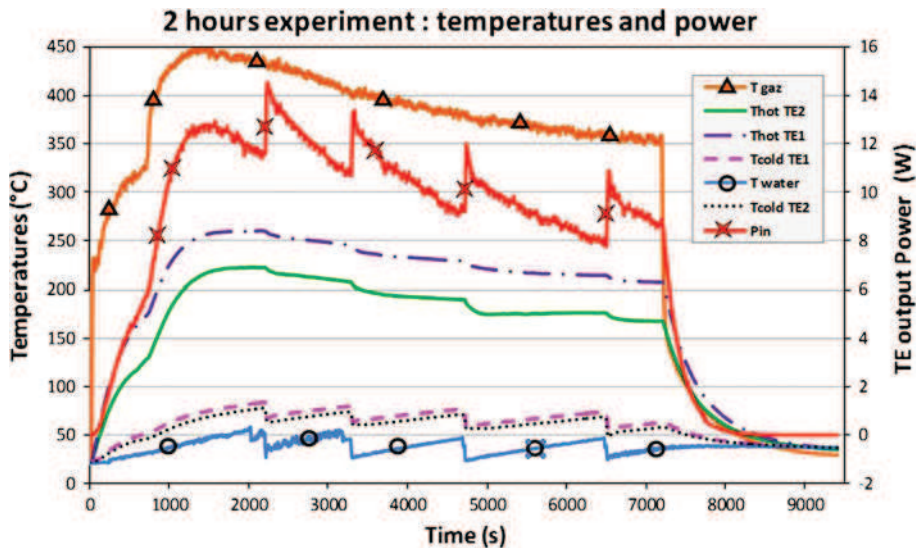


Fig. 15. Temperatures and electrical power of a 2-h experiment of the TEG.

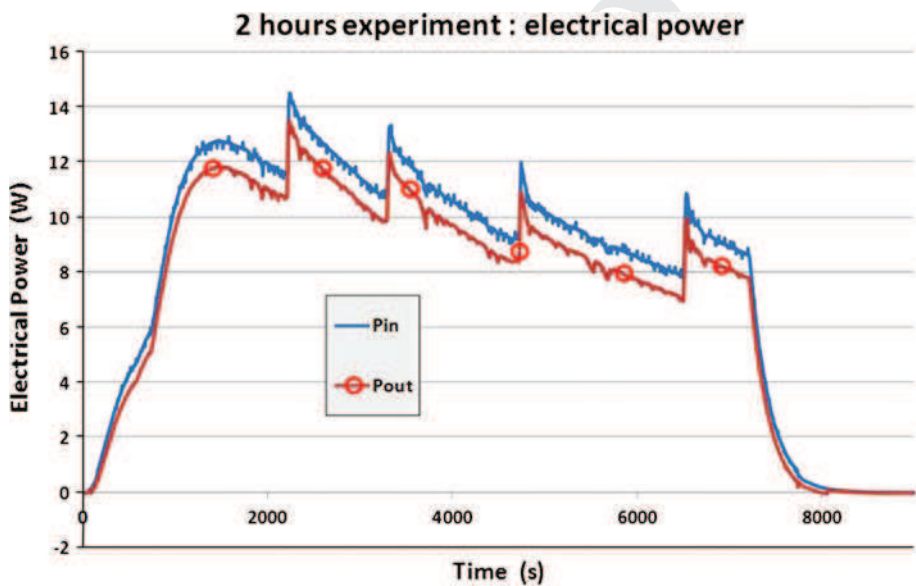


Fig. 16. Input and output electrical power of the DC/DC converter for a 2-h experiment of the TEG.

406 typical measurements of the output voltage of the
 407 TE generator as inputs, allows the choice of an
 408 optimal value for the increment of Dc. The design
 409 shows that, in the case of unknown noise sources,
 410 the Dc increment has to be chosen between 2% and
 411 5% to maximize the energy efficiency. When the
 412 TEG is used in the Planète Bois cooking stove in an
 413 isolated house, noise will come from the commuta-
 414 tion of the converter and will be known. In this case,
 415 a choice of 2% will optimize the converter for all the
 416 various operating conditions of the stove. With this
 417 choice of 2% for the Dc increment and with the
 418 actual thermal cycle, calculations show that we can
 419 expect a MPPT efficiency of 99.5%.

Test of the DC/DC Converter

420
 421 A DC/DC converter driven by an MC9S08
 422 microcontroller was built and tested. The electronic
 423 components were chosen in order to have good
 424 conversion efficiency. The electronic efficiency of the
 425 DC/DC boost converter was tested for different
 426 power input values (Fig. 11).

427 The power efficiency within the normal operating
 428 range is better than 90%. This efficiency is limited
 429 by the technology of the components and therefore
 430 mainly by price.

431 The MPPT algorithm was installed in the micro-
 432 controller. To avoid problems at very low voltages

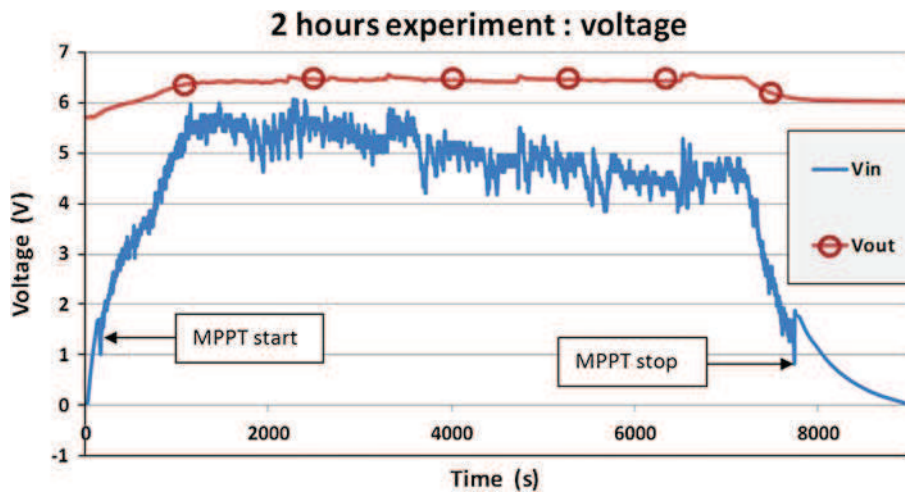


Fig. 17. Input and output voltage of the DC/DC converter for a 2-h experiment of the TEG.

Table I. Electrical energy produced and its possible uses for different cooking cycles

Cycle	One Cooking (2 h)	Two Cookings per Day	Two Cookings (One Long) per Day
Electrical energy stored (Wh)	18.2	36.5	54.7
Use example*	Fan, one phone charge, and 3 h of light	Fan, two phone charges, and about 6 h of light	Fan, two phone charges, and about 10 h of light

* Phone battery of 3.7 V, 1050 mAh. Light consumption of 4 W. Fan 1 W during cooking.

Table II. Economic study of the TEG

	<5	<100	<1000
Number of systems	<5	<100	<1000
Price (€)	200	120	70

and currents (mostly because of false measurements due to noise), conditions on the voltage and power level were added to the algorithm. A sleep mode was also added so that there would be no consumption of electrical energy when the TEG is not in use.

The MPPT algorithm was tested using a voltage source E_{oc} with very low internal resistance. For this reason, a fictitious internal resistance with a value equivalent to the TE module resistance had to be added. Figure 12 shows the evolution of the input voltage of the converter when the open-circuit voltage of the generator was increased in steps. It shows the fluctuations due to the P&O algorithm around the adapted voltage ($E_{oc}/2$).

The power efficiency of the MPPT algorithm was calculated by comparing the measured output power of the converter with the power obtained in the case where the load is perfectly adapted ($E_{oc}^2/4R_i$). The results presented in Fig. 13 show that the goal of energy efficiency above 99% is reached as soon as the input power is significant.

The power consumption in sleep mode was also measured and found to be less than 30 mW.

The next step was to test the energy efficiency of the converter using a typical cycle of the stove.

TRIAL OF THE COMPLETE TE GENERATOR

The next step was to test the TE generator with the MPPT DC/DC converter on the prototype TEGBioS (Fig. 1) already described. The two thermoelectric modules (Bi_2Te_3 modules from Thermoamic, reference TEP1-12656-0.6) were connected in series, and pressure of 5 bar was applied to ensure good thermal and electric contacts. Electricity was stored in a 6-V battery. Laboratory testing of the generator was performed using a gas burner, as the installation of a wood stove is not possible in the laboratory premises. A small gas (butane) tank supplies the burner.

The smoke duct which heats the hot water in the cooking stove was replaced by a thermally insulated metal pipe. Heat was generated by a 3-kW gas burner, and the hot gases were blown into the pipe right under the TEG by a fan.

Figure 14 shows a schematic diagram of the test bench used to test the whole system. The fan was set to achieve a gas speed in the duct similar to that of the combustion gases from a cooking stove. The heat source was a moving airstream at about 400°C, and the cold source was a water tank of 9 L. Glass wool (not shown in the schematic diagram) was used as thermal insulation.

483 Temperature, voltage, and current were recorded
 484 by using an Agilent 34970A data logger. The mea-
 485 surement system gave precision of $\pm 0.01\%$ for the
 486 voltage, $\pm 0.1\%$ for the current, and $\pm 0.5^\circ\text{C}$ for the
 487 temperature.

488 A typical 2-h cooking experiment was carried out.
 489 The test protocol respected the traditional use of the
 490 cooking stove. The hot water tank was emptied as
 491 soon as its temperature reached 50°C , being refilled
 492 with cold water. This was done four times during
 493 the cooking. The results are presented in Fig. 15.

494 The temperatures T_{hotTE1} , T_{hotTE2} , T_{coldTE1} ,
 495 and T_{coldTE2} were measured on the heat
 496 exchangers near the hot and cold sides of the two TE
 497 modules. The difference between the two modules is
 498 due to the slight asymmetry of the burner. The
 499 temperature of the gas was measured just before the
 500 heat exchanger in the middle of the hot gas flow.
 501 The plotted temperature of the water was measured
 502 at the bottom of the tank (it was measured to be 5 K
 503 to 7 K less at the top, but this is not plotted).

504 The temperature of the gas decreased slowly be-
 505 cause of the decrease in the butane flow in the
 506 burner (reduction in pressure in the cylinder of
 507 butane gas during the experiment), but the experi-
 508 ment is still representative of a cooking period.

509 The power generated by the two TE modules (P_{in})
 510 and also the power output (P_{out}) of the DC/DC con-
 511 vector are plotted in Fig. 16. Peak power occurs
 512 immediately after changing the water in the tank.
 513 Fluctuations in power due to the algorithm and
 514 noise are visible in the figure as expected from the
 515 simulation. The maximum power reaches about
 516 14.5 W on the input side of the converter.

517 Figure 17 shows the startup of the MPPT algo-
 518 rithm. The converter works at a constant Dc until
 519 1 W is reached. At this time, the input voltage
 520 decreases quickly to $E_{oc}/2$ and then follows this
 521 value, which increases with the temperature dif-
 522 ference. After the end of the combustion cycle, the
 523 MPPT stops at the same value and then the DC/DC
 524 controller goes into sleep mode.

525 The measurements shown in Fig. 16 allow calcula-
 526 tion of the energy produced by the TE modules and
 527 stored in the battery by integrating the curve. Then,
 528 the electronic energy efficiency of the DC/DC convertor
 529 can be calculated and was found to be equal to 90.7%.

530 Multiplying this efficiency by the efficiency of
 531 Fig. 13 we obtain the global energy efficiency of the
 532 DC/DC converter, which is around 90%.

533 It is also possible to evaluate the efficiency of the
 534 thermoelectric modules by measuring the heat
 535 transmitted to the water during the experiment.
 536 Assuming that the heat converted to electrical
 537 power is negligible, and if we neglect the losses
 538 around the water tank, this heat is the energy
 539 entering the TE modules. An efficiency of 2% was
 540 measured. This efficiency is low, but one must keep
 541 in mind that the energy that flows through the
 542 generator is not wasted because it is used to heat
 543 water in the tank.

544 From this experiment, it is possible to predict the
 545 electrical energy produced each day depending on
 546 the lifestyle of the inhabitants. Cooking techniques
 547 vary widely across the world; for example, simmer-
 548 ing lasts far longer than grilling. Two lifestyles were
 549 considered: 1 day including two short cooking peri-
 550 ods of 2 h, one in the morning and one in the
 551 afternoon, and 1 day including one short cooking
 552 period in the morning and a 4-h cooking period in
 553 the afternoon (representing the preparation of a
 554 dish such as a tajine in rural Morocco, for example).
 555 The nature of the cooking style has little influence
 556 on the operation of the stove. The heat radiated by
 557 the cooking plate is very important, and the effect of
 558 adding a pan does not really modify the production
 559 of hot water and therefore the production of elec-
 560 tricity. Time is the main parameter for electricity
 561 generation.

562 The use of the produced electrical energy was
 563 then distributed in the following manner over a
 564 period of 24 h: circuit power consumption in sleep
 565 mode (30 mW) outside the period of cooking, con-
 566 sumption of the fan (1 W) during cooking times, one
 567 or two charges of a mobile phone, and the rest in
 568 light with 4-W LEDs. The results are presented in
 569 Table I.

570 As this TEG is for people with low income, these
 571 results were completed with an economic study as
 572 presented in Table II; the price includes the cost of
 573 the TE modules, the heat exchanger, and the DC/DC
 574 converter. The price decreases mostly with the
 575 number of units, due to the reduction in price of the
 576 TE modules when they are bought in large quantities.

577 The promising results of Table I combined with
 578 the reasonable cost in Table II show that the use of
 579 TE modules on cooking stoves should enable people
 580 living in isolated houses to have light for several
 581 hours in the evening and to charge their phones. Of
 582 course it also permits the use of improved cooking
 583 stoves with a fan, allowing almost perfect combus-
 584 tion. TEGs are a potentially important contributor
 585 to the supply of electricity to rural areas.

586 CONCLUSIONS

587 In this paper, optimization of the electric part of a
 588 TEG designed for cogeneration in efficient cooking
 589 stoves has been presented. The DC/DC converter
 590 uses a P&O MPPT algorithm in order to always
 591 match the load to the fluctuating characteristics of
 592 the TE modules due to the temperature variation. A
 593 model-based design of the DC/DC converter was
 594 conducted to determine the increment of Dc of the
 595 MPPT algorithm that optimizes the energy effi-
 596 ciency of the converter. With the optimized incre-
 597 ment, the MPPT algorithm shows energy efficiency
 598 over 99%, which gives global energy efficiency for
 599 the electrical convertor of over 90%. A first experi-
 600 ment made with a hot gas generator simulating the
 601 exhaust of the combustion chamber inside a cooking
 602 stove allowed the evaluation of the potential of this



603 system. This TEG is certainly a low-cost solution for
 604 houses that are far from the electrical power grid in
 605 developing countries. This TEG has been developed
 606 to be combined with a stove designed by Planète
 607 Bois; however, it can be easily adapted to be used in
 608 stoves that have a hot water tank. Its use is not
 609 limited to developing countries but could also be
 610 adapted to make autonomous high-technology
 611 stoves requiring some electronic control.

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