# Solar multi-generation in the Mediterranean area, the experience of the STS-MED project

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## Abstract

A solar multi-generation approach has been implemented through four demonstrative plants in Italy, Cyprus, Jordan and Egypt based upon solar concentrating collectors. Different design options have been developed, including technologies that have been adapted and downsized from the utility scale of CSP plants, with the aim to be integrated at building, settlement and community scale. Demo plants have been conceived as living labs in order to support the further development of the technologies in a real-life environment, supporting the local smart specialization strategies in collaboration with SMEs, local stakeholders and citizens.

Keywords: *multi-generation, solar thermal, CSP, storage, concentrating solar collectors, solar cooling, building integration, smart specialization, living labs*

## 1. Introduction

Global space cooling energy consumption increased by 60% between 2000 and 2010, reaching 4% of global consumption (OECD/IEA Report 2013), meanwhile the production of heat accounts for more than 50% of global final energy consumption (OECD/IEA Report 2014). The seasonal switch among the winter demand of heat and the summer demand of cold is already a characteristic of the solar belt regions, including the Mediterranean area. Therefore, specific efforts are needed in piloting innovative approaches to cover the complex mix of heat, electricity, cold and other energy driven services by an optimized harvest, storage and conversion of the solar radiation. As a matter of fact, seasonal demand can be holistically managed at a settlement level by multi-generative solar concentration systems; the collection of high quality solar radiation, mostly available in summer periods, can feed a solar cooling system in the hot days, while the same collectors can cover the moderate heat demand in winter-time. Electricity can be generated from small turbines or integrated PV panels. Residual heat can be used to drive other services, as the purification of brackish, waste water or sea water desalination. Since November 2012, such a challenge is undertaken through the Small scale Thermal Solar district units for Mediterranean communities (STS-Med) project, supported by the ENPI- CBCMED program, with the construction of 4 pilot plants:

- in Palermo, Italy, led by Consorzio ARCA - coordinator of STS-Med - in the campus of the University of Palermo, in partnership with the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) for the Thermal Energy Storage (TES) system,
- in Aglantzia, Cyprus, led by the Cyprus Institute (CyI), in the campus of the institute,
- in Markaz Belbes, Egypt, at Sekem Hospital, led by Academy of Scientific Research and Technology (ASRT) and built by Elsewedy Electric,
- in Irbid, Jordan, led by Al Balqa Applied University (ALBUN) and built by Millennium Energy Industries.

The 4 plants demonstrate that a smart integration and optimization of both commercially available and innovative solar technologies can open a way towards the goal of "zero energy" communities in the Mediterranean region (Rashad et al. 2015 and Kiwan et al. 2016).

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Figure 1. Novel Technologies Laboratory (left), rooftop of the University College in Irbid (right)

The buildings concerned self-produce the energy they need through sustainable systems, integrated at a settlement level, with a significant reduction of $CO_2$ emissions and consumption especially in seasonal peak. The design of each demo site has been adapted accordingly with the result of specific energy audits and the availability of either ground or roof space for the collectors. Local communities have been involved in awareness activities and local SMEs have been invited to take part into educational activities during the preparatory and erection phases.

In Italy, the collectors are installed in a field nearby the building and the plant is generating electricity by an existing ORC (Organic Rankine Cycle) and heat/cold with the help of an absorption chiller integrated on the HVAC system. The case-study in Cyprus is located in the premises of the Cyprus Institute in Aglanzia (district of Nicosia), Cyprus. The objective of the plant is to support the heating, cooling and hot water system of the Novel Technologies Laboratory (NTL, Figure 1, left) by reducing the use of the existing electric heat-pumps. NTL was designed to be a “near to zero energy” building (Papanicolas 2015 et al.) by a specific selection of the materials and orientation of the windows and walls, which minimize the energy demand for air-conditioning. A 14.5 kW peak power photovoltaic generator covers a part of its electricity consumption. In Jordan the collector is installed on the roof of one of the buildings at University College in Irbid (Figure 1, right). As for the Cypriot plant, the system is installed on the roof a public building (Figure 2, right). The objective of the plant is to provide heating and cooling to classrooms of the university and hot water in case of over-production. A small steam turbine can be activated to generate electricity. The pilot plant in Egypt is located in Belbes to support Sekem medical center HVAC, at 60 km from Cairo city center as the crow flies. The collector is installed on plain field next to the hospital. A small ORC turbine is generating electricity balancing the seasonal demand of cold.

## 2. Solar collectors

As shown in Figure 2 and Figure 3, solar fields in Cyprus, Egypt and Italy are based on North-South aligned Linear Fresnel Collectors (LFC) or Linear Fresnel Reflectors (LFR). The installed LFRs, specifically designed for integration in built environments, have been developed by Idea (Vasta 2013 et al.), an Italian company affiliated to Consorzio ARCA. In Jordan the plant relies on a Parabolic Tough Collector (PTC, Figure 3) manufactured by the Italian company Soltigua. The characteristics of the collectors are detailed in Table 1. Platforms are located at different latitudes, from 30°25'05.5"N in Egypt to 38°06'01.0"N in Italy.

Figure 2. LFR at Palermo, Italy (left) and Nicosia, Cyprus (right)

Figure 3. PTC at Irbid, Jordan (left) and LFR at Egypt Markaz Belbes (right)

Table 1. Characteristics of the solar fields

| | Cyprus | Egypt | Italy | Jordan |
|---|---|---|---|---|
| Location | Aglantzia, on the roof of a school, next to the NTL | Markaz Belbes, nearby the Sekem medical center | University of Palermo, on the ground at ARCA premises | Irbid, roof a building of the Balqa University College |
| *Latitude*<br>*Longitude*<br>*Elevation (Above the sea level)* | *35°08'28.1"N*<br>*33°22'50.7"E*<br>*176m* | *30°25'05.5"N*<br>*31°38'07.8"E*<br>*35m* | *38°06'01.0"N*<br>*13°20'37.3"E*<br>*50m* | *32°29'13.2"N*<br>*35°53'24.0"E*<br>*648m* |
| Average DNI per year (Source: SolarGis) | 2142 kWh.m$^{-2}$ | 1958 kWh.m$^{-2}$ | 1703 kWh.m$^{-2}$ | 2377 kWh.m$^{-2}$ |
| Type of collector | LFR - Idea | LFR - Idea | PTC - Soltigua | LFR |
| Global aperture area | 184.32 m$^2$ | 299.50 m$^2$ | 483.84 m$^2$ | 163.2 m$^2$ |
| Thermal oil, Heat Transfer Fluid (HTF) | Duratherm 450 | Therminol 66 | Paratherm NF | Seriola eta 32 - Total Lubmarine |
| Peak thermal power | 70 kW | 115 kW | 190 kW | 85 kW |
| Total receiver length | 32 m | 52 m | 84 m (3 x 28 m receivers rows) | 38.56 m |
| Working temperatures (outlet) | 170°C | 140°C | 280°C | 240°C |

All the collectors are working with thermal oil as heat transfer fluid (HTF) at different temperature: from 140°C to 280°C. The total thermal peak power of the plants is 460kW. The platform in Palermo is the main contributor with 190kW with 3 identical LFC parallel loops. Figure 4 shows a simplified layout of the solar plant installed in Sicily.

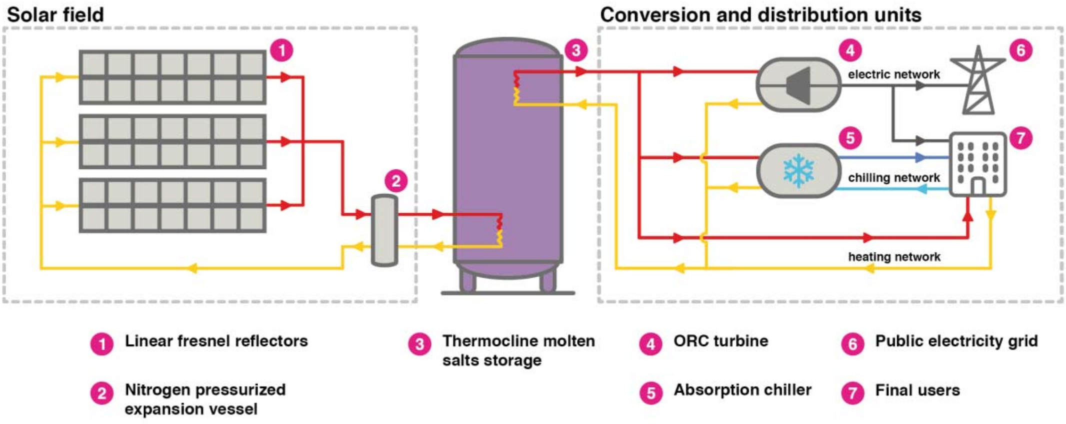

Figure 4. Layout of the field at ARCA (Sicily)

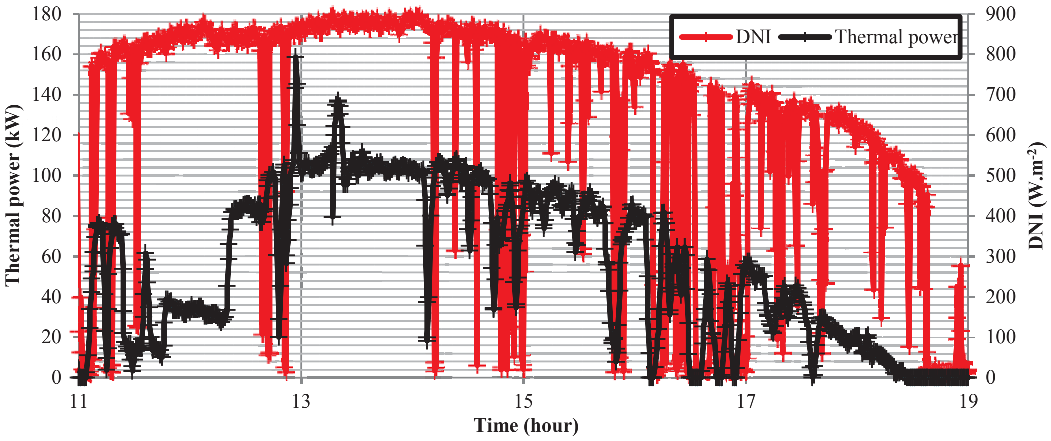

**Figure 5. DNI and thermal power on the 6th of September 2016 (Italy)**

The thermal power and DNI on the 6th of September 2016 are shown in Figure 5. A peak of 160kW was achieved at 12.30PM. In Cyprus 70kW peak power is installed. On the 26th of July 2016, the Fresnel collector was commissioned. Thermal power and DNI are show in Figure 6. The output power reached 68.7 kW with a DNI of 800 W.m$^{-2}$ at 12.52PM.

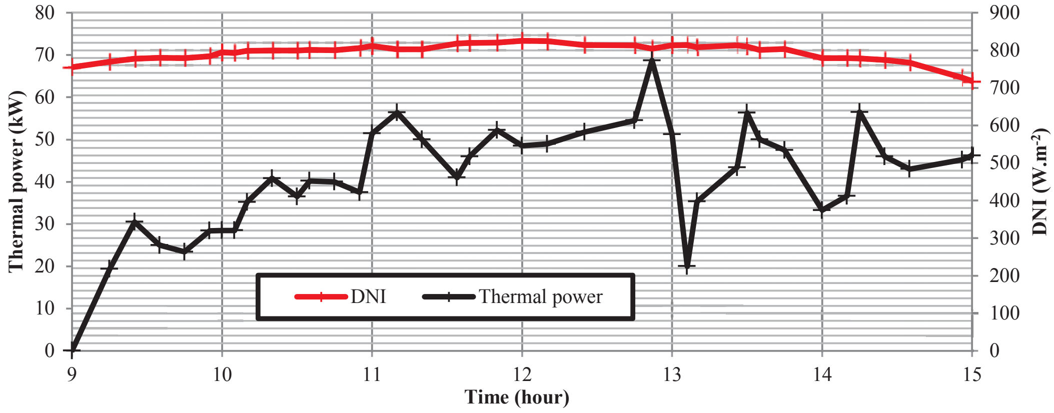

**Figure 6. DNI and thermal power on the 26th of July 2016 (Cyprus)**

The peak power installed in Egypt is 115kW and 85kW in Jordan. All the 4 for plants are equipped with a vacuum receiver and with the association of a secondary reflector for the LFRs in Cyprus, Egypt and Italy with estimated 90% optical efficiency. DNI is the highest in Jordan with 2377kWh.m$^{-2}$ per year. DNI in Cyprus is 2142kWh.m$^{-2}$ per year and in Egypt 1958kWh.m$^{-2}$ (Source: SolarGis Imaps, Beták et al. 2012). DNI in Palermo is the lowest with 1703 kWh.m$^{-2}$ per year. The solar fields were all completed in September 2016. Dimension of the mirrors of the 3 LFRs are identical: 0.32m x 2.000m. Cypriot LFR was the first to be installed on the island (Montenon and Fylaktos 2016). It is composed of 288 mirrors with a reflective area of 184.32 m$^2$, driven by 72 DC motors (4 mirrors per motor). In Egypt, the system is composed of 468 mirrors and the reflective area is 299.52 m$^2$, but driven by 13 DC motors (36 mirrors per motor). The Italian field is hybrid: 2 LFC modules are configured as in Egypt and the third collector is configured according to the Cypriot model. In this way it is possible to lead comparisons between the two strategies. On the one hand in Cyprus the flexibility of the field is higher but requires more maintenance due to larger number of motors: if one motor fails, the system will be only slightly impacted and can continuously operate with the rest of the 71 motors. On the other hand, the Egyptian collector relies on fewer motors, so requiring less maintenance, but if one motor has to be changed a larger area of the solar field will be impacted; furthermore, tracking angles of the motors is not independent and the whole field cannot be placed in flat position for cleaning purpose for instance. In Cyprus and Italy, HTF loops are separated from the thermal storage medium. Nonetheless, small buffers are installed in the HTF loops in order to stabilize the temperatures.

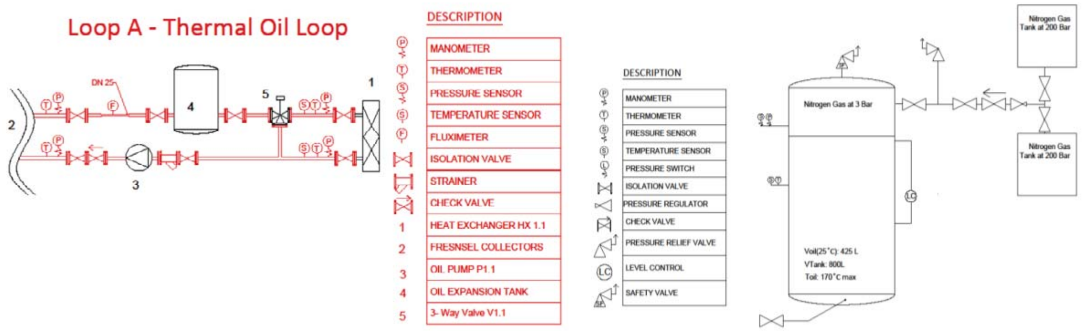

**Figure 7. HTF Loop at CyI (Cyprus) : oil loop (left) and pressurized vessel (right)**

As shown on the main layout (Figure 4), in Sicily, on the field installed at ARCA a buffer tank is also integrated in the HTF loop with a total volume of 800L containing 500L of thermal oil (Paratherm NF) pressurized with nitrogen at 3bar (for a thermal storage capacity of 22kWh). In Cyprus the thermal oil (Duratherm 450) is stored temporarily in an 800L tank (containing 425L of oil), pressurized with nitrogen at 3bar (Figure 7). A 3kW electric heater is wrapped around the tank to pre-heat the oil in case of cold start-up. The role of these tanks is also to stabilize the outlet temperature of the piping. Pre-heating the oil decreases the viscosity of the HTF and increases the Reynolds number to maintain it above 10,000 (turbulent flow). Based on experience, the solar absorber pipe bends at low ranges of the Reynolds number, due to thermal gradients, and it may get in contact and break the external glazing pipe. As soon as the oil inside the buffering tanks is heated to a satisfactory value, the inverter pump of the HTF loop starts. The control of the platforms in Cyprus and Italy aims to correlate the output with the real time value of the DNI. To that end, two pyrheliometers are installed on the respective sites (Figure 8).

**Figure 8. Pyrheliometers at ARCA (left) and the Cyprus Institute (right)**

## 3. Thermal storage

Thermal storage is a key element of the four platforms. It permits to buffer the production for some minutes to several hours. Details of the thermal storage in use in the 4 platforms are exposed in Table 2. In the plants built in Jordan and Egypt, the HTF is directly stored respectively at 240°C and 140°C. In both Cyprus and Italy, a heat-exchanger transfers the heat from the oil to TES system. In Cyprus thermal storage is based on water pressurized with nitrogen up to 146°C ensuring 2 hours of autonomy for cooling in summer or 4 hours for heating in winter. The same nitrogen tank is used to pressurize the thermal oil (Figure 9). Storage with water is a low cost technology and vessels are available on Cypriot market.

**Table 2. Thermal storages**

| | Cyprus | Egypt | Italy | Jordan |
|---|---|---|---|---|
| Medium | Pressurized water | Thermal oil (Therminol 66) | Ternary molten salts mixture | Thermal oil (Seriola eta 32 - Total Lubmarine) |
| Storage Volume | 2.0 $m^3$ | 2.8 $m^3$ | 8 $m^3$ | 1.3 $m^3$ |
| Storage capacity | 100 kWh | 21 kWh | 400 kWh | 30 kWh |
| Average temperature | 146°C | 140°C | 260°C | 240°C |

**Figure 9. Buffer of oil, expansion vessel, thermal storage tank (left to right) at CyI (left) and molten salts storage, oil storage and expansion tank (left to right) at ARCA (right)**

Safety relief-valves are installed on the tank in case of over-pressure. The developed TES integrated in the pilot plant built in Sicily includes innovative features. Different options have been reviewed. TES systems commonly applied in conventional CSP plants operate with “solar salts” (molten nitrates mixture $NaNO_3/KNO_3$ 60%/40% of weight distribution), in two-tanks heat storage system operating from 290°C (cold tank) to 385°C (hot tank) when oils are used as HTF in the solar field (Lovegrove and Stein 2012). In small CSP plants (lower than 1MW range) it is rather difficult to replicate such a complex scheme due to the lower operative temperatures (280°C maximum in Sicily) and principally due to the need of expert personnel to manage molten salts loops too. Therefore, an innovative TES system has been specifically developed in STS-Med project. It is also based on molten salts, but the management of the TES is eased. This is lower than the melting point “solar salts”, which is around 220°C (Serrano et al. 2013). Hence, the temperature range is much more compatible with the above-mentioned small-medium CSP temperatures (up to 300°C). Also the “two-tanks” configuration is replaced by a single-tank system avoiding any external pumping of the molten salts and the critical management of pipelines against freezing. In the developed TES at ARCA, all the typical operations of a CSP plant of charging and discharging are achieved inside the single buffer tank where given temperature gradients and molten salts circulation are easily determined. Therefore, besides lower equipment volume and cost reduction potentials, the plant operator does not have to manage molten salts flows. Thus, the developed TES is tailored for residential users and fits into the STS-Med requirements. The developed TES system is represented in Figure 10. The operation concept is based on the properties of unmixed molten salts in the tank to thermally stratify along the vertical axis, as an effect of their low thermal conductivity and the density variability with temperature. Two heat exchangers are immersed in the zones where the temperature is lower (bottom) and higher (top) to be operated during the charging and discharging phases. In a conventional two-tanks TES systems with the high temperature tank at $T_{S\text{-high}}$ = 385°C (and the low temperature tank at $T_{S\text{-low}}$ = 290°C) about 280 $m^3$ of “solar salts” shall be loaded to store 20 MWh thermal energy, to drive a steam Rankine cycle.

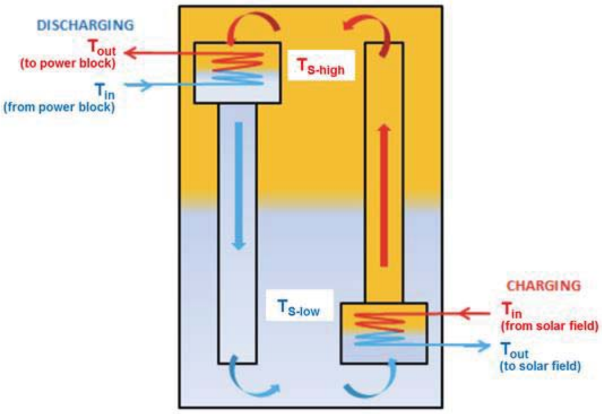

**Figure 10. Optimized TES system developed for STS-Med: general scheme with explanatory working conditions (left) and prototype drawings (right)**

The same principle can be applied to a smaller TES system with maximum temperature of 300°C, combined with an Organic Rankine Cycle. In the pilot plant in Sicily, TES is filled up with about 7 $m^3$ of eutectic ternary salt mixture (42%/15%/43% of weight distribution). Considering the reduction of the overall amount of salt, the use of a single tank instead of two tanks and the avoidance of external molten salt pumps and pipelines, the cost (€/kWh thermal) of this optimized heat storage system developed can compete with the large scale CSP benchmark.

In the framework of the STS-Med project a small TES prototype of 0.96 $m^3$ has been designed, built, installed and successfully tested at ENEA-Casaccia research center (Rome) in order to validate the concept before the installation in the pilot plant in Sicily. Loading, mixing, and melting procedures of the salts in the TES have been studied. The experimental results and concept validation with the prototype enhanced the design of an up-scaled TES for the demonstration plant in Palermo. Specifically, further optimizations and improvements have been performed in a "new" version of the TES installed in the STS-Med pilot plant in Sicily. This upgraded prototype is designed to work in a thermal range of 160-280°C. It is characterized by an inner volume around 8.0$m^3$ (1.8m diameter, 4m height) corresponding to effective heat capacity of about 400kWh (thermal). The charging/discharging thermal power averages 250/125 kW (thermal). The tank has been insulated with a 20cm coating of rock wool.

## 4. Cooling, heating and hot water

### 4.1. Cooling

Cooling is the central task of all the STS-Med platforms, due to climate considerations in the Mediterranean areas concerned by the project. The 4 plants rely on absorption chillers (Figure 11) to provide chilled water at 7°C. The global cooling capacity of the platforms averages 110.1kW. Chillers in Cyprus, Egypt and Italy are LiBr (Lithium Bromide) based, while in Jordan it is ammonia based. In Cyprus, the model used is YAZAKI WFC-SC10. It is water-fired at low temperature (88°C inlet, 83°C outlet). Its cooling capacity is 35kW with a COP (Coefficient of Performance) of 0.7.

**Table 3. List of absorption chillers**

| | Cyprus | Egypt | Italy | Jordan |
|---|---|---|---|---|
| Model | YAZAKI<br>WFC-SC10 | YAZAKI<br>SH10 | Broad<br>BCT 23 | Robur<br>ACF 60-00 HT |
| Type | LiBr – Single effect | LiBr – Single effect | LiBr – Double effect | Ammonia – Single effect |
| Firing medium | Water | Thermal oil | Thermal oil | Thermal oil |
| Cooling capacity | 35 kW | 35 kW | 23 kW | 17.1 kW |
| Inlet temperature | 88°C | 88°C | 200°C | 240°C |
| COP cooling | 0.7 | 0.7 | 1 | 0.6 |
| Heating capacity | | 48.3 kW | 23 kW | |

Figure 11. Absorption chiller and cooling tower at CyI (left) and at ARCA (right)

The heat is transferred to the absorption chiller from the thermal storage medium through a heat-exchanger (pressurized-water and water). Then the heat is stored in a 500L tank of water. This stabilizes the inlet temperature for the chiller. A cooling tower dissipates the heat from the absorber and condenser chambers (Figure 11). In Egypt the same capacity chiller is used but the heat medium is thermal oil instead of water. In Italy, the double effect absorption chiller is the most performant with a COP of 1 and it includes its own cooling tower (Figure 12). The cooling capacity is 23kW. The Jordanian chiller is a Robur HT model with a cooling capacity of 17.1kW at COP 0.6. Its working temperature is 240°C.

### 4.2. Heating and hot water

The absorption chillers in Egypt and Italy are also heating in winter with better COP than cooling. Heating capacity is 48.3 kW in Sekem and 23 kW in Palermo (Figure 11). In Cyprus the absorption chiller is simply by-passed to heat directly two water stratified tanks (2000L each). The heat is supplied to the Air Handling Units (AHU) and the Fan Coil Units (FCU) for the offices of the NTL. In Jordan, the absorption chiller is also by-passed in winter. If the available solar energy exceeds the cooling and electricity generation demands, the excess heat is released to hot water network through shell and tubular heat-exchanger. The heated water is then stored in a tank. If the excess heat exceeds the storage capacity, it is dissipated by dry cooling.

## 5. Electric power units

Platforms in Egypt and Italy (Figure 12) cogenerate with ORCs (Organic Rankine Cycles) fired with thermal oil. They both have an electric capacity of 10 kW and gross efficiency of 10% (Table 4) and need a cooling tower to dissipate the heat rejection. They produce electricity in parallel with heating or cooling. The ORC in Egypt works with inlet temperatures of 125°C to 150°C. In Jordan the oil exchanges its heat with a steam loop to operate a demonstrative steam turbine of 1.2kW of electric power (Figure 12).

**Table 4. Power units in Egypt, Italy and Jordan**

| | Egypt | Italy | Jordan |
|---|---|---|---|
| Element | ORC | ORC | Steam turbine |
| Electric power | 10 kW | 10 kW | 1.2 kW |
| Medium | Thermal oil | Thermal oil | Steam |

**Figure 12. Steam turbine during the installation in Irbid (left) and ORC Rank turbine in Palermo with cooling tower (right)**

## 6. Conclusions

Nowadays solar concentration platforms are designed to produce several thermal MW and generally for electricity generation in desert places. STS-Med project demonstrated the possible application of solar concentrating technologies within integrated multi-generative plants at small/middle scale in built environment either on the ground (Egypt and Italy) either on roofs (Jordan and Cyprus). Production of heat to directly drive absorption chillers through thermal energy storage permits to avoid the stage of transformation to electricity. The residual heat can be used for electricity production with the help of ORCs. Thus, the co-generation of heat and electricity reduces the global balance of the energy consumption of buildings and not only the electric part. The thermal storage permits to shift the production at peak load with good flexibility. In the plant built in Sicily an innovative thermal energy storage system based on the use of molten salts and specifically tailored for small scale concentrating solar applications has been integrated. The main limitation to downscale solar cooling is the lack of commercial small scale absorption chillers and ORCs. At the same time COP of absorption chiller, even with double-effect, is still poor if compared to electric heat-pumps. Efficiency of small ORC turbine is also poor and their application at the project scale (5-10 kW) can be considered as demonstrative of larger (50-100kW) applications. In this scope, the 4 plants have been conceived as living labs, introducing the technology mix into different real-life environments acting as showcases for the respective local communities. Comparative studies of design options and subsystems will permit to identify the best strategies for the overall optimization of both efficiency and cost; at the same time the local academic and technical communities will have a joint and open access to the demo facilities as platforms for future collaborations and developments.

## 7. Acknowledgments

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