Application of SEPIC DC-DC converter for low-voltage energy harvesting systems

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ABSTRACT

Energy harvesting systems (EHS) have been known as a concept to obtain energy from a clean source and convert it into other energy, including electricity. EHS can be classified into four sources: light, electromagnetic, thermal, and kinetic energy. Unfortunately, most harvester devices generate electricity within the low-voltage level, so voltage conditioning is needed to achieve a feasible level. Single-ended primary-inductor converter (SEPIC) DC-DC converter becomes one of the solutions to realize it, which works by increasing DC level voltage. In this study, the role of SEPIC DC-DC converter for HES applications focusing on three of four sources along with its harvester devices, i.e., light by PV, gradient temperature by TEG, and pressure by a piezoelectric device, are reviewed. Also, the overview of challenges and the possibility of HES obtained are described. Then, the application of each harvester device and the SEPIC DC-DC converter is explained to low-voltage EHS applications, for instance, in renewable energy power plants, street lighting, small-scale power applications, or power sources at wearable devices. Lastly, the primary issue in the SEPIC DC-DC converter and research information that may be carried out in future studies are given.

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1. INTRODUCTION

The increasing energy need has forced the world to find alternative solutions outside of using crude oil or coal as the primary source. For more than five-decade, policy-makers, along with scientists, have been working hard to obtain other energies that are more clean, sustainable, have no pollution, and promise [1]. Energy harvesting systems (EHS) have been known as a concept to harvest green energy into other energy, including electricity [2]. Several familiar sources are obtained from light, electromagnetic, thermal, and kinetic energy.

Transforming EHS into electricity involves a harvester device depending on the energy source. However, the challenges faced by EHS obtain a worthy power conversion. In addition, the low voltage resulting from the EHS device needs to enhance, so a step-up converter is needed [3], [4]. A boost converter is the basic DC-DC topology to enhance the DC voltage level. Nonetheless, the boost converter generates a large ripple in current and voltage, high voltage stress in the switches, gain limitation, reverse recovery effect, and low efficiency result [5]. Therefore, the development of the DC-DC converter functioned to the step-up voltage is continuously conducted, one of single-ended primary-inductor converter (SEPIC) topology.

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Studies by [6]–[10] involve SEPIC converters to achieve high voltage conversion in photovoltaic modules-based EHS. For the waste heat from thermal energy conversion, [11], [12] employs the SEPIC converter to enhance output voltage from a (TEG) thermoelectric generator. In addition, the SEPIC converter has been utilized to increase the output voltage from the rectifier that used piezoelectric as HES converter devices in [13], [14]. Furthermore, numerous innovative SEPIC DC-DC converters have continuously been proposed to improve base architecture performances. It solves the classical problems in step-up converters' topology, such as low gain, ripple, voltage stress, hard switching, and efficiency [15]–[18].

This paper reviews the application of the SEPIC DC-DC converter and its modification for low-voltage EHS. The review focuses on three EHS: light by PV, gradient temperature by TEG, and pressure by a piezoelectric device. The second section describes an overview of challenges harvesting energy systems. The role of SEPIC DC-DC converter for low-voltage EHS application followed by the research trend is given in section 3. Also, the pros and cons are given in the same section. Finally, the conclusion of this study is explained in section 4.

2. OVERVIEW OF CHALLENGES ENERGY HARVESTING SYSTEMS

Figure 1 shows the general classification of energy harvesting sources, wherein each proposed system is usually dedicated to a single energy source. For instance, a PV module uses for converting light/solar energy, catching electromagnetic radiation from radio frequency, applying pyroelectric or TEG to convert the thermal gradient, and pressure or vibration resulting from kinetic energy is converted by piezoelectric. Unfortunately, most HES availability in an ambient environment is inconsistent. Consequently, it impacts small resulted power conversion and is insufficient for commercial users. For example, light energy obtained from solar energy is unavailable at night, in dark environments, or on rainy days, so the PV module does not work and does not generate electricity [19]. Then, kinetic energy can be found in structural and machinery vibrations [20], human activities [21], water waves [22], or wind flows [23]. Nonetheless, it will fluctuate, and insufficient the load demand due to each human need to rest, water waves or wind flow may not happen all the time, and a machine may not operate continuously. So, the conversion of HES from kinetic energy will be ineffective. In the same case, it may occur in thermal energy due to unpredictable temperature fluctuations/gradients [24].

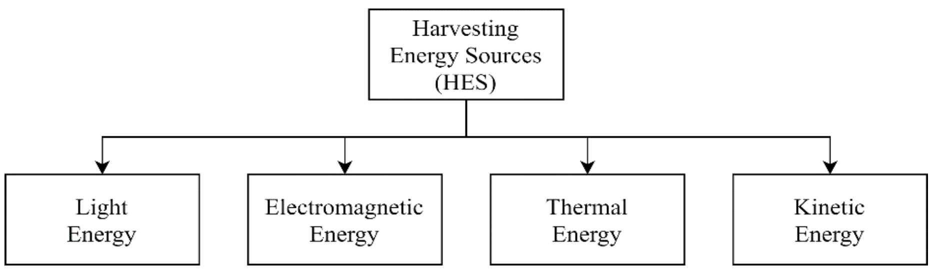
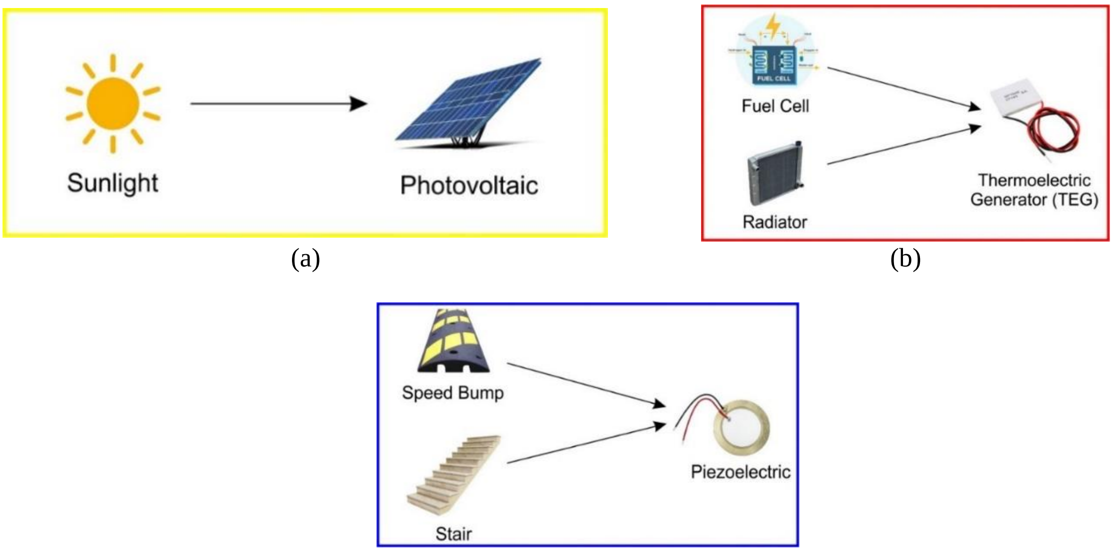


Figure 1. General classification of energy harvesting source

Regarding the harvester devices mentioned before, conversion by PV is the most that has been conducted, starting for module single applications, solar home systems (SHS), standalone systems, grid-connected systems, and microgrids. Furthermore, applying TEG to obtain power conversion from thermal gradient by utilizing Seebeck effects and piezoelectric from pressure. Figures 2 (a) to (c) illustrates the possibility of HES obtained to employ three harvester devices. PV converts photons from sunlight [25]–[27], TEG obtains the waste heat from fuel cells [28]–[31] or vehicle radiators [32]–[34] and piezoelectric works due to pressure resulting from speed bumps [35]–[37] or footsteps [38]–[40] in stairs. However, these generate electricity within the low-voltage level, which means a voltage conditioner is still needed to be attached to a harvesting energy system involving them. Table 1 shows the average output voltage generated by the PV, TEG, and piezoelectric modules.



(a) (b) (c)

Figure 2. The possibility of HES obtained to employ three harvester devices: (a) light energy, (b) thermal energy, and (c) kinetic energy

Table 1. The output voltage range from harvester devices

Energy sources	Harvester devices	Output voltage ranges	Voltage type
Light energy	PV module	12 – 72 V	DC
Thermal energy	Thermoelectric generator	0.5 – 12 V	DC
Kinetic energy	Piezoelectric	0.1 – 0.6 V	AC

3. THE ROLE OF SEPIC DC-DC CONVERTER FOR LOW-VOLTAGE ENERGY HARVESTING SYSTEMS

The capability of the SEPIC DC-DC converter, which can increase or decrease the voltage level without reversed polarity, causes this topology to apply much as a power conditioner. SEPIC DC-DC converter will enhance the input voltage when the charging time for the inductor is longer than the discharging time. It means the ON-time switching period is longer than the OFF-time. Otherwise, the SEPIC converter works as the step-down mode to decrease the input voltage. The SEPIC DC-DC converter output voltage can be computed by (1), in which V_{out}, V_{in}, and D present output voltage, input voltage, and duty cycle. The inductance values are estimated by (2) and (3), in which Δi_{L1} and Δi_{L2} are current ripples in inductors 1 and 2, and f_s is the switching frequency. Meanwhile, capacitors 1 and 2 are calculated by (4) and (5), wherein ΔV_{C1}, ΔV_{out}, and R are voltage ripples in capacitor 1 and the output voltage and load capacity, respectively. The configuration circuit of the SEPIC DC-DC converter entirely is depicted in Figure 3.

$$V_{out} = V_{in}\left(\frac{D}{1-D}\right) \quad (1)$$

$$L_1 = \frac{V_{out}\, D}{\Delta i_{L1}\, f_s} \quad (2)$$

$$L_2 = \frac{V_{out}\, D}{\Delta i_{L2}\, f_s} \quad (3)$$

$$C_1 = \frac{D}{R(\Delta V_{C1}/V_{out})f_s} \quad (4)$$

$$C_2 = \frac{D}{R(\Delta V_{out}/V_{out})f_s} \quad (5)$$

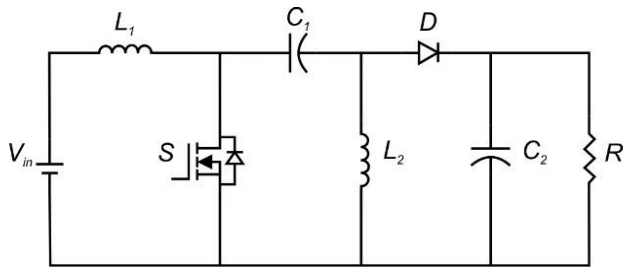


Figure 3. General circuit of SEPIC DC-DC converter

Due to offered feature, the SEPIC DC-DC converter can be utilized along with the abovementioned harvester devices to obtain a system with feasible voltage. Figures 4, 5, and 6 show a block diagram of the SEPIC DC-DC converter's role in harvesting light, thermal, and kinetic energy sources, respectively.

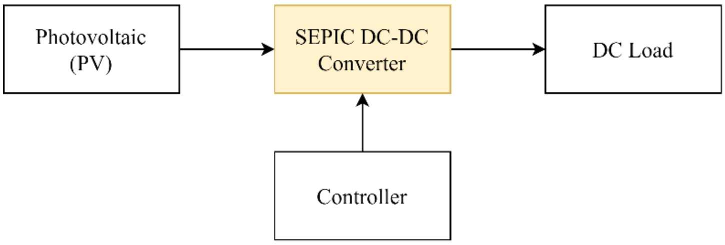


Figure 4. Block diagram of SEPIC DC-DC converter role in harvesting light energy source

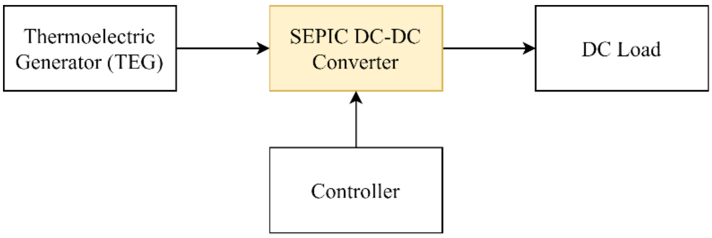


Figure 5. Block diagram of SEPIC DC-DC converter role in harvesting thermal energy source

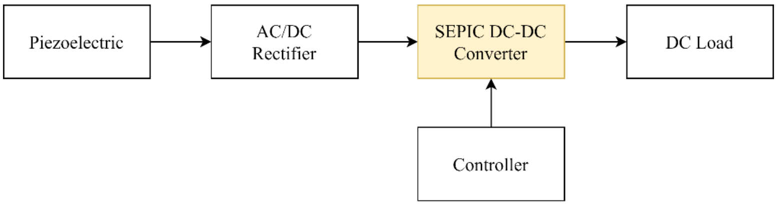


Figure 6. Block diagram of SEPIC DC-DC converter role in harvesting kinetic energy source

As mentioned before, PV is the most way to harvest energy from sunlight. It makes the research trend involving them still considered by many researchers worldwide to improve the performance of each part in PV systems. Furthermore, it is followed by TEG and piezoelectric, which started to generate energy from availability in an ambient environment. By employing SEPIC DC-DC converter, the output voltage generated by them will be possible in realizable value for daily use, for instance, in renewable energy power plants, street lighting, small-scale power applications, or power sources at wearable devices. Table 2 shows the applications of SEPIC DC-DC converter for low-voltage energy harvesting systems.

Table 2. The applications of SEPIC DC-DC converter for low-voltage energy harvesting systems

Energy type	Harvester devices	Ref	Applications
Light energy	PV module	[41]–[45]	Renewable energy power plants either standalone or grid-connected systems
Thermal energy	Thermoelectric generator	[46]–[50]	Supporting electrical in the vehicle and industrial applications, energy storage, and PV-thermal systems,
Kinetic energy	Piezoelectric	[13], [51], [52]	Automatic barrier gate, combination to the street lighting system, and stair light

Related to the role of SEPIC DC-DC converter to obtain feasible voltage from mentioned harvester devices, it can be concluded that gain conversion is the primary issue and should be fulfilled. Hence, this topology becomes an alternative solution to realize it compared to applying a boost converter. It is because of the limited voltage gain resulting and a significant ripple in current and voltage. Moreover, to reach a high performance of SEPIC DC-DC converter, many researchers, the SEPIC DC-DC converter combines an auxiliary diode and a capacitor to form a non-isolated structure without magnetic coupling. It shows a static gain achieved more than ten times with decreased switch voltage [53]. Furthermore, it was modified in [54], adding one more diode to construct a voltage doubler circuit and enhance the output voltage result.

A study in [55] made a slight modification by changing the placement of the additional capacitor to the series with the output capacitor. This way makes the operation of the modification converter achieve steady-state conditions faster. Then, a modified SEPIC DC-DC topology was introduced by integrating a diode-capacitor component in series and boost converter to a basic SEPIC topology [56]. Ten times voltage gain conversion can be obtained. The voltage stress, input current ripple, and output voltage ripple can be reduced. Nonetheless, these studies and research trends on modified SEPIC DC-DC converters are mainly dedicated to harvesting light energy using PV modules. Therefore, researchers can consider investigating its performance in TEG and piezoelectric for future work.

4. CONCLUSION

This study has presented the role of SEPIC DC-DC converter for HES applications focusing on three sources along with its harvester devices, i.e., light by PV, gradient temperature by TEG, and pressure by a piezoelectric device. Also, the possibility of HES obtained to employ it is explained, comprising PV converts photons from sunlight, TEG obtains the waste heat from fuel cells or vehicle radiators, and piezoelectric works due to pressure resulting from speed bumps or footsteps in stairs. These generate electricity within the low-voltage level, so the SEPIC DC-DC converter is needed to obtain a system with a feasible voltage for daily use, for instance, in renewable energy power plants, street lighting, small-scale power applications, or power sources at wearable devices. Nonetheless, research trends on SEPIC DC-DC converter and its modification topology are majority dedicated to harvesting light energy using PV modules. For future work, researchers can consider proposing or investigating the modification of SEPIC DC-DC converter in TEG and piezoelectric.

REFERENCES

[1] R.D. Chang, J. Zuo, Z.-Y. Zhao, G. Zillante, X.-L. Gan, and V. Soebarto, “Evolving theories of sustainability and firms: History, future directions and implications for renewable energy research,” *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 48–56, 2017.

[2] G. Saini and M. S. Baghini, “An energy harvesting system for time-varying energy transducers with FOCV based dynamic and adaptive MPPT for 30 nW to 4 mW of input power range,” *Microelectronics Journal*, vol. 114, p. 105080, 2021.

[3] T. Sutikno, H. Satrian Purnama, R. A. Aprilianto, A. Jusoh, N. Satya Widodo, and B. Santosa, “Modernisation of DC-DC converter topologies for solar energy harvesting applications: A review,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 28, no. 3, p. 1845, Dec. 2022, doi: 10.11591/ijeecs.v28.i3.pp1845-1872.

[4] R. A. Aprilianto, S. Subiyanto, and T. Sutikno, “Modified SEPIC Converter Performance for Grid-connected PV Systems under Various Conditions,” *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 16, no. 6, p. 2943, Dec. 2018, doi: 10.12928/telkomnika.v16i6.10148.

[5] S. Nahar and M. B. Uddin, “Analysis the performance of interleaved boost converter,” in *2018 4th International Conference on Electrical Engineering and Information & Communication Technology (iCEEiCT)*, Sep. 2018, vol. 8, pp. 547–551, doi: 10.1109/CEEICT.2018.8628104.

[6] K. S. Tey, S. Mekhilef, M. Seyedmahmoudian, B. Horan, A. T. Oo, and A. Stojcevski, “Improved differential evolution-based MPPT algorithm using SEPIC for PV systems under partial shading conditions and load variation,” *IEEE Transactions on Industrial Informatics*, vol. 14, no. 10, pp. 4322–4333, 2018.

[7] S. Kalimuthukumar, K. Rajesh, B. Kannapiran, G. Manikandan, and R. Selvameena, “A SEPIC Converter with Adaptive Sliding Mode Control for Grid-Connected Solar PV Systems,” in *2021 3rd International Conference on Advances in Computing, Communication Control and Networking (ICAC3N)*, 2021, pp. 1023–1026.

[8] V. Kumar, S. Ghosh, N. K. S. Naidu, S. Kamal, R. K. Saket, and S. K. Nagar, “A current sensor based adaptive step-size MPPT with SEPIC converter for photovoltaic systems,” *IET Renewable Power Generation*, vol. 15, no. 5, pp. 1085–1099, 2021, doi:

10.1049/rpg2.12091.
[9] D. S. Sankaralingam, M. S. B. Natarajan, M. Muthusamy, and S. B. Singh, “A novel metaheuristic approach for control of SEPIC converter in a standalone PV system,” *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 2, pp. 1082–1092, 2022, doi: 10.11591/ijpeds.v13.i2.pp1082-1092.
[10] B. N. Abramovich, D. A. Ustinov, and W. J. Abdallah, “Modified proportional integral controller for single ended primary inductance converter,” *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 2. Institute of Advanced Engineering and Science, pp. 1007–1025, 2022, doi: 10.11591/ijpeds.v13.i2.pp1007-1025.
[11] N. Jaswanth and G. R. Dheep, “Performance evaluation of thermoelectric generator employing SEPIC converter and incremental conductance maximum power point tracking for electric vehicles,” in *Journal of Physics: Conference Series*, 2022, vol. 2327, no. 1, p. 12005.
[12] S. Poluthai and N. Jirasuwankul, “Simulation of a Miniature SEPIC Converter with PI Controller for Thermoelectric Generator Module,” in *2018 International Electrical Engineering Congress (iEECON)*, 2018, pp. 1–4.
[13] H. Y. Yong, N. I. Rusli, and M. F. N. Tajuddin, “Output voltage control of dual input single ended primary inductor converter (SEPIC) for hybrid photovoltaic-piezoelectric system,” in *2017 IEEE Conference on Energy Conversion (CENCON)*, 2017, pp. 349–354.
[14] N. A. Kong, D. S. Ha, A. Erturk, and D. J. Inman, “Resistive impedance matching circuit for piezoelectric energy harvesting,” *Journal of Intelligent Material Systems and Structures*, vol. 21, no. 13, pp. 1293–1302, 2010.
[15] I. D. Kim, J. Y. Kim, E. C. Nho, and H. G. Kim, “Analysis and design of a soft-switched PWM Sepic DC-DC converter,” *Journal of Power Electronics*, vol. 10, no. 5, pp. 461–467, Sep. 2010, doi: 10.6113/JPE.2010.10.5.461.
[16] R. A. Aprilianto, E. Firmansyah, and F. D. Wijaya, “Review on Control Strategy for Improving The Interleaved Converter Performances,” in *2021 4th International Seminar on Research of Information Technology and Intelligent Systems (ISRITI)*, Dec. 2021, pp. 312–317, doi: 10.1109/ISRITI54043.2021.9702804.
[17] R. M. Ariefianto, R. A. Aprilianto, H. Suryoatmojo, and S. Suwito, “Design and Implementation of Z-Source Inverter by Simple Boost Control Technique for Laboratory Scale Micro-Hydro Power Plant Application,” *Jurnal Teknik Elektro*, vol. 13, no. 2, pp. 62–70, Dec. 2021, doi: 10.15294/jte.v13i2.31884.
[18] T. Sutikno, H. S. Purnama, N. S. Widodo, S. Padmanaban, and M. R. Sahid, “A review on non-isolated low-power DC-DC converter topologies with high output gain for solar photovoltaic system applications,” *Clean Energy*, vol. 6, no. 4, pp. 557–572, 2022, doi: 10.1093/ce/zkac037.
[19] A. El Fathi and A. Outzourhit, “Technico-economic assessment of a lead-acid battery bank for standalone photovoltaic power plant,” *Journal of Energy Storage*, vol. 19, no. February, pp. 185–191, Oct. 2018, doi: 10.1016/j.est.2018.07.019.
[20] S. Bhuvana, H. Prathiksha, V. T. Sindhu, and H. Vasudha, “Design and analysis of piezoelectric cantilever based vibration sensor,” in *2018 IEEE International Conference on System, Computation, Automation and Networking (ICSCA)*, 2018, pp. 1–6.
[21] E. Maghsoudi Nia, N. A. Wan Abdullah Zawawi, and B. S. Mahinder Singh, “Design of a pavement using piezoelectric materials,” *Materialwissenschaft und Werkstofftechnik*, vol. 50, no. 3, pp. 320–328, 2019.
[22] R. M. Ariefianto, Y. S. Hadiwidodo, and S. Rahmawati, “Experimental Study of a Wave Energy Converter Using a Unidirectional Cascaded Gear System in a Short-Wave Period,” *International Journal of Technology*, vol. 13, no. 2, pp. 321–331, 2022, doi: 10.14716/ijtech.v13i2.5071.
[23] T. Sutikno, S. H. Wahid, R. A. Aprilianto, A. C. Subrata, and A. Jidin, “An Automatic Wind Turbine Braking System on PLTH Bayu Baru through a Fuzzy Logic Controller,” *Jurnal Nasional Teknik Elektro*, vol. 11, no. 1, pp. 1–7, 2022, doi: 10.25077/jnte.v11n1.887.2022.
[24] H. Liu, H. Fu, L. Sun, C. Lee, and E. M. Yeatman, “Hybrid energy harvesting technology: From materials, structural design, system integration to applications,” *Renewable and Sustainable Energy Reviews*, vol. 137, no. October, p. 110473, 2021, doi: 10.1016/j.rser.2020.110473.
[25] X. Xing, Y. Xin, F. Sun, W. Qu, H. Hong, and H. Jin, “Test of a spectral splitting prototype hybridizing photovoltaic and solar syngas power generation,” *Applied Energy*, vol. 304, p. 117779, 2021.
[26] R. D. Bhagiya and R. M. Patel, “PWM based double loop PI control of a bidirectional DC-DC converter in a standalone PV/battery DC power system,” in *2019 IEEE 16th India Council International Conference (INDICON)*, 2019, pp. 1–4.
[27] R. Das, S. De, S. Sinha, and S. Hazra, “Modelling of PV based DC-DC boost converter using P&O algorithm under varying environmental conditions,” in *2021 Innovations in Energy Management and Renewable Resources (52042)*, 2021, pp. 1–5.
[28] M. Alam, K. Kumar, and V. Dutta, “Dynamic modeling and experimental analysis of waste heat recovery from the proton exchange membrane fuel cell using thermoelectric generator,” *Thermal Science and Engineering Progress*, vol. 19, no. August 2019, p. 100627, 2020, doi: 10.1016/j.tsep.2020.100627.
[29] R. A. Aprilianto and R. M. Ariefianto, “The Utilization of Waste Heat From Polymeric Electrolyte Membrane Fuel Cells (PEMFC) Using Thermoelectric Generator (TEG): A Review,” *Journal of Sustainable Energy*, vol. 12, no. 2, pp. 60–65, 2021, [Online]. Available: file:///C:/Users/rizky/Dropbox/5. JSE/v12-n2-2.pdf
[30] W. J. Zou, K. Y. Shen, S. Jung, and Y. B. Kim, “Application of thermoelectric devices in performance optimization of a domestic PEMFC-based CHP system,” *Energy*, vol. 229, 2021, doi: 10.1016/j.energy.2021.120698.
[31] C. T. Hsu, G. Y. Huang, H. S. Chu, B. Yu, and D. J. Yao, “Experiments and simulations on low-temperature waste heat harvesting system by thermoelectric power generators,” *Applied Energy*, vol. 88, no. 4, pp. 1291–1297, 2011, doi: 10.1016/j.apenergy.2010.10.005.
[32] B. Abderezzak and S. Randi, “Experimental investigation of waste heat recovery potential from car radiator with thermoelectric generator,” *Thermal Science and Engineering Progress*, vol. 20, p. 100686, 2020.
[33] J. Kim *et al.*, “Dynamic reconfiguration of thermoelectric generators for vehicle radiators energy harvesting under location-dependent temperature variations,” *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 26, no. 7, pp. 1241–1253, 2018.
[34] H. Yang *et al.*, “Prediction-based fast thermoelectric generator reconfiguration for energy harvesting from vehicle radiators,” in *2018 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, pp. 877–880, 2018.
[35] G. J. Song *et al.*, “Performance of a speed bump piezoelectric energy harvester for an automatic cellphone charging system,” *Applied energy*, vol. 247, pp. 221–227, 2019.
[36] J. H. Hyun, N. Chen, and D. S. Ha, “Energy Harvesting Circuit for Road Speed Bumps Using a Piezoelectric Cantilever,” in *IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society*, 2018, pp. 4219–4223.
[37] E. Ekawati, R. Y. Mardiah, and H. Parmana, “Speed bump with piezoelectric cantilever system as electrical energy harvester,” in *2016 International Conference on Instrumentation, Control and Automation (ICA)*, 2016, pp. 154–159.
[38] M. Logeshwaran, J. J. J. Sheela, and A. P. Priya, “A High-Efficiency Power Generator by Footsteps Using Piezoelectric Effect,”

in *2022 Second International Conference on Artificial Intelligence and Smart Energy (ICAIS)*, 2022, pp. 1547–1553.
[39] D. Singh, J. Alam, S. Alam, and L. Varshney, "Performance Analysis of Footstep Power Generation using Piezoelectric Sensors," in *2021 International Conference on Intelligent Technologies (CONIT)*, pp. 1–5, 2021.
[40] A. Kamboj, A. Haque, A. Kumar, V. K. Sharma, and A. Kumar, "Design of footstep power generator using piezoelectric sensors," in *2017 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)*, 2017, pp. 1–3.
[41] M. Vaigundamoorthi, R. Ramesh, V. V Prabhu, and K. A. Kumar, "MPPT oscillations minimization in PV system by controlling non-linear dynamics in SEPIC DC-DC converter," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 6. Institute of Advanced Engineering and Science, pp. 6268–6275, 2020, doi: 10.11591/IJECE.V10I6.PP6268-6275.
[42] E. Mamarelis, G. Petrone, and G. Spagnuolo, "Design of a sliding-mode-controlled SEPIC for PV MPPT applications," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3387–3398, 2013.
[43] A. J. Sabzali, E. H. Ismail, and H. M. Behbehani, "High voltage step-up integrated double Boost–Sepic DC–DC converter for fuel-cell and photovoltaic applications," *Renewable Energy*, vol. 82, pp. 44–53, Oct. 2015, doi: 10.1016/j.renene.2014.08.034.
[44] A. Ghasemi, S. Fazlollohzadeh Eilaghi, and E. Adib, "A new non-isolated high step-up SEPIC converter for photovoltaic applications," in *2012 3rd Power Electronics and Drive Systems Technology (PEDSTC)*, Feb. 2012, pp. 51–56, doi: 10.1109/PEDSTC.2012.6183383.
[45] A. M. S. S. Andrade, L. Schuch, and M. L. da Silva Martins, "Analysis and Design of High-Efficiency Hybrid High Step-Up DC–DC Converter for Distributed PV Generation Systems," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 3860–3868, May 2019, doi: 10.1109/TIE.2018.2840496.
[46] D. E. Schwartz, "A maximum-power-point-tracking control system for thermoelectric generators," in *2012 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2012, pp. 78–81.
[47] N. Phillip *et al.*, "Modelling and simulation of a thermoelectric generator for waste heat energy recovery in low carbon vehicles," in *2012 2nd International Symposium On Environment Friendly Energies And Applications*, 2012, pp. 94–99.
[48] T. H. Kwan and X. Wu, "The Lock-On Mechanism MPPT algorithm as applied to the hybrid photovoltaic cell and thermoelectric generator system," *Applied Energy*, vol. 204, pp. 873–886, 2017.
[49] J. A. B. Vieira and A. M. Mota, "Thermoelectric generator using water gas heater energy for battery charging," in *2009 IEEE Control Applications,(CCA) & Intelligent Control,(ISIC)*, 2009, pp. 1477–1482.
[50] C. E. Kinsella, S. M. O'Shaughnessy, M. J. Deasy, M. Duffy, and A. J. Robinson, "Battery charging considerations in small scale electricity generation from a thermoelectric module," *Applied Energy*, vol. 114, pp. 80–90, 2014.
[51] N. Nakahigashi and H. Yamada, "SEPIC-based Vibration Power Generation System With Variable Equivalent Resistance Control," in *2021 24th International Conference on Electrical Machines and Systems (ICEMS)*, 2021, pp. 192–196.
[52] N. Nakahigashi and H. Yamada, "Vibration Power Generation System Using a Piezoelectric Element with a Variable Resistance Control for Optimal Generated Power," in *2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia)*, 2022, pp. 906–910.
[53] R. Gules, W. M. dos Santos, F. A. dos Reis, E. F. R. Romaneli, and A. A. Badin, "A Modified SEPIC Converter With High Static Gain for Renewable Applications," *IEEE Transactions on Power Electronics*, vol. 29, no. 11, pp. 5860–5871, Nov. 2014, doi: 10.1109/TPEL.2013.2296053.
[54] S. Saravanan and N. Ramesh Babu, "Analysis and implementation of high step-up DC-DC converter for PV based grid application," *Applied Energy*, vol. 190, pp. 64–72, Mar. 2017, doi: 10.1016/j.apenergy.2016.12.094.
[55] S. Saravanan and N. R. Babu, "A modified high step-up non-isolated DC-DC converter for PV application," *Journal of Applied Research and Technology*, vol. 15, no. 3, pp. 242–249, Jun. 2017, doi: 10.1016/j.jart.2016.12.008.
[56] S. Saravanan and N. R. Babu, "Design and Development of Single Switch High Step-Up DC-DC Converter," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6777, no. c, 2017, doi: 10.1109/JESTPE.2017.2739819.

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