FROM 1885 TO NOWADAYS: A (SHORT) TECHNO-HISTORICAL REVIEW OF SOLAR ORGANIC RANKINE CYCLE SYSTEMS

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ABSTRACT

Since the first solar ORC system built by Charles Tellier in 1885, *hundreds* of solar ORC systems have been imagined, built, tested, operated and, in most cases, abandoned along the past century. Aiming to emphasize the technical maturity of these existing but yet little-known works, this paper presents some of the most innovative technological developments of SORC thanks to six existing examples. These systems have been selected to cover various sizes, technology and applications, from the end of XIXth century to nowadays.

1 INTRODUCTION

In 1885, Charles Tellier, a French inventor known as the father of refrigeration, built a strange apparatus made of flat dark panels and a motor-like device that managed to pump water from a nearby well. Unlike the other solar-driven engines developed by Mouchot, Pifre or Eneas, Tellier used ammonia as working fluid to permit his vapour system to operate at lower temperatures. The first solar organic Rankine cycle (SORC) was born. Since then, *hundreds* of solar ORC systems have been imagined, built, tested, operated and, in most cases, abandoned around the world. Little known by nowadays researchers, the SORC technology features a richful history of successes and failures all along the XXth century. The goal of this paper is to give back credit to these pioneering works and provide a glimpse of the technical maturity achieved back in these days.

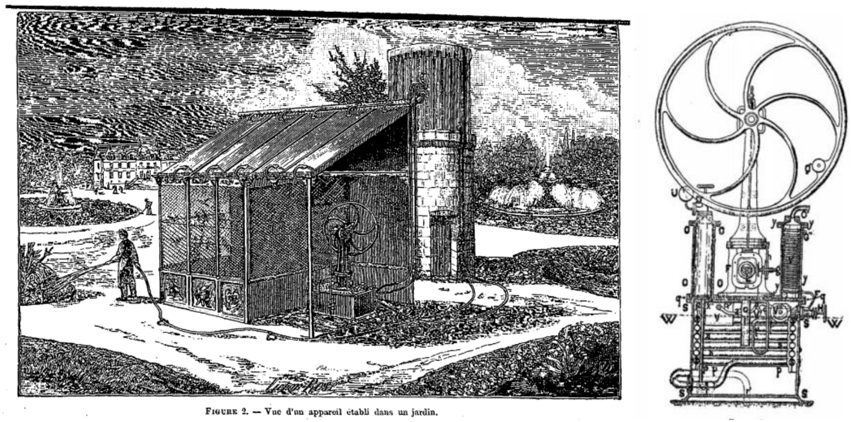

Figure 1: Artistic view and scheme of the first SORC built by Charles Tellier (Tellier, 1890).

The present paper is a (very) short summary of more global historical review conducted by the authors (Dickes et al., 2022). It presents few of the most important and innovative developments of SORC via a description of six different systems. These systems have been selected to cover various sizes, technology and applications. For ease of presentation, all the technical details of these SORC systems are summarized in Table 1 and are referenced via an index number (e.g. #1 for Tellier's SORC).

Table 1: Technical details of the selected SORC systems.

Index/ Manuf.	Year/ Location	Application	Solar Field		ORC		
			Type	HTF	Power	WF T_{min}/T_{max}- P_{min}/P_{max}	Expander
#1 Tellier	1885 Auteuil (France)	Irrigation	FPC (42m²)	NH_3+ H_2O	1kW$_m$	NH_3 25/70°C -1/4bar	Piston
#2 Willise & Boyle	1905 Needle (USA)	Irrigation	FPC (185m²)	Water	11kW$_m$	SO_2 30/71°C-5/15bar	Piston
#3 SOMOR	1949-1955 Various (Italy,USA Africa, Costa Rica)	Irrigation or Power	FPC (12m²)	SO2	0.1kW$_m$ – 2.6 kW$_m$	SO_2 33/37°C-4/6bar	Piston
#4 Ormat	1984 Beith Ha Rava (Israel)	Power	SGSP (250000m²)	Brine	5MWe	R114 27/85°C-2/10bar	Turbine
#5 Barber-Nichols	1983 Rosamond (USA)	Power	PDC (117m²)	Toluene	25kWe	Toluene 50/430°C-0.1/41bar	Turbine
#6 UTRC	1981 Phoenix (USA)	Cooling	PTC (122m²)	H2O	16kWm	R11 45/141°C-2/17bar	Turbine (inside turbo-compr.)
#7 Turboden	2014 Ait Baha (Morocco)	Power	PTC (6160m²)	Air	2MWe	HMDSO	Turbine

2 WILLSIE AND BOYLE'S PIONEERING ENGINES WITH THERMAL STORAGE

Following Tellier's premiere, SORC development was brought forward by the Americans Henry E. Willsie and John Boyle, who built a series of prototypes from 1892 to 1909 (Spencer, 1989). Their collectors were horizontal insulated boxes made of readily available materials, the boxes being of wood with hay or sand insulation, lined with black tar-paper, and glazed with window glass. A shallow pool of water, which was contained in the collectors, heated by the sun, and circulated to a heat exchanger to boil the adopted working fluid. Different fluids were tested in their various prototypes, including ammonia, ether and sulphur dioxide. Depicted in Figure 2, their last engine incorporated many significant features and, most notably, what can be considered as the first implementation of a sensible thermal storage: the hot water from the collectors could be stored in an insulated basin and then fed to the boiler as needed, thus allowing to run the solar engine also in the absence of sunlight. This last system is reported to have heated water to 82°C and the boiler pressure quoted corresponded to a saturation temperature of 71°C. The slide-valve/piston expander generated a measured mechanical power of the order of 11kWm. Mainly intended for irrigation purposes, other applications were also considered. Willsie wrote in a patent that the invention was "designed for furnishing power for electric light and power, refrigerating and ice making, for milling and pumping at mines, and for other purposes where large amounts of power are required". Despite their technical successes and innovative designs, the competition from new oil-derivative fuels becoming available after WWI soon removed the incentive to develop similar plants, and these researches were discontinued

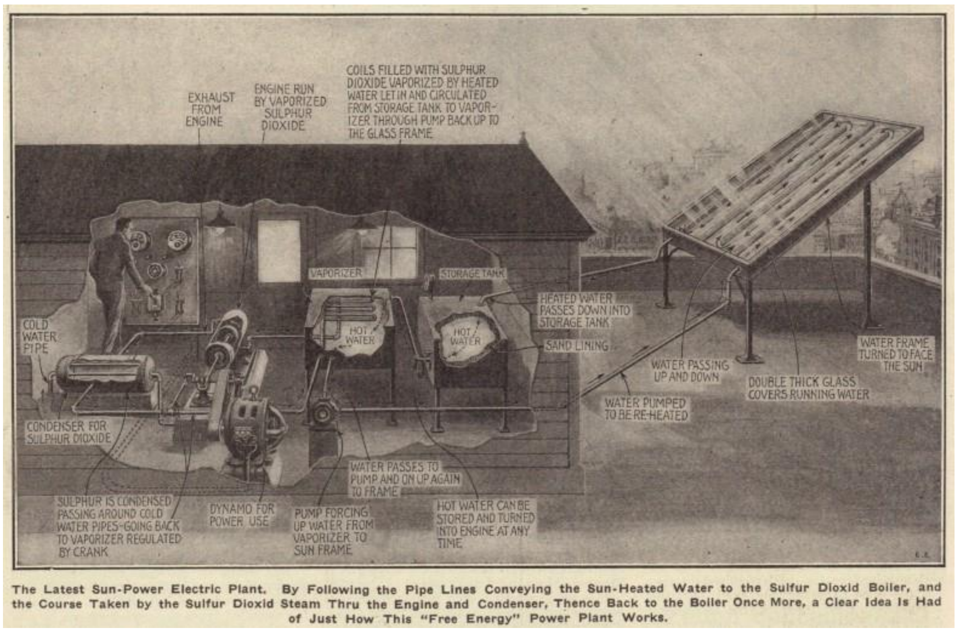

Figure 2: Artistic view of the 4th SORC prototype of Willsie and Boyle, installed in Needle, USA (image published in the Electrical Experimenter magazine, 1909)

3 THE SOMOR PUMPS USING SOLAR TRACKING COLLECTORS

Given the growing abundance of cheap fossil fuel and the rapid progresses in internal combustion engines and gas turbines, the development of solar-powered ORC machines was characterized by few experimental work during the first half of the XXth century. Interestingly, all reported activities occurred in Italy. Among them is the SOMOR story.

In 1935, Daniele Gasperini, an italian artisan from Trento, built with the help of Giovanni Andri a low temperature solar engine by inverting a refrigeration cycle working with sulphur dioxide. The system was first exhibited at a fair in Turin, and then in Tripoli, Lybia, in 1936. The advancements of Gasperini's project were blocked by the Second World War and were resumed only in the late 40's when Gasperini started a collaboration with the engineer Ferruccio Grassi, developing a solar motor pump based on a project of Prof. M. Dorning (D'aquino, 1992). The system was composed by a piston hydraulic pump run by a piston engine. The working fluid, sulphur dioxide, directly flew in flat plate collectors with side boosters to be evaporated by solar radiations. The fluid reached a maximum temperature of around 40°C at the outlet of the collectors. Given the low working temperatures, the ORC engine unit was characterized by a low conversion efficiency of the order of 2% (heat to mechanical power). In 1949, Ferruccio Grassi and Daniele Gasperini established the SOMOR company in Lecco, Italy, with the aim to market a compact solar motor pump. Five different pump models were developed, with an engine capacity ranging between 0.11kWm and 2.6kWm. The possibility of adding a dynamo to generate electricity was available for the three largest models. The SOMOR collectors were equipped with an automatic azimut tracking system and the unit required low maintenance work (see Figure 3). The company sold around 30 systems in Italy and other countries - among which the U.S., Somalia, Egypt and Costa Rica - and reached large popularity when a SOMOR unit was exhibited at the first fair on solar energy held at Phoenix, Arizona, in 1955. Following this interest, a research group from Stanford University experimentally analyzed the operation of a SOMOR pump model II (Eustis et al., 1956). The study demonstrated that the effective performance of the solar pump were far below expectations. A prototype with parabolic trough collectors was built too, but no record of performance was found. After the death of Gasperini in 1960, the company was folded in 1963 by F. Grassi due to lack of demand.

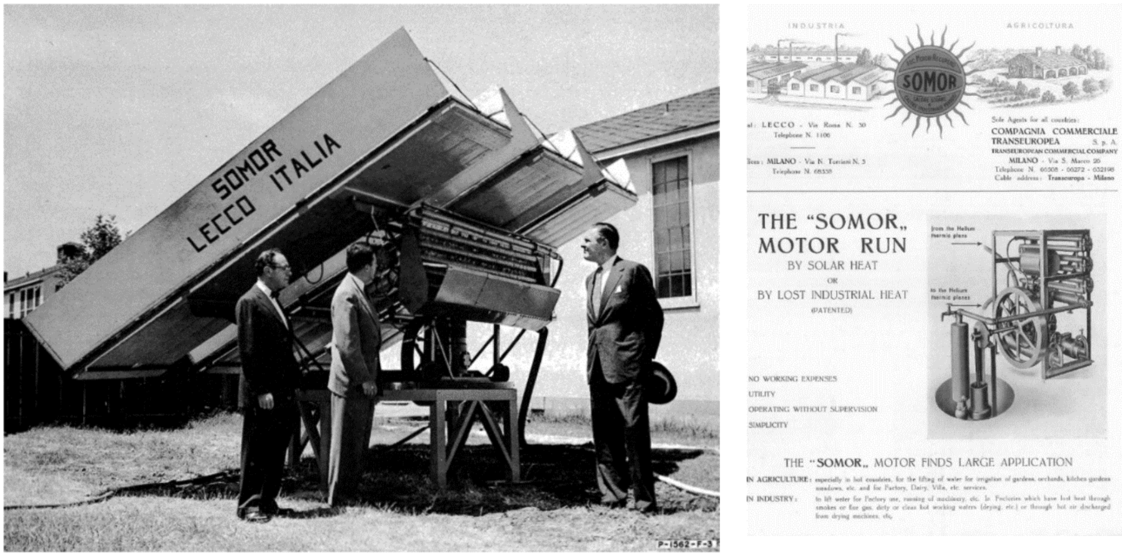

Figure 3: Somor Solar Pumps. (Silvi, 2000)

4 THE 5MW ORMAT POWER UNIT COUPLED TO A SOLAR POND

R&D and commercial activities in the field of solar ORC systems had a spike in the 70's and 80's, as a consequence of rising fuel prices during the oil crisis. In that period, Israeli institutions deeply investigated salt-gradient solar ponds (SGSP) for power generation. Following two successful prototyping experiences of 6kWe and 150kWe, a large-scale solar pond with a collection area of 250,000m² was installed in Beith Ha'Rava, Israel (see Figure 4). Hot brine at 85°C fed a 5MWe Ormat unit generating electricity on the national grid for more than 4 years. The solar pond stored enough heat to operate the ORC engine at full power for about 2000 hours per year. The system used R114 as working fluid and multi-stage turbine for the expansion process. The net thermal efficiency of the ORC reached 5.5% with an annual pond efficiency of 16%. Out of these experiences, the collection efficiency was shown to be very sensitive to the water turbidity and the salt gradient quality. To ensure a proper gradient profile, turbulences had to be avoided in the pool. To this end, some systems installed wind-breakers at the pool surface and low velocities were used for the brine extraction/injection. High turbidity was also mandatory and contamination issues due to algae and pipes corrosion were encountered and solved. Due to low conversion efficiencies, thus requiring large collection areas, and the decreasing price of fossil fuels, these solar pond power plants became soon uneconomical and further developments were dropped.

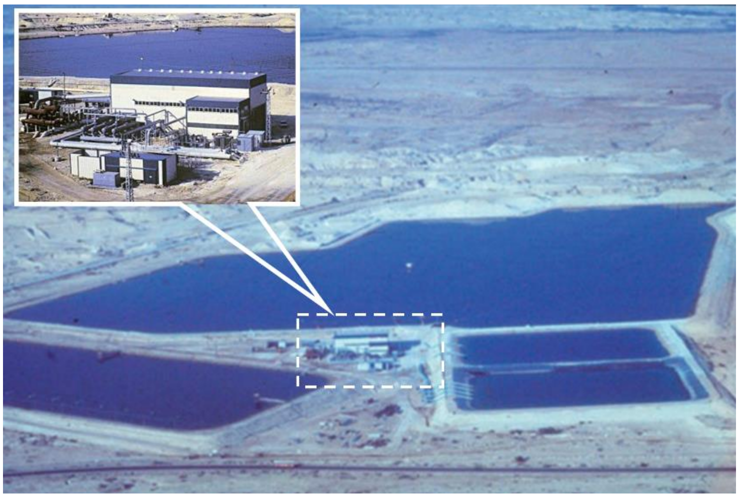

Figure 4: 250 000m² SGSP and 5MWe Ormat unit in Beith'Ha Rava (Tabor and Doron, 1990).

5 THE HIGH-TEMPERATURE POWER MODULE FROM BARBER-NICHOLS

In 1981, in the framework of the Small Community Solar Thermal Power Experiment (SCSE) project (U.S. Department of Energy, 1981), Barber-Nichols designed and developed an ORC power module to be coupled with a parabolic dish collector. The prototype targeted a net power output of 25kWe for use in a 100kWe multi-module solar power plant. Despite the project was halted before construction of the multi-module plant took place, an ORC engine was built and tested at the Parabolic Dish Test Site operated by the U.S. Jet Propulsion Laboratory (JPL) between 1981 to 1982. The cavity receiver was designed to heat toluene at 430°C and 41.3bar, aiming to result to a net thermal efficiency of 30 % with a nominal thermal input of 107 kW_{th}. The rotating parts (single-stage impulse turbine, centrifugal pump, and permanent magnet alternator) were mounted on a single shaft rotating at 60,000 rpm. The same working fluid was also used for bearing lubrication. The ORC engine was air-cooled and a cut-view of the unit is shown in Figure 5. During tests, the fluid temperature at receiver outlet was controlled at 400 ±5°C and a maximum net power conversion efficiency (heat to electricity) of 22% was achieved with a total thermal power at the receiver of 70 kW_{th}. A net solar-to-electric conversion efficiency as high as 15% was measured. A total of 34 hours of on Sun testing were performed, notwithstanding the unfavorable test conditions and a number of occurred malfunctions related to major shortcomings in the bearing design.

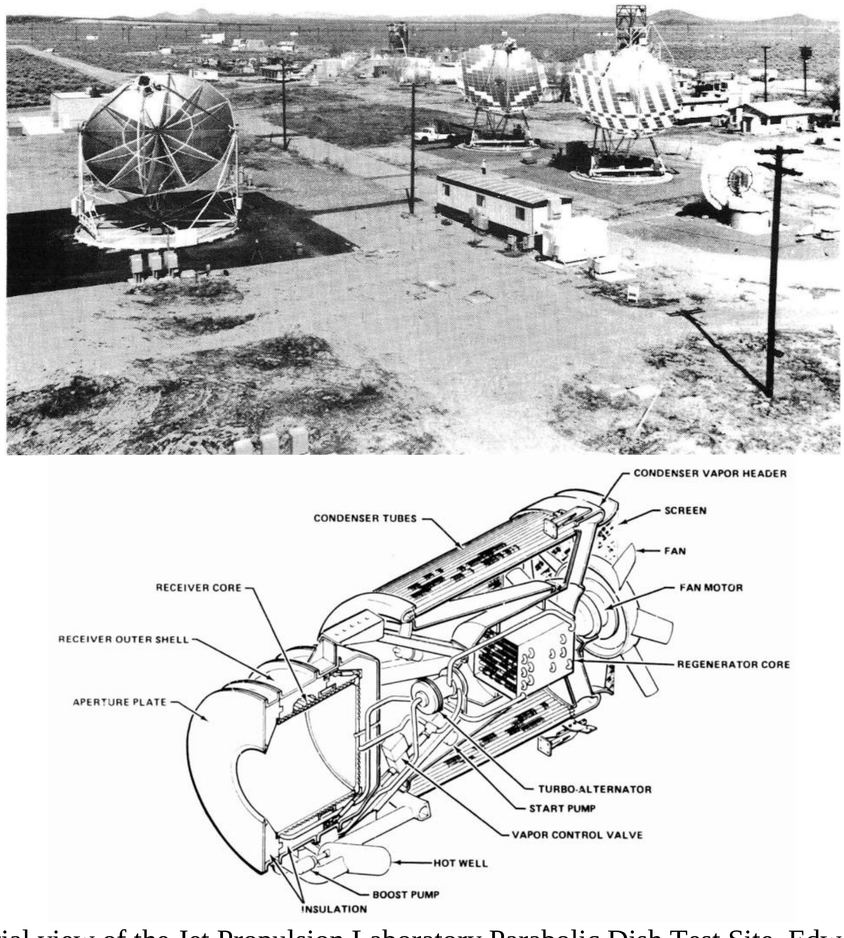

Figure 5: Aerial view of the Jet Propulsion Laboratory Parabolic Dish Test Site, Edwards Air Force Base. Barber-Nichols ORC engine for the SCSE project (Kiceniuk, 1985).

6 THE HIGH-SPEED TURBO-COMPRESOR UNITS FOR SOLAR COOLING

Still in the 70's and 80's, several SORC cooling projects were conducted in an effort of replacing gas-based absorption chillers and electric vapor compression units. In such solar ORC-based cooling systems, the Sun energy input is transformed into mechanical work to drive a conventional vapor compression system. Despite the low efficiency, the refrigeration system allows use of auxiliary electric energy to run the compressor when Sun is not available or to generate power when cooling is not needed (i.e. by integrating a generator on the shaft coupling the Rankine engine with the chiller compressor). Numerous projects were conducted in this field, involving several American, Japanese or Saudi Arabian partners. Among them is the project undertaken by the United Technology Research Center (UTRC) in collaboration with Hamilton Std. Their work led to the development of several solar turbo-compressors, from a 5-ton proof-of-concept unit to an advanced 18-ton air-cooled system. Depicted in Figure6, the key component was a hermetically-sealed turbo-compressor permitting a single-loop architecture. If no Sun was available, a gas furnace furnished the required thermal energy and the solar cooling unit was coupled to a two-tank storage. Refrigerant R11 was employed as working fluid and the turbo-compressor had a design rotational speed of 42 000 rpm. Heating operations were also supported. In 1981, within the framework of the SOLERAS program, a 18-ton machine was installed in Phoenix, Arizona. Water circulating in a 122.3m² tracking parabolic through solar field was heated up to 150 °C, providing the thermal energy for operation of the unit. Promising results were recorded during the campaign (Biancardi et al., 1982).

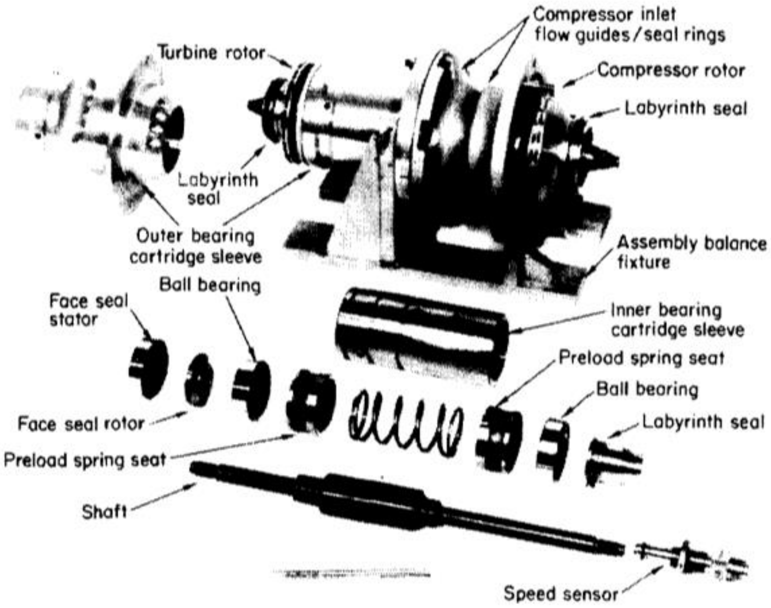

Figure 6: UTRC turbo-compressor module for cooling applications (Biancardi et al., 1982).

Once more, as no solar cooling market was developed, all these projects remained in the category of expensive, made-to-order, individual cooling packages. The decreasing research budget on solar cooling and the lack of a clear-cut advantage of solar Rankine system led to a stop of most of solar cooling research based on the mechanical approach.

7 LARGE-SCALE HYBRIDIZATION

Following the active R&D periods of the 70's and 80's, fewer SORC activities were reported in the 90's. It is only in the early 2000's that a strong regain of interests was observed as for the other applications of organic Rankine cycles. To conclude this short review, the recent SORC system installed in Ait Baha, Marocco, is reported to illustrate an increasing trend of solar applications: hybridization to other heat sources. In this system, depicted in Figure 7, a 6190m² field of parabolic trough collectors is used to boost a pre-existing 2MWe ORC plant recovering heat from a cement factory. Featuring innovative concrete structures, this solar field uses air as heat transfer fluid to provide an extra 3.9 MW_{th} through a single-tank packed-bed storage. This innovative collector design permits to increase the air temperature from 270°C to 600°C with collection efficiency close to 60%. The ORC unit, on the other hand, is a standard Turboden 18HR module using hexamethyldisiloxane as working fluid and a multi-stage axial turbine. The ORC module features a gross conversion efficiency close to 25% at nominal operating conditions.

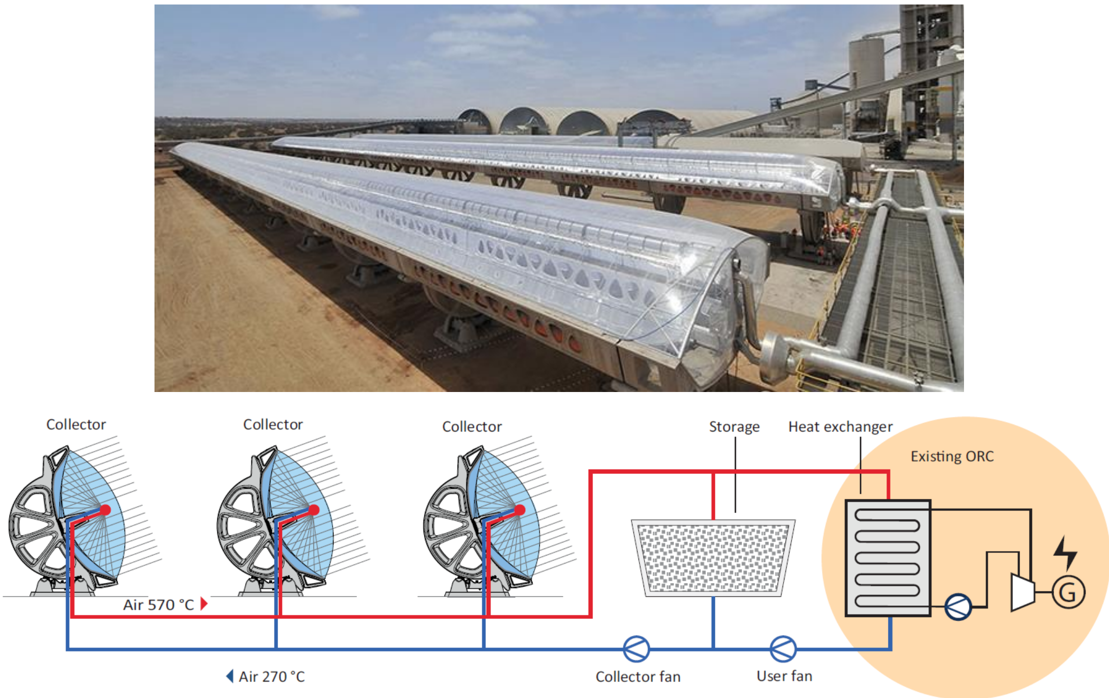

Figure 7: Solar field (top) and system scheme (bottom) of the Ait Baha hybrid SORC system (NREL, 2015)

8 CONCLUSIONS

The reported systems are six examples among the hundreds of SORC units developed in the past years, but they emphasize well the technical maturity reached in the past decades. Countless details regarding design decisions, experimental feedbacks or operational failures can be learned, all these aspects being an amazing source of information for future developments. For the interested reader, a more complete review of the long history of SORC will be soon published by the authors.

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