Power Generation from Salinity Gradient Solar Ponds Using Thermoelectric Generators

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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‘Perita manus mens exculta’ *(Skill hand, cultivated mind)*

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- ***“We must accept that we have to make hard choices in this generation to bring about real changes for the future generation and the planet. Politicians and the industry must get real.” – World Energy Council***

- ***For the generation who looking for greener earth, this work is dedicated to you.***

- ***“For wisdom will come into your heart, and knowledge will be pleasant to your soul; discretion will watch over you, understanding will guard you.”***
  Proverbs 2:10-11

- ***What makes a man a man?***

- ***Cogito, ergo sum. [I think, therefore I am]***
  -René Descartes

Abstract

The thermoelectric devices have been introduced for over 50 years and numerous research and methods have been carried out to improve its conversion efficiency, represented by the figure of merit, ZT. Despite having a low conversion efficiency compared to other heat engine, thermoelectric is gaining attention owing to its stationary and simplest operating condition that requires no maintenance. From the literature study conducted, most of the applications of the thermoelectric generators are focusing on generating electricity from a non-storage heat source, which means in order to avoid intermittency in the power supply due to temporary unavailability of adequate heat source; a battery storage system is needed. In order to address an alternative for the aforementioned scenario, a thermal storage system that will able to constantly providing sufficient heat for power generation is proposed, which introduces the solar pond (SP) as the heat source. Acting as a solar energy collector as well as thermal storage, solar ponds have been available in large scale for providing low grade heat source from 50 ºC to 100 ºC. Moreover, in terms of scalability, both thermoelectric generators and solar pond are highly scalable in size. As the thermoelectric cells are able to work interchangeably between heat pump and heat engine, it results in two variations of the thermoelectric cells available in the market, being sold as Peltier cooler and thermoelectric generators, with a significant price difference (the former is costing less than the latter). This study has started by investigating the performance and reliability of the thermoelectric cooler available functioning as thermoelectric generator. Later, in the next chapter, the performance of the thermoelectric cells is incorporated and coupled with a transient heat transfer for solar pond, in order to set up the potential of the thermoelectric-solar pond power generation system. Two practical power generation systems have been brought to fruition and presented in this thesis, which are a plate type power generation unit operating at atmospheric pressure and a submersible type thermoelectric power generation unit, and their comprehensive investigation have been delineated separately in the following chapters. Finally, the outcomes from the prior chapters (the system's performance via transient model and prototype testing) are joined in the last part of this thesis, to form a sound feasibility study of the system. From the establishment of theoretical framework to the examination of the system's feasibility from the potential and practical viewpoint, this thesis had attended the essential of power generation from solar pond using thermoelectric generators.

Keywords: energy conversion, power generation, thermoelectric, solar pond

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Chapter 1: Introduction

1.1 Research Background

1.1.1 Renewable Energy: A Global and Local Scenario

Up to this point, coal, oil, gas, and nuclear remains the major sources of world energy consumption, while renewable energy resources such as solar energy, hydropower, wind energy, biomass, geothermal remain a relatively small portion of the global energy sources. When we deal with the choice of energy, energy trilemma appears and often, policy makers made a compromise between the reliability of the resources for current and future demands, its adorability and the environmental impact (Fig. 1). From the year 1993 to 2011, the world electricity production had risen from 12607 TWh to 22202 TWh per year and fossil source of energy occupied 82% of the primary energy supply, renewable energy (including hydropower) and nuclear energy filled up the remaining energy sources with 13% and 5%, respectively. With the increasing demand of electricity supply and the status of the fossil as the main source of energy (which is also the source of CO_2 emission) remains unchanged, the total CO_2 emissions has increased by almost 50% from 1993 to 30 Gt CO_2 per year (World Energy Council, 2014). Hence, discernibly, the trade-off resulted from the energy trilemma to date is clear, the reliability and affordability of the source of energy overweight the consideration of environmental impact.

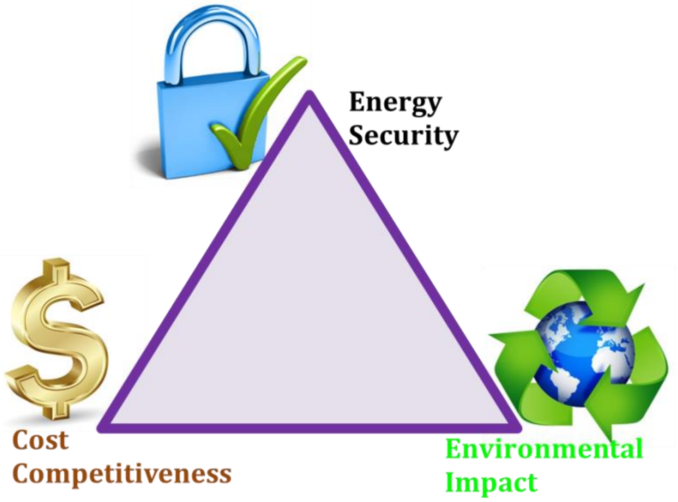
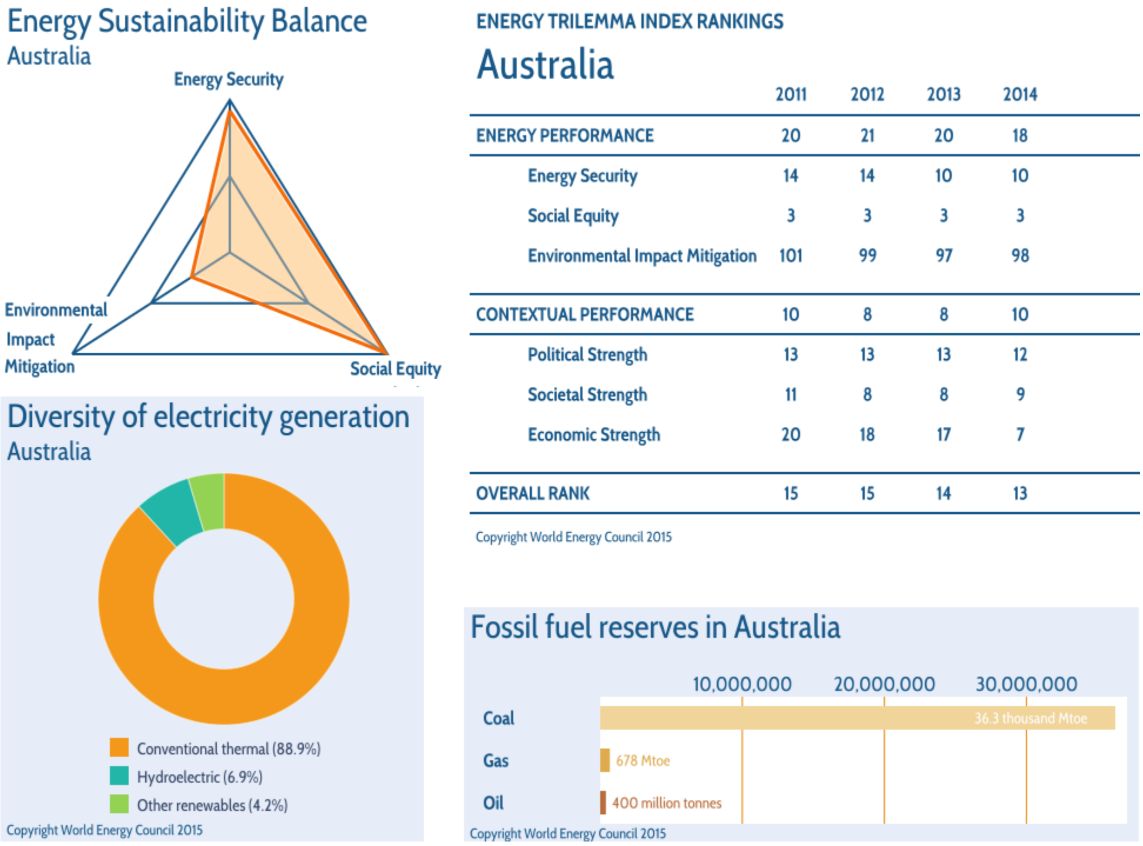


Fig.1. Energy trilemma.

In the local context, Australia relies on the conventional thermal power plant for electricity production using coal, gas, and oil. Australia ranked high on providing a secure, affordable and accessible supply of electricity in the world. However, in terms of environmental sustainability, Australia performs weakly, compared to other advanced economies (Fig. 2).

The latest report published by British Petroleum (June 2014) on statistic review of global energy consumption reveals that renewable energy consumption in Australia accounts for 1.2 % (the equivalent of 3.4 million tons of oil) of global renewable energy consumption (BP, 2014). Meanwhile, solar energy has been widely used as a source for power production using solar photovoltaic (PV) panel. With the extensive application of solar PV, Australia ranked 8th globally with an installed capacity of 1.0 GW (Pazheri, 2014).



ENERGY TRILEMMA INDEX RANKINGS

Australia

	2011	2012	2013	2014
ENERGY PERFORMANCE	20	21	20	18
Energy Security	14	14	10	10
Social Equity	3	3	3	3
Environmental Impact Mitigation	101	99	97	98
CONTEXTUAL PERFORMANCE	10	8	8	10
Political Strength	13	13	13	12
Societal Strength	11	8	8	9
Economic Strength	20	18	17	7
OVERALL RANK	15	15	14	13

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Fig. 2. Energy in Australia. (World Energy Council, 2014)

1.1.2 Solar Pond and Thermoelectric Generators: An Amalgamation for Remote Area Power Supply

The power supply for a remote area often relies on the off-grid power supply on one hand, which can be either with the use of the solar panel, wind turbine, geothermal sources, diesel or biofuel generator, micro hydro turbine. On the other hand, in terms of power storage, often deep cycle batteries are being used. Without a storage system, the solar energy utilisation will be in the form of instantaneous usage, be it solar hot water, solar PV or wind turbine.

Despite the need of external storage system, solar pond with a different design as a large-scale solar energy collector and storage has been used extensively in process heating, desalination or solar power generation (El-Sebaii et al., 2011; Garmana & Muntasser, 2008).

The heat stored in the bottom part of the solar pond and hence possesses the highest temperature, while the top part of the pond will remain almost identical to daily average ambient temperature. This pool of saltwater requires constant replenishment of salt due to surface evaporation and hence, the facility is normally built in the area within proximity with salt supply (e.g. sea side). It is worthwhile to mention that the largest solar pond operated, Beit HaArava of Isreal with built area of 210,000 m^2 had produced 5 MW of electricity, as a result from the scalability of energy output with the solar pond area, like other selection of renewable energy generation. With a typical efficiency of 20% (Wang & Akbarzadeh, 1982), a solar pond will able to provide 40 W/m^2 of heat at annual average solar radiation of 200 W/m^2.

Meanwhile, the use of thermoelectric generators (TEGs) as a potential source of for both large scale electric powers as well as alternative source for low power generation from the temperature difference created from the heat input at hot and cold junction had been delineated by Rowe that presented in his previous publications (Rowe 1992; Rowe 1994; Rowe 1999). Apart from being environmentally friendly, from the economics point of view, the increase of fuel cost will lead to the demand of alternative mean for power generation. The inclusion of externalities consideration will certainly favour the use of TEGs as a supplement for electrical energy production (Patyk, 2013).

From the review conducted, which will be presented in the forthcoming chapter, a thermal-storage based heat source (e.g. in this study, the solar pond) could be utilised for small-scale electric power generation, despite its usual function as low-grade heat source provider through heat extraction. With the abundant of heat available in the solar pond, electric power can be produced by using the simplest possible method, and in this case, thermoelectric modules which are working under static condition will be favourable for small-scale electric power generation.

1.2 Research Significance

While solar energy is one of the extensive sources of renewable energy that being sought after along with the booming interest exploring greener method replacing the conventional source of energy, solar pond offers both the functions as solar energy collector and solar energy storage. This work will delineate the study on one of the methods for electric power generation using the heat stored from the solar pond using thermoelectric generators (a static device that offers a lifespan of 200,000 hours to 300,000 hours). From the study of physical attribute on solar pond, to the design and fabrication of the electric power generation unit, until the evaluation on the prospect of electric power generation, this work provides a *comprehensive and niche study on an alternative method of electric power generation, particularly to be availed in remote area* where electric grid connection is out of reach, not to mention its environmentally friendly nature of electric power generation in line with developing the application of the renewable energy for the future. While the heat from the solar pond can be the heat source for power generation unit, *the off-pond electric power generation unit conceived, in a broader context, the unit will able to be extended for recovering the waste heat of the high-temperature waste* water from the industry (e.g. steel cooling), or using the hot water accessible from the hot water solar collector. Hence, the off-pond power generation unit designed will able to cater and apply for recovering the waste heat from the water. Nevertheless, the outcomes of this research on the performance of the electric power generation unit can be used as the benchmark or baseline study for the application of power generation using thermoelectric modules, aiming to avail consulting engineer in the decision making on project implementation, in view of the possible advancement of TEGs' performance in the future.

1.3 Research Rationale

Different methods have been used for the electric power generation with solar pond such as the use of organic Rankine cycle to power a turbine for power generation. Recent work carried out by Singh et al. (2011) had shown that the electric power generation with the exclusion of bulky devices such as boiler and turbine can be achieved by integrating the thermosiphon and thermoelectric modules. The main motivation that drives this study is to achieve an electric power generation system design that is fully passive, low cost, reliable and simple.

To date, there exist knowledge gap on assessing the feasibility of the power generation from salinity gradient solar ponds using thermometric generators via both fully passive design and active design. Certainly, this study will provide the insight on how much cost and electrical output one should expect from thermometric generators via fully passive design as well as active design. This work will delineate a thorough methodology on assessing a novel electrical power generation design starting with the conceptual design, to the fabrication and performance assessment of the proposed system.

1.4 Scope

The intent of this work is not to sensationalize sustainability or disseminate it as an elixir that can remedy all development and environmental concerns, but rather to realistically address a single question: “Will the synthesis of solar pond and thermoelectric generators creates an auspicious alternative for electric power generation, particularly in a remote area?”

In light of the concern stated, the scope of this work will concentrate on the modelling, design and the testing of an innovative electric power generation using the heat available from the solar pond. As the overall reliability and verification of the SP-TEGs system require an on-site installation and undergo long-term field test (which could possibly at least a year). Thus, this scope was not covered in this thesis.

1.5 Objectives

i. To examine the prospect of electric power generation by using solar pond with thermoelectric generators.
ii. To develop thermoelectric power generation unit for electric power generation using the heat available from the solar pond.
iii. To provide an insight on the economics feasibility on electric power generation using low-grade heat from the solar pond.

1.6 Research Questions

i. How will the commercially available thermoelectric modules perform under the operating temperature of solar pond and the reliability of the thermoelectric module?
ii. How much electrical power generation one should expect from the proposed system annually, e.g. per m^2 solar pond? How will the proposed electric power generation systems perform under solar pond build in different climate condition (i.e. different region in the world) and/or different solar pond design parameters?
iii. Under limited number of thermoelectric modules (i.e. limited expenditure), for a given dimension of the solar pond as well as certain temperature profile (heat source), what kind of configuration of power generation unit in plate type design will result in maximum electric power generation with minimum amount of cooling water usage? Also, how much output power we could expect?
iv. For small scale electric power generation, what are the design parameters that will contribute to the optimal design of electric power generation using solar pond at lower convective zone with fully passive design and how do the parameters influence the system performance?
v. Furthermore, in line with research questions (ii–iv), in economics point of view, what is the cost and benefit for the system with the given size? Is the design both performance and economically feasible to be extended for large scale power production?

The research questions are constructed and refined in such a way that the research questions (i) and (ii) are linked to objective (i), research questions (iii) and (iv) are linked to objective (ii) and finally research question (v) is linked to objective (iii). There are strong originalities in this work and RMIT is the pioneer in trying to study the combined SP-TE system. As a result, the completion of this study will lead to one publication from each of the five research questions addressed, which are presented through a series of publication and incorporated as Chapter 3 to Chapter 7 in this thesis respectively.

1.7 Original Contributions

The original contributions in this work through the series of publication included in this thesis are listed as follows:

i. Delineated a method of continuous electricity generation from solar energy without the use of a battery.
ii. Theoretical modelling of the transient thermal performance of solar pond under heat extraction mode for various climatic conditions along with validation.
iii. Evaluated the full potential of solar pond-thermoelectric power generation under various climatic condition and heat extraction modes.
iv. Established the range of thermal-electric conversion efficiency of the solar pond-thermoelectric system as a rule of thumb.
v. Evaluated the performance and reliability of commercially available thermoelectric cells for power generation under continuous and thermal cycling operation.
vi. Modelled, designed and tested an open channel plate type thermoelectric modules-embedded power generation unit operating at atmospheric pressure.
vii. Evaluated the performance enhancement of plate type power generation unit with copper mesh insertion.
viii. Modelled, designed and tested a passive syphon-based multilayer power generation module with solar pond.
ix. Established the feasibility of solar pond-thermoelectric power generation.

1.8 Publication List and Thesis Structure

The publications listed below have been *peer reviewed and published* as the first author:

i. **Ding, L.C.**, Akbarzadeh, A. and Date, A., 2016. Performance and reliability of commercially available thermoelectric cells for power generation. *Applied Thermal Engineering*, 102, pp.548-556. (As Chapter 3)

ii. **Ding, L.C.**, Akbarzadeh, A. and Date, A., 2016. Transient model to predict the performance of thermoelectric generators coupled with solar pond. *Energy*, 103, pp.271-289. (As Chapter 4)

iii. **Ding, L.C.**, Akbarzadeh, A. and Date, A., 2016. Electric power generation via plate type power generation unit from solar pond using thermoelectric cells. *Applied Energy*, 183, pp.61-76. (As Chapter 5)

iv. **Ding, L.C.**, Akbarzadeh, A., Date, A. and Frawley D.J., 2016. Passive small scale electric power generation using thermoelectric cells in solar pond. *Energy*, 117, pp. 149-165. (As Chapter 6)

v. **Ding, L.C.**, Akbarzadeh, A., Singh B.,and Remeli M.F., 2017. Feasibility of electrical power generation using thermoelectric modules via solar pond heat extraction. *Energy Conversion and Management*, 135, pp. 74-83. (As Chapter 7)

The work listed below has been *submitted and under review* for publication (fully integrated as Chapter 2-Literature Review):

vi. **Ding, L.C.**, Akbarzadeh, A. A Review on Solar Pond for Power Generation and Its Alternative with Thermoelectric System. *Renewable & Sustainable Energy Reviews*.

This thesis was structured by using “thesis with publication” method. This thesis is started by the Introduction section (as Chapter 1), followed by Literature Review section (as Chapter 2), and then Chapter 3 to Chapter 7 with the publications as listed above in ordinal. Finally, the conclusions (both general and specific) and recommendation are presented in Chapter 8. As the bibliography of the references for Chapter 2 to Chapter 7 is readily available in the journal published, *only the list of references for Chapter 1 is provided at the end of Chapter 1*.

1.9 Expected Deliverables

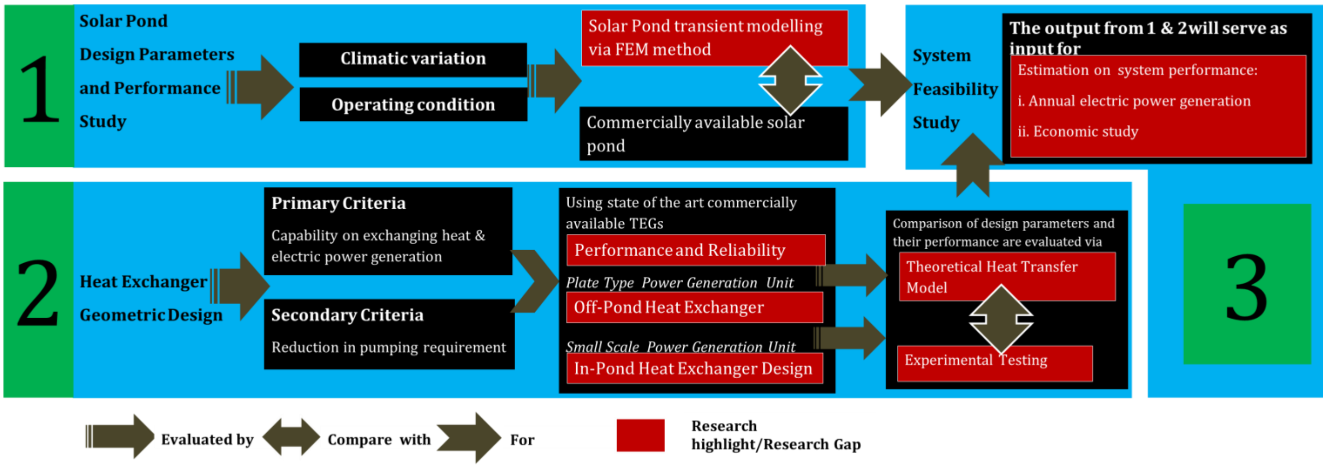

Fig. 3. Schematic of research framework.

The framework for this research work is delineated in Fig. 3. Consequently, following workflow is adopted in order to achieve the objectives and comply with the framework.

i. *Thermal and electrical characteristic testing of thermoelectric cells*

Thermal and electrical characteristic were modelled and studied in order to perform theoretical modelling and parametric study of the heat exchanger in stage (iii and iv).

ii. *A transient modelling on the solar pond on the solar pond's performance*

The thermal performance of the solar pond was studied by using finite element method. The finding established will be used to predict the annual performance of the solar pond, which includes the performance in terms of thermal performance as well as the prospect of annual electrical power generation using the solar pond.

iii. *Electric power generation using solar pond with off-pond heat exchanger design*

The concept of a plate type heat exchanger was explored by incorporating thermoelectric cells. Heat exchanger design was optimised by taking into the account the dimensions of the heat exchanger, the flow rate of the system, the gap between hot and cold plates. The design selection will base on the consideration on maximum net power and maximum specific power of the system. An experimented test rig was built and fabricated according to the optimised design in order to verify and to compare with the theoretical model.

iv. *Electric power generation using solar pond at lower convective zone with fully passive design*

A submersible type siphoned based heat exchanger will be conceived for the in-pond small-scale electrical power generation. Different polygon geometry will be explored for both the outer and inner tube. Since this method requires no pumping power, hence the design with maximum output and minimum volume are most desirable. This fully passive design will further extend to the fabrication of the test rig as proof to the concept developed.

v. *Amalgamating the annual performance of solar pond and prototype performance to estimate annual system performance in conjunction with economics analysis*

The outcome from the stage (ii) will combine with the outcome from the stage (iii and iv). The ultimate outcome when reaching this stage is, for a given annual solar insolation data, the annual power generation from the system can be estimated. Besides, the work performed at this stage will provide two main desired which are the cost of electricity and carbon dioxide emission reduction.

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Chapter 2: A review on power generation with thermoelectric system and its alternative with solar ponds

A copy of the manuscript submitted is attached following the end of this thesis.

Chapter 3: Performance and reliability of thermoelectric cooler for power generation

Published As: Ding, L.C., Akbarzadeh, A. and Date, A., 2016. Performance and reliability of commercially available thermoelectric cells for power generation. *Applied Thermal Engineering*, **102**, pp.548-556. doi:10.1016/j.applthermaleng.2016.04.001
http://www.sciencedirect.com/science/article/pii/S1359431116304847

Chapter 4: Transient model to predict the performance of thermoelectric generators coupled with solar pond

Published As: Ding, L.C., Akbarzadeh, A. and Date, A., 2016. Transient model to predict the performance of thermoelectric generators coupled with solar pond. *Energy*, **103**, pp.271-289. doi:10.1016/j.energy.2016.02.124
http://www.sciencedirect.com/science/article/pii/S0360544216301864

Chapter 5: Electric power generation via plate type power generation unit

Published As: Ding, L.C., Akbarzadeh, A. and Date, A., 2016. Electric power generation via plate type power generation unit from solar pond using thermoelectric cells. *Applied Energy*, **183**, pp.61-76.doi:10.1016/j.apenergy.2016.08.161.
http://www.sciencedirect.com/science/article/pii/S0306261916312703

Chapter 6: Passive small scale electric power generation using thermoelectric cells in solar pond

Published As: Ding, L.C., Akbarzadeh, A., Date, A. and Frawley D.J., 2016. Passive small scale electric power generation using thermoelectric cells in solar pond.*Energy*, **117**, pp.149-165.doi: 10.1016/j.energy.2016.10.085
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Chapter 7: Feasibility of electrical power generation using thermoelectric modules via solar pond heat extraction

Published As: Ding, L.C., Akbarzadeh, A., Singh B.,and Remeli M.F., 2017. Feasibility of electrical power generation using thermoelectric modules via solar pond heat extraction. *Energy Conversion and Management*, **135**, pp. 74-83.doi: 10.1016/j.enconman.2016.12.069
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Chapter 8: Conclusion & Recommendations

8.1 Conclusion

8.1.1 General

This thesis had presented a comprehensive study on the potential of electric power generation from the solar pond using thermoelectric modules. The work had been started by evaluating the suitability of commercially available Peltier cells in terms of performance and reliability for power generation. Upon the confirmation of its applicability, the tested performance of the TECs was used in the estimation of the transient performance of the TECs operate with the solar ponds (SPs). A validated transient heat transfer model was coupled with the actual performance of the TECs in order to have a good estimate of the potential (i.e. upper limit) of the SP-TE system. Then, the evaluation of the SP-TE system was subjected to experimental testing after the design optimisation. Two different designs had been conceptualised and realised, which were in the plate type counter flow configuration and also submersible power generation unit. Overall, the SP-TE system is infeasible for large-scale application and hence SP-TE system is only suitable for auxiliary electrical supply. The specific conclusion to the research questions is as in the following subsection.

8.1.2 Specific Answers to Research Questions

- *How will the commercially available thermoelectric modules perform under the operating temperature of solar pond and the reliability of the thermoelectric module?*

This research question has been addressed in the publication corresponds to Chapter 3. In the first part of the testing on commercially available thermoelectric cell (normally used for cooling application), it provides a direct answer on the thermal resistance, thermal-electric conversion efficiency and the estimation of the electric output of power generated by the cells that will be embodied in the heat exchanger in terms of the temperature difference, ΔT across the TEC. On average, a commercially available TEC is able to convert the thermal heat supplied to electricity at conversion efficiency in the vicinity of 8.67% of its Carnot efficiency. Also, it had been shown that, exposing the cells at high temperature for prolonged period should be avoided since it eventually leads to a permanent reduction of the electrical output generated. Furthermore, from the testing conducted, commercially available TECs tested are reliable to be used under thermally cycled hot side temperature < 90 ºC and cooled at ambient temperature, for at least 500 cycles as tested. However, one may encounter TECs malfunction when the TEC is exposed to a thermal cycling to a hot temperature in vicinity of 150 ºC.

- *How much electrical power generation one should expect from the proposed system annually, e.g. per m^2 solar pond? How will the proposed electric power generation systems perform under solar pond build in different climate condition (i.e. different region in the world) and/or different solar pond design parameters?*

This research question has been addressed in the publication corresponds to Chapter 4. In order to address this research question, various considerations had been explored, which include the effect climates, the possibility of manipulating the rate of heat transfer to optimise the generation of electrical power as well as the effect of temperature polarisation on the performance of the system. The solar pond that operates in Riyadh (Bwf) will perform the best, followed by Granada (Csa), while the solar pond in Kuala Lumpur (Af) and Melbourne (Cfb) will have almost similar performance in generating electricity. For a typical SP with UCZ, NCZ and LCZ thickness of 0.2 m, 1.0 m and 1.0 m, respectively; the theoretical performances of the SP-TE system in terms of electrical energy at the above-mentioned location with a typical 15% of annual average horizontal solar radiation are: Riyadh (4.834 kWh/year-m^2), Granada (3.173 kWh/year-m^2), Kuala Lumpur (2.498 kWh/year-m^2) and Melbourne (2.412 kWh/year-m^2). Even though the thermal-electrical conversion efficiency η_t is in the range of 1% – 1.5% from the heat extracted, the unconverted thermal energy extracted (which is about 98.5% – 99%) could be beneficial for any industrial process that requires low grade heat source from solar pond.

- *Under limited number of thermoelectric modules (i.e. limited expenditure), for a given dimension of the solar pond as well as certain temperature profile (heat source), what kind of configuration of power generation unit in plate type design will result in maximum electric power generation with minimum amount of cooling water usage? Also, how much output power we could expect?*

This research question has been addressed in the publication corresponds to Chapter 5. In order to address this research question, a proof of concept on the electric power generation by TECs with solar ponds had been carried out experimentally and operated under different conditions. The plate type power generation unit (PTPGU) proposed was subjected to an open channel flow, which consists of 20 plates with 25 TEGs (at 5 × 5 arrays) as a result of the optimisation along with estimating the electric output using the performance curve of single TEC. The PTPGU fabricated was then tested after ensuring a good flow distribution via visualisation. From the testing conducted, electrical power output of 35.9 W was generated under the condition of $\dot{V}_c$ =18.5 LPM and $\dot{V}_h$ =5.1 LPM at the temperature of $T_{c,in}$ =25 °C and $T_{h,in}$ =81 °C, which corresponds to 0.43% thermal to electrical conversion efficiency and power density of 3.3 kW/m^3. The flow rates tested in the experiments are within the regime of laminar flow (achievable by using the supply from the main without the use of pump), hence there will be no significant different or improvement due to the flow increment within this regime. It had been shown that the theoretical model proposed is adequate to predict the performance of the PTPGU after comparing the performance of the PTPGU obtained experimentally with the theatrical prediction. Furthermore, it has been shown that, small degree in performance enhancement of the PTPGU is possible through copper mesh insertion. A separate test on the PTPGU shows that, the water head requirement is about 0.4 mH_2O (4 kPa) in delivering 4.5 LPM for each channel, which was tested at twice the maximum flow rate of the testing result presented. The head required is much lower than regulated maximum water supply pressure under building regulation, which is around 5.0 mH_2O (e.g. plumbing code of Australia).

- *For small scale electric power generation, what are the design parameters that will contribute to the optimal design of electric power generation using solar pond at lower convective zone with fully passive design and how do the parameters influence the system performance?*

This research question has been addressed in the publication corresponds to Chapter 6. In order to address this research question, an immersive type power generation unit (PGU) was devised. The unit is expected to be submerged in the LCZ of the solar ponds, and the cold water at the UCZ is circulated through the PGU with the use of siphoning action. Beginning with the theoretical modelling, the estimated performance for different geometries at varying gap size and the flow rate was studied. Based on the outcome derived from the theoretical study, a PGU with Q-Q configurations was selected, due to its simplicity and there is no significant different on the geometry selection to its maximum performance. In order to include a higher number of TECs in the PGU, a dual layer PGU was fabricated in this work. From the tests conducted, additional 67% of the number of TECs at outer layer into inner layer will generate extra 44% of output power. The PGU produced a maximum power of 40.8 W under the condition of T_h =99 ºC. Realistically, under the normal operation of solar ponds, the LCZ will have a temperature lies in the range of 40 ºC – 80 ºC. Thus, maximum output in the range of 19.5 W – 27.4 W is more realistic for this SP-TE system proposed with the heat to electric conversion efficiency ranges between 0.37% – 0.68 %.

- *Furthermore, in line with research questions (ii-iv), in economics point of view, what is the cost and benefit for the system with the given size? Is the design both performance and economically feasible to be extended for large scale power production?*

This research question has been addressed in the publication corresponds to Chapter 7. The feasibility study of the SP-TE system was analysed in different operating climate condition, which are Group A, B, and C of Köppen climate classification represented by Kuala Lumpur, Riyadh, Melbourne, and Granada. The feasibility study was based on the combination of a verified theoretical transient model for SPs and experimentally tested TE system. The cost of this system was analysed in terms of area per unit power, giving the flexibility in the sizing of the system. Furthermore, since the itemised cost of the SPs was presented, it provides the reader with the information on the practical costing for the solar pond. Later, the energy cost of the SP-TE system by considering its lifetime operation as well as the carbon emission reduction by the operation of SP-TE system was analysed and discussed. Overall, the SP-TECs system is at least 10 times costly compared with other renewable energy sources solar PV system with storage at the cost of \$5.4/ kWh_e for ideal case and of \$41.9/ kWh_e for the practical case. The lowest cost of \$5.4/ kWhe presented was based on (tested) conservative efficiency ratio with r =8.85%. If the thermoelectric module used has a *ZT* value of 1.3, then it is equivalent to efficiency ratio of 20%. With the increase of electrical power generated, the lowest cost of the system will reduce by 2.25 times, to \$2.4/ kWh_e. This value suggests the SP-TE system is not a profitable mean for large power generation; rather, it serves as an option of electricity generation in meeting limited electrical energy demand. Also, this study provides the insight on the potential of the SP-TE system and reveals that, under its best operating climate (which is Riyadh), this system will able to achieve annual CO_2 reduction of 2.38 kg/m^2-year in practical case.

8.2 Recommendations

As the SPs possess a limited range of hot water temperature in the LCZ, it limits the widespread of the SP-TE system. Hence, it is viable to embrace another type of heat source that utilise solar energy for higher output power and conversion efficiency such as augmented solar collector. The SP-TE system is a viable option for small scale electric power generation and as found from this work, submersible power generation unit will be able to generate adequate electric power to power some on-site facilities (such as lighting) that require a relatively small amount of electric power. However, this study has not addressed the long term reliability of this system when the TECs operate in the hot saline condition in LCZ. Thus, this opens another research question that can be investigated further. SP is a reliable supply of low-grade heat. Generating the electricity from the heat available by using certain mechanism (such as ORC, or TECs as in this study) will result in the diminishing of overall system efficiency (from incoming solar radiation to electric output) since the overall system conversion efficiency is the product of SP's efficiency and thermal to electrical conversion efficiency of the mechanism adopted. Put it the other way around, despite generating electricity from the SP directly, research can be explored on how the heat from the SP can be used for reducing heating demand for the particular heating process. It will able to reduce the electricity consumption and indirectly 'generated' positive balance of electric supply.

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A Review of Power Generation with Thermoelectric System and Its Alternative with Solar Ponds

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Highlights

- A review of the recent research of thermoelectric generators is presented.
- The research on the solar pond as a heat source is discussed.
- Power generation with thermoelectric generators and solar ponds is possible.

Abstract

By using the Seebeck effect to produce electrical voltage, thermoelectric as a highly scalable, stationary and silent heat engine has undergone a state of vigorous research. Starting with the review on thermoelectric generators, it shows that thermoelectric is gaining more attention since the past decade. Generally, the research conducted on the thermoelectric generators concentrate on the material development, mathematical and numerical model development as well as the application of thermoelectric generators. For this article, attention is given to the application research of the thermoelectric generators. From the survey conducted, most of the application research carried out is based on intermittent electrical power generation (e.g. the direct use of solar energy available or waste heat recovery). Hence, it opens an opportunity for the research on the application of thermoelectric generators by utilising a heat source that is continuously ready for thermal-electrical energy conversion, such as phase change material, geothermal heat or solar pond. In the later section, the review is continued by introducing solar pond, a facility that has been used as a supply of low-grade heat source at the remote area or industrial process heating. The research on the fundamentals of solar pond and its applications, but not limited to, the power generation has also been summarised. The ultimate idea of this review is to provide an insight that a thermal-storage based heat source (e.g. in this review, the solar pond) could be useful for small-scale electric power generation, despite its ordinary function as low-grade heat source provider via heat extraction.

Keywords: Renewable energy; Power generation; Thermoelectric; Solar energy; Solar pond

1. Introduction

Countries around the globe have been aware of the rise in global average temperature and start to implement energy policies that will hopefully curb the temperature rise below 2° C at the end of the century. Some researchers have argued that the notion of global temperature rise is invalid and using the temperature rise as an ‘achievement indicator’ is futile due to its incapability in fathoming human activities that undermining the earth [1]. The Kyoto Protocol set up in 1997 aimed to reduce the emission of greenhouse gasses with an average cut around 5% relative to 1990 levels by 2012. Seemingly, not all of the countries with the binding target successfully achieve the aim and overall, the change in the global CO_2 emission had increased by 11.3 GT from 1990 to 2011, with China and other developing countries contribute the most increment in CO_2 emission. It was only in the recent COP21 meeting at Paris, a clear binding agreement in reducing the in CO_2 emission and aiming to keep the temperature rise at 1.5°C in the end of the century. Clearly, in order to achieve the mission, there is a need to speed up the move to low carbon electric producing technology and preferably renewable energy. The selection of technology in implementing renewable energy power supply is depending on the types green resource that is conveniently available due to geographical advantage, human resources or technological resources that a country readily advanced. With the abundance of heat available, either from the sources that are freely available such as solar energy, geothermal energy or unutilised energy in the form of waste heat. This paper begins with a review on the thermoelectric generators (TEGs), a device that producing electric power as a result temperature difference through the flow of heat with the focus on recent development of TEGs’ application. Current development on the thermoelectric materials is impeded by thermoelectric figure of merit, ZT. Unless there is a quantum leap in the breakthrough of , otherwise thermoelectric technology in driving a primary role in the electric source is impossible and it will remain as an supplementary technology that enhances the performance of current renewable energy power generation. Then, in the later part, the review of the solar pond, a facility that collects and stores solar energy is delineated. Realising the electrical storage-based system (i.e. the use of batteries at the post-electric generation stage) will be the most commonly adopted method for the long term power storage. Overall, through this review, the authors would like to introduce the option of thermal storage-based electric power generation system using TEGs.

2. Thermoelectric Generator (TEG)

The use of TEGs as a potential source of for both large scale electric powers as well as an alternative source for low power generation had been delineated by Rowe that presented in his publications [2, 3]. From the life cycle analysis conducted, apart from being environmentally friendly, from the economics point of view, the increase in fuel cost will lead to the demand of alternative mean for power generation. The inclusion of externalities consideration will certainly favour the use of TEG as a supplement for electrical energy production [4].

2.1 Properties, Material, Structure, and Characteristics

Dueto the existence of temperature gradient, the TEG's operation is based on Seebeck effect and Peltier effect. The former phenomenon, refers to the relation between thermoelectric potential under open circuit condition and the temperature difference is correlated by the Seebeck coefficient, α (V/K). Hamid Elsheikh et al. [5] in the recent review described the important parameters that govern the performance of the thermoelectric cells. The authors analyse the parameters from the viewpoint of thermoelectric properties and material properties, and extended the discussion on the life expectancy of the thermoelectric cells. They strongly believed that the study on the relation of both electrical and thermal conductivity is the key for improving the performance of thermoelectric cells.

There are different materials available for TEG in order to cater a different range of operating temperature. Different categories of materials had been explored, such as ceramics [6], alloys [7], bulk material [8], complex crystals, oxide materials [9, 10], nano-composites. Table 1 summarises the TEG materials, working temperature as well as the *ZT* value of these materials.

Table 1

TEG materials and its performance [11-13].

Operating Temperature, °C	Type	Materials	Maximum *ZT*
<150	p	$Bi_{0.5}Sb_{1.5}Te_3$	1.4
	n	$Bi_2Se_{0.3}Te_{2.7}$	1.0
	p,n	Bi_2Te_3	0.8
150-500	p	Zn_4Sb_3	-
	p,n	PbTe	0.7-0.8
	p	TeAgGeSb	1.2
500-700	p	$CeFe_4Sb_2$	1.1
	n	$CoSb_3$	0.8
700-900	p,n	SiGe	0.6-1.0
	p	LaTe	0.4

From Table 1, it is clearly seen that under current development, the BiTe-based material is the most suitable commercially available material to suit the need of recovering low-grade heat (<150°C). Although the TEGs operate base on the temperature difference across its hot and cold junction, there exists a difference in maximum electric power in spite of the fact that the temperature difference across the junction remains constant, since the specification of temperature difference gives two degrees of freedom for the values of cold and hot temperature. Specifically on Bi_2Te_3, which operates at temperature <150°C, for a fixed temperature, there exist both upward and downward concavity in the graphs of maximum power versus mean temperature (average of temperatures at the hot and cold junction). In the other words, in order to achieve similar maximum power output, for a given fixed temperature difference, the number of thermoelectric cells needed varies [14]. For the middle and high range of temperature, research had been carried out in the searching and characterisation of new thermoelectric materials [15] and reducing the cost for TEG [10].

2.2 Mathematical and Numerical Model Development of TEG

In the mathematical modelling of the TEG, often the heat transfer between the TEG and its environment are modelled by Newtonian heat transfer law with the heat transfer rate, $\dot{Q}$ is directly proportional to the temperature difference, ΔT. In order to take into account the thermodynamics irreversibility of TEG, Chen et al. [16] developed an advanced model of TEG by considering the irreversibility characteristic of TEG. The five heat transfer laws under consideration were Newtonian, linear phenomenological, radiative, Dulong-Petit as well as special complex transfer law. The study showed, external heat transfer model using Newtonian law yield highest efficiency and power output compared the other four heat transfer laws, and external heat transfer models considered will vary working electrical current that results the optimum operating condition of TEG. Besides, Montecucco et al. [17] proposed the solution to the 1-Dimension transient heat conduction equation by incorporating the internal heat generation of TEG. As a result, without fixing the hot side and cold side temperature of the TEG, the transient characteristic of TEG can be evaluated.

With the advancement of the computational method, TEG model can be accurately simulated [18,19]. When the TEG is exposed to the heat source with a temperature difference, the device is undergoing transient state before the thermal and electrical dynamically stabilise. Peltier, Seebeck, Thomson, and Joule are the main effects that taking place in the TEG. Montecucco and Knox [20] modelled the response of TEG under the changing operating condition by using a computer aided model. By taken into account of the important thermoelectric effect such as Joule heating and Peltier effect, the computer model developed will able to predict the TEG response in high accuracy. Although the model did not include the Thomson effect, however, according to Nguyen and Pochiraju [21], Thomson effect is significant in giving impact on the power generation rather than the thermal behaviour of the TEG.

2.3 Recent Development on TEGs' Application

The TEG can be integrated into various systems, such as, but not limited to heat exchanger system, exhaust gas heat extraction, solar heat extraction, industrial waste heat recovery, or couple with other renewable energy sources, e.g. solar photovoltaic system, forming a hybrid system for better power conversion efficiency as delineated by Kreamer et al. [22]. TEG may also be used for electricity generation for terrestrial application by using optical concentrator and solar absorber with wavelength-selective surface [23] or generating electricity from human body heat with the aid of heat sink [24, 25]. Although the use of TEG for remote area power supply is far away to be realised. However, it had been shown from the experimental study that the use of TEG in powering autonomous sensor at the remote area is feasible [26]. The innovative design of heat exchanger for electric power generation using TEG had been conducted. Different design of heat exchanger were considered: (i) roll cake type heat exchanger; a helical flow system, (ii) cylindrical multi-tubes design; including counter flow, parallel flow and isothermal heat exchanger [27-29].

2.4 TEG in Solar Heat Extraction System

As a source of green energy, solar energy can be utilised to generate electricity through the photovoltaic panel, space heating, or solar thermal energy storage via the solar collector. The research on generating electricity with TEG by harvesting the solar energy was mainly conducted base on the concentration of solar radiation in order to achieve higher hot side temperature for higher conversion efficiency. The sunlight concentration was either achieved via parabolic concentrator [30] or with the use of a lens to focus the light beam at the hot surface of the TEG. Besides using lens to increase the hot side temperate of the TEG, the performance of the TEG can be further enhanced by concentrating the thermal energy to the TEG with the use of a thermal absorber, thermal collector or in the recent study, the use of carbon nanotubes sheet to absorb the solar energy [31]. In 2011, the NanoEngineering research group from MIT made a breakthrough in the development of flat-panel solar thermoelectric generator with high thermal concentration at high performance. The solar TEG (STEG) system (shown in Fig. 1) was conceived to capture the heat resulted from solar radiation and serve as the heat source for TEG to generate electric power. The theoretical study [32] of STEG had been established and according to Chen, the efficiency of the STEG is depending on both opto-thermal efficiency and the TEG efficiency, the improvement in the hot side temperature will favour the increasing of TEG efficiency [33] but such increment will cause a reduction in the opto-thermal efficiency of the STEG. Hence, according to the model, there exists an optimum point of hot side temperature for maximum system efficiency. Subsequently, for low-grade heat for electric power generation, using the commercially available TEG with Bi_2Te_3 in STEG system will able to achieve efficiency greater than 5%, theoretically. With the same layout as depicted in Fig. 1, Kraemer et al. [34] conducted the experimental study on the STEG system and verified that such system can achieve an efficiency at a record-breaking 7.4% with concentrated solar irradiance of 211kW/m^2 With the advancement of the figure of merit, ZT of the thermoelectric material, the STEG efficiency can be improved further. The research on the STEG had been studied theoretically in terms of exergetic analysis [35, 36], geometrical optimisation [37] and performance estimation through finite elements computational modelling [38, 39]. Also, The operation of STEG ($Si_{80}Ge_{20}$) at high concentration ratio (>100) and high temperature (>450 °C) had been modelled and validated by Pereira et al. [40].

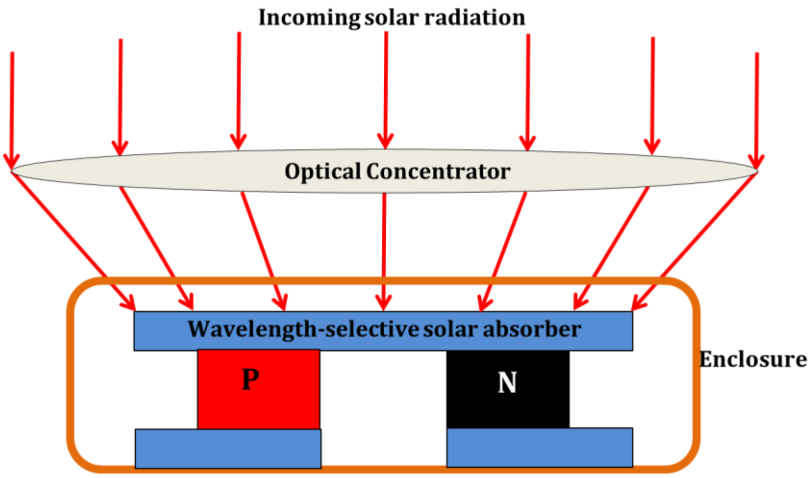

Fig.1. The STEGsystem.

Furthermore, Tayebi et al. [41] suggested a potential improvement of the planar thin film thermoelectric devices for solar power generation through the deposition and patterning of thermoelectric layers and the substrate coating selection. The study of introducing spectrally selective high-temperature absorber coating (which is stable up to 512°C) on the STEG had been investigated by Candadai et al.[42]. Their study illustrated that a conversion efficiency of 4.7% can be achieved in their STEG system at hot side temperature of 300 °C and cold side temperature of 30°C for commercially available Bi_2Te_3 TEG of $ZT = 0.4$. So far, at a conversion efficiency of 3%, the work conducted by Amatya and Ram [43] is the highest efficiency reported by using commercially available Bi_2Te_3 modules under optical solar energy concentration of 66 suns. However, the alleged performance of the aforementioned studies should be subjected to further justification via a long term operation at hot side temperature of 300 °C since previous study conducted by Ding et al. [44] indicates that at continuous operation at hot side temperature > 200 °C will result in the degradation in the performance of the comercially available Bi_2Te_3 thermoelectric module. For improving the performance of STEG system, minimizing the heat loss through maintaning a vacuum condition in the enclosure of the STEG system is equally important. The effect of the enclosure pressure on the performance of STEG had been addresed in the publication by Sudharshan et al. [45]. It is worthwhile to mention, for microscale electric power generation to power devices with low input power such as wires sensors, flexible thin film STEG by using BiTe as base material had also been researched recently [46, 47].

The application research of concentrating the sunlight using Fresnel lens coupled with TEG had been reported by Olsen et al.[48] and Nia et al. [49]. The system investigated by Nia et al. is shown in Fig. 2. In contrast to the use of a flowing working fluid (usually water) to provide the cooling at the cold side of TEG, Date et al. [50] carried out an experiment by using different cooling approach as depicted in Fig. 3. In the system proposed, heat pipes were being used to transfer the heat to a water tank, which in turn, the heated water in the hot water tank is ready for domestic consumption. As heat pipe is an efficient heat transfer device that possesses high thermal conductivity and hence has the potential to improve the heat transfer performance of the STEG system. In addition to the study carried out by Date et al., theoretical [51] and experimental study [52] had been carried out to explore the system with STEG-heat pipe combination.

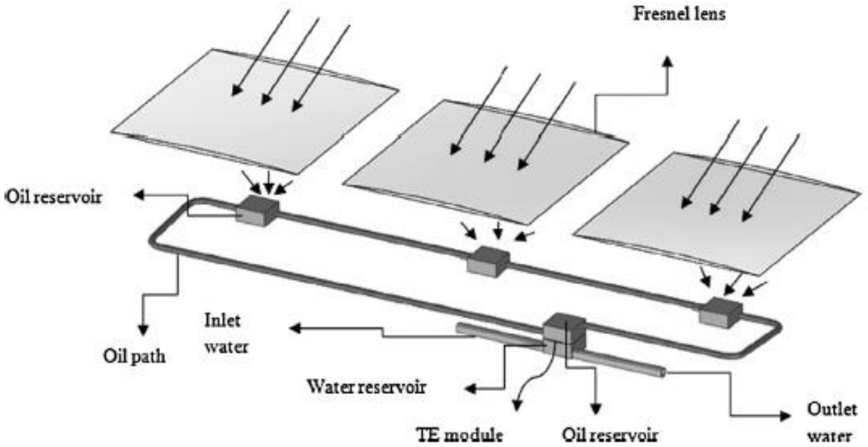

Fig.2. The cogeneration STEG system using the thermoelectric module and fresnel lens [49].

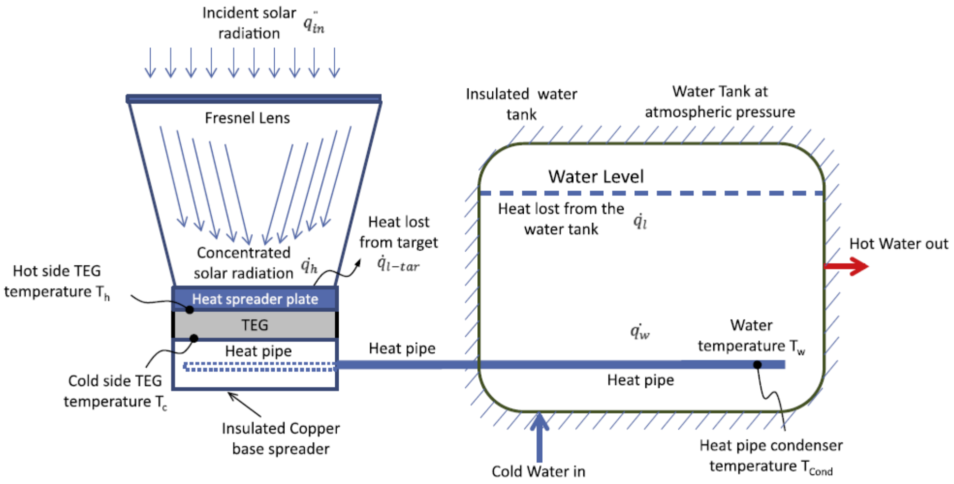

Fig.3. The heat pipe cooled thermoelectric generators using concentrated solar thermal energy [50].

With the concentrated solar radiation and a vacuum environment that reduce the heat loss to the surrounding, the investigation had been carried out for incorporating the TEG into solar evacuated tube to achieve the functions as both hot water supply and generating electric power. Dai et al. [53] through their experimental study, investigated the possibility of generating electric from the solar hot water system with the additional aid of a parabolic concentrator as shown in Fig. 4. Introducing the TEG into the solar evacuated tube requires careful consideration since the high resistance across the thermoelectric elements is a favorable condition for the operation of the TEG. However, imposing the high resistance from the TEG on the solar evacuated tube will detriment the performance of the solar evacuated tube since least thermal resistance is desired for the heat transfer in the solar evacuated tube.

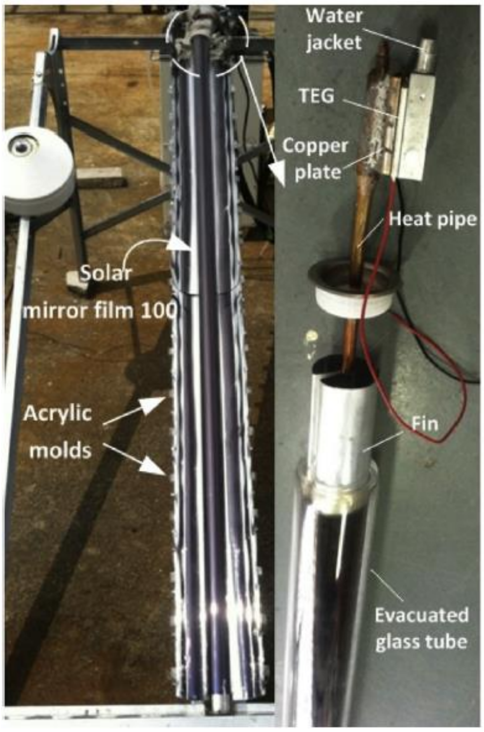

Fig.4. Mini-CPC hybrid STEG unit [53].

In order to maximize the net electric power output generated by the TEG system, ideally the need of external pumping for the cooling of the system should be avoided. Furthermore, the amount of electric power generated from the solar evacuated tube relies on several environmental factors such as solar insolation that location dependent [54], atmospheric temperature [55] and wind speed. The influence of parameters mentioned earlier on the performance of the TEG system has been addressed by Li et al. [56]. Generally, higher solar insolation is beneficial since this will improve the conversion efficiency of the system, although thermal losses are greater at higher solar insolation. Meanwhile, the study concluded concluded that the increase in the wind speed and environmental temperature possess a negative effect on the performance of this system. On the flip side, the importance of the existence of wind in providing the cooling of the TEG to improve the performance of the TEG has been demonstrated by Moraes et al. [57] since in this study, the wind serves as an important mean to dissipate the heat at the cold side of the TEG.It had also been shown that, still air will result in extremely low electric power generation and by introducing the wind at even relatively low speed (<1 m/s), it will result in a steep increase in the amount of power generated. Similarly, Özdemir et al. [58] designed and tested a TEG-solar evacuated tube system by using a wind chimney to serve as the heat sink with a reported maximum power output of 0.83 W with single Bi_2Te_3 thermoelectric module that consists of 126 junctions.

Moreover, apart from desalinating the water with the use of a solar still, several research had been done in combining the solar still with TEG. A typical design of the solar still-TEG system is presented in Fig. 5, from the experimental work conducted by Shafii et al. [59] with the use of solar evacuated tube. The energy from the condensed vapor was utilised for electricity conversion. Due to the cost consideration, instead of using expensive TEG, thermoectric coolers which have an interchangeable function as TEGs were used.The power generated by the thermoelectric modules (highest value of 1.32W) was used to power the propeller fan in the condensation chamber. As a result of introducing forced convection via the power generated from the TEG, the highest hourly water yield increased from 0.97 kg/m^{2}h to 1.11 kg/m^{2}h.

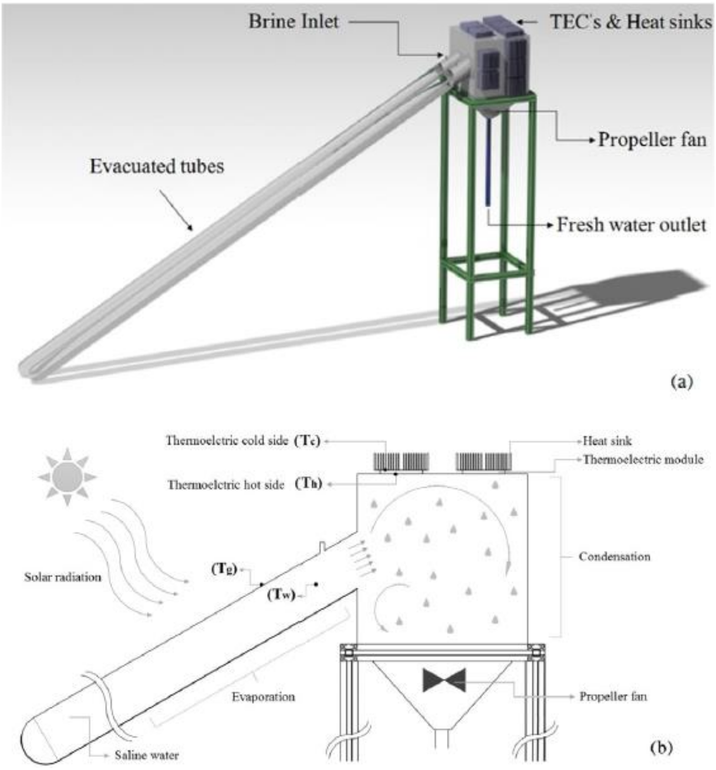

Fig.5. The evacuated tube collectors and thermoelectric modules equipped solar still [59].

Solar photovoltaic (PV) system and TEG have a common aim of generating electricity. Throughout the years, numerous research had been conducted to amalgamate these two systems. Regular crystalline silicon PV system utilise the solar energy in the lower range of wavelength in the radiation spectrum and filters out the radiation in the wavelength higher than 1200 nm in the infrared radiation since radiation at the wavelength higher than 1200 nm is unusable and contributes to the heating of the PV cells. Realising the need of segregating the solar radiation according its wavelength, Li et al. [60] proposed a spectrum beam splitting technique and using the unusable solar radiation energy in PV electric generation for converting it into electricity through TEG. According to the calculation, the system proposed was having a potential of 30% improvement in the output power. However, the improvement is depending on the how the comparison was done. The integration of the PV-TEG will also lead to a poorer performance in terms of efficiency compared with the PV system alone, as discussed by Bjørk [61] after examining recent works conducted in the hybrid PV-TEG system. Theoretical study on the hybrid PV-TEG system had been conducted on the generalized thermodynamic model given by Kwan et al. [62], and analytical model of the PV-TEG system had been developed by Su et al. [63] for their performance optimization study, in addition to the previous work on the general performance optimization methodology published by Kraemer [22]. Current work on the novel PV-TE hybrid system had focused in the photon management, but not limited to the work carried out by Xu et al. [64]. The work presented by Da et al. [65] proposed the photon and thermal management of the PV-TE in order to improve the efficiency of the system. Particularly in the photon management, in order to reduce the reflection loss of the photons, a moth-eye structured surface had been discussed and analysed. For ZnO based dye-sensitised solar cell, Dou et al. [66] demonstrated a Bi_2Te_3/ZnO composite photoanode that will able to convert both photo and thermal energy simultinously at an improved efficiency of 4.27%. In their design, Bi_2Te_3 nanotubes were embeded into ZnO nanoparticles, providing a direct path for the electrons transfer and eventually improving the efficiency of dye-sensitised solar cell.

2.5 TE Power Generation Using Waste Heat

The heat generated during the operation of the equipment will normally be wasted and discharged to the environment. Instead of being disposed, certain amount of heat can be recovered and be used to convert the energy from the waste heat into another form of energy. The analysis of power generation using waste heat had been studied by Wu [67]. Considering a hot junction with 400K and a temperature difference of 100K across hot and cold junction, an ideal Carnot cycle tells us that the efficiency of the system will be at 25% efficiency. However, due to thermodynamics irreversibility, an ideal system for waste heat recovery using TEG could only achieve efficiency of 4% for the boundary condition specified. Without transforming the energy from the waste heat into electrical energy, the energy recovered will able to serve as the energy source for a preheating process, for instance pre-heating in space heating, by the mean of utilising a heat exchanger. Recent prototype study on the use of liquid metal as the medium to transfer waste heat to the TEG showed favourable result and leave a room for future exploration [68]. If the electrical energy is the desired output from the waste heat recovery process, then the use of Organic Rankine Cycle (ORC) or thermoelectric power generation will serve as a candidate for reaching the outcome. For a waste heat recovery system using ORC, working fluid with low boiling temperature and low operating pressure is used, such as R123 refrigerant (which will be phased out under Montreal Protocol). Both of the TEG and ORC can be combined into a system, according to Shu et al. [69] and theoretically, the system can achieve better efficiency compared to using ORC alone. There are several source of low-grade waste heat, for instance from cogeneration process, solar thermal, geothermal, and industrial waste thermal.

Recently, thermoelectric cogeneration system for domestic use had gained attention. Besides the potential for reducing the CO_2 emission, such system is able to perform both electric power generation and pre-heating process for domestic heating [70]. However, to date, the exploration of the application of TEG for domestic purpose is still limited. In order for a TEG to perform well with minimal variation in the amount output power generated, a relatively stable heat source is required. In the residential area, the most common appliance that can serve as the heat source for the TEG is, but not limited to the water heater. The water heater can be either gas-fired type or electric powered or a combination of solar heating. For the case of the gas-fired water heater, Qiu and Hayden [71] conceived a self-powered heating system by the heat generated from the natural gas-fired burner. In their further work [72], the design of the system was improved by preheating the air prior entering the burner with a heat recuperating process. From the study, the total power output generated from the TEG is 1072W, with heat recuperation and a burner operating temperature of 1082°C.

Nuwayhid et al. [73] explored the feasibility of electricity generation using TEG through the heat extraction from the commonly available item in the house-the stove-top, which is beneficial to the area with inconstant power supply. In the study, low cost and simplistic were the main pillar of the design for the system. By using commercially available Bi_2Te_3 modules and subjected to hot side temperature fluctuation of the stove, a 3.3W power production from a bare TEG module (i.e. without insulating wafer) was achievable. Nonetheless, with the option to upgrade the cost of TEG module, 6.5 W of power generation is attainable. On the other hand, Champier et al. [74] found, the use of Bi_2Te_3 modules (which is a combination of four thermoelectric modules) in biomass cook stoves was able to produce 6 W of electricity power to end user, after considering the trade-off of power losses as the result of power conversion.

In the country which the use of geothermal power generation is feasible, the geothermal low power heat can be utilised to serve as the heat source for the electricity power generation using TEG. Some studies had been attempted, on the electricity generation from geothermal heat source using TEG. It included, but not limited to the research carried out on the modelling and geometrical optimisation of the stack, combining the counter flow heat exchanger and the TEG modules [75], or even crossflow heat exchanger [76]. Moreover, it is worth to mention the successful work demonstrated by Sasaki et al. [77] in harvesting the hot spring thermal energy for electrical energy conversion using TEG. With a capacity of generating 900 W of electricity, the prototype fabricated coupled with the hot spring was able to generate 1.927 MWh in 8966 hours of operation throughout one and a half year of field test.

Another source of heat that can be recovered for electric power generation is via automobile exhaust. There were numerous studies had been conducted, for example, Yu and Chau [78] on the waste heat recovery automotive vehicle exhaust since it is one of the medium-high range of waste heat source for TEG application. Tzeng et al. [79] pointed out, besides the temperature difference across the TEG being the main parameter affecting the performance, other factor such as the operating condition of the TEG is crucial for electric power generation for automotive vehicle exhaust heat recovery. Under the operating condition domain, the study focused on the flow rate and the temperature of the inlet hot air as well as the flow rate of cooling air. Besides automobile exhaust as a subject for waste heat recovery for electric power generation, the study had been extended to recovering the heat from internal combustion engine, and the electric power generated is stored in the battery which control method adapted [78]. Low-grade heat can also be recovered from the heavy industry. The possible heat source for recovering the waste heat to generate electricity using TEG are from the furnace in the industry[80].

2.6 On the Performance and Efficiency Improvement of TE Power Generation System

Several designs of test rig were proposed for the performance testing of TEG [81-85]. One of the challenges of the testing and development of TEG was the characterisation of TEG. The main issue lies on the measurement of heat flow, which the heat loss during the process of transferring heat from heat source to the hot side surface of TEG cannot be quantified accurately. As pointed by Rauscher et al. [81], the use of reference material to evaluate the heat flow by measuring the temperature difference can lead to systematic error. Due to the relatively high temperature difference between the heat source (i.e. heater) and the ambient conditions, significant heat transfer via radiation happened. Hence in the efficiency measurement conducted by Rauscher et al. [81], Takazawa et al. [82], Anatychuk and Havrylyuk [83], the research had used a radiation shield around the heat source in order to reduce the radiation heat exchange to the surrounding. After the aforementioned precaution measure was implemented, the calculation for the efficiency should be based on the heat flow at the cold side of TEG, together with the power generated by the TEG.

There are few external parameters that will affect the power generation by the TEG when the TEG is coupling with the exchanger. The parameters such as load resistance, the flow rate of the working fluid and its properties, design of heat exchanger play a significant role in the power generation using TEG. Their respective influence on the power generation had been studied [86, 87]. With the currently available technology, the power conversion efficiency of TEG falls into the range of 5-6%. In order to produce the temperature difference across the thermoelectric modules, often the hot side is attached to a heat source and the cold side is attached to a heat sink. The heat sink can be either air-cooled or water-cooled. An interesting finding discovered by Chen et al. [88] revealed that the water flow rates as well as the flow pattern at the heat sink had an insignificant effect on the power generation of TEG and they further concluded that the heat source is the defining part on giving the TEG better performance. Meanwhile, Gou et al. [89] have different findings, in their study; they concluded that the heat dissipation by the heat sink will provide significant improvement on the TEG performance.

When a TEG is used as a device to generate electricity from the source of waste heat, a good strategy coupled with an efficient design of the heat harvesting system to capture the waste heat is crucial in order to yield a promising electrical output. Hence, optimisation should be performed on the attachment of TEG to the heat source. There were numbers of study performed on the design improvement in order to enhance the heat transfer from the heat source to the TEGs. Lee [90] pointed out those parameters such as the efficiency, power, and geometry of thermoelectric elements as well as the thermal resistance of heat sink were essential in optimising the design. An important conclusion from the dimensional analysis was, for a known heat source and heat sink temperature, there is an optimum design available.

When there is a number of TEGs attached together in order to produce greater power output, the spacing between TEG modules will give significant impact on the density of output power generated. Hence, the spacing between the TEG modules needs to be optimised.

As reported, the used of a spreader, attached between the surface of heat source and the hot side of the TEG will give a better temperature distribution on the hot side of the TEG and by the better temperature distribution, higher power density can be achieved [91]. In any thermofluids, the reduction of energy when the fluid travel downstream due to the heat transfer losses cause the variation on the temperature on a surface where the fluid passing by. When there is arrays of TEGs connected in either series or parallel in order to yield greater output power of the system, such ununiformed temperature profile creates an ununiformed temperature gradient across the TEGs and this means that each TEG will experience different temperature difference across their hot and cold surface. Eventually, this will result in, the significant reduction in the actual output power compared to the predicted maximum total output power. In regards with the aforementioned condition, Montecucco et al. [92] studied the mismatch condition of TEGs, by using 3 TEGs connected in both series and parallel. They summarised, such temperature maldistribution condition can cause significant power loss. However, by comparing the connection in series and parallel, the connection in parallel will cause more power loss compare with the connection in series, due to the fact that the connection in series will able to minimise the Joule heat loss in the system.

Furthermore, in recovering the waste heat from the automotive vehicle, particularly at the exhaust, from the study, it had been shown that, after certain number of TEGs attached in the heat recovery system, the total electric power generated will not increase as desired. In the other words, there will be a reduction of average power generated per TEG, since the “marginal power”, which is the power generated of the last TEG introduced into the system is reduced. Such condition happened, due to the limit of heat available to be recovered, causing the reduction of temperature of exhaust gas as it travels along the exhaust pipe [93]. The aforementioned scenario can be explained theoretically and had been modelled by Gou et al. [94], which stated that there will be a limit of electric power generated even though with the increasing area of cold side heat exchanger. Although logic tells us that more power can be produced if there are more TEGs being used in electric power generation using TEG, however, there exists a room for optimisation by altering the occupancy rate, which is was defined by Faveral et al. [95] to produce highest electric power using genetic algorithm. For the cases studied, maximum power was achieved when the TEGs do not occupy the whole range of hot side of heat exchanger, which is in accordance with the finding reached by Weng and Huang [93]. Reddy et al. [96] performed a study on multistage integrated TEG based on thermoelectric-hydraulic principle. As illustrated in Fig. 6, this system consists of thermoelectric element bonded with high thermal and electric conduction material with hollow rectangle flow channel. From the numerical study, the increase in the length of the thermoelectric leg, d will optimise the maximum power, and both the increase in the volume or temperature of hot fluid flowing into the channel will enhance the performance of the system.

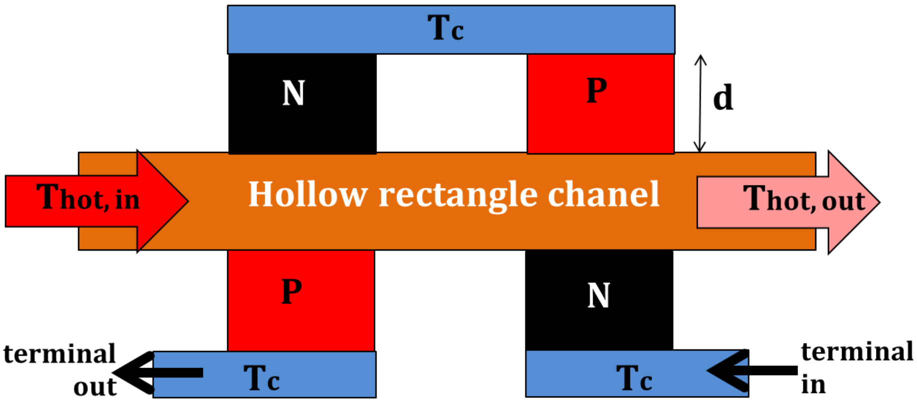

Fig. 6. Multistage integrated TEG [96].

2.7 The Storage of Thermoelectric Power

So far, the studies on the thermoelectric power generation were mainly focus on the production of the electricity. Most of the time, the production of the electricity was instantaneous, for example in the exhaust heat conversion and energy conversion from solar energy. Hence, in this case, the power generated is either need to the instantaneously consumed or, being stored in batteries. The process of maximising power extraction for the charging of the battery is often equipped with maximum power point tracking (MPPT) and it has gained attention over the wide range of thermoelectric power generated, from the magnitude of $\times 10^{-6}$ W [97, 98] to $\times 10^{3}$ W [99]. The objective of the continuous power supply can be achieved via two means, either through the continuous withdrawal of electricity from a battery (storage of electrical energy) or, continuous withdrawal of thermal energy from the heat storage of thermal energy [100]. However, thermal energy storage will result in the higher storage volume, which is strongly dependent on the specific energy capacity of the storage material. Moreover, due to the low thermoelectric conversion efficiency, the amount of thermal energy to be stored is relatively higher than the storage of electrical energy. The utilisation of the heat available from energy storage for electric power generation with TEG had been demonstrated by the research carried out by Jaworski et al. [101]. Furthermore, a proof of concept on the using the low-grade heat available from solar pond had also been performed by Singh et al. [102] and Tundee et al. [103]. With a maximum possible temperature difference of 100°C, the system open channel power generation unit constructed by Singh et al. (in Fig. 7) was generating 0.6 W per TEG from his 16-TECs system at low flow rate. Furthermore, a transient model by coupling the TEGs with a solar pond for electric power generation had revealed that with a TEG's ZT value of 1.0, the solar pond at the climate with high annual solar insolation has the potential of generating electric energy of 9.7 kWh/year-m^2 [104].

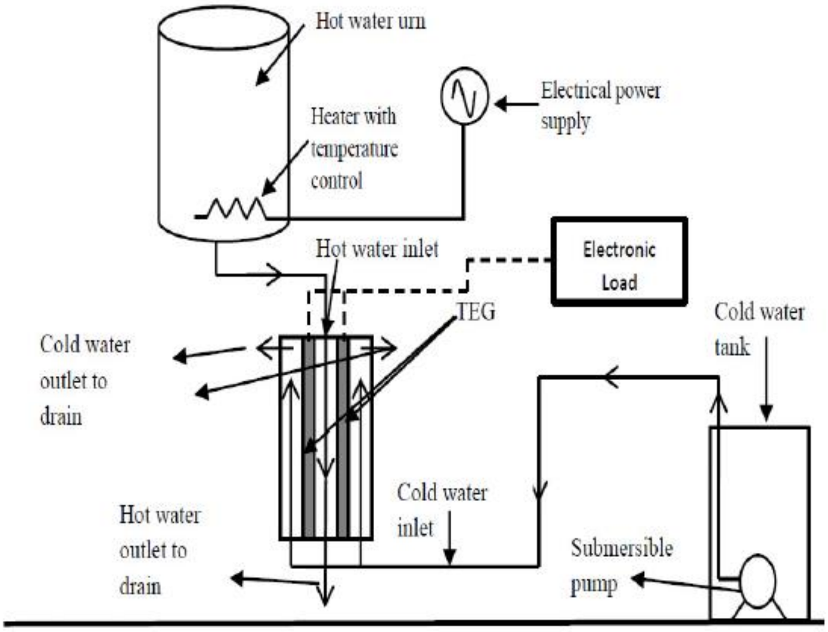

Fig. 7. The open channel power generation unit by Singh et al. [102].

2.8 Summary

At low temperature heat source <150°C, BiTe–based material remains the most common material for thermoelectric application, despite there will be potential of evaporation of tellurium at high temperature operation. The research on the application of TEG in producing electric power in the range >1W was mainly focused on two heat sources, which are waste heat recovery as well as the conversion from solar energy. With the benefit of no moving part and having long term reliability in its operation, the TEG remains a favourable mean for energy conversion although low ZT value appear to the biggest hurdle for the widespread of TEG application and in turn, possess low economic feasibility. As pointed out by Muto [105], in order for TEG to compete with Rankine cycle for existing solar thermal plant, a TEG material with ZT =15.5 is needed, due to the fact that Rankine cycle has a much higher fraction of Carnot of ≈65%. Thus, it is reasonable to not anticipate thermoelectric technology emerge as a dominant position in large scale electricity generation. The best that a thermoelectric system could achieve is to serve as an auxiliary power generation system.

From the survey conducted, the research on the application of thermoelectric system is yet to address the issue in the intermittency of the power supply if the thermoelectric technology kicks in since either of the waste heat supply or solar (radiation) energy supply is usually intermittent, unless additional heat storage or battery storage is available.

3. The Solar Pond

As reported by Anderson [106], and followed by the series of observation around the world from 1960’s to 1970’s [107-111], the discovery of solar pond phenomena had excited the scientific community and since then, the solar pond became a famous method to extract low-grade heat for decades, at an operating temperature of 40°C to up to boiling point ≈100°C. The descriptions for the different types of solar pond had been summarised by El-Sebaii et al. [112]. Historically, different types of solar ponds had been designed to enhance its heat storage capability such as salinity gradient solar pond (SGSP), partitioned solar pond, viscosity stabilised solar pond, membrane stratified solar pond, shallow solar pond [113] as well as saturated solar pond.

3.1 Salinity Gradient Solar Pond (SGSP)

Later in 1980’s, researchers around the world had started to research in detail on the characteristic of salinity gradient solar pond (Fig. 8) and massive work had been conducted on the parametric study on the performance of a solar pond as well as the stability criterion on maintaining salinity gradient from thermophoresis point of view [114]. At the same time, researchers had devoted themselves to understand the hydrodynamics of the solar pond. Detail discourse on the hydrodynamics of solar pond was discussed by Zangrando [115], especially on the maintenance and stability of the salinity gradient. Research had shown that the coexistent of distinct molecular diffusivity of salt and water as well as the buoyancy force contribute to the transport and mixing of these binary substances [116, 117].With some proper controls [118], such as controlling the salinity at the upper zone, or a routine heat extraction from UCZ, high temperature operation of the SGSP (Fig. 8) can be maintained. Some salient parameters that affect the performance of solar ponds as depicted in Fig. 9 from the research conducted are summarised in Table 2.

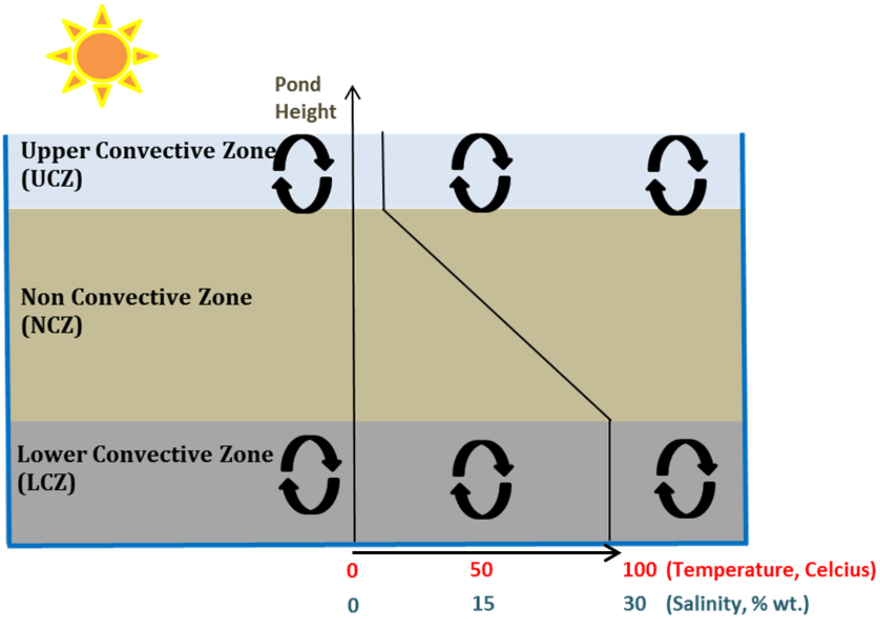

Fig.8. Salinity gradient solar pond.

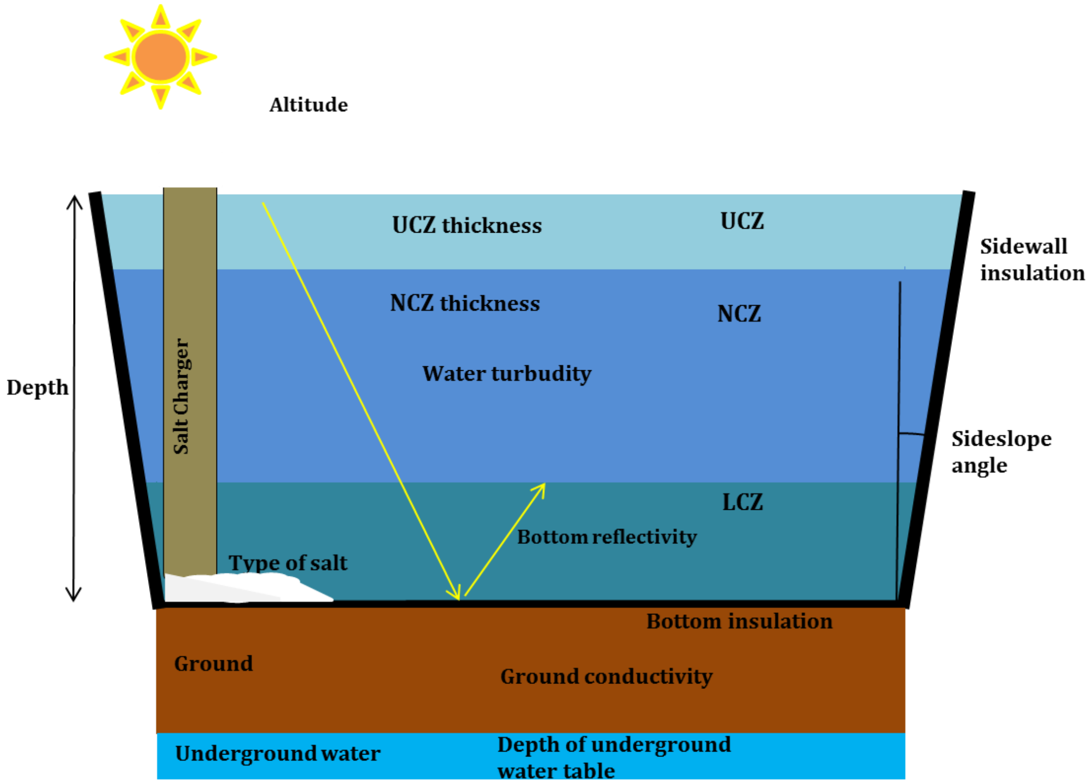

Fig.9. Parameters that influenced the performance of the solar pond.

Table 2
Parametric study on the performance of the solar pond.

Parameters	Findings
Shape of the solar pond	Circular solar pond performs better than rectangular solar pond [119].
Side slope of the solar pond	The slope of the solar pond will affect the steady state salinity profile [120]. The losses through side wall increase with the decrease

	in side-slope angle. Hence, with increasing the side-slope angel improves the temperature at LCZ [119].
Size of solar pond	The maximum temperature at the LCZ increases asymptotically up to 10000 m^2 [119]. Insignificant changes on thermal loading per unit area pond size when the pond becomes larger [121].
Ground conductivity	Lower ground conductivity will significantly increase the temperature at LCZ [119]. Ground thermal insulation should be provided for the case of high underground water level [122]. Site with deep underground water flow should be favourable to reduce further heat loss [123]. However, there exist a depth of water table whereby further depression of water table will not further improve the maximum temperature at LCZ [124].
Thickness of NCZ	Increasing the thickness of NCZ will reduce the sun radiation penetration into NCZ. Decreasing the thickness of NCZ will enhance the conduction heat loss to the surface of solar pond [123].
Thickness of the UCZ	Increasing the thickness of UCZ will dissipates the solar radiation into the solar pond. Reducing the UCZ thickness will increase the solar pond performance [122]. However, this will expose to higher risk of perturbation by the rain [119].
Solar pond bottom reflectivity	High bottom reflectivity is more detrimental to the functionality of a shallow SGSP (about 1-2 m) than a deeper SGSP [125]. Increasing the reflectivity will drastically reduce the temperature at LCZ [123].The existence of undissolved salt will increase the reflectivity of the pond while the accumulation of the dirt has insignificant changes on the performance of the solar pond [126].
Insulation	Side wall insulation is important for the small scale solar pond (<100 m^2). For larger solar pond (>100 m^2), bottom insulation is crucial [121].
Water turbidity	The magnitude of extinction coefficient (the availability of fraction of incident radiation at the different level of SGSP) is affected by turbidity of water [127]. High turbidity level retards the solar pond ability to store energy [128].
Type of salt	Sodium carbonate (Na_2CO_3) [129] and seawater (bittern) [130] are both suitable to be used as the salt in the solar pond for heat storage.
Insulation	With sidewall insulation, the rise in the effective temperature of SGSP promotes the movement of solute molecule. Hence, the thickness of LCZ will increase and at the same time, the thickness of NCZ reduces.
Altitude	Owing to seasonal variation, a solar pond located at higher altitude will require deeper depth [131].

3.2 *Closed Cycle Salt Gradient Solar Pond (CCSGSP)*

Due to the evaporation at the surface of the solar pond, which cause a loss of water and increase in the salinity at the UCZ, fresh water supply is needed in order to maintain the salinity and water level at the upper surface. In Australia, Alagao et al. [132] proposed the design and construction of a closed cycle salt gradient solar pond, as shown in Fig. 10. Later, a similar study was conducted on the design methodology and the maintenance of closed-cycle SGSP based on the climate at Libya, a subtropical semi-arid climate by considering both summer and winter [133, 134]. Inasmuch as the evaporation loss, the salinity at the UCZ increases and hence the portion of the water at the UCZ need to be removed and replaced by fresh water. The extracted water from the UCZ is sent to an external evaporation pond, to extract the salt in the mixture before being recycled to the salt charger. Alternatively, since the actual evaporation rate is abstruse in most of the cases, as emphasised by Alagao et al. [132], the estimation of the evaporation should be done in a careful manner.

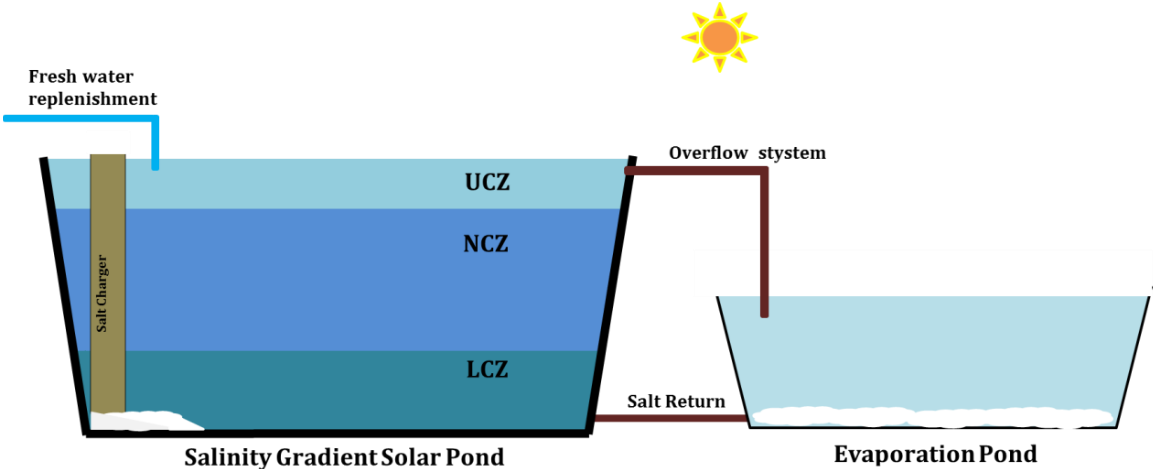

Fig.10. Closed cycle salt gradient solar pond.

3.3 *Solar Pond in Different Climatic Condition*

As solar pond at cold climates is more susceptible to freezing in winter, and the impact of shading due to the lower elevation angle of the sun, the feasibility study of the use of solar pond for the northern cold climate in Scandinavia was incepted by Lund and Routti [135]. The research shown, in northern cold climate, large scale solar pond for the use of district heating surpass the use of small solar pond for the heating of the single house in terms of both economic and efficiency consideration.

The study on the performance of the solar pond in the tropics had been conducted at Bangalore, India [119]. Throughout the five years of the experimental period, the temperature in the LCZ (storage zone) for the 240 m^2 solar pond fluctuated within 50°C- 75°C, with the ability to extract up to 1200 MJ of heat with average heat extraction efficiency of 13%. As one of the main characteristic with tropical climates is its high rainfall during the monsoon period, along with the study, the maximum penetration of rainfall during monsoon period is about 50 cm from the surface of the solar pond. A comparative study had been conducted by Hawlader [131] in order to compare the performance of the solar pond located at different altitude. In the study, solar pond located in Singapore (tropical rainforest climate) was compared the solar pond located at Kew, UK (temperate oceanic climate). Despite the fact that the solar pond located at Kew achieved lower temperature under the comparative study, yet, the heat from the solar pond will still able to supply adequate thermal energy for space heating.

Previous research had been conducted for the solar pond transient behaviour located in southern part of Tunisia, which possesses a steppe climate [136]. SGSP has been successfully operated under such climate condition, with the maximum heat extraction capacity of 80W/m^2 and the potential of operating with a desalination plant. Meanwhile, under a Mediterranean climate, Haj Khalil et al. [137] explored the potential of electric power generation in that region. Potentially, 5 MW of electric power can be generated with a solar pond area of 1.5 km^2. For a solar pond in the Mediterranean climate, highest exergy efficiency and the energy efficiency of the solar pond is reported to be 28% and 27%, respectively [138]. A recently built 50 m^2 ×3 m (depth) small solar pond at Catalonia (north-east of Spain) showed, maximum temperature of 55°C can be reached in summer [139] and it was predicted that maximum temperature of 75°C can be achieved for the solar pond built at south-east region of Spain [140].

3.4 Numerical Study on Solar Pond

The advance of computational science in the recent decades avail the development for the simulation of the salinity gradient solar pond and different modelling approaches emerge since then, as shown in Table 3. For the SGSP, unless the environmental parameter (such as climatic condition) does not vary throughout the year, else, the solar pond should be modelled under transient state condition [141]. Besides utilising the numerical model to study the transient behaviour of SGSP, in the earlier year, Alagao [142] had developed a one-dimensional numerical model for the closed-cycle SGSP, as a tool to estimate the minimum area of evaporation pond needed for a specific solar pond available. In the study conducted by Kurt et al. [143], instead of using numerical approach, a machine learning method had been used to predict the density and temperature in the solar pond. By using artificial neural network method, this study opens an alternative technique to evaluate the performance of SGSP; in spite of the input for the training of the network will be case specific. A series of a comprehensive guide on the simulation procedure and the parametric study on the solar pond is given by Subhakar and Murthy [144, 145]. The use of finite element method such as Crank-Nicholsen method [146] revealed that the use of daily variation of ambient data as the input for the simulation performs as best as the hourly variation data input. In turn, this resulted in a reduction in computational cost.

Table 3

Numerical studies on solar pond.

Numerical models	**Key findings**
1-dimensional transient model	For a SGSP, the replenishment of salt at LCZ and the flushing of fresh water at UCZ is a must in order to guarantee the sustainability of the solar pond for the long run. The thermodiffusion (Soret effect) will destabilise the salinity gradient layer, especially under the condition of high temperature and salinity gradient [147, 148].
1- dimensional transient model	By using finite element approach, the temperature and density profile of SGSP can be predicted in good agreement. The minimum density difference between UCZ and LCZ in order to establish salinity gradient for NaCl-based SGSP is 216 kg/m^3.
1- dimensional transient model [150]	The numerical study on heat extraction at both NCZ and LCZ was conducted. It was found that extracting the heat from NCZ only will reduce the density stability of the SGSP [149].
1- dimensional transient model	Numerical study on heat extraction at both NCZ and LCZ was carried out and a simple method to estimate the SGSP performance using a new definition for instantaneous efficiency for SGSP [151].
2-dimensional transient double diffusive convective model (Suárez et al., 2010)	The exclusion of the double-diffusive convection will overestimate the temperature at the LCZ [152].
2- dimensional transient model (Mansour et al., 2006)	Hot seasons will favour the solar heating effect than cold season. Extracting heat at the LCZ will aid to stabilise the temperature profile at LCZ. Besides, SGSP with low turbidity will tend to develop instability in the temperature profile of SGSP [153].
2-dimensional computational fluid dynamics (CFD) model	The study of heat extraction scheme for solar pond is studied via CFD simulations is possible, provided realistic boundary conditions are given [154]. The impact of internal Rayleigh number and aspect ratio of the solar pond onto the temperature, velocity and

	concentration distribution in SGSP was conducted by Boudhiaf and Baccar[155].

3.5 Solar Pond Research in Recent Decade

The heat stored at the LCZ is extracted via two methods. The first method of heat extraction is via circulating the working fluid in an in-pond heat exchanger located at the bottom of the solar pond, for example, the solar pond at Pyramid Hill, Australia [156]. Alternatively, by using external heat exchanger located outside the solar pond, saturated hot brine in the LCZ is pumped out from the pond and exchanging heat with cold inlet water at the external heat exchanger before returning to LCZ. This method had been used to extract the heat at the 3000 m^2 solar pond at El Paso [157]. By using these conventional heat extraction methods, the thermal efficiency (defined as the ratio of total heat extraction to total solar radiation incident on the pond surface) was around 15-18% [158]. Andrews and Akbarzadeh [156] in their studies, instead of extracting heat through conventional methods, additional heat was extracted at NCZ by extending the heat exchanger looping to the side wall of NCZ. Using this method, the thermal efficiency of the solar pond can be boosted up to 55%. Furthermore, concentrating the surface discharge of saline in an evaporation pond followed by its re-circulation to the base of the pond via a salt charger had also proven to be a method that could enhance the both thermal and mechanical efficiency of the SP [159].

The aforementioned research were mainly focusing on improving the system efficiency. In order to reduce the energy cost (defined by the price of producing unit electric energy), either the efficiency of the system has to be improved or the cost (both fixed and variable cost) of the system has to be reduced in order to achieve this goal. Straatman and van Sack [160] conducted a cost optimisation study for a hybrid solar thermal electricity generation system consists of ocean thermal energy conversion and offshore solar pond (OTEC-OSP). In the design, the low cost floating solar pond serves as a medium to enhance the temperature input for the OTEC plant for power generation. With a low operation and maintenance cost couple with the capability to produce electricity continuously, the OTEC-OSP system design was found to have the lowest energy cost of 0.04 €/kWh for all solar thermal electricity system.

Despite the disadvantage in low thermal to mechanical conversion efficiency, Akbarzadeh et al. [161] proposed a system that combines solar chimney with SGSP (Fig. 11). The heat from the LCZ of the solar pond was transferred via a heat exchanger and being released in the chimney. Due to the density difference exists between ambient air and the heated air inside the chimney, air movement was induced and powered the air turbine.

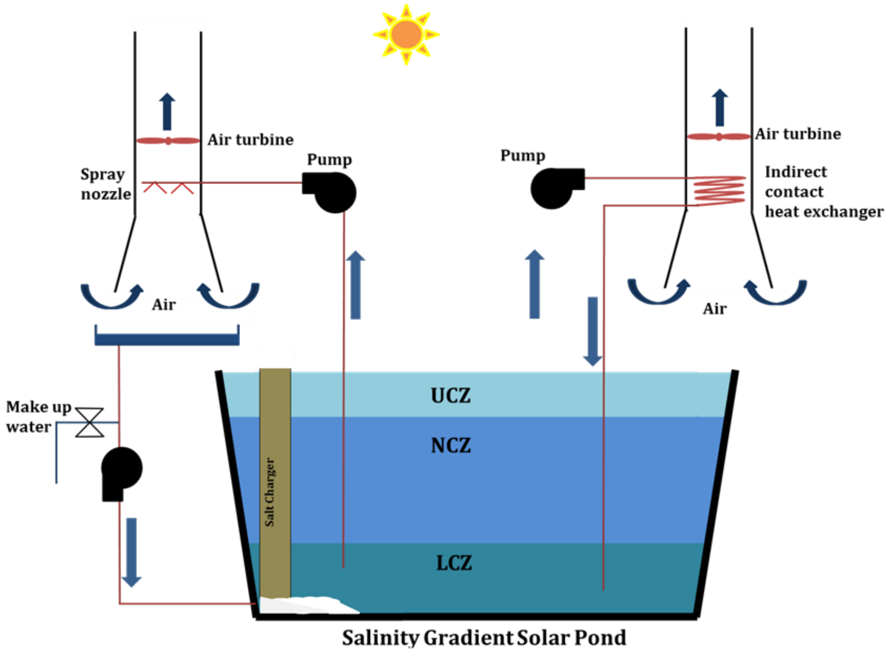

Fig.11. Combined solar chimney with SGSP [161].

For increasing the temperature at the storage zone (LCZ), Husain et al. [162] in their study suggested the introduction of a 5 cm intermediate zone between UCZ and LCZ, which is illustrated in Fig. 12. However, for such system, continuous maintenance work is needed in controlling the salinity for this additional layer in order to maintain the overall salinity stability of the SGSP.

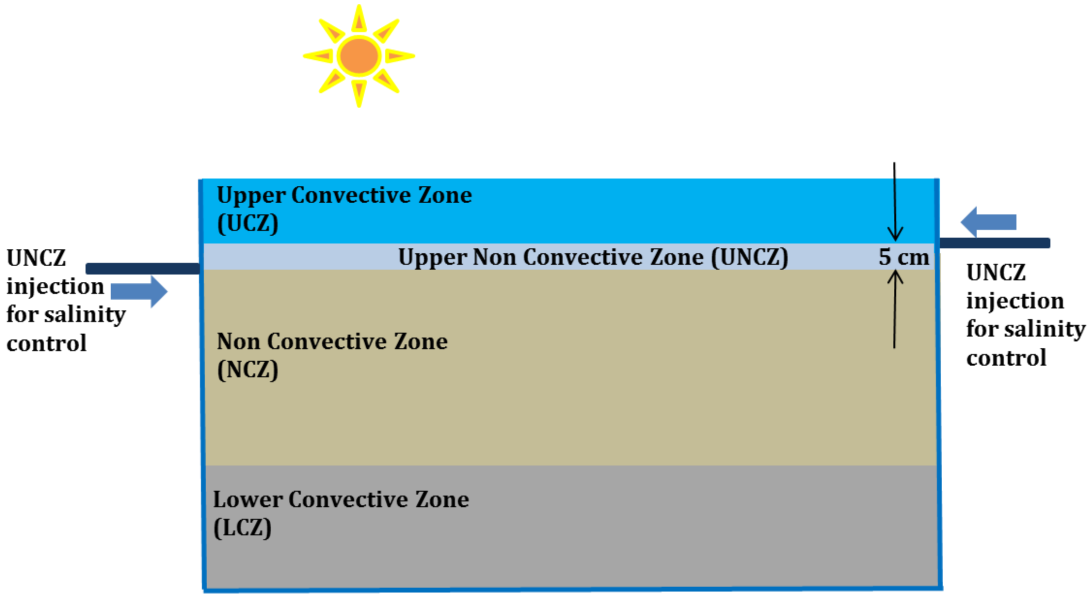

Fig. 12. The introduction of a 5 cm intermediate zone between UCZ and LCZ.

The evaporation at the top surface of the solar pond and the growth of algae and microbes are the common problems faced by the solar pond. Evaporation at the top surface causes heat loss from solar pond via entrainment, while the growth of algae at NCZ blocks the penetration of sunlight to LCZ. Mimic to the concept of a shallow solar pond, a two layer nanofluid solar pond that is able to eliminate the deficiencies of solar pond operates with brine as mentioned before has been researched [163]. The nanofluid solar pond consisted of a transparent mineral oil layer at the top and a water based nanofluid at the bottom. By making use of the nanofluid in the solar pond, it was found that nanofluid pond outperformed in terms of energy stored per unit area with the capacity storing the heat of 2.16 times than a brine pond. Besides, Malik et al. [164] found that the use of diluted hydrochloric acid (HCl) will able to reduce the pH and turbidity at NCZ. However, this method should be done judiciously, since acid injection near to the LCZ will lead to crystallisation due to the reaction of the acid with high salinity solution exists in the LCZ. Nevertheless, as pointed out earlier, evaporation at the top surface of the solar pond is undesired since it causes evaporative heat loss from the solar pond. By using some floating elements (such as floating disc and floating hemisphere) [165], the evaporative heat loss from the solar pond can be reduced. Thus, more heat can be withdrawn from the NCZ and LCZ of the SGSP. The growth of algae and microbes in the solar pond has an adverse effect in increasing the turbidity of solar pond and retard the transmissibility of sunlight to LCZ and its growth along the heat exchanger pipeline is obvious (for example, RMIT solar pond in Fig. 13). The experiment has been conducted on the use of low-cost chemical, such as alum ($KAl(SO_4)_2.12H_2O$) was able to mitigate the problem of high turbidity for turbidity control [166].

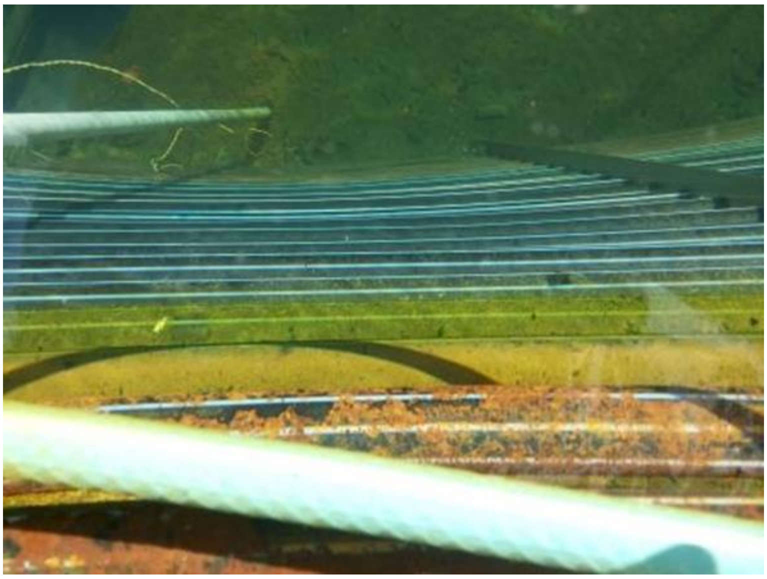

Fig.13. Algae problem in the solar pond.

In addition to water desalination process using desalination unit with solar pond [167, 168], the solar pond can be combined with a solar still. Utilising the evaporation process to produce distilled water from saline water, studies had shown, with some modifications by incorporating a mini solar pond into a solar still as a medium to preheat the saline water will able to augment and double the production of distilled water [169, 170]. A similar concept had been researched by El-Sebaii et al. [171]. Through the study an active single basin solar still with a shallow solar pond will increase the daily production of distilled water up to 200%.

Both solar collector and solar pond are two distinct systems that utilising solar energy as the heat source for renewable energy system. For the renewable energy system designer, a dilemma exists, on choosing the most suitable system in their design. For the underfloor heating system, solar collector system avails in terms of economic consideration compare to solar pond system attributed to lower electrical energy consumption in catering the underfloor heating [172]. From the research conducted on solar ponds over decades, it was found that most of the studies on the solar pond were performed under laboratory scale or by conducting theoretical modelling of the system. The research studies on a large scale solar pond in long run are relatively limited. The underlying reason, besides the high setup cost of the large scale solar pond, large-scale solar pond is venerable to the change in climatic and environment condition if it is not properly maintained

3.6 Solar Pond for Power Generation

Finally, for electric power generation with solar ponds, ORC has been a successful method to generate electric power from the solar pond. The system illustrated in Fig. 14 represents a solar pond-ORC power plant with a typical efficiency of solar to electrical efficiency of 0.8% to 2%. A review on low-grade heat conversion using ORC is already available from the literature presented by Tchanche et al. [173] which included solar pond-ORC system. The overall performance for the solar pond-ORC power plants reported isis summarised in Table 4.

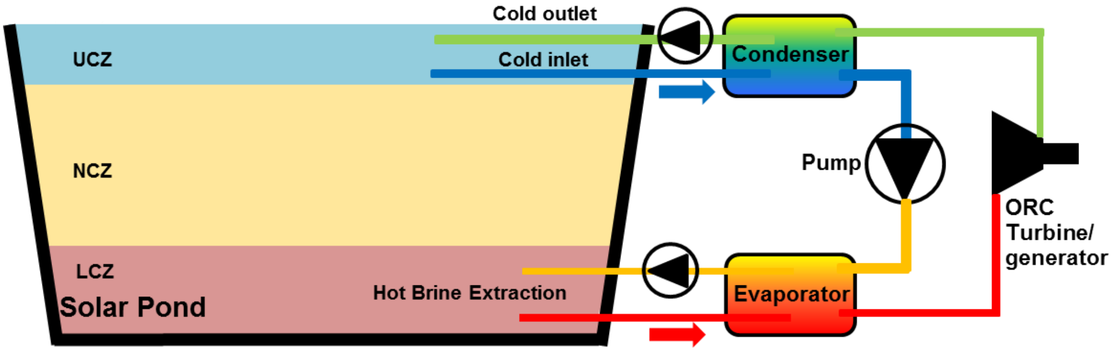

Fig. 14. Electric power generation from the solar pond using ORC.

Table 4

Power generation from the solar pond using ORC [173].

Location/Size	**Capacity**
Ein Bogek (Israel), 6250m^2	150kW
Beith Ha'Arava (Israel), 25000m^2	5000MW
Alice Spring (Australia) 1600m^2	15kW
El Paso (USA), 3350m^2	70kW (electric); 330kW (thermal)

For small-scale electric power generation using the solar pond, a novel method of integrating heat pipes and TEG for electric power generation in the solar pond (Fig. 15) was first demonstrated by Singh [174] through the proof of concept. A temperature difference of 40-60 °C is readily available across UCZ and LCZ in the solar pond. Hence, by transferring the heat from LCZ to UCZ using wickless heat pipes, electric power can be generated by using TEG, to a temperature difference as low as 27 °C. Later, the research was continued with a transient model to study the potential of power generation from the solar pond using TEGs. After taking into account the effect of climatic variation, the conversion efficiency of the TEGs, the amount of heat extraction from the solar pond as well as the efficiency of the heat exchanger; it was concluded that BiTe-based TEGs that operate at 20% of its Carnot efficiency will able to produce electricity up to 10.9 kWh per m^2 of solar pond in a year [104]. Furthermore, two different experimental units had been tested, which were an open channel plate type power generation unit [176] and a submersible power generation unit [177] with TEGs. Both experiments had attempted to eliminate the use of the pump in transferring both hot and cold fluids to the TEGs in ensuring net positive electric power generation. The idea of eliminating the use of the pump in the solar pond-TEGs system is achievable since as mentioned in the previous section, a proper maintenance of solar pond requires a low-flow, constant fresh water flushing at the solar pond's surface. The water used for this process is usually supplied by main water services and this is applicable to an industrial size solar pond. By incorporating the piping of power generation unit into solar pond's maintenance services, a pumpless power generation system is possible while generating electric power of 40 W.

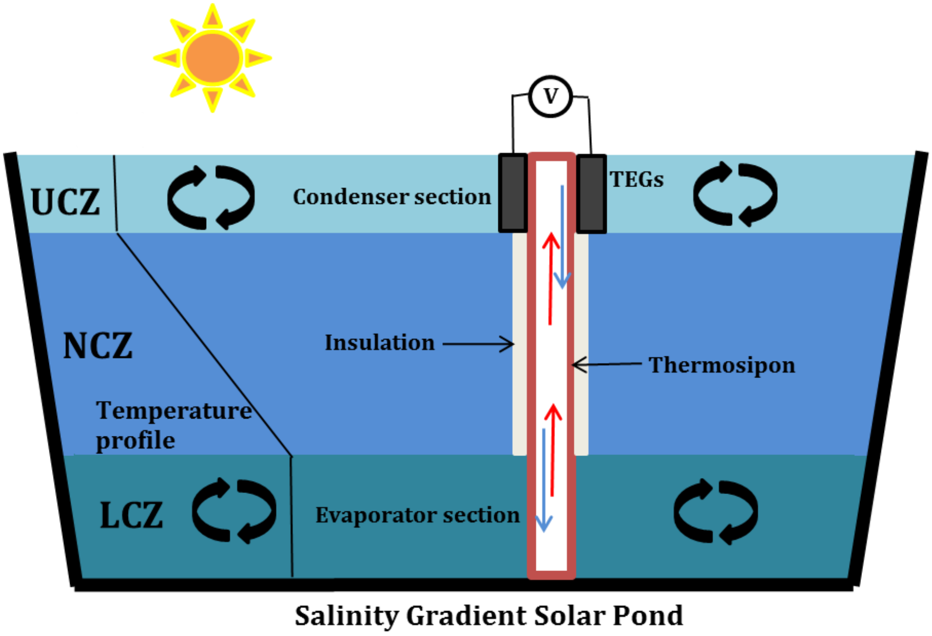

Fig. 15. Integration of thermosiphon and TEG for electric power generation.

3.7 Summary

The solar pond has been a reliable supply for the low grade heat source. To date, the macro scale parametric study on the performance of solar pond is considered established. However, the fundamental physics on the behaviour of the solar pond continue to be a subject that captivates researchers, supported by the advancement of computational science. For electric power generation, organic Rankine cycle has been a successful method of for generating electric power. For thermal-electric conversion, the use of solar pond as the heat source requires a large area due to low conversion efficiency of the system (as a result of the multiplication of solar pond efficiency and efficiency of the heat engine) and large area of solar pond requires a careful upkeep such as controlling the growth of algae and density gradient maintenance.

4. Concluding Remarks

This review has introduced the solar pond, particularly on the design parameters study since the inception of the solar pond as a way to provide the low-grade heat source and numerical approach that can be adopted to characterise the solar pond. Owing to its reliable supply of heat, it has been an ancillary resource in reducing heating demand in industrial scale. Its potential in generating electricity in large scale has been demonstrated through successful projects in the past. Meanwhile, as discussed in the beginning of this review, the ability for TEG to generate electric from the available heat opens a chance for electrical power generation from the solar pond, besides using the conventional method with organic Rankine cycle.

Functioning as both collector and storage of solar energy, the operation of the solar ponds has a setback which is the efficiency limit and the amount of heat that can be withdrawn without risking its normal operation. In order to increase the heat extraction, the solar pond has to pursue the expansion in size (either with or without modular approach) or extent the heat extraction zone to non-convection zone, while the latter has need of a careful design to avoid disturbing the stability criteria of the solar pond. At the same time, the combination of solar pond-TEGs system will possess a limit of the amount of electric power for a given surface area of the solar pond, due to the combined limitation of solar pond's efficiency caused by the attenuation of solar radiation in water and the current ZT limit of the TEG. However, there exists a silver lining as a result of the combination of both systems, which is the elimination of the electrical energy storage system and open up another option for electric power generation utilising solar energy in small scale.By using the same concept, the TEG system could be potentially coupled with other storage-based heat source such as phase change material. In the other words, the electric power generation could be in 'on-demand' basis. For the heat to electric conversion using TEG, the heat extraction from the solar pond through heat exchanger in solar pond is necessary, which share the common ground with the existing solar pond functionality as an industrial scale provider for low-grade heat. This means, there will be no difference for the heat extraction technique and hence, the solar pond with electric power generation through TEG will able to work interchangeably between providing heat and electric power.

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