FEASIBILITY OF VARIOUS SMALL-SCALE LOW-TEMPERATURE SOLAR THERMAL ELECTRICITY TECHNOLOGIES

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ABSTRACT

A desired feature of solar power systems would be to continue producing at high output a few hours after sunset in order to cover local peak loads. An energy storage system would be able to help with solving this problem. The simplest and most cost-effective energy storage method is a thermal accumulator, where hot water or another fluid is stored at a given temperature higher than the surroundings. Conversion of thermal energy into mechanical power when compared to photovoltaic systems, however, is limited in efficiency and requires comparatively complex equipment, which might not be as cost-effective as desired, suffer from low reliability and require frequent maintenance.

The thermal path of converting solar energy into electricity is certainly promising but has largely been underestimated and underutilized. Several thermal-to-electricity energy conversion technologies already exist in either conventional form or at close-to-commercialization phase and can be further optimized and adapted to low-cost low-temperature solutions. Combined heat and power (cogeneration) facilities at small scales can be attractive for a quicker and wider deployment in solar-rich locations.

This study evaluates and compares several candidates for the conversion of low-temperature solar thermal energy into power and examines their technical feasibility and thermodynamic performance, as well as their potential for low-investment strategies and integration with thermal energy storage. With temperatures in the solar collectors limited to 150 ^{o}C (300 ^{o}F), the suggested energy conversion techniques include flat plate and evacuated tube solar collectors combined with low-parameter steam Rankine cycles or turbocharger derivative Brayton cycles, organic Rankine cycles and novel thermoelectric solutions.

Results show that common steam, organic, or air expansion cycles optimized for low parameter applications are feasible for further development and deployment in the near future, based on established components featuring turbines derived from commercial products. Thermal-to-electricity efficiency of around 5% - 12% and solar-to-electricity efficiency of around 4 – 8% can be achieved by some of the cycle alternatives at their best operational conditions.

1. INTRODUCTION AND BACKGROUND

Solar energy is usually available in abundant quantities in places where highest electricity peak loads due to air conditioning coincide with high insolation. However, the high loads especially in residential areas extend into the evening hours when the sun is not shining anymore, including a continued use of air conditioning far beyond sunset after a hot sunny day. A desired feature of solar power systems would be to continue producing at high output a few hours after sunset. Any kind of energy storage solution would be able to provide such a solution. The simplest and most cost-effective energy storage method is a thermal accumulator, where hot water or another fluid is stored at a given temperature higher than the surroundings. Conversion of thermal energy into mechanical power, however, is limited in efficiency and requires comparatively complex equipment, which might not be as cost-effective as desired and might suffer from low reliability and require frequent maintenance.

The present work attempts to provide a quick review and to systemize the potential candidates for distributed power production from low-tech and low-temperature solar thermal technology, summarize the potential for practical deployment, and primarily build up the basis for a wider proliferation of such systems upon which various detailed development and optimization studies can hopefully be initiated. The thermal path of converting solar energy into electricity is certainly promising but has largely been underestimated and underdeveloped. Several thermal-to-electricity energy conversion technologies already exist in either conventional form or at close-to-commercialization phase and can be further optimized and adapted to low-cost low-temperature solutions. Combined heat and power (co-generation) facilities at small scales can be attractive for a quicker and wider deployment in solar-rich locations.

This study evaluates and compares several candidates for the conversion of low-temperature solar thermal energy into power and examines their technical feasibility and thermodynamic performance, as well as their potential for low-investment strategies. With temperatures in the solar collectors limited to 150 ^oC (300 ^oF), the suggested energy conversion techniques include flat plate and evacuated tube solar collectors combined with low-parameter steam Rankine cycles or turbocharger derivative Brayton cycles, organic Rankine cycles and novel thermoelectric solutions, or several of the above combined into hybrid systems utilizing solar heat at different temperatures for distributed heat and power production.

The results show that innovative thermoelectric technology holds a promising future, however common steam, organic, or air expansion cycles optimized for low parameter applications are feasible for further development and deployment in the very near future, based on established components featuring turbines derived from commercial products. Thermal-to-electricity efficiency of around 10% and solar-to-electricity efficiency of around 6 – 8% can be achieved by some of those alternatives at their best operational conditions. The target application is in residential homes or small commercial buildings, from micro-scale units installed at a single house and up to 100 kW such serving a neighborhood block of houses or a public or commercial building.

The possibility to integrate thermal energy storage with a power extraction unit allows for extending the operating hours and effectively converting the solar powered unit into a quasi-dispatchable power generator.

The advantages of low-temperature solar thermal energy integrated with distributed power generation can be summarized as follows:

- Utilizing low-cost low-tech solar technology;
- Allowing for thermal energy storage for cogen applications and extending the operational hours;
- Longer life span than PV systems, unlikely deterioration of performance with age;
- Do not require high-tech production lines and do not use rare or toxic materials, the hardware is recyclable, therefore having a much smaller environmental footprint than electrical batteries;
- Most, if not all of the components can be designed, produced, installed and maintained entirely by local businesses.

The expected disadvantages of low-T energy conversion units can be summarized as follows:

- Costs might be higher if compared with PVs;
- Require larger space than PVs;
- Have low overall energy conversion efficiency, however comparable to low-tech PVs;
- The power extraction and ancillary equipment may require maintenance and show poor reliability;
- Double-phase power cycles require cooling for steam condensation. Their performance deteriorates quickly with rising condenser pressure. Water consumption may be too high unless air cooling is applied.

Integration of solar thermal with heat storage and a thermal-to-electricity energy converter can be a valuable supplement to both residential and commercial buildings in all parts of the world where solar resources are available for economic utilization. The heat storage provides also for local heat loads such as hot water and space heating (if necessary in the cold season), or the power production can assist the air conditioning system which is the major electricity load during hot summer days. Solar thermal systems would allow covering of both heat loads and partially electrical loads with low-tech distributed solar methodology. For example, in the North Eastern USA (New England states) residential and commercial buildings are still firing large quantities of oil for local space heating. A large part of it can be replaced with solar thermal heating systems, something that has been claimed to provide a much better environmental result and a much higher return on investment if compared to installing PV systems [1].

2. <u>THERMAL PATH TO ELECTRICITY PRODUCTION</u>

Interest in the recovery of low-grade heat from all types of sources, from geothermal power through piston engines and industrial process waste heat, to low concentration solar thermal, has been steadily growing in the past decades. The focus has been mainly on evaluating and improving various Organic Rankine Cycle (ORC) fluids and configurations. Other systems such as air Brayton cycles or thermoelectric technology have not been given the deserved attention.

The power generation efficiency from low temperature heat sources is severely limited by the potentially low second law efficiency. For heat supply at 100 ^{o}C (212 ^{o}F), assuming ambient temperature of 37 ^{o}C (100 ^{o}F) and a perfect heat sink, the maximum idealized efficiency of energy conversion through any heat engine is hardly reaching 17%, reaching up to 27% for 150 ^{o}C temperature of heat input. A good energy converter may have the ability to recover about half of the second law potential, resulting in overall efficiency of thermal energy conversion of around 10%, which is a promising value that compares well to that of aged and overheated PV panels.

2.1 Organic Rankine Cycles (ORC)

ORC solutions for waste heat utilization and solar thermal systems have been carefully assessed both in theory and in the form of pilot experimental cases by various authors. A good review of all recent development work worldwide has been summarized by Quoilin et al. in [2] & [3]. Figure 1 shows the simplified conceptual layout of a typical ORC unit, where the evaporator can be supplied with low grade heat from any source, including solar thermal. Different ORC configurations and fluids are suitable for different temperature levels of heat supply. The most commercialized ORC solutions today are primarily targeted to operate with heat input temperatures of around 100 ^{o}C (212 ^{o}F). Their primary application is solar-driven water desalination systems [4], while some standardized commercialized solutions are used in geothermal applications or even for utilizing very low temperature waste heat between 70 ^{o}C - 90 ^{o}C such as solar thermal systems or district heating networks in summertime for allowing cogen plants to continue producing electricity [5], [6].

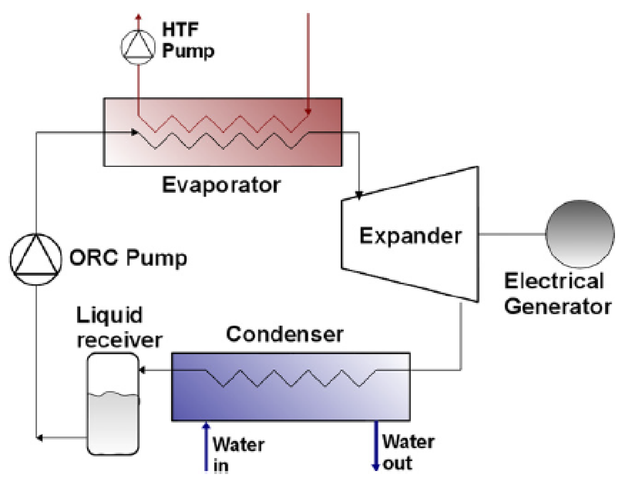

Fig. 1: Simplified layout of a typical non-regenerative ORC system for low temperature heat utilization [3].

ORC systems have been proven to reach 10% efficiency in theory. Nevertheless, practical configurations have hardly measured above 6 – 7 %, as per the sources mentioned above, in an overall solar-to-electricity perspective. ORC systems operating at temperatures of heat supply around 100 ^{o}C are showing best overall performance reaching close to 10% practical efficiency of thermal-to-electrical energy conversion [6], due to increasing internal irreversibility and specific fluid limitations at higher temperatures. Further optimization and improvements, as well as cost reductions would be possible if the market spins up and the production numbers for such systems start to grow rapidly.

At that temperature range and using established working fluids, the ORC system will not be employing an internal heat exchanger in the form of a regenerator/recuperator, saving also costs in view of simpler architecture and avoiding additional thermal and pressure losses.

2.2 Low-parameter conventional steam cycles

Standard water-steam cycles are considered unsuitable to low temperatures and small-scale applications due to the specific thermodynamic properties of water and the complexity and high specific pressures of the system if compared to ORC units. The small mass flows and low specific volume of steam eventuates in very tiny turbine geometry, making the steam turbine ineffective at small scales. If more allowing sizes and steam flow rates are considered, well designed steam systems can be expected to compete with ORCs for power generation application from low-grade heat sources.

A complex double- or triple-pressure steam cycle including flashing stages can be proposed for such applications. Its advantages are the more or less conventional architecture, non-hazardous working fluid, comparatively low pressure ratios and the utilization of radial inflow steam turbines close in geometry to turbocharger designs. The authors of this study have simulated such a steam system whose possible applications at various temperature levels range from waste heat recovery of internal combustion engines, industrial waste heat, geothermal heat and low-temperature solar thermal systems. Its simulation chart is presented in Figure 2. The cycle design and heat balance simulations (steady state) simulations were performed with the commercial software code PROSIM [7].

For heat supply temperature of 150 ^{o}C the cycle including major losses and internal power consumption for auxiliary equipment but excluding some additional limitations, is able to reach 12% efficiency a thermal-to-electricity perspective.

Indeed the configuration complexity is high and its practical implementation in this format is unlikely to take place. Still, there are no technological challenges to such a system and all components can be considered as standard with the exception of the steam turbine, which needs to be specifically optimized.

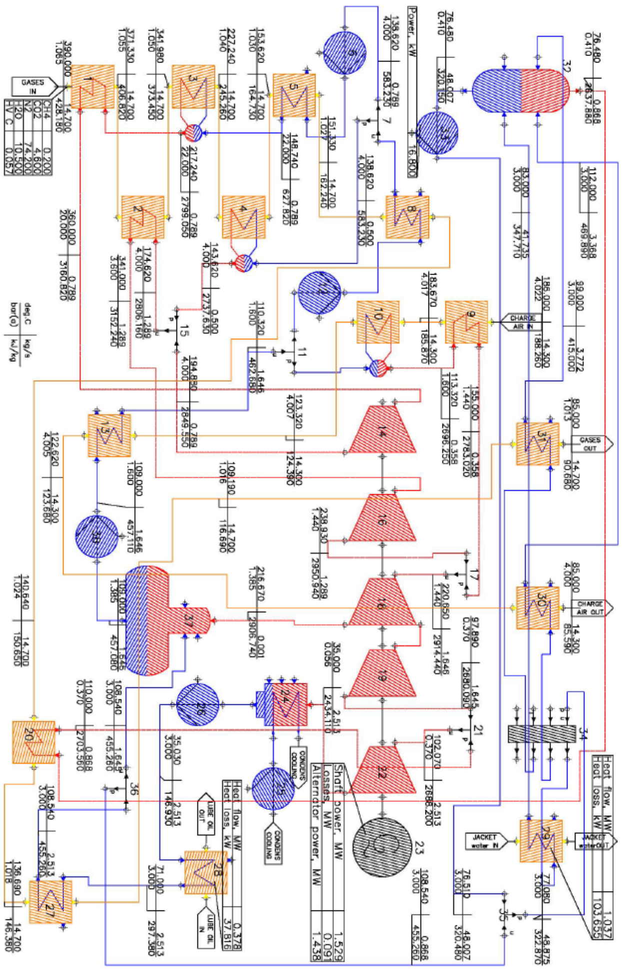

Fig. 2: The detailed configuration of the multi-pressure steam cycle with flashing stages for low-temperature thermal energy conversion, simulated by the authors, able to reach 12% net thermal-to-electricity efficiency at 150 ^{o}C heat input.

Simpler steam cycle configurations would be able to deliver in the order of 9 % thermal-to-electrical efficiency for optimized double-pressure mid-size systems at the same level of thermal energy input and condenser parameters.

2.3 Brayton air expander cycles

Gas turbine cycle architectures can also be applied for low-temperature solar heat utilization. Very low pressure ratios would be used, with air as a working fluid. The compressor and expander wheels can be directly derived from radial turbocharger topologies, matching comfortably the geometry and the sizes necessary. Typical pressure ratios of around 2 would allow for the conversion of a heat input at 150 ^{o}C into power with acceptable efficiency.

The authors have simulated such proposed turbocharger-derived air compressor-expander units, with varying isentropic efficiencies and additional losses. The working fluid flow rates would be comparatively high, as the specific work output per unit air flow is very low. Assuming plausible isentropic efficiencies in the order of 80 % for both the compressor and expander (radial wheels of good design and precise manufacture of the size typical to heavy truck engine turbochargers), the net thermal-to-electricity efficiency would reach 8 % in the best case.

The heat exchange between the solar thermal collector and the air working fluid would pose challenges and require large surfaces. One possibility is to let the working air fluid flow directly through the solar collectors, however they might be standardized water-filled units also integrated with the heating system and heat storage at the location. Thus, a water to air heat exchanger seems to be a universal solution.

Recuperation would not be applied in the air Brayton cycle as the temperatures of the air does not leave any room for that. On the other hand, intercooling and reheat can successfully be applied for enhancing the performance up to an extent when the incurred additional losses jeopardize the profitability of more stages of intercooling or reheat.

Air Brayton cycles of the hereby proposed architecture have been simulated using the software code PROSIM [7]. Figure 3 shows the simplified layout of the optimum configuration with 2-stage intercooling and reheat, with a free power turbine. Variations of such an arrangement can be built by a set of several turbocharger-derived units connected in series. The air to air intercooling heat exchange can be accomplished in equipment similar to intercoolers in car or truck engines.

The most attractive feature of the turbocharger derived air turbine assembly is its simplicity and ease of construction, operation and maintenance. This cannot be rivaled by any double-phase fluid system such as water-steam or ORC. Despite the generally lower efficiency potential at limited temperatures compared to Rankine cycles, air Brayton cycles offer a nearly limitless flexibility and low cost potential, especially if standardized turbocharger modules can directly be used. The air turbine configurational variability for adapting to specific part-load conditions or particular application areas is also unrivaled.

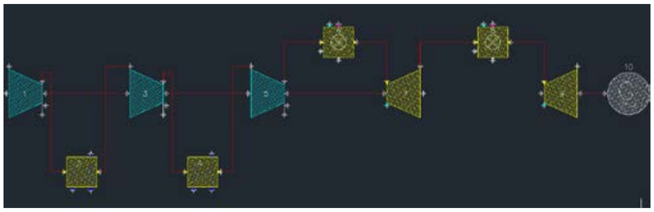

Fig. 3: The simulation layout of an intercooled and reheated air compressor-expander unit based on turbocharger derivative technology, promising a thermal-to-electrical efficiency of 8% with unrivaled compactness and simplicity.

2.4 Thermoelectric energy converters

The thermoelectric effect is known since a very long time and has diligently been utilized in thermocouples for temperature measurements. The reverse process is applied for simplified fail-free refrigeration applications. The thermoelectricity performance has been tested and evaluated several decades ago for many types of waste heat utilization applications. The delivered efficiency is comparatively low, but the absence of moving parts and the extreme simplicity and compactness of the energy converter are very attractive features that help reviving the interest.

Recently, modern developments and advancements in nanostructures promise considerable improvements in efficiency. If these expectations become commercialized, thermoelectric units would be a primary candidate for all types of heat utilization applications including low temperature solar thermal such. A good overview of the theory and applications of thermoelectrical devices for harvesting low temperature heat energy from various sources can be found in [8], among others. The basic principle of thermoelectric effect is presented and explained in Figure 4.

The thermoelectric effect is still bound by the second law limitation as it also represents an irreversible process of the conversion of heat directly into electrical power with interactions on molecular level. The expected thermal-to-electricity conversion efficiency of state-of-art [8] thermoelectric devices is around 4 – 5 %, for heat inputs between 90 ^{o}C and 150 ^{o}C. This is sufficient to provide a preference for a thermoelectric device to any mechanical turbine based one, owing to its simplicity and compactness. Such devices are directly applicable to solar thermal power generation and there are no technical restrictions to that. However, the thermoelectric effect performs best at very high temperature differences, and may prove very inefficient at low temperatures. Internal losses (primarily heat transfer from hot to cola end) are also growing at higher temperature differences. A generalized graph for the variability of thermoelectric efficiency with temperature, for different materials, is show in Figure 5.

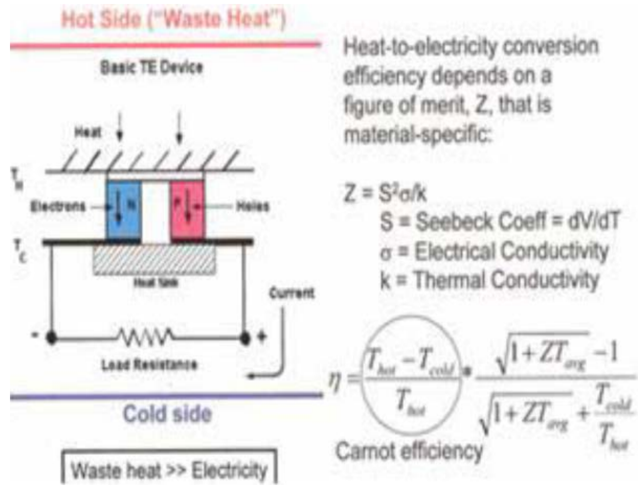

Fig. 4: Basic principle of the thermoelectric effect [8].

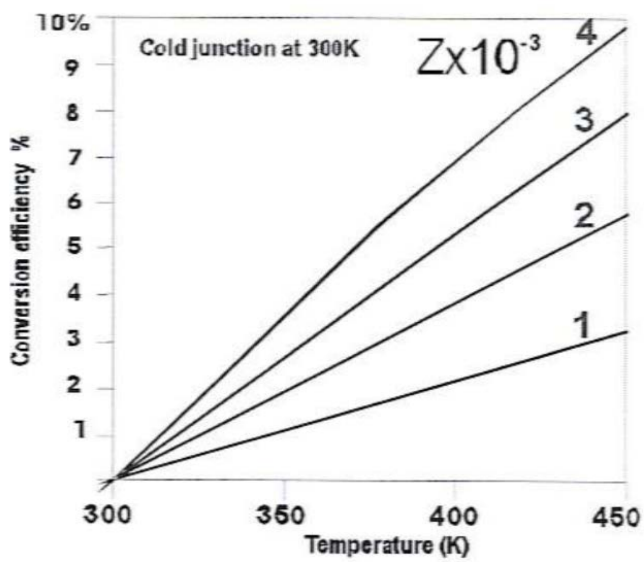

Fig. 5: Idealized performance of thermoelectric materials at comparatively low but varying temperature at hot end [8].

3. COMBINATIONS AND HYBRID SOLUTIONS

Various combinations are of the different thermal energy conversion cycles are feasible and can be well adapted to a given range of heat input temperatures. For proper utilization of the heat resource, cooling of the heat supply medium needs to be done as deep as possible, thus a double-pressure Rankine cycle or a combination of two or more energy conversion methods – each of them optimized for a certain temperature level – can be recommended. Combined cycles for low temperature heat sources can not only divide the temperature ranges between themselves, but also utilize each-others heat sinks as conventional combined cycles do.

Traditionally, steam and gas cycle can profitably be combined and hybridized if necessary. Thermoelectric devices can also match well in combination with a mechanical turbomachinery unit.

A summary of the efficiency details and parameters as presented above is given in Table 1 below.

TABLE 1: A SUMMARY OF PLAUSIBLE CONCEPTUAL THERMAL CYCLE SOLUTIONS FOR THE CONVERSION OF SOLAR THERMAL ENERGY TO ELECTRICITY AT SMALL SCALES AND DISTRIBUTED APPLICATIONS

Cycle type /parameters	*th-to-el eff.*	*sol-to-el eff.*
ORC	10 %	7 %
Water-steam low-T	12 %	8 %
Brayton air expander	8 %	5 %
Thermoelectric	5 %	4 %

4. CONCLUSIONS AND DISCUSSION

Solar thermal energy can serve as a raw source for electricity production at small scales and distributed applications unstalled at the end user side. The technology alternatives are available, even if some of them are not particularly accepted for small applications. There are no technical challenges to the wider deployment of solar thermal energy converters based on low-tech solar collectors such as flat plate and evacuated tube, providing temperatures of up to 150 ^{o}C.

The energy conversion methods are available and deliver acceptable efficiencies in the range of 5% to 12 % thermal-to-electricity conversion depending on technology and complexity level, and about half those values for solar-to-electricity efficiency. These are comparable to the performance of aged and overheated PV panels. With little optimization and improvements the thermal path towards solar energy conversion at small scales and low temperature solutions will prove to be not only technically but also economically feasible.

Careful economy analysis needs to be done, however it is difficult (except to a certain extent for ORC units) as there are no commercial solutions freely available for comparisons. Pilot projects would always be more costly than PV panels. If a market emerges and starts to grow, cost reductions through technology improvements, component standardization and prefabricated packaged solutions can be expected.

Solar thermal energy offers the chance to store heat locally and thus provide low-cost energy storage solution that would aid with both residential heat supply and distributed power production for load peak leveling purposes, back-up power and contingency mitigation in local grids, where both the consumer and utility would benefits from.

5. REFERENCES

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