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Critical Analysis of Optimized Energy Harvesting at Small-Scale by Thermally Coupled Photovoltaic-Thermoelectric Systems

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Abstract

The prospect of combining, at small-scale, a photovoltaic cell and a thermoelectric generator has emerged as a promising approach to enhance the non-recovered and unexploited heat from a photovoltaic cell. The increase of efficiency compared to standalone photovoltaic systems has varied, in some cases, up to 30% compared to the measured base efficiency. With the potential of improving the electrical energy generation capabilities of solar photovoltaic cells, it is no surprise innovative research regarding these hybrid photovoltaic-thermoelectric (PV-TE) systems has substantially increased over the last few years. In this analysis, electrical aspects of thermally coupled photovoltaic-thermoelectric energy harvesting systems observed in research are discussed and their main properties and specificities are reviewed and analyzed. A particular focus is made on the possible electrical connection between the photovoltaic cell and the thermoelectric generator within the hybrid system. The control mechanism for maximum power point tracking (MPPT) to achieve optimized power extraction, based on studies, is also addressed. Additionally, limitations and possible improvements are discussed regarding power extraction due to their specific needs for an electronic interface.

Highlights

- Impact of series, parallel, electrically isolated connections on PV-TE hybridization
- Review of control and MPPT techniques applied to hybrid PV-TE systems
- How concepts used in large-scale systems can be relevant to small-scale systems
- Analysis of the gaps of knowledge regarding the hybridization of PV-TE devices

Keywords: Photovoltaic, Thermoelectric Generator, PV-TE, hybridization, MPPT, electrical connection

Review Article (Word Count: 9473)

Abbreviations

PV-TE: Photovoltaic-Thermoelectric

TEG: Thermoelectric Generator

MPPT: Maximum Power Point Tracking

IoT: Internet of Things

PCM: Phase Change Material

MPP: Maximum Power Point

PWM: Pulse Width Modulation

WR-ZCS: Wide Range-Zero Current Switching

FOCV: Fractional Open Circuit Voltage

PV: Photovoltaic

PCB: Printed Circuit Board

PI: Proportional Integral

CMOS: Complementary Metal Oxide Semiconductor

TM: Time Multiplexed

AZCD: Accurate Zero Current Detector

TE: Thermoelectric

MIC: Multiple Input Converter

TDM: Time Division Multiplexing

PZ: Piezoelectric

FM: Frequency Modulation

PLL: Phase Locked Loops

P&O: Perturb-and-Observe-Method

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30 1. Introduction

31

32 The strain on resources and the environment has forced research towards renewable energy technologies to
33 accelerate. In particular, solar photovoltaics, i.e. the conversion of solar energy into electricity, is one of the
34 most capable electricity generation technologies. Since the first silicon photovoltaic cell in 1954 [1], it has
35 seen exceptional growth and has a vital contribution toward the energy transition in connection with
36 renewable energy.

37 Solar PV plays a vital role in many different application fields, from providing power to earth-orbiting
38 satellites, to remote locations through solar farms [2]. These applications are focused more on large scale,
39 but research is also being conducted keeping more small-scale applications in mind. One field that is being
40 explored is the internet of things (IoT) sector where PV generators are being integrated with self-powered
41 IoT nodes [3]. The benefits and versatility of PV systems seem endless, but solar photovoltaics also have
42 intrinsic limitations.

43 Solar photovoltaic cells operate with the principle of the photoelectric effect [4]. Sunlight consists of a vast
44 spectrum. Only a small portion of that spectrum can be utilized for power generation as not all of the
45 incident photons can excite electrons to the conduction band. A significant part of incident energy thus
46 results in the production of heat [5]. The performance of PV devices degrades with the increase of
47 temperature [6]. Utilization of this generated and unexploited heat to improve the performance of PV cells
48 is thus a key research issue, particularly at small-scale where self-power IoTs are planned. To do so, a
49 promising auxiliary device, in terms of additional electrical power generation, is the thermoelectric
50 generator (TEG) [7].

51 TEGs operate based on the Seebeck effect which converts thermal energy to electrical energy [8], [9]. In
52 the case of an integrated hybrid energy harvesting system at small-scale, one possible way to facilitate the
53 heat transfer from the PV cell to the TEG would be to couple them together thermally. This can be especially
54 effective at small-scale as the dimensions of the PV and TEG would be similar. This is imperative, as many
55 losses though conduction, radiation, and convection can occur. In this case, to minimize losses and
56 maximize the heat transfer between these two energy harvesting sources, a specific and efficient thermal
57 interface can be placed between the two electrical generators, thus creating an optimized hybrid PV-TE
58 device [10].

59 Indeed, hybrid energy harvesters have attracted a lot of interest [11]. In particular, numerous recent research
60 studies have focused on PV-TE hybridization [12]. Some have shown innovative ideas applying a similar
61 framework but using the Peltier effect instead of the Seebeck effect. In this case, the TE device operates in
62 refrigeration mode and cools down the PV instead of generating power [13]. There is another case where
63 both the Seebeck and Peltier effect are applied [14]. Many have shown prospects in larger scale such as
64 Shen et al., where several TEGs are combined with a PV panel, without using a dedicated thermal interface
65 [15]. Others have shown the potential in small-scale IoT applications with hybrid PV-TE devices. [16],
66 [17]. From the previous research studies, it is clear that the hybridization of PV and TEGs has huge
67 potential. However, one may wonder how this potential energy will be optimally harvested and converted
68 into electrical energy, as efficiently as possible.

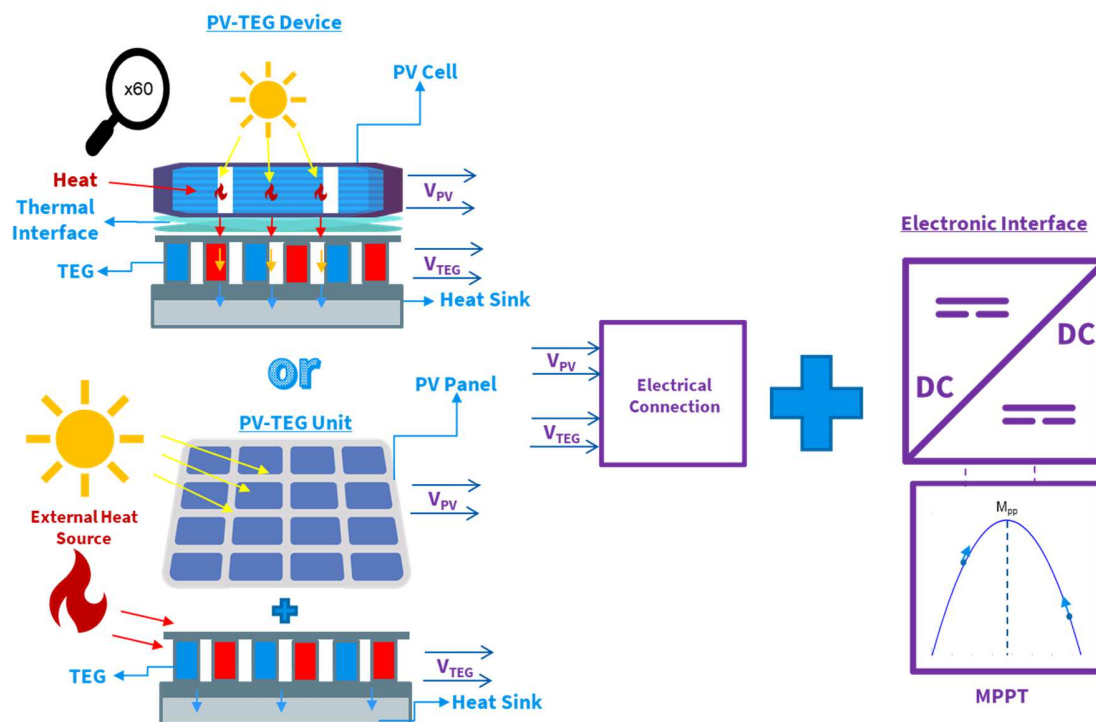


Figure 1: Hybrid PV-TE System Composed of the Energy Harvesting Device or Unit, Electrical Connection and Electronic Interface

69
70
71
72 Figure 1 illustrates the two possible hybridization of the PV and TE components. The hybridization does
73 not necessarily need to operate at a fixed scale, both large and small-scale energy harvesting are applicable.
74 The designs may also vary and incorporate different components. The so-called “PV-TE devices” include
75 both energy sources thermally coupled (PV cell and TEG), and a dedicated thermal interface. Therefore,
76 the entire area of the back side of PV cell can be utilized for heat transfer. However, the so called “PV-TE
77 unit” does not require a thermal interface as the PV and TEG are physically separated and thus, not
78 thermally coupled. The limitation of this is that the TEG must now be given an external heat source to be
79 of use. Based on studies, it seems that PV-TE devices are more targeted towards small-scale energy
80 harvesting while PV-TE units are steered more toward large-scale energy harvesting. One may assume that
81 this is due to the possibility to connect more TEGs in PV-TE units compared to the single TEG in a PV-TE
82 device. However, additional losses may be present for PV-TE units applying this methodology as there may
83 be additional connections linking the TEGs together.

84 To maintain clarity within the review, henceforth PV-TE units will refer to energy harvesting at a large-
85 scale and PV-TE devices will be associated to small-scale energy harvesting. In addition, we mention here
86 that the so called “Hybrid PV-TE system” in the following, is composed of the PV-TE energy harvesting
87 device or unit, the electrical connection and the electronic interface (see Figure 1).

88 What is clear from Figure 1 is that regardless of the nature of the considered PV-TE system (device or unit),
89 a specific electronic interface with maximum power point tracking (MPPT) capabilities is a necessity to
90 have an efficient energy harvesting system. Therefore, even though in the following the focus will be on
91 thermally coupled hybrid PV-TE devices for energy harvesting at a small-scale, many innovative theories
92 in terms of electrical connection and MPPT techniques developed for energy harvesting at a large-scale can
93 still be beneficial and will be also discussed in this review. Moreover, the research available for large-scale

94 harvesting is just as abundant compared to harvesting at a small-scale. For all these reasons, we thus believe
95 that this study can be very useful for research in the field of PV-TE energy harvesting at a small-scale or in
96 similar fields of research, like multi-source energy harvesting [18].

97 In this review, the main components of a hybrid PV-TE energy harvesting system will be briefly discussed
98 but emphasis will be placed on the electrical aspect of energy harvesting. This aspect has been neglected or
99 seldomly discussed upon, even in other review articles [19]. This review will highlight research that has
100 been carried out regarding electrical connections between the two sources (PV cell and TEG), and
101 maximum power harvesting (MPPT), as well as the electronic interface needed for optimal power
102 conversion and control. In addition, this review will discuss how the ideas proposed at large-scale from this
103 research could possibly be applied to thermally coupled PV-TE hybrid systems used in small-scale energy
104 harvesting, based on an integrated PV-TE device. To our current knowledge, there has not been a review
105 focusing on these topics.

106 The methodology in place for this review was to thoroughly review research within energy harvesting
107 hybridization with an emphasis on photovoltaics and thermoelectricity. A deeper analysis would take place
108 if there was any mention of an electronic interface, the electrical connection, or MPPT. After this final
109 analysis was complete and clear conclusions could be drawn, the review was made. The best effort was
110 made to research and include work from as many articles as possible, from various journals, within the
111 construction of this review.

112 2. PV-TE Hybridization

113
114 A possible solution for the electrical energy conversion of the intrinsic thermal losses in photovoltaic cells
115 lies in PV-TE hybridization. This PV-TE hybridization is comprised of photovoltaic cells and
116 thermoelectric generators integrated into a single energy-producing system. These systems can be classified
117 into two categories: i) hybridization based on spectrum splitting and ii) PV-TE hybrid devices [20], [21].

118 In spectrum splitting PV-TE electrical systems, the thermoelectric generator is combined with the PV
119 module using a solar beam splitter, forming a hybrid unit capable of absorbing a broad spectrum of solar
120 irradiance. The spectral beam splitter allows shorter wavelengths with sufficient photon energy to reach the
121 PV receiver, while directing the longer wavelengths with insufficient energy towards the TEG. The radiant
122 energy from the spectral splitter is used to generate a high heat flux for the thermoelectric device, thereby
123 improving the energy efficiency of the hybrid system [20]. In PV-TE hybrid devices, the TEG is merely
124 attached to the back side of the PV cell as depicted in Figure 2, utilizing the waste heat from the PV module
125 to produce energy.

126 In both types of technologies, other than increasing energy output, the coupling with a TEG acts as a cooling
127 system, lowering the operating temperature of the PV module, concurrently enhancing its efficiency [20],
128 [22], [23].

129

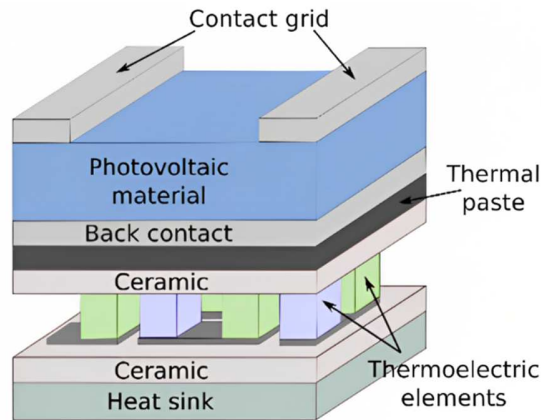


Figure 2: Schematic of a PV-TE Hybrid Device

130

131

132 In addition, much of the conducted theoretical and experimental investigations have demonstrated that
 133 using solar concentration technology increases the electrical power output of the PV-TE hybrid energy
 134 systems depending on the solar concentration ratio [24]–[26]. The experimental work by Yin et al. showed
 135 an 8.7 % improvement in the electrical power output of single junction GaAs-based PV-TE hybrid devices
 136 when the concentration ratio is increased from 120 to 255 [27].

137 Furthermore, the application of PV-TE hybrid devices has been extending to the relatively new types of PV
 138 technologies. Dye sensitized solar cells with a much lower production cost than silicon-based photovoltaics
 139 have been implemented in PV-TE hybrid devices [28], [29]. Regarding the promising perovskite materials,
 140 Lorenzi et al. demonstrated an efficiency gain over 3% by combining a perovskite solar cell with a TEG
 141 [30]. Studies have also proposed novel ideas for hybrid energy-producing devices with a focus on the
 142 electrical or thermal coupling mechanism between the PV and the TEG devices. Park et al. achieved lossless
 143 electrical coupling between the PV and TEG devices by matching the thermoelectric internal resistance to
 144 the PV internal resistance. The study showed approximately 30 % improvement in the efficiency of the PV
 145 device in the hybrid system, compared with the PV device alone [31].

146 Kim et al. focused more on the thermal coupling at the physical interface between the PV and the TEG. In
 147 their study, a high-performance monolithic PV-TE hybrid device is presented, integrating an acrylic film-
 148 based photothermal interface [32]. Zhang et al. removed the top part of a conventional TEG and replaced
 149 it with a thermal lubricant to enhance the heat transfer capabilities of the integrated PV-TE device [33].

150 Nevertheless, despite the technological progress achieved in PV-TE hybrid devices reported in previously
 151 mentioned studies, in-depth research on the electrical aspects of PV-TE hybrid systems is still lacking.
 152 Hybrid PV-TE systems are complex systems, and they incorporate multiple disciplines. Therefore, a study
 153 of the PV-TE system requires considering various disciplines which is often challenging for
 154 monodisciplinary oriented research. In the following, this study will focus on the types of electrical
 155 connection (between the PV cell and the TEG) and on the electronic interface and MPPT control. These
 156 areas that are usually neglected in research in the study of hybrid energy harvesting systems based on PV-
 157 TE devices. In the following sections, we will present an in-depth review of the possible types of electrical
 158 connection between the PV and the TEG and discuss the possible electronic interfaces as well.

159

3. Electrical Connection

While it is apparent that hybrid PV-TE systems have sparked extensive interest in research in the last decade, it can be stated that relatively less attention has been dedicated towards the electrical aspects of the hybrid systems. Most of the work done in research primarily focuses on the design of the PV-TE hybrid device, overlooking fundamental aspects such as the electronic interface and MPPT for energy harvesting in their study. However, a highly efficient PV-TE hybrid device is not of much benefit at system level if connected to an inefficient electronic interface or MPPT.

First, it is essential to determine the suitable mode of electrical connection and then, optimize the electronic interface for the most efficient transfer of electrical power to the load. In the following, we present a review of work on these electrical aspects of hybrid PV-TE systems, which to our knowledge has not been conducted before. This section focuses more in-depth on the various modes of electrical connection between the PV and the TEG in hybrid systems that are discussed in the research.

Three basic modes of electrical connection exist: parallel connection, series connection, and electrical isolation. As the isolated electrical connection is less commonly discussed compared to the series and parallel connection, an example of the connection can be seen in Figure 5 [28]. In this section, the three different configurations will be discussed in detail and their key advantages and drawbacks will be summed up in Table 1. The configurations can be classified based on the number of electrical wires used to connect the energy sources to the electronic interface(s). Thus, there are two-wire and four-wire connection modes. The series and parallel configurations fall under the two-wire connection mode, having both PV and TEG terminals interconnected. This implies that there is a single positive terminal and a single negative terminal for connection purposes. In the isolated configuration, because the PV and the TEG are electrically isolated, four wires are required to connect to the interface. This means that there will be two positive terminals and two negative terminals. One positive terminal and one negative terminal will be allocated for the PV and the other pair for the TEG.

The most common mode of electrical connection for both small-scale (case of PV-TE devices) and large-scale (case of PV-TE units) applications is the isolated configuration. We detail the preference in research for this connection mode in sub-section 3.3. There is also a wide application of the series connection although some gaps remain in research for this type of configuration as discussed later in section 3.2. The parallel mode is the least common connection mode applied in research partly because it has been newly studied, in comparison to the other two connection modes.

3.1 Parallel Connection

The parallel mode of connection is an uncommon electrical connection mode studied by Zhang et al., and it involves connecting the similarly charged terminals of the PV and the TEG together [34]. A schematic showing the connection between the two pairs of similarly charged terminals is depicted later, in Figure 9.

To our knowledge, there are very few applications of this parallel configuration in small-scale hybrid PV-TE systems that exist in studies. Truly, in this case, the PV and TEG parts require voltage matching exactly at the optimum operating point of the PV cell and TE elements to perform lossless hybridization [35], which is a major constraint. However, this connection mode has some major advantages that can be exploited for small-scale applications. One of them is that it allows the use of a single electronic interface and a single MPPT control.

Another feature of the parallel connection mode that may be fundamental in small-scale applications is the lower sensitivity of this configuration to the TEG internal resistance compared to the series connection. In

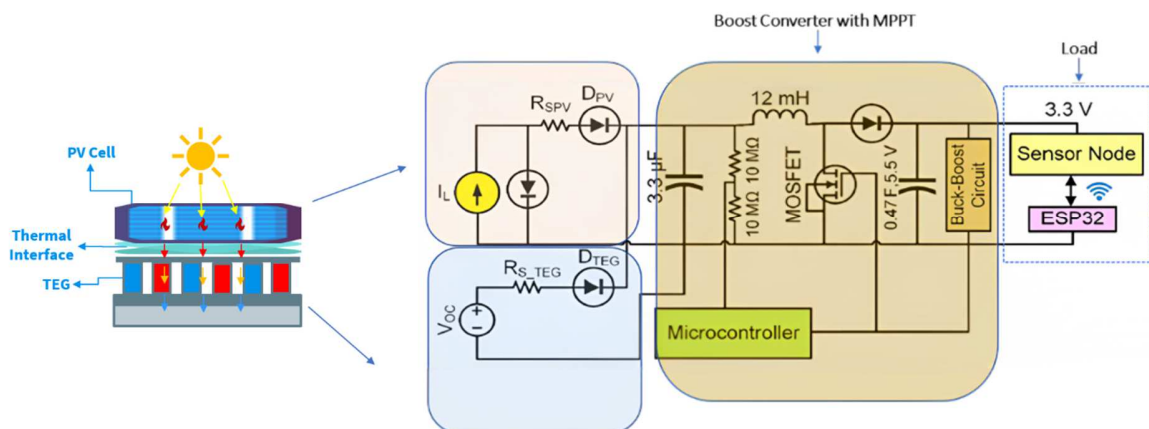
203 general, the TEG energy contribution in the hybrid energy device is significantly lower than the energy
 204 contribution of the PV cell. In the parallel connection, in large scale, because of low sensitivity to the TEG
 205 resistance, a larger number of TEGs can be attached to the PV panel backside and therefore, the TEG
 206 contribution is larger compared to the series connection. Furthermore, given that the electronic interface
 207 and the PV cell are optimized, the increase in the number of TEGs indicates that the parallel connection has
 208 the potential to produce more output power than the series connection [34].

209 However, the application of this configuration in small-scale applications can be limited by energy losses
 210 incurred as a result of PV and TEG voltage mismatches. Because the PV and the TEG are placed in parallel
 211 with each other, both the PV and TEG voltages must be constantly matched despite the changes in
 212 environmental parameter. As a matter of fact, achieving the voltage matching under fluctuating solar
 213 irradiance is a major challenge. Therefore, fluctuations in the solar irradiance are usually accompanied by
 214 high power losses.

215 According to studies conducted by Zhang et al. for a PV-TE hybrid unit, the output power in the parallel
 216 connection case was 33% lower than the series connected system, when the solar irradiance was reduced
 217 from 1000W/m² to 200W/m² at a constant temperature gradient. Unlike the parallel connection, the series
 218 connected PV-TE system, discussed in the following sub-section, depends more on the PV and TEG
 219 currents than their voltages and hence it is less affected by these fluctuations in the solar irradiance [34].

220 However, one of the innovative ways to minimize these power losses is by incorporating phase change
 221 materials in the PV-TE hybrid systems [36]. The phase change material reduces the fluctuations in the PV
 222 cell temperature and thus maintains the thermal operating conditions of the system almost constant.
 223 Therefore, in this scenario, the solar irradiance does not have a direct impact on the TEG voltage.

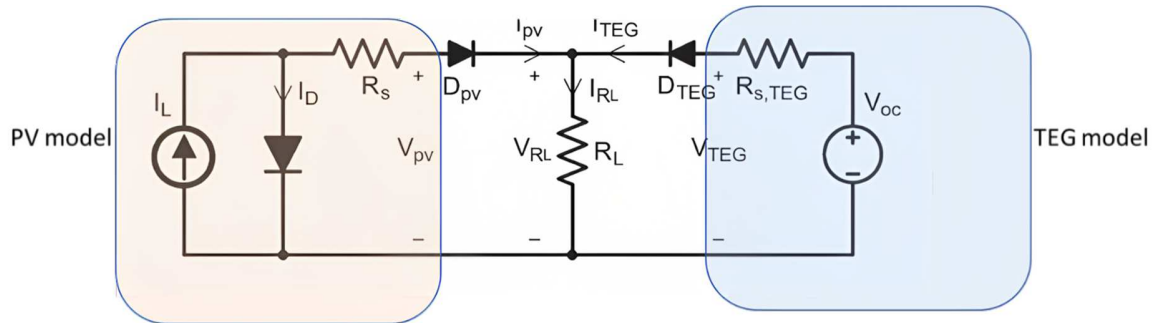
224 As stated, the parallel connection has not been extensively studied yet, especially in small-scale
 225 applications. However, there are a few relevant studies in which the parallel connection was implemented
 226 in the case of a hybrid PV-TE devices. One of the few notable innovations was proposed by Mishu et al.
 227 where a hybrid PV-TE device was used to power a network of wireless enabled sensors [16]. In this study,
 228 the parallel connection mode was chosen because it prevents the use of multiple electronic interfaces. The
 229 authors acknowledge that mismatches in the PV and TEG impedances can limit the performance of this
 230 hybrid unit. Figure 3 shows the electrical model and prototype of the hybrid device developed in this study.



231
 232 Figure 3: Model of the Ambient Based PV-TE Hybrid System as Proposed by Mishu et al.[16].

233 Tan et al. also implemented the parallel connection for a hybrid PV-TE system with a single electronic
 234 interface and MPPT circuit [37]. An ultra-low power fixed voltage reference method with very low power

235 losses was used. To ensure that there is maximum power transfer from the PV and the TEG to the load, a
 236 closed loop feedback voltage control was implemented. The power management circuit consisted of a boost
 237 converter with MPPT, control circuitry and a pulse width modulation (PWM). Figure 4 shows a schematic
 238 of the designed parallel connected PV-TE hybrid system proposed in this study. Tan et al. also acknowledge
 239 that the system has issues related to impedance mismatch caused by the parallel connection [37].



240

241

Figure 4: PV -TEG Hybrid System with a Parallel Connection as Proposed by Tan et al.[37]

242 3.2 Series Connection

243 Similar to the parallel connection, the series connection is a two-wire connection, as depicted later, in Figure
 244 8. As explained in section 3.1, the series connection is characterized by a high sensitivity to the TEG
 245 resistance unlike the parallel connection. As a consequence, series connected hybrid PV-TE devices usually
 246 consist of fewer thermoelectric elements, connected in series to form the TEG. Thus, it also means that the
 247 contribution of the TEG to the output electrical power is lower compared to the parallel connected PV-TE
 248 hybrid devices. Nonetheless, at large scale, the lower number of TEG legs attached to the backside of the
 249 PV improves the simplicity of the system, making it easier to assemble.

250 The series configuration is compatible with the use of a single circuit for the electronic interface, performing
 251 power conversion and optimization, which lowers the complexity and the overall cost of hybrid PV-TE
 252 systems. In the studies presented and discussed in the research, internal power losses in the series
 253 connection are considerably much lower than the losses observed in the parallel connection, precisely for
 254 hybrid PV-TE units exposed to fluctuating solar irradiance [34].

255 Clearly, the series connection mode is more common than the parallel connection for small-scale energy
 256 harvesting systems, based on PV-TE devices. The biggest knowledge gap that has limited the widespread
 257 implementation of this configuration is the unknown maximum power point of operation of the system
 258 when the PV and the TEG are placed directly in series with each other. Certainly, the electrical behaviour
 259 of a separated PV cell and TEG when exposed to solar irradiance and a temperature gradient respectively,
 260 is a subject that has been well and widely discussed in the research [31]. PV cells and TEGs each have a
 261 well-known maximum power point of operation and many techniques and algorithms have been studied to
 262 track these points of operation. However, when the PV cell and the TEG are placed in series with each
 263 other, the maximum power point of operation of such a hybrid configuration is still unclear.

264 To improve the development of the series connection mode in small-scale applications, several attempts
 265 have been made in studies to better understand the electrical behaviour of PV-TE series connected hybrid
 266 devices. In studies done by Park et al., the performance of a series connected hybrid device was analysed
 267 by varying the temperature gradient across the TEG [38], [39]. The results of this study demonstrated an
 268 improvement in the output electrical power of the hybrid device compared to isolated PV cells, as high as
 269 6.7 %.

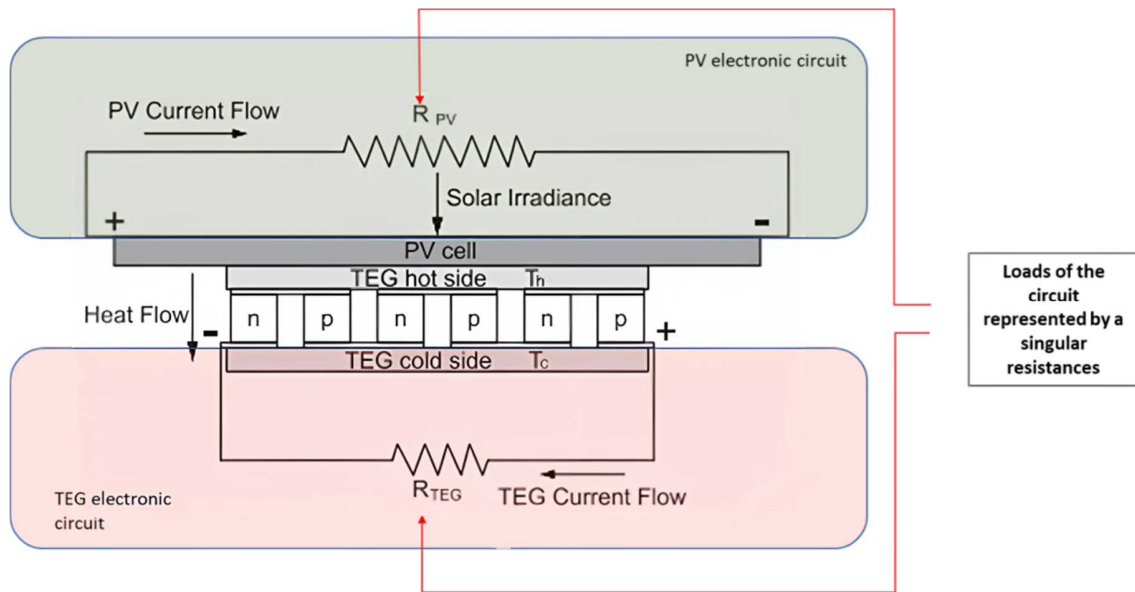
270 Furthermore, the small-scale application of the series configuration has been partly limited by the energy
 271 losses incurred when current mismatches occur between the PV cell and the TEG. A major loss occurs due
 272 to the voltage drop that takes place across the internal resistance of the TEG. Moreover, as the same current
 273 crosses the PV and TEG devices, it is difficult for both sources to reach their maximum power point of
 274 operation simultaneously. The increase in PV current increases the energy losses due to the TEG resistance
 275 and hence, the TEG acts as a mere voltage drop, if the TEG generated voltage is not large enough (case of
 276 a small thermal gradient across the TEG). Therefore, the electrical power output of such a configuration
 277 can be lower at higher solar irradiances, compared to PV alone [34].

278 3.3 Isolated Sources

279 The electrical connection mode commonly used in both small-scale and large-scale applications is the
 280 isolated configuration. In the isolated configuration, each of the PV and TEG sources has its own separate
 281 electronic interface and power optimization circuit for MPPT. Besides having separate electronic interfaces
 282 for the PV and the TEG, the electrical loads can be either isolated or shared between the two sources. An
 283 illustration of the isolated configuration is shown in Figure 5.

284 One of the major advantages of the isolated configuration is that conventional MPPT algorithms can be
 285 used, for the PV and the TEG as well. Nevertheless, using two separate electronic interfaces has its own
 286 disadvantages pertaining to the costs of the system and to the power losses due to the additional power
 287 converter [33]. Despite the electrical isolation of the two energy sources, a highly efficient thermal coupling
 288 between PV and TEG sources in the hybrid device must be maintained to facilitate effective heat transfer
 289 from the backside of the PV to the TEG.

290 Thus, electrically separating the PV and the TEG has some advantages over the series and parallel
 291 connections. Besides the easier design of energy harvesting electronic interfaces (if classical and separate
 292 electronic interfaces are implemented), this configuration minimizes power losses caused by voltage and
 293 current mismatches. Therefore, the isolated system is more flexible contrary to the other methods in the
 294 sense that the electrical features of the two energy sources are independent from each other. In other words,
 295 the distinction between the electrical features of the two sources does not alter the performance of the PV-
 296 TE hybrid system.



297
 298 Figure 5: Schematic of the Isolated Configuration in PV-TE devices [28]

299 Thus, one can say that the isolated configuration has formed the basis of energy harvesting and MPPT
 300 circuit design for PV-TE hybrid energy systems. Innovative designs focusing on energy harvesting and
 301 MPPT for the isolated mode have been proposed. Zhang et al. proposed a time multiplexed energy
 302 harvesting circuit with high efficiency and small volume [40]. In this study, a single electronic circuit is
 303 time-shared to extract power from both PV and TEG sources. Moreover, the use of a single, multiple input
 304 DC-DC converter for the isolated PV and TEG has also been proposed in research [41]. This innovation
 305 has the potential to reduce the gap between the four-wire mode and the two-wire mode in terms of system
 306 costs. One can think that the use of a single electronic circuit reduces power losses, although it has not been
 307 discussed and validated in the mentioned studies.

308 The isolated configuration is quite useful in large-scale hybrid PV-TE applications where the PV and the
 309 TEG are not integrated together. In these cases, the PV and the TEG are separated from each other and an
 310 external heat source is used to drive the TEG. A classic example of such an application is the dual harvesting
 311 of PV power and waste heat from exhaust to form a hybrid energy harvesting unit. Innovative designs have
 312 been proposed for energy harvesting in such system [42], [43]. A review of the different electronic
 313 interfaces for control and MPPT proposed in research will be discussed in detail in section 4.

314

315

Table 1: Summary of Key Advantages and Disadvantages of the Studied Electrical Connections

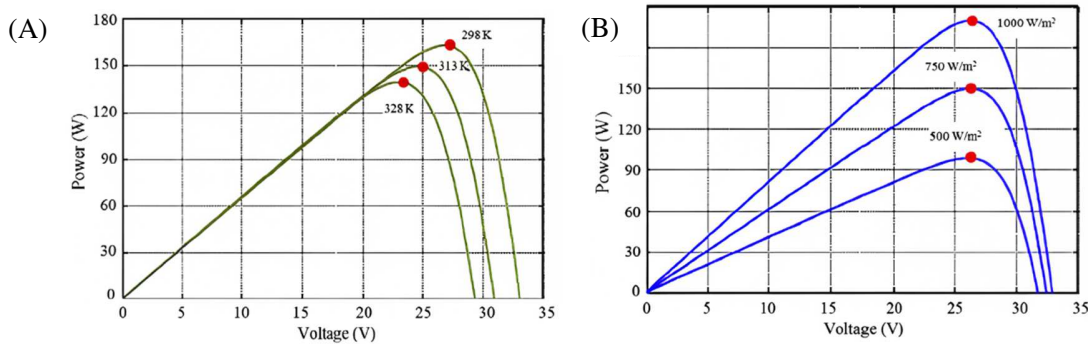
Electrical Connection	Key Advantages	Key Disadvantages
Parallel	<ul style="list-style-type: none"> • Requires a single electronic interface. • Lower sensitivity to TEG resistance. 	<ul style="list-style-type: none"> • High complexity due to possible voltage mismatches. • Lower output power compared to other configurations. • Higher sensitivity to fluctuations of solar irradiance.
Series	<ul style="list-style-type: none"> • Requires a single electronic interface. 	<ul style="list-style-type: none"> • Significant voltage drop across the TEG internal resistance. • Custom electronic interface required to accommodate both TEG and PV characteristics.
Isolated	<ul style="list-style-type: none"> • Conventional MPPT algorithms can be applied. • Power losses are minimized due to dedicated electronic interface for each source. 	<ul style="list-style-type: none"> • More components required if two separate electronic interfaces are implemented. • Higher cost.

316

317 **4. Electronic Interfaces for Control and MPPT**

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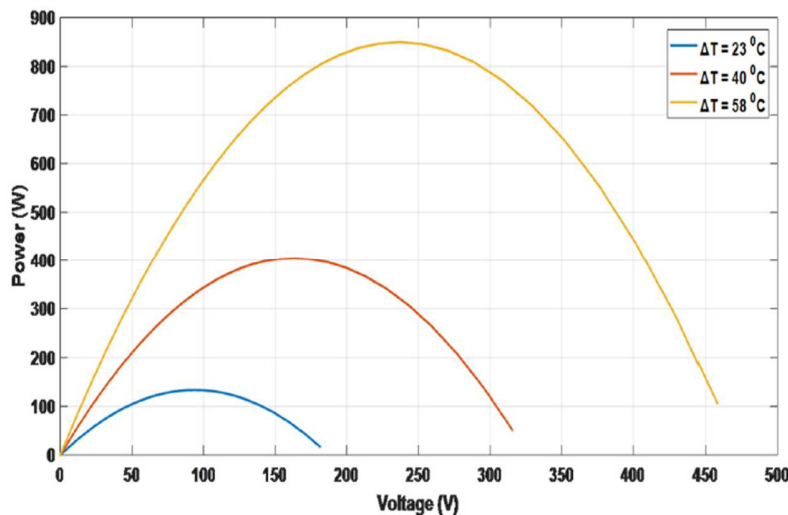
319 To fully maximize the potential of PV-TE hybrid devices or units, energy extraction must take place at the
320 system's maximum power point (MPP). The difficulty surrounding this topic is that external conditions
321 such as irradiance and temperature, which fluctuate, have a significant influence on the maximum power
322 point [44]. Furthermore, the PV and TEG have their own unique characteristics. Figure 6 illustrates how
323 the maximum power point (MPP) of a typical 200 Watt panel changes with temperature (Figure 6A) and
324 irradiance (Figure 6B) in case of photovoltaics [45]. The MPP shifts to the left with an increase of
325 temperature and shifts downward as irradiance reduces.



326

327 Figure 6: Variation of MPP for PVs with the Change of (A) Temperature and (B) Irradiance, extracted from [45]

328 In case of TEGs, the magnitude of the temperature gradient has a significant effect on the characteristic
329 curves of TEGs. This, in turn, changes the location of the maximum power point. Figure 7 demonstrates
330 the evolution of the TEG characteristic curve when the temperature gradient varies and the corresponding
331 effect on the maximum power point [46].



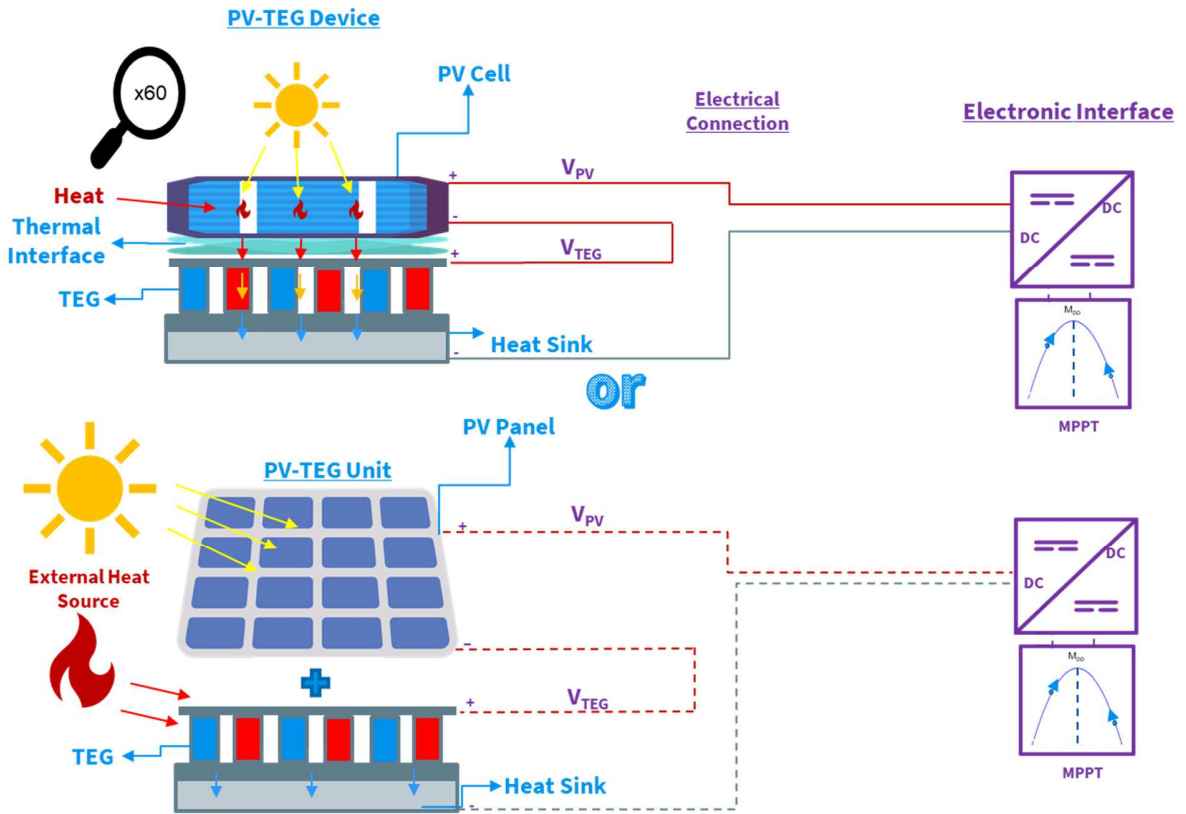
332

333 Figure 7: The Change of MPP with the Adjustment of the Temperature Gradients, Extracted from [46]

334 Many different MPPT techniques and algorithms have been developed and applied to both PVs [45] and
335 TEGs [46]. They consist of well-known algorithms which are controlled and operated by various electronic
336 circuits [44], [47]–[50]. How are these techniques and electronic circuits modified for hybrid PV-TE
337 devices? Does it depend on the mode of connections of the PV and TEG sources? The research conducted

338 in this area will be examined and segregated hereafter in four different categories, (1) sources in series, (2)
 339 sources in parallel, (3) isolated sources with their own converter, and finally (4) isolated sources with a
 340 single shared-converter.

341 **4.1 Sources in Series**



342
 343 Figure 8: Hybrid PV-TE Representation for Sources in Series

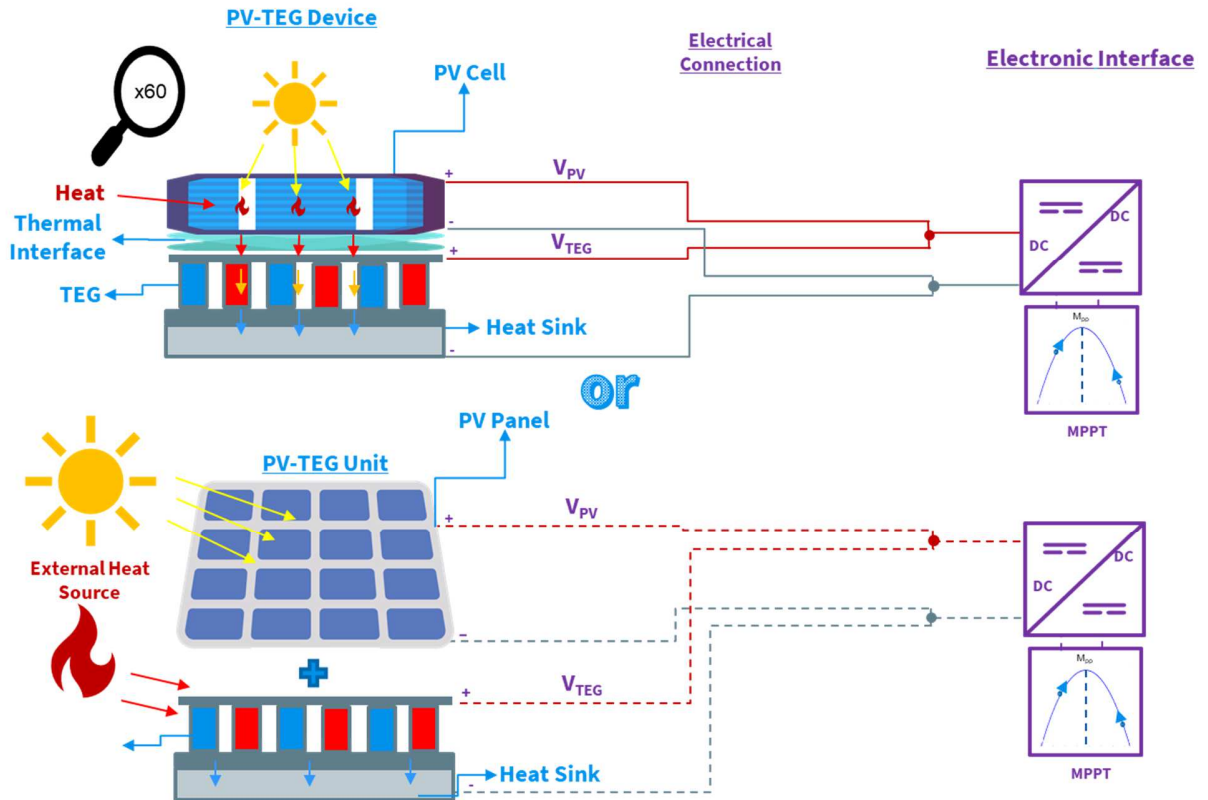
344 To our current knowledge, few research studies have been focused on the MPP of sources connected in
 345 series. Papers [38], [39] applying a series connection between the PV and TEG do not clearly mention the
 346 MPPT methodology used, or the electronic circuit used to apply the necessary control. They are mostly
 347 focused on the hybrid PV-TE device alone (and in particular on the thermal interface between the PV and
 348 TEG) and authors have not considered the system point of view, neither the electronic interface for MPPT.
 349 Only few research articles pinpoint the maximum power point using numerical methods, or experimentally
 350 such as Park et al. in [31] and Park et al. in [38].

351 The research conducted by Zhang and Xuan regarding the comparison between a parallel and series
 352 connection for hybrid PV-TE devices shows more insight towards MPPT for a series connection [34]. A
 353 series connection would require just one electronic interface circuit but may lead to more complexities such
 354 as mismatching of electrical features between the PV and TEG. The MPPT method applied was the perturb-
 355 and-observe method (P&O). The electronics used to employ this technique was the IAP15W4K58S4 single
 356 chip microcomputer [34].

357 This shows that conventional algorithms such as P&O can still be applied for MPPT in series connection
 358 as well as commercially available controllers [34]. Unfortunately, this method will still not extract the

359 maximum power that could be extracted if the sources were electrically separated due to the differences in
 360 the electrical characteristics between the PV and TEG sources. Undeniably, as the PV and TEG are in series,
 361 they will influence each other electrically.

362 4.2 Sources in Parallel



363
 364 Figure 9: Hybrid PV-TE Representation for Sources in Parallel

365 Similar to the series connection, based on the studies available, there is not abundant research focused on
 366 the MPP of sources connected in parallel. This lack of interest could be due to the lower output electrical
 367 power of the parallel connection compared to other connections [34]. Fortunately, one detailed paper
 368 describing the electronics involved and the MPPT technique employed was found and will be elaborated
 369 upon [37]. Tan et al. employed a parallel configuration considering small-scale applications meant for
 370 power electronics, which is more in line with the desired application field for this study. Their electronic
 371 interface and energy management circuit are composed of three main building blocks, a boost converter
 372 with MPPT and PWM for the control mechanism, supercapacitors acting as the storage element, and a
 373 regulating buck converter to provide constant voltage to wireless sensor nodes or other loads. Figure 10
 374 showcases this architecture.

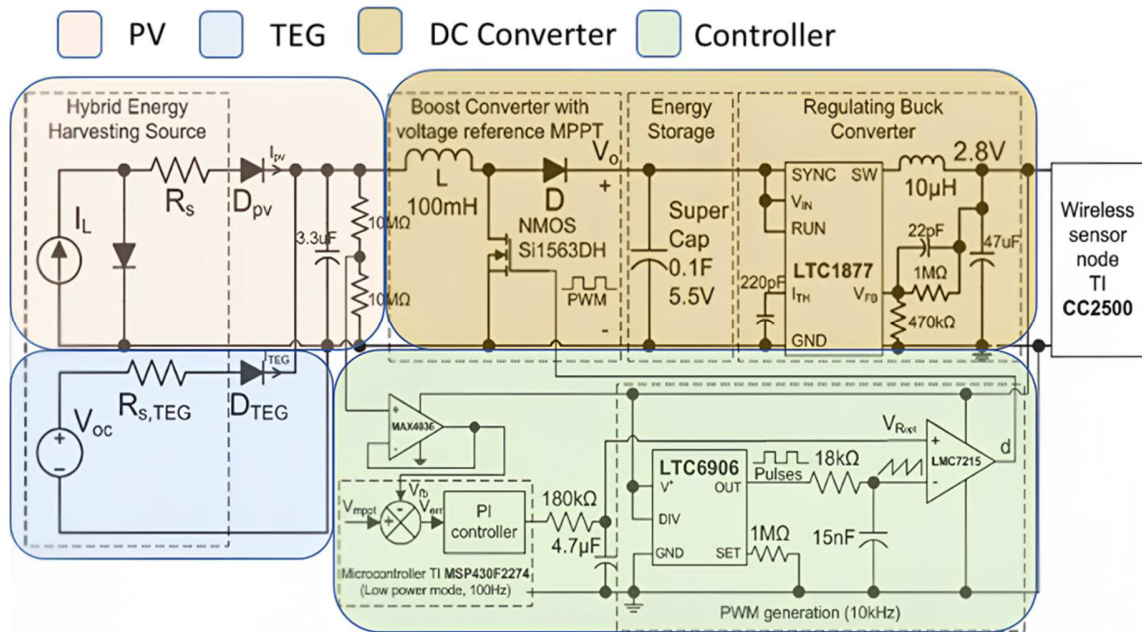


Figure 10 : Energy Harvesting System Proposed by Tan et al. [37]

375
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377 The operation of the boost converter was based on the MPPT reference voltage signal which was compared
378 with the feedback voltage signal from the output of the hybrid energy harvester. The resultant error signal
379 was passed through a proportional integral controller (PI) which was embedded with a Texas Instruments
380 microcontroller (TI MSP430F2274) to produce a low frequency (PWM) signal meant to control the boost
381 converter. The lower clock speed of the TI microcontroller substantially reduced the power consumption
382 of the system.

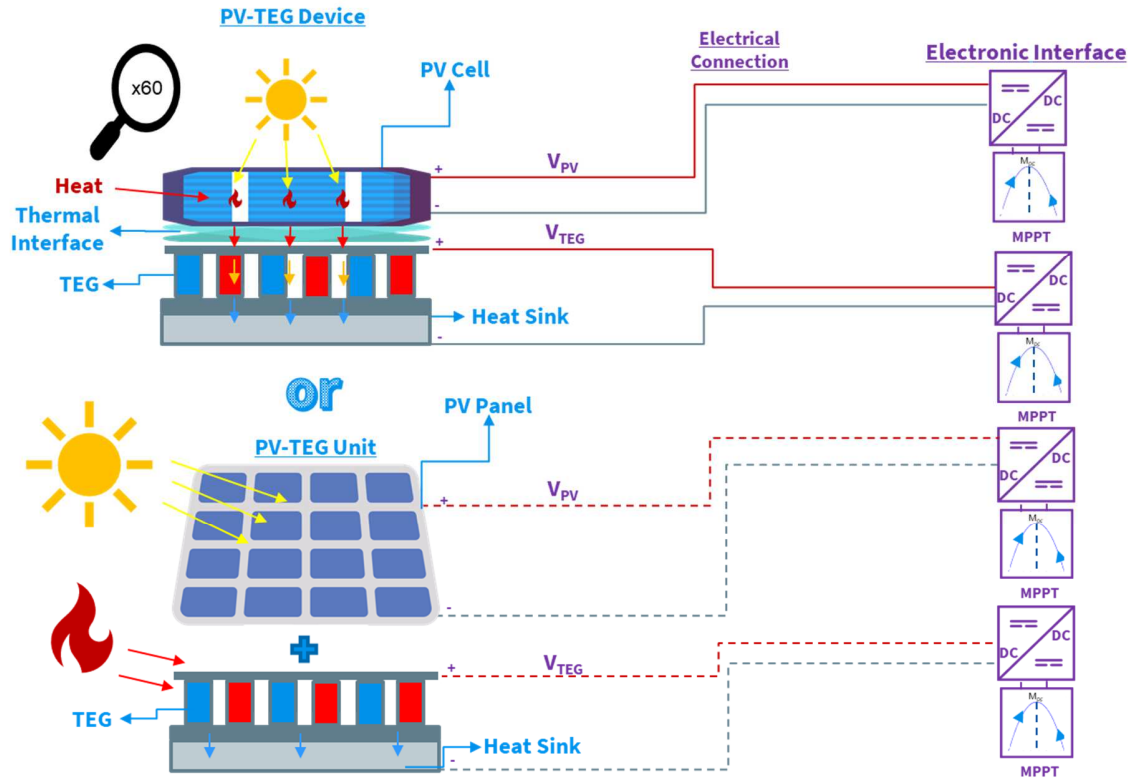
383 To maintain the compact size of the hybrid system, smaller passive components must be used. To facilitate
384 this, the low frequency PWM control signal generated is transformed to a higher switching frequency. This
385 is accomplished by using a low power PWM generation circuit composed of a precision programmable
386 oscillator (LTC6906), necessary to produce sawtooth waves, and a CMOS comparator (LMC7215). The
387 low frequency PWM signal which represented the MPPT reference voltage was first filtered by a low-pass
388 filter and the subsequent DC signal was compared with the sawtooth signal. This was done to generate the
389 duty cycle of the high frequency PWM control signal meant for the control of the boost converter [37].

390 The supercapacitor was utilized to provide energy in a short period of time, when conditions were not
391 favorable for rapid power generation through the PV or TEG sources which was likely due to the indoor
392 environment of the study. The last building block consisted of a switched-mode voltage regulator
393 (LTC1877), placed after the supercapacitor, to provide a consistent operating voltage to power the wireless
394 sensor node or any other electronic circuit with similar characteristics [37].

395 The design proposed by Tan et al. is ideal for small-scale energy harvesting and thus may benefit the IoT
396 sector. The paper provided detailed information regarding the management circuit as well as the MPPT
397 strategy which is normally lacking in similar papers. However, the indoor environment may limit the
398 capabilities of the implemented management scheme. To overcome that limitation, the sources could be
399 thermally coupled with a thermal interface to make the most out of the incident irradiance. Nevertheless, it
400 showcases the possibility to implement an electronic interface focused on energy harvesting at a smaller
401 scale.

402 For research to progress, challenges related to the electrical matching of the energy sources in parallel must
 403 be resolved. Tan et al. also raise the possibility of impedance mismatch [37] which reinforces the parallel
 404 connection issues. Like the series connection, the electrical influence of the interaction of both sources must
 405 be considered to properly control the electronic converter to achieve maximum power extraction.

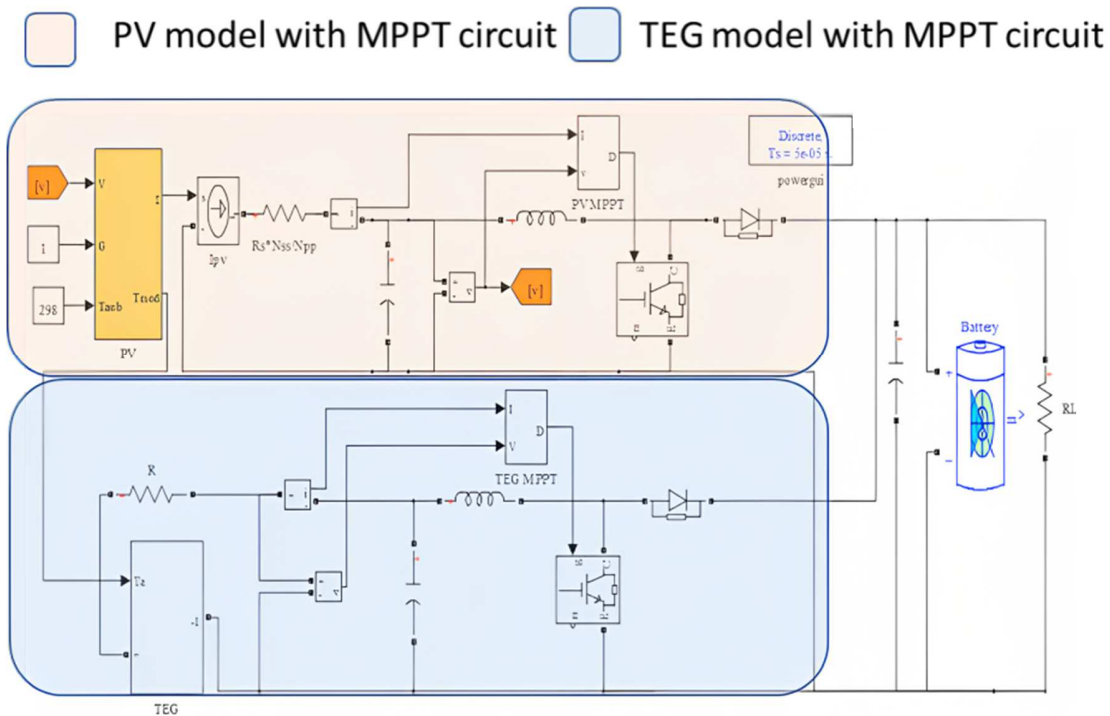
406 **4.3 Isolated Sources with their Own Converters**



407
 408 Figure 11: Hybrid PV-TE Representation for Electrically Isolated Sources

409 As mentioned previously, using two sources with their own MPPT control or their own dedicated electronic
 410 converter may increase the system cost as more components would be required. Nevertheless, the benefits
 411 of this configuration cannot be overlooked. Since each source has its own dedicated MPPT system,
 412 conventional techniques can be easily applied and achieve great results. In this section, we highlight some
 413 of the related research [15], [51].

414 Verma et al. [51] presented models (in the Matlab/Simulink environment) for not only an energy harvesting
 415 PV-TE hybrid system but also for MPPT in standalone PV and TEG systems at large scale. In case of the
 416 MPPT algorithm implemented for the PV, the classical P&O method was used, based on the output voltage
 417 of the PV source. They also explain the significance of the boost converter and provide guidelines to size
 418 the necessary inductors and capacitors. Verma et al. [51] also detailed the MPPT control designed for the
 419 TEG, using the P&O method but based on the TEG current. The DC-DC converter was constructed on the
 420 same basis as the sole PV system. Figure 12 shows the integration of both systems to form the hybrid PV-
 421 TE unit. A battery is incorporated in the model to prevent any power shortage.



422

423

Figure 12: Developed Mathematical Model for PV-TE Hybrid System proposed by Verma et al. [51]

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429

Verma et al. [51] have applied specific parameters in their models to successfully emulate commercially available PVs and TEGs, namely the MAX60 solar cell and the Be_2Te_3 semiconductor for the TEG [51]. It can be observed that since each source has its own dedicated MPPT controller, the number of components required is substantial, at least for small-scale energy harvesting. However, the power losses may restrict the capability of powering devices designed with a capacity of a few Watts, such as IoT nodes. The design proposed by Verma et al. might be more suitable for large-scale grid-connected applications [47]–[51].

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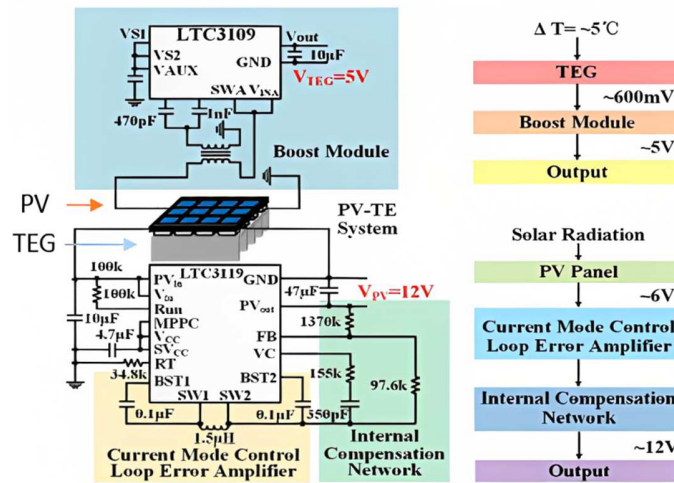
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438

Shen et al. [15] utilized a similar topology by applying commercially available converters. To produce their stable voltage-conversion circuit based on positive feedback amplification, they integrated the commercial buck-boost converters LTC3119 and the Ultralow Voltage Step-Up Converter and Power Manager LTC3109, for the TEG and PV sources, respectively (see Figure 13). The output voltages obtained were 5V for the TEG and 12V for the PV. They also exhibited the actual printed circuit board (PCB), experimental setup, and the results. They applied an average current mode modulation in their designed compensation network current loop. The internal current mode control loop error was compared with the detected average inductor current and drove the average inductor current to cycle between the SW1 and SW2 pins (see Figure 13) [15].

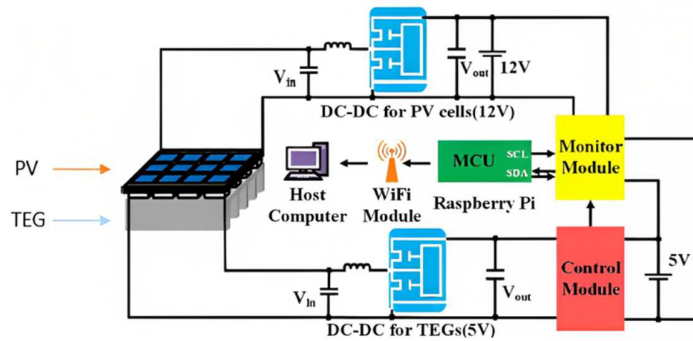


439

440

Figure 13: Compensation Network using Average Current Mode Modulation Proposed by Shen et al. [15]

441 Thus, Shen et al. [15] proposed a very intuitive control and monitoring system. The energy generated by
 442 the PV would be supplied to a battery pack while the energy generated by the TEG would be used to power
 443 the control and monitoring system. The strategy applied was an intelligent power-track switching technique
 444 and was embedded into the control module to control the direction of current generated by the TEG. When
 445 the control module is powered on, the monitoring system is activated and checks the entire system. When
 446 it is powered off, the current is transferred to battery packs thus minimizing energy expenditure. To achieve
 447 high-precision timing and measurement, the monolithic timing circuit TLC555 and the INA19 chip were
 448 combined with the control and monitoring circuit. Raspberry Pi was used to establish communication
 449 between the monitoring module. Figure 14 illustrates the control and monitoring strategy [15].



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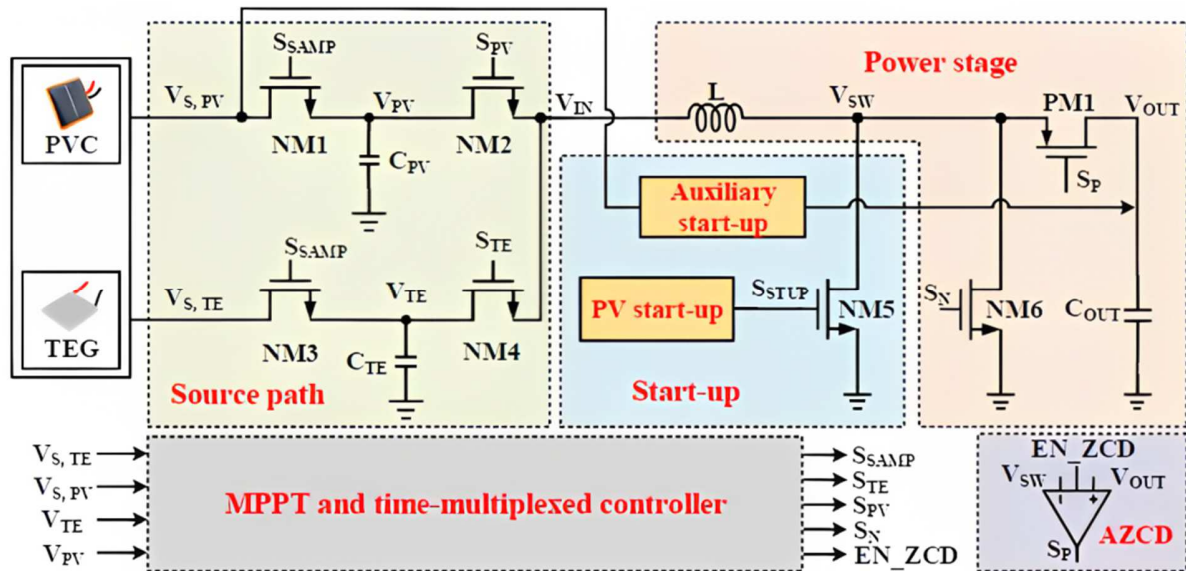
Figure 14: Control and Monitoring Strategy Proposed by Shen et al. [15]

452 Shen et al. utilized both sources well and provided a unique way of making use of the power produced by
 453 the TEG. One could add a dedicated thermal interface between the PV and the TEG which may harness
 454 more heat compared to just a concentrator, as proposed by [24]–[27], [36]. Another way to improve the
 455 design may be to provide some sort of redundancy. For example, if the TEG is damaged then the control
 456 and monitoring system would not have a continuous power source as the battery pack would eventually
 457 fully discharge. Like Verma et al. [51], the design proposed by Shen et al. may contain too many
 458 components for small-scale energy harvesting but the experimental results show great potential and might
 459 help generate novel ideas for energy harvesting with hybrid PV-TE devices.

460 **4.4 Isolated Sources with a Single-Shared Converter**

461 We have just seen systems where a converter or entire MPPT system was dedicated toward each source.
 462 As mentioned earlier, this type of topology may not be most suitable for small-scale implantation due to
 463 the large number of required components. As it will be discussed in this section, in order to reduce the
 464 number of components, research has been carried out to develop an electronic interface with a single
 465 converter to be shared by the two sources. These specific electronic interfaces also apply very distinctive
 466 types of maximum power point tracking, which will be discussed in this section.

467 Liu et al. [52] proposed a topology that utilized the single inductor approach to reduce the number of
 468 components. Figure 15 displays the proposed architecture for the electronic interface. The power stage
 469 includes a single boost converter. The start-up circuit is responsible for starting the interface circuit without
 470 any external influence. The MPPT and time-multiplexed (TM) controller determine the states of the
 471 switches. S_{AMP} is 0 when the open circuit voltages of the TEG or the PV are sampled, otherwise it has a
 472 value of 1. The PV is harvested when S_{PV} is 1 while S_{TE} is 0 and vice versa when energy is harvested from
 473 the TEG. With the adjustment of S_N or the period, the MPPT and time-multiplexing enable the interface to
 474 harvest energy at the MPP. The accurate zero current detector (AZCD) was used to improve the power
 475 conversion efficiency [52].

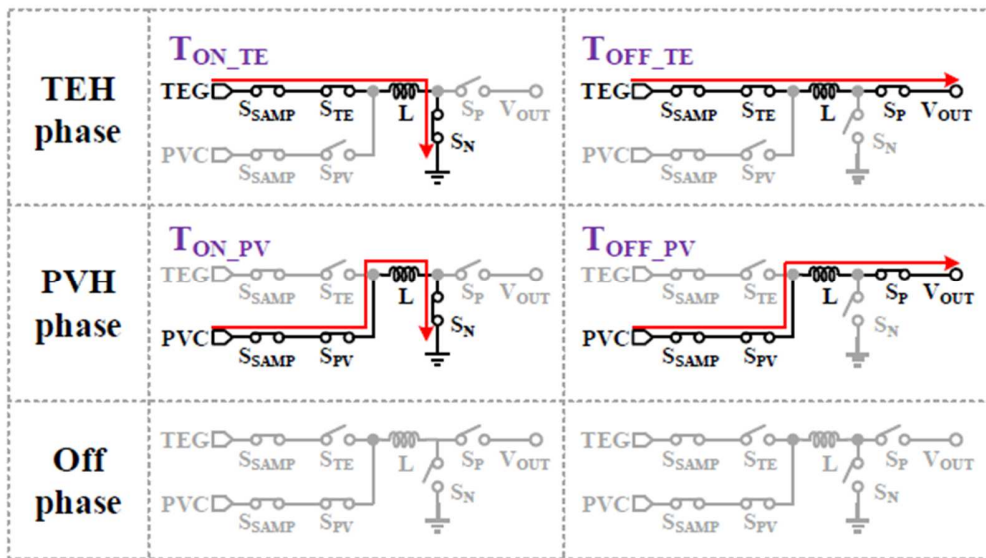


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Figure 15: Block Diagram of Proposed Electronic Interface proposed by Liu et al. [52]

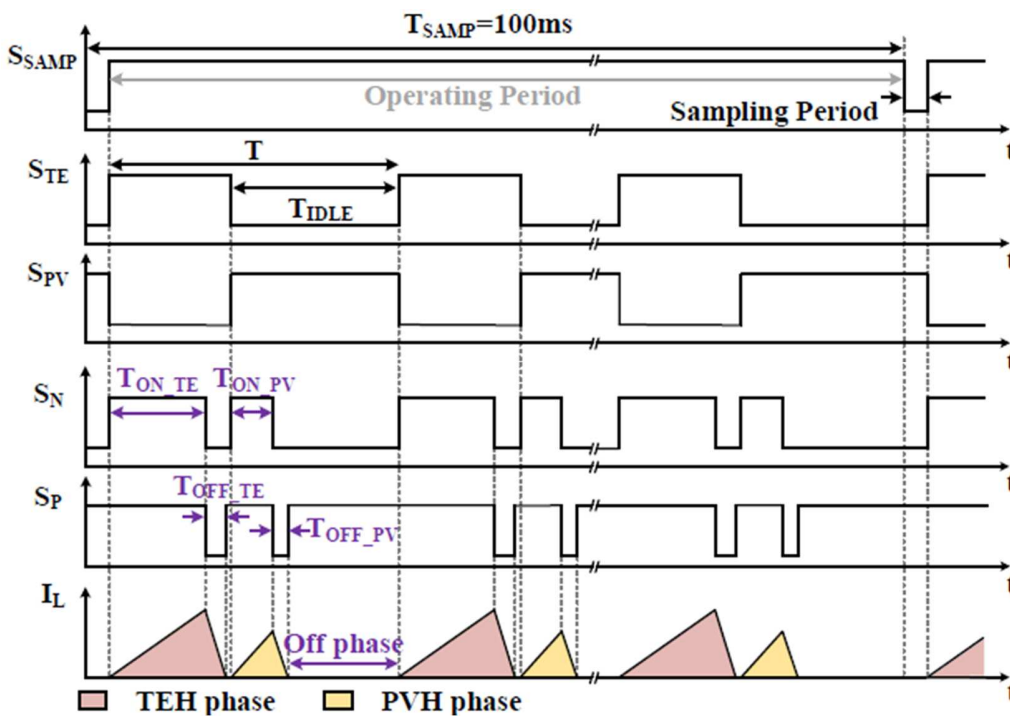
478 Thus, the various switch configurations in the paper of Liu et al. [52] allowed energy to be harvested from
 479 the different sources. Figure 16 shows different configurations possible: when the TEG is the energy source,
 480 when the PV is the energy source, and when the open circuit voltages are sampled (off-phase). Figure 17
 481 displays the corresponding timing diagram, exhibiting the output waveforms.



482

483

Figure 16: Switch Configurations and Power Pathways in the electronic interface proposed by Liu et al. [52]



484

485

Figure 17: Timing Diagram Waveforms for the electronic interface proposed by Liu et al.[52]

486 The MPPT and TM controller were composed of two sample and hold circuits (S&H1 and S&H2), two
 487 comparators (CMP1 and CMP2), two 5-bit counters (where Q_{A1} - Q_{E1} and Q_{A2} - Q_{E2} are the binary outputs
 488 from counter one and counter two respectively) a TEG conduction time generator TCG, a PV conduction
 489 time generator, and finally a logic processing circuit. The MPPT circuit allowed the optimal operating point
 490 to be found, thus resulting in the maximum output of the source. Figure 18 displays the layout of the control
 491 circuit [48].

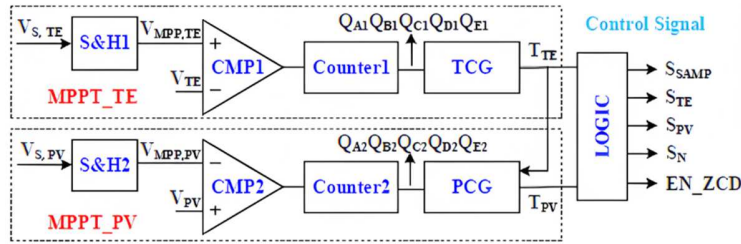
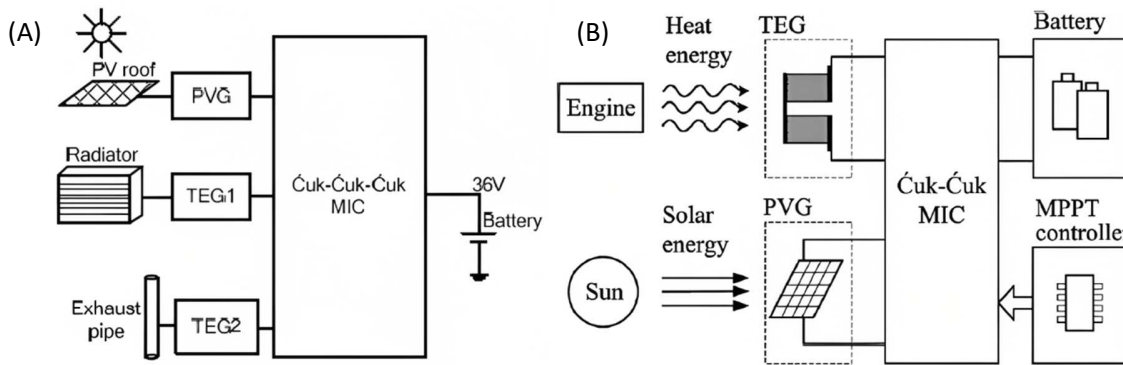


Figure 18: Layout of MPPT and TM Controller proposed by Liu. et al.[52]

492
493

494 In the same spirit, Zhang and Liu [40] proposed a nearly identical system and applied the same MPPT
 495 methodology. A few differences between Liu et al. and Zhang and Liu were that the latter showed the
 496 connections with the control circuit while Liu et al. provided more details of each block presented in their
 497 block diagram. There was more elaboration present in Liu et al. regarding the electronics involved and
 498 operation of their proposed electronic interface. Both designs utilized a well-known MPPT approach
 499 utilizing the fractional open circuit values of the TEG and PV, limiting the complexity of the interface.
 500 However, a possible anomaly may be found in the timing diagram shown in Figure 17. It can be observed
 501 that harvesting from the TEG occurs longer than that of the PV which is odd considering that the PV is the
 502 more efficient device. One could attribute this anomaly to the use of a large TEG for the energy harvesting.
 503 More explanation regarding this phenomenon could help provide more clarity.

504 Ideas for energy harvesting at a small-scale can also come from systems designed for applications at a much
 505 larger scale. For instance, Fan et al. [42] and Zhang and Chau [43] both developed hybrid energy units
 506 using multiple input converters intended for the automotive industry. Zhang and Chau intended to harvest
 507 from two sources while Fan et al. designed the system to harvest from three sources with an extra TEG.



508
509

Figure 19: Comparisons of two designs with multiple input converters proposed by: (A) Fan et al.[42] (B) Zhang and Chau [43]

510 The electronic components used in both designs being nearly identical, we chose to explain the operation
 511 based on Fan et al. [42]. The different operating modes of the electronic circuit (multiple input converter
 512 (MIC) in Figure 19) are briefly summarized and illustrated by Figure 20 (B).

513 In mode one, the power switch S (S_1 - S_3) is turned on. The voltage source u_s (PV, TEG1 and TEG2) charges
 514 the inductor L_s (L_1 - L_3). The capacitor C_s (C_1 - C_3) creates a path for the output current I_o and the energy
 515 stored in the capacitor is released. Due to the voltage of the capacitor, the diode D (D_1 - D_3) is reverse biased
 516 and is represented by an open circuit.

517 In mode two, the power switch S (S_1 - S_3) is turned on and the voltage source (PV, TEG1 and TEG2)
 518 continues to charge the inductor L_s (L_1 - L_3). The energy of the capacitor C_s (C_1 - C_3) has been fully discharged

519 at this point, so the voltage V_c decreases to zero. The diode D (D_1 - D_3) provides a pathway for the output
 520 current I_o .

521 Finally, in case of mode 3, the switch S (S_1 - S_3) is turned off. Both voltage sources (PV, TEG1 and TEG2)
 522 and the inductor charge the capacitor C_s (C_1 - C_3) and increases the voltage across the capacitor C_s (C_1 - C_3).
 523 The diode D (D_1 - D_3) provides a path for both the inductor current I_{L_s} (I_{L1} - I_{L3}) and the output current I_o .

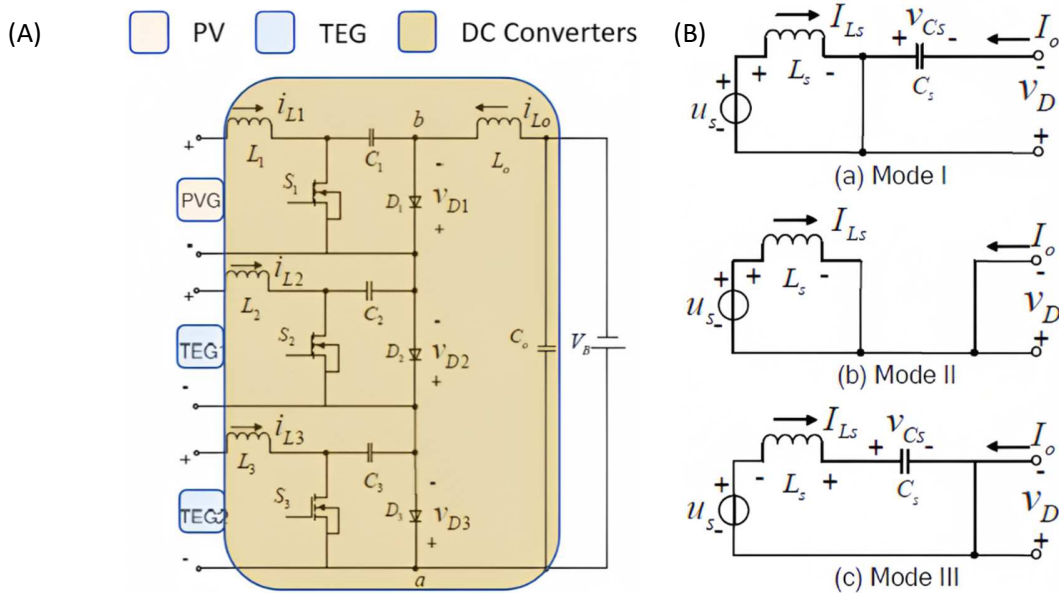


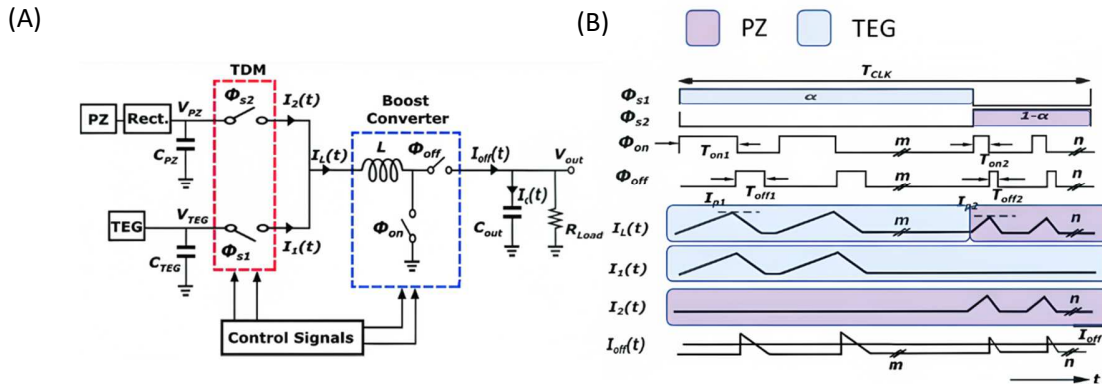
Figure 20: (A) Ćuk-Ćuk-Ćuk MIC proposed by Fan et al. with (B) Conduction Modes [42]

526 Concerning the MPPT for the depicted electronic circuit, both Fan et al. and Zhang and Chau designs used
 527 the P&O algorithm, by adjusting the duty ratio of the switches' control at a fixed switching period. Due to
 528 the independent nature of the MIC, the switches can be triggered both synchronously and asynchronously
 529 [42]. This allows for greater flexibility of the system.

530 The proposed systems were tested at both simulation and experimental levels on a 100 W experimental
 531 board. Furthermore, the authors claimed that the proposed system has the potential to be used in larger
 532 power systems (up to 1 kW), similar to the ones present in the automotive industry.

533 In these PV-TE systems, the integration of a thermal interface between the PV and TEG is not relevant nor
 534 possible as the PV would be placed on the roof of the vehicle and the TEG near the exhaust. This makes it
 535 quite difficult to employ the proposed designs for energy harvesting at small-scale. However, these studies
 536 still demonstrate ways to create more compact designs. It also shows the possibility of asynchronous control
 537 and of flexibility in the MPPT of hybrid devices based on PV and TEG sources.

538 Lastly, Yehia et al. proposed a very insightful energy harvesting system using TDM (Time Division
 539 Multiplexing) with a dynamic MPPT controlled by a global duty factor (known in the paper as a TDM
 540 factor) [53]. Figure 21A shows a representation of the proposed system.



541

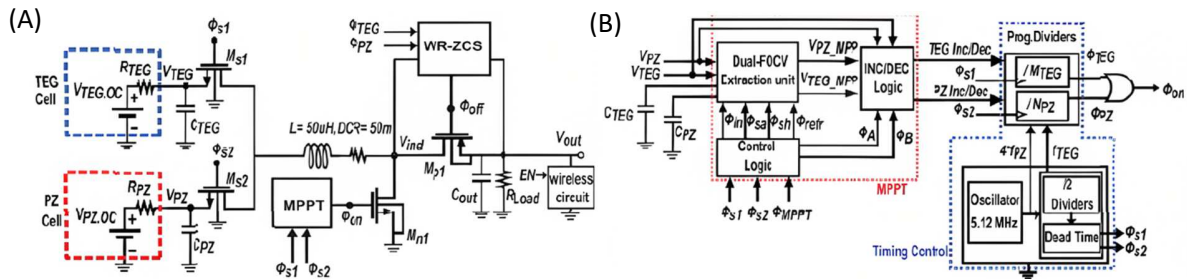
542

Figure 21: (A) Energy Harvesting System proposed by Yehia et al. with (B) corresponding Timing Diagram [53]

543 In this case, two energy sources are considered: a TEG and a piezoelectric (PZ) transducer. This paper is
 544 of interest in the review as the idea used for the rectified PZ (Figure 21A) can be applied to a PV or TEG.
 545 The capacitors C_{TEG} and C_{PZ} were used to smoothen operating voltages while C_{out} was used to produce a
 546 stabilized DC output voltage. TDM was applied to merge the harvested energy at the output load by
 547 periodically switching between the TEG and the PZ. V_{TEG} and V_{PZ} were the voltages stored across C_{TEG}
 548 and C_{PZ} correspondingly. ϕ_{s1} and ϕ_{s2} corresponded to the control signals meant for source selection, ϕ_{s1} for
 549 the TEG and ϕ_{s2} for the PZ. Finally, ϕ_{on} and ϕ_{off} were the control signals for inductor charging and
 550 discharging [53].

551 The timing diagram (Figure 21(B)) displays the source selection signals as well as the inductor current
 552 control signals during a complete harvesting cycle T_{CLK} . The number of charging and discharging cycles
 553 for each harvester was represented by m and n , and their allocated time was represented by αT_{CLK} and $(1 -$
 554 $\alpha) T_{CLK}$, respectively. As mentioned earlier, α was the TDM factor. $I_1(t)$ and $I_2(t)$ were current waveforms
 555 for the TEG and PZ, while $I_L(t)$ symbolized the inductor current and $I_{off}(t)$ signified the load current. T_{on1}
 556 and T_{on2} indicated the time spent charging the inductor by each source, while T_{off1} and T_{off2} represented the
 557 complete discharge of the inductor. During operation, the inductor current rises to the maximum values of
 558 I_{p1} during TEG harvesting and I_{p2} during PZ harvesting. During off times, the inductor current decreases
 559 and the output voltage increases [53].

560 Regarding the MPPT mechanism, impedance matching for each energy source allowed maximum power
 561 to be delivered to the load. The equivalent impedance seen by each source can be viewed as the ratio
 562 between its operating voltage and the average current drawn from the source in one harvesting cycle [53].
 563 In case of both the TEG and the rectified PZ, the maximum power is extracted by maintaining a voltage at
 564 half the open circuit voltage [54]. Figure 22 shows the MPPT mechanism applied. The working principle
 565 of the circuit Figure 21(A) will be more detailed hereafter.



566

567

Figure 22: (A) MPPT Mechanism proposed by Yehia et al. and (B) corresponding Internal Control Circuits [53]

568 The switches M_{s1} and M_{s2} connect the energy sources to the boost converter and are controlled by ϕ_{s1} and
 569 ϕ_{s2} . The fixed duty cycle frequency modulation (FM) method was used with programmable dividers that
 570 were regulated by MPPT in order to correct the ϕ_{on} for the regulation of M_{n1} . In the timing control block,
 571 the timing signals were created using a 5.12 MHz oscillator and powered with V_{out} . Dedicated dividers are
 572 used to generate f_{PZ} , f_{TEG} , f_{CLK} . The dead time circuit generated non-overlapping clock phases ϕ_{s1} and ϕ_{s2} to
 573 maintain TDM operation [53].

574 The MPPT block consists of a dual-fractional open circuit voltage (FOCV) extraction unit with an
 575 INC/DEC logic which are all controlled with a control-logic component. The control logic generated all the
 576 necessary signals for the extraction unit while the dual FOCV oversaw sampling and generating the
 577 optimum points $V_{TEG-MPP}$ and V_{PZ-MPP} . The INC/DEC logic periodically compared the source operating
 578 voltages V_{TEG} and V_{PZ} against their corresponding generated optimum voltages to properly control ϕ_{on} .
 579 The algorithm they applied is similar to the working principle of phase locked loops (PLL) but with the
 580 produced frequency being controlled by digital logic circuits [53].

581 Overall, Yehia et al. have proposed a very unique topology for dual source harvesting. They applied a global
 582 duty factor, in their paper denoted as a TDM factor. They also provide much more detail regarding the
 583 electronic interface and MPPT technique they used which is not as apparent in other research papers. More
 584 elaboration regarding their choice of a TDM factor of 50% could clarify its importance as well as seeing
 585 how it is affected under different conditions. Further research could be carried out on this aspect. Still, this
 586 work highlights the possibility and potential for dual source energy harvesting for applications meant for a
 587 smaller scale. As such, studies have already begun to make advancements based on this work [55].

588 5. Discussion and Future Directions

589
590

Table 2: Key Findings from Research Review

Topic	Yes (%)	No (%)
Mention of Electrical Connection between PV and TEG	72%	28%
Mention of MPPT Strategy	34%	66%
	Large-scale (%)	Small-scale (%)
Scale of Energy Harvesting based on Research Review	52%	48%

591

592 In this study, we have reviewed the research searching for studies regarding PV-TE hybrid energy
 593 harvesting both at small-scale and large-scale. Key findings from the research are displayed in Table 2. A
 594 few evident observations have been made regarding the comparison with standalone PV, modelling
 595 approach taken, the electrical connections considered and MPPT.

596 The performance of hybrid PV-TE systems are usually compared with the performance of a standalone PV
 597 cell. The main significance of the TEG is to assist the PV cell to increase its output electrical power and its
 598 overall performance by harnessing the PV cell's excess heat. The TEG uses this heat to establish a larger
 599 temperature gradient and generate output power. Most papers show slight improvement but others show
 600 that the hybrid system is only useful within a certain irradiance range [38] or express that the maximum
 601 power, as a function of solar irradiance, of a standalone PV cell can be better than a hybridized PV-TE
 602 device connected in series, as shown in the supplementary information provided by Park et al.[39]. In most

603 cases, commercial components (PV and TEG) are used in the presented experiments and the chosen
604 connection type is not the most favorable such as the three referenced cases where a series connection is
605 applied [31], [38], [39]. One might suggest that standard commercially available components are not
606 sufficient to obtain a significant increase in the performances when hybridization is addressed (compared
607 with the PV cell alone).

608 Particular care must be taken when designing each of the PV and TEG components, without neglecting the
609 key role of the physical interface between the PV and TEG. The thermal coupling between the two devices
610 must also be investigated to optimize the hybrid system. Park et al. have shown that, without any PV-TE
611 interface, the temperature gradient between the backside of the PV cell and the topside of the TEG increases
612 with rising irradiance. Conversely, both interfaces they tested, boron nitride with and without graphene
613 oxide, showed significant reductions in the temperature difference between the backside of the PV cell and
614 the topside of the TEG even under higher irradiance [39].

615 If we consider a PV-TE device, each element of the system can be thoroughly tested separately to optimize
616 their respective performances. However, when they are assembled together, the interactions between all the
617 components may hinder their individual performances and thus reduce the efficiency of the overall system.
618 Therefore, it is critical to examine and analyze at the system level and consider the global physical, thermal,
619 and electronic potential contributions of all components [56].

620 Regarding the modelling aspect, conventional models have been applied with slight variations. For
621 example, some authors have used the double diode representation for the PV [57] and many others have
622 applied the single diode model [24], [25], [37], [51], [58]–[60]. In case of the TEG, the typical model with
623 a single variable voltage source and internal electrical resistor has been utilized. However, from the research
624 reviewed, no paper has showcased a fully electrical model including the effects of a dedicated thermal
625 interface, placed between the PV and the TEG. When coupling the hybrid PV-TE device, the use of a
626 conventional gel or thermal paste [38] has been investigated for the heat transfer from the PV to the TEG.
627 More research efforts can be focused here to improve the heat transfer between sources.

628 Although there has been some research modelling the thermal resistances of the PV, TEG and hybrid PV-
629 TE [61], to our knowledge there has been nothing showcasing the specific thermal impact of the interaction
630 between the PV and the TEG [44]. Even papers with more complex thermal interfaces did not model them
631 electrically, authors concluded about their effects through experimental characterization of the global
632 system and utilized those values in simulations and analyses [39]. Therefore, integrating a thermal interface
633 into the modelling of the hybrid PV-TE device would allow to provide vital data regarding the exact
634 influence of a thermal interface at small-scale and pave the way towards optimal PV-TE coupling.

635 As previously described in this review, several electrical connections between PV and TEGs have been
636 reported in the research. Interestingly, many of the papers do not explicitly state the type of connection
637 applied. Note that it can often be deduced from the connection diagrams provided [57], [59]. Very few
638 papers applied a parallel connection between the sources due to the complexity of electrical compatibilities
639 [14], [34], [37]. One paper did extensive research on this configuration and concluded that the potential of
640 a parallel connection is quite limited compared to a series connection [34].

641 Relevant research work has been done to date to investigate the optimal conditions of operation and to
642 enhance the performance of the series connected PV-TE devices. One aspect that has been a focal point of
643 research is the effect of the thermal interface between the PV and the TEG on the performance of the series
644 connected system. The study conducted using three different hybrid devices with unique thermal interfaces
645 showed that thermal interfaces with a high thermal conductivity and high solar absorptivity significantly
646 improved the performance of hybrid PV-TE systems [39].

647 Finally, there is the electrically isolated connection which is applied in many papers such as [15] and [53].
648 Conventional practices and calculations can be applied but more electronic components are required for the
649 overall system which would incur more costs and increase power consumption. Overall, each connection
650 mode has its own positives and negatives, and the feasibility also depends on the application considered.

651 In terms of MPPT and the electronics involved, existing research is limited [31], [34], [38], [42], [43], [52]
652 and there is considerable opportunity for further research. In particular, in the case of the series connection,
653 further research is needed to find compatible MPPT techniques in order to make this connection mode
654 viable. As stated earlier, in case of isolated sources with their own electronic interfaces, conventional MPPT
655 techniques like P&O or fractional open-circuit voltage can be applied. However, they would need to be
656 more compact and less power demanding for them to be viable for energy harvesting at a small-scale.
657 Finally, the potential of a shared, single converter for multiple sources has been highlighted in [52] and
658 [53]. More research effort should be applied to the optimized value of the global duty cycle and how it is
659 affected by modifications of external conditions. Overall, there is a vast scope of research that can be carried
660 out in this field such as a thorough sensitivity analysis.

661 With the immense expansion expected in the IoT sector, it will become crucial to meet the power demand
662 while remaining environmentally friendly. This will not be an easy task as there are plenty of difficulties
663 and challenges to overcome [62], [63]. Hybrid PV-TE devices may be a way to accommodate the power
664 requirements of green IoT [64]. Studies has been showcased to articulate the potential of the hybridized
665 system with regards toward energy harvesting at a small-scale and IoT applications [65]. The PV-TE device
666 may help bridge the gap to the power requirements of more complex and advanced sensors or nodes that
667 cannot be powered by standalone PVs. More research and time will be required to provide definitive
668 answers.

669 6. Conclusion

670
671 Despite the surge in popularity of hybrid PV-TE systems, relatively less attention has been given to the
672 electrical aspects of hybrid systems. This research review presents an in-depth analysis of the state of the
673 art regarding the electrical aspects of PV-TE hybrid systems, a subject that is often neglected in the
674 optimization of these systems. This work is limited to the research available within the time of the review,
675 and as such allows plenty of opportunity to add to what is stated in this review in the future.

676 First, the primary focus of the review was on the three modes of electrical connection between the PV and
677 the TEG sources. Each of the three modes of connection was discussed and analyzed. There is widespread
678 application of the isolated mode of connection for small and large-scale applications because the
679 performance of each source is independent of the electrical characteristics of the other. There is also
680 potential for the series connection to be used in small-scale applications, especially in combination with
681 phase change materials. To enhance the small-scale implementation of the series connection, more research
682 is required to investigate how to minimize the detrimental and unavoidable voltage drop at the series
683 resistance of the TEG.

684 Second, we proposed a review of studies on the electronics for control and MPP using the parallel, series
685 connection and the isolated configuration. The few reported studies have shown that conventional methods
686 such as P&O algorithms are currently being applied to track the maximum power point of operation for the
687 series connection. For both the series and parallel connection, the techniques applied in the electronic
688 circuits for control and MPP were not elaborate, and more investigations are required. As for the isolated
689 connection, two subclasses of PV-TE hybrid systems were identified, single and dual converter interfaces.

690 There is a need to increase the compactness of the electronic interfaces for the isolated connection mode to
691 make them viable for small-scale applications.

692 Finally, the design of both PV-TE devices and units must be looked upon at a system level perspective.
693 This can be done by determining the global physical, thermal and electronics potential contributions. A
694 thorough understanding of the significance of these contributions may help progress the development of
695 PV-TE hybrid devices and make them an ideal power source for the IoT industry in the future.

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