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D 4.5
IMPACT ASSESSMENT OF THE CASE STUDIES FOR A BROADER IMPLEMENTATION OF INNOVATIVE SOLUTIONS

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D 4.5 IMPACT ASSESSMENT OF THE CASE STUDIES FOR A BROADER IMPLEMENTATION OF INNOVATIVE SOLUTIONS

4.5.1 Benchmarking of case studies for CS toolbox

The set of case studies collected in Task 4.4 constitute the benchmark pattern of CS toolbox of STS-Med. The summary of the components and subsystems are used in these case studies is compiled in D 4.4 and D5.1 reports. To assess the impact of these case studies from technical and economic point of view, we need to define a technical and economic indicators.

4.5.2 Technical Indicator

To evaluate the technical performance of small scale concentrated solar systems used for poly-generation, the concept of utilization factor will be used. Since the main idea of the multi-generation is to maximize the utilization of the incident solar energy on the solar field, it will be convenient to use the utilization factor which basically measures the amount of converted useful energy relative to the available energy from the source. It is defined as the ratio of the annual useful energy (thermal and electrical) produced by the system to the total annual incident energy on the system. The useful energy includes the energy produced for heating, cooling, water desalination and electricity generation. That is

$$\varepsilon = \frac{Usuful\ \ Energy\ \ Collected\ \ per\ \ year}{Annual\ \ Incident\ \ Solar\ \ Irradiatio\,n\ on\ the\ solar\ \ feild} \tag{1}$$

$$\varepsilon = \frac{E_h (kWh/\ year) + E_c\ (kWh/\ year) + E_{ele}\ \left(kWh/\ year\right) + E_w\ \left(kWh/\ year\right)}{\overline{DNI}\ x\ A} \tag{2}$$

Where DNI is the annual average direct normal solar irradiation in kWh/m^2/year incident at the location. The energy used for water desalination is calculated as

$$E_w = M\ (kg/year)*\left(h_{fg} + 4.18*(100-20)\right)(kJ/kg)\ *(1/3600\ s/hr) \tag{3}$$

M: is the total mass of water desalinated per year, h_{fg} (2200 kJ/kg) is the specific enthalpy for vaporization for water at ambient conditions.

The energy output of the heating system, E_h, is calculated as

$$E_h = \sum_{i=1}^{N} \dot{m}\ c_p\ \left(T_i - T_o\right) \tag{4}$$

Where N is the number of hours in the year when the heating system is operating. m is the average hourly flow rate of the fluid conveying heat to the space in (kg/s), and T_i is the hourly average of the temperature of the fluid entering the heating coil and T_o is the hourly average temperature of the fluid leaving the heating coil.

The energy output of the cooling system, E_c, is calculated as

$$E_c = \sum_{i=1}^{NN} \dot{m}\, c_p\, \left(T_{co} \text{-} T_{ci}\right) \quad (5)$$

Where NN is the number of hours in the year when the cooling system is operating. m is the average hourly flow rate of the fluid conveying heat to the space (kg/s), and T_{ci} is the hourly average of the temperature of the fluid entering the cooling coil and T_{co} is the hourly average temperature of the fluid leaving the cooling coil.

The total annual energy from the electricity generation system is E_{ele} in kWh.

4.5.3 Economic Indicator

Typically there are five economic indices used to address renewable energy system economics

A. Net Present Value (NPV)
B. Benefit Cost Ratio (BCR)
C. PayBack Period (PBP)
D. Internal Rate of Return (IRR)
E. Levelized Cost Of Energy (LCOE)

The economic indicator for CS-poly-generation systems is more complex than the technical indicator for the following reasons:

1- The energy output of a poly-generation system consists of different forms. Heating, cooling and electricity, in addition to, desalinated water in some plants. Each of these forms has different market price and, therefore, cannot be accounted as one unit of energy. This make it difficult to use the concept of levelized cost of energy (LCOE).

2- As any renewable energy system, the question is: What is the real value of energy converted by the CSP poly-generation plant? If the benefits are evaluated from a nation's point of view, apart from the mere value of energy produced, the benefits of generating power through a clean and environment-friendly technology should be quantified and added to the price of the produced energy. Social costs involved in other technologies, which are hidden, also can be added to the benefits of the system. These issues make it difficult to use the payback period (PBP) and IRR concepts.

Based on the above arguments and the complex nature of the CS poly-generation systems addressed in (1) and (2) above, the most suitable indicator is the benefit cost ratio (BCR). Benefit cost ratio is the ratio of the accumulated present value of all the benefits to the accumulated present value of all costs, including the initial investment. In this indicator we can convert the benefits into money according to the market price of the energy produced and, therefore, concern in (1) above is eliminated. Also, one can add the worth any other benefits such as socio-economic, clean energy (carbon emission) … etc to the total benefits of the system. The BCR is expressed as:

$$BCR = \frac{B_A\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right]}{C_I\left[1 + m\left(\frac{(1+I)^n - 1}{I(1+I)^n}\right)\right]} \quad (6)$$

Where B_A is sum of the annual benefits of the system (in Euro), I the real rate of discount, n is the lifetime of the system, C_I is the initial investment of the system, and m is the cost of annual O&M as percentage of the initial system cost. Now, if BCR is greater than one, then the project is success.

4.5.4 Evaluation of different subsystems and components

A comprehensive desk research is conducted on identifying and locating case studies related to CS technology. These case studies are reported in D 4.4. Different systems components and subsystems related to CS multi-generation technology are identified. The systems components and subsystems are further evaluated from technical, availability and economic points of views. The following table summarizes the main findings for typical subsystems that are used or can be used in CS poly-generation systems.

Table 4.5.1 Summary of subsystem and components related to CS poly-generation systems

Component	Technology	Availability in the market in required size	Cost per unit output	% of cost of the system	Comment
Solar Field	PTC	Yes			
	Linear Fresnel	Yes			
	CPC	Yes			
Tracking System		Yes			
Power Block	Steam Turbine				
	ORC				
	Steam Engine				
Steam Generator					
Thermal Energy Storage	Molten Salt				
	PCM				
	Water	Yes			
HTF	Oil	Yes			
	Molten Salt	Yes			
Water Desalination	MFD				
	MED				
Cooling System Absorption	SF	Yes			
	MF	Yes			
Cooling Adsorption					
Cooling: Desiccant cooling for air-conditioning					

4.5.5 Impact assessment of technical solutions and management methodologies

It is very difficult and sometime irrelevant to apply the economic and technical criteria developed above to the case studies listed in D4.4 for the following reasons:

- Lack of detailed information about the case studies especially the cost
- The variation in cost between the time these case projects developed and now

Instead, it is decided to apply the technical and economic criteria to the pilot projects that will be developed and built through this project. It should be noted that at the time of completing this part of the report, most partners have already identified their systems, carried out simulations to predict the technical performance of the project and purchased most of subsystems and components. That is, most of the figures and numbers used in the cost analysis are actual numbers. At the same time, the output of the systems (useful energy) are still estimated values.

4.5.5.1 Jordan's Pilot Project

The project is described in detailed in other part of this project. However, for the sake of completeness of this report, we will briefly describe the main components and feature of the project. The plant consists of 100 kWth parabolic trough collectors. The HTF is thermal oil. The collected heat will be used to drive an absorption chiller of 17 kW cooling in summer. In winter, the collected heat from the PTC will be extracted from the thermal oil in a heat exchanger and delivered to fan coil units to provide heating to the designated space. The system has a power block to run a steam turbine. Therefore, steam is generated in a steam generator and supplied to the steam turbine. The nominal size of the steam turbine is 5 kW. The cost of subsystems is evaluated and analyzed. Table 4.5.2 shows the summary of the cost based on subsystems/components classified according to the nature of the energy outputs from the system.

Table 4.5.2 breakdown of the cost of the pilot project in Jordan

Sub System/Component	**Size**	**Unit**	**Cost per unit size**	**% Share**
Solar Field	100	kWth	1778	50
Solar Cooling Cycle	17	kW	3120	15
Solar Heating Cycle	12	kW	1726	6
Power Cycle	5	kWe	6148	9
Electric wiring and cables	100	Kwth	114	3
Control	100	Kwth	358	10
Installation and commissioning*	100	kwth	278	8

- Estimated values

Figure 4.5.1 shows the pie chart of the distribution of the percentage of system cost. It is clear from this figure and the above table that the solar field cost 50% of the project. While the heating system costs about 6%. It is worth mentioning most of this cost goes to the fan coil units. These unit were not available in the space.
Figure 4.5.2 shows the normalized cost of subsystems and components deeded to produce certain type of energy. For example, the cost of the solar chiller and the dry cooler

compromise the main components for the solar cooling system. Their cost share is 15 % , as shown in Table 4.5.2, and their cost 3120 Euro/kW.

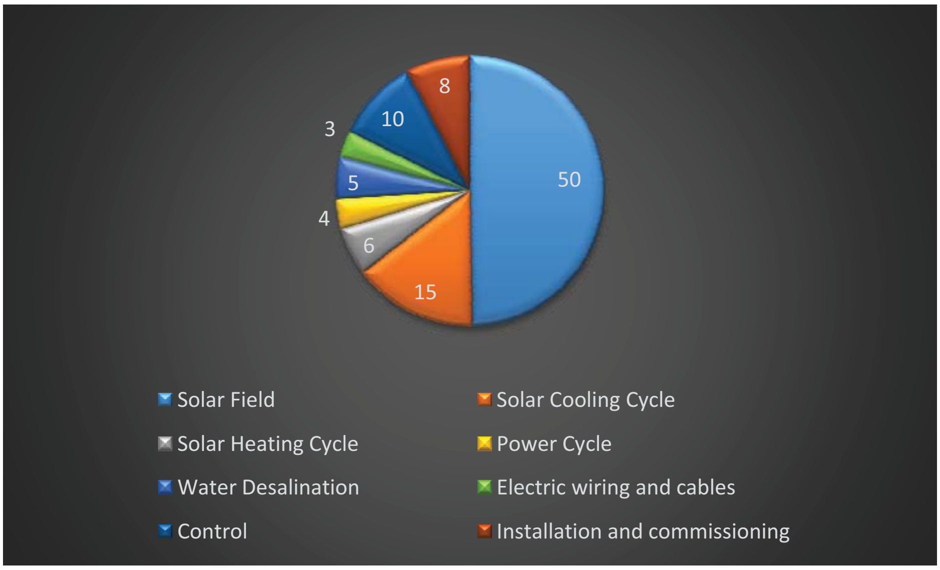

Figure 4.5.1. Percentage of cost for the CS-Polygeneration system in Jordan's pilot project

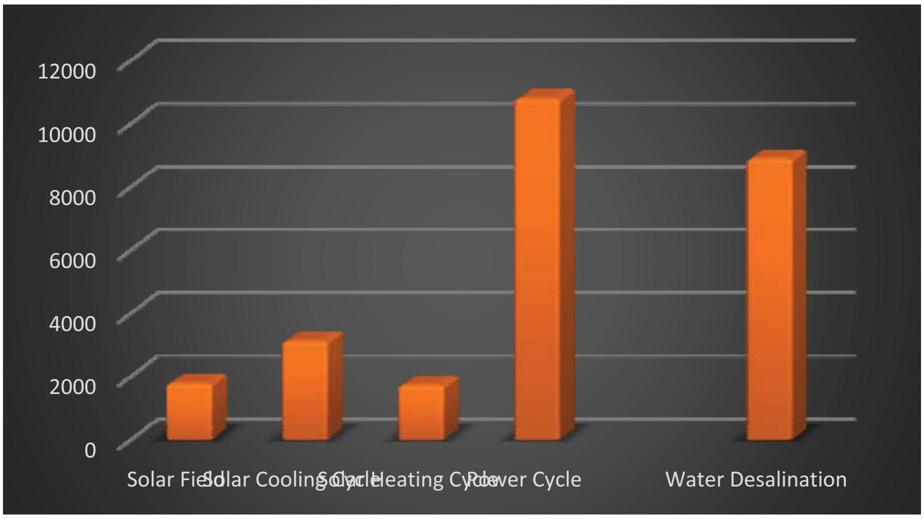

Figure 4.5.2. Normalized Cost (per Unit Output) for system components in Jordan's pilot project

System Output

The CS system proposed to be erected in Jordan as pilot project is simulated using TRNSYS. The weather data for the site was input to the simulation in addition to the performance characteristics of each component in the system. The results of the simulation indicated the outputs shown in Table.

Table 4.5.3. Energy and benifts extracted from the system in one year

Sub System	Quantity output/year	Unit	Annual Output kWh th	Annual Benift (Euro/year)
Cooling	2618	kWh_{th}	2618	655
Heating	12240	kWh_{th}	12240	3060
Distilled water	360	m^3	220500	18000
Electricity	1825	kWh_{elec}	1825	456
		Total	**237183**	**22171**

The data in the above table is calculated using the equations (3-5) and assuming the COP of conventional A/C is 3. The real discount rate of 5%, and the annual operation and maintenance cos 2% of the initial cost. The lifetime of the system is assumed to be 20 years. The cost of electricity sold to the facility is 0.25 euro/kWh (large consumer Tariff).

Based on the data given in the above table and applying equations (1) and (6) respectively, we obtain:
The utilization factor is ε= 0.66 and the Benifit Cost Ratio BCR= 0.62.
Figure 4.5.3 shows that the income coming from selling distilled water contributes about 80% to the total Benifts of the system.

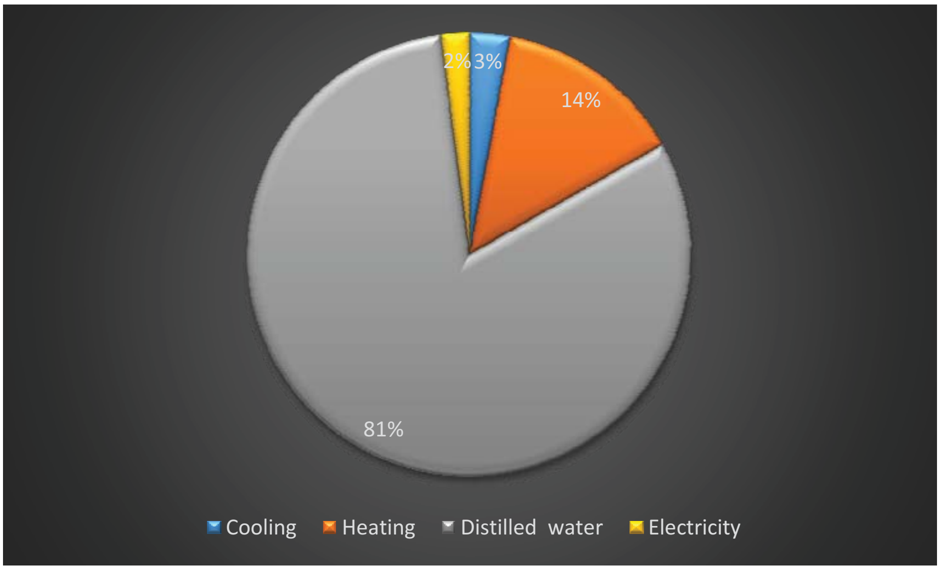

Figure 4.5.3 Percentage share of system benefits for Jordan's Pilot Project

4.5.5.2 Italy Pilot Project

The STS-Med Italian pilot project, which is under construction in Palermo, is located inside the University park, close to the offices of Consorzio ARCA.

It covers an area of about 2,000 m^2. The solar field consists of 21 modules of Linear Fresnel Concentrators, divided in three rows (they works in a parallel configuration), with about 470 m^2 of collecting surface.

We estimate a peak power of 220 kW with an annual thermal energy higher than 310 MWh.

The working fluid (HTF) is an ecological diathermic oil and it will work in operative condition till 270°C.

For the thermal energy balance, and regulation, an oil tank will be used, in order to operate as an expansion vessel and manage the fluctuations of the outlet oil temperature.

Furthermore, a ternary molten salt thermocline storage will placed in order to produce the thermal energy.

The thermocline storage is designed with a thermal capacity of 400 kWh_{th} (8 m^3 of ternary molten salt), and operate between 160°C to 260°C.

The annual energy gained will be used to drive an absorption chiller used to integrate the existent and convectional HVAC providing the thermal comfort to the ARCA's offices.

The absorption chiller is a double effect machine with a cooling and heating capacity of 23 kW with a thermal COP of 1.1.

Thermal energy drives an Organic Rankine Cycle machine able to produce 10 kW of electric power, with a net conversion efficiency of 10%.

The table 4.5.4 shows the summary of the cost based on subsystems/components.

Table 4.5.4 breakdown of the cost of the pilot project in Italy.

Sub System/Component	Size	Unit	Cost per unit size	Share [%]
LFR SOLAR FIELD	230	kW	€ 687	41.6%
PIPING & BOP	230	kW	€ 96	5.8%
STORAGE	400	kWhth	€ 125	13.2%
HEATING & COOLING SYSTEM	23	kWth	€ 870	5.3%
ORC ELECTRIC POWER GENERATION SYSTEM	10	kWe	€ 7,000	18.4%
ELECTRIC WIRING, CABLES & CONTROL SYSTEM	230	kW	€ 87	5.3%
INSTALLATION & COMMISSIONING	230	kW	€ 174	10.5%

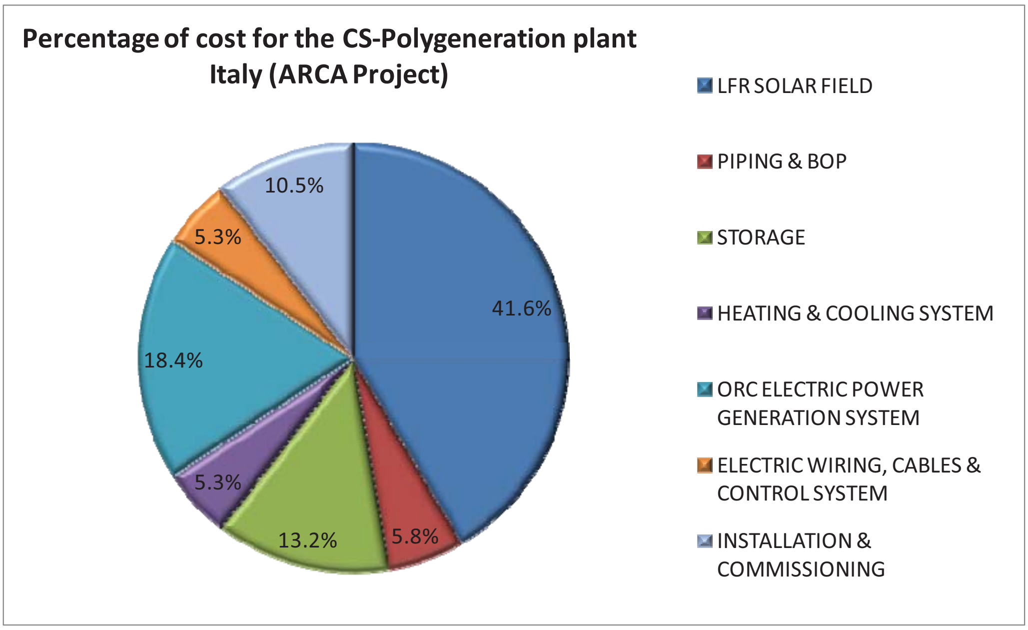

Figure 4.5.4. Percentage of cost for the CS-Polygeneration system in Italy's pilot project

As shown in Figure 4.5.4, the greater part of system cost is assigned to the solar field. The second greater cost is related to the ORC machine. The storage is an innovative solution, with ternary molten salt, which was supplied by local manufactures.

Other costs are very close to the costs of other conventional energy plant.

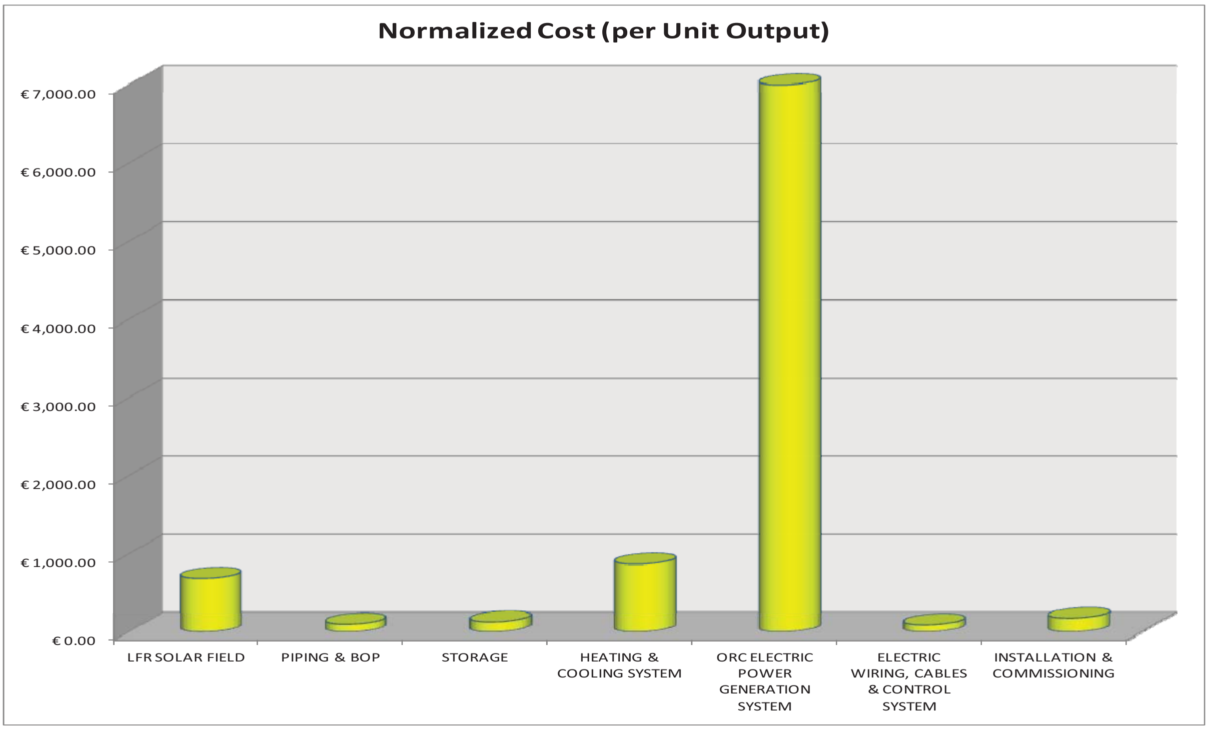

Figure 4.5.5. Normalized Cost (per Unit Output) for system components in Italy's pilot project

System Output

The LFR Solar field system, building for the Italian pilot STSMed project, has been simulated using TRNSYS. The weather data for the simulation, type 109 of TRNSYS, were provided by the INAF (National Institute of Astrophysics of Palermo), measured in a building very close to the University.

The total annually solar energy is estimated to 310 MWh of thermal energy. The monthly distribution is indicated in Figure 4.5.6.

The annual average value of LFR Solar field efficiency reaches 38%.

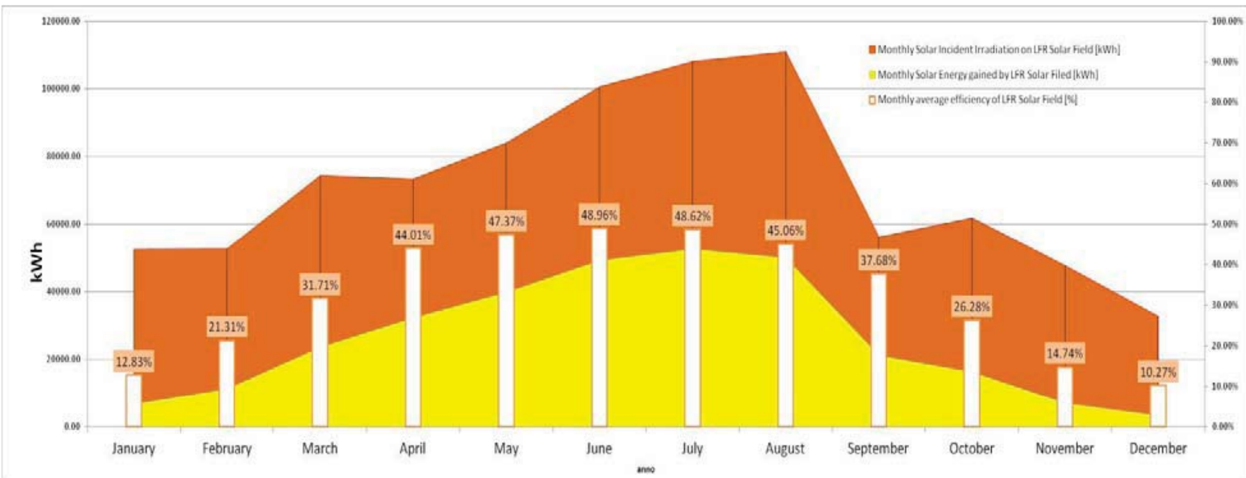

Figure 4.5.6. Histogram of monthly Solar Incident Irradiation and Energy gained on LFR Solar Field (in thermal kWh) and monthly average efficiency of LFR (in percentage).

In our model we also considered the plant self consumption of thermal and electric energy, so we can calculate an annual useful collected energy by LFR solar field around 36% of annual solar incident irradiation on the solar field, as following described:

$$\varepsilon = \frac{Useful\ Energy\ Collected\ \ per\ year}{Annual\ Incident\ Solar\ Irradiatio\,n\ on\ the\ solar\ \ feild} = 0{,}36$$

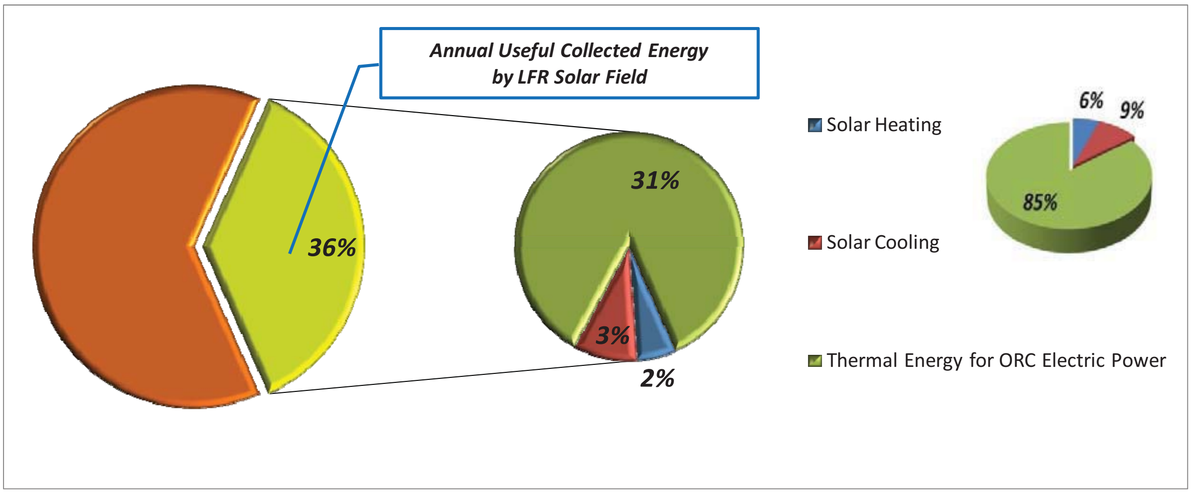

Figure 4.5.7 Percentage share of system benefits for Italy's Pilot Project

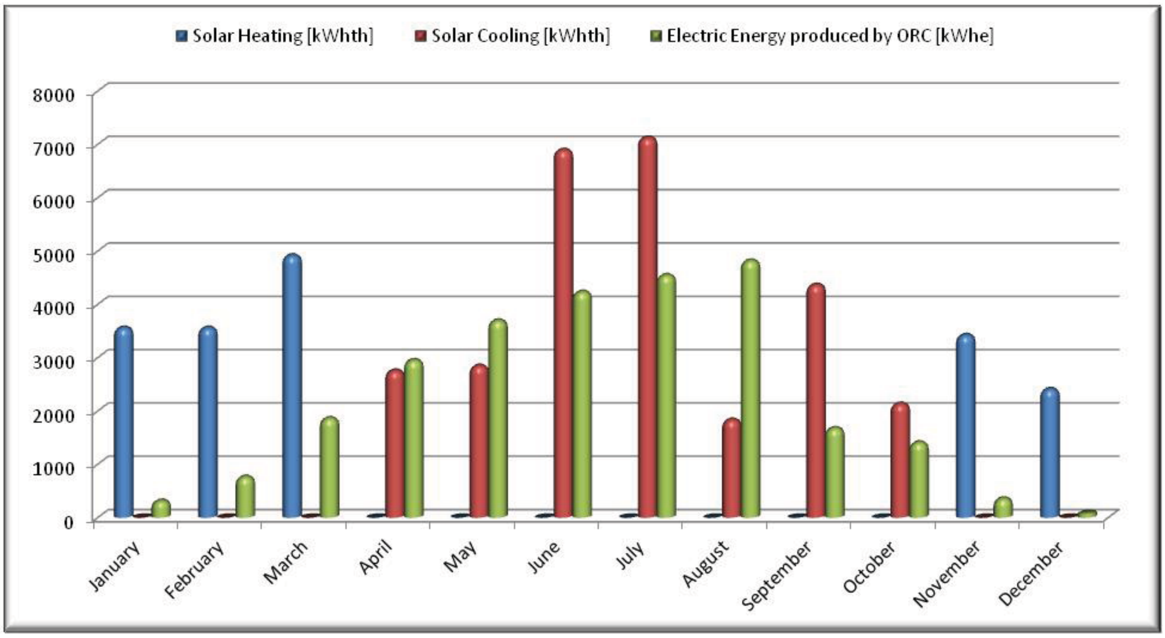

Figure 4.5.8. Histogram of monthly Useful Collected Energy gained by LFR Solar field, divided for kind of energy benefit.

In our simulations, we assume to provide thermal energy to the cooling and heating system to integrate the thermal needs of existent HVAC system, covering the 10% of the total thermal needs. The 85% of useful energy gain can be provided to the ORC machine to produce electricity, covering 19% of actual electric energy consumptions in ARCA.
Overall, we can expect to reduce the electric energy demand of ARCA in 46,000 kWh, with an energy saving of 33%.

Table 4.5.5. Energy and benefits extracted from the system in one year

Sub System	Quantity output/year	Unit	Annual Output [kWh th]	Annual Benift for Energy Saving (€/year)	Public Incentive for Renewable Electric Energy generated by CSP Power Plant [0.36 €/kWhe]	Global annual economic benefit [€/year]
Cooling	27991	kWh_{th}	27991	€ 3,000.00	-	€ 3,000.00
Heating	17894	kWh_{th}	17894	€ 1,888.00	-	€ 1,888.00
Electricity	26770	kWh_{elec}	267703	€ 6,693.00	€ 9,637.00	€ 16,330.00
		Total	***313588***	***€ 11,581.00***	***€ 9,637.00***	***€ 21,218.00***

The data table 4.5.5. is calculated using the equations (3-5) and assuming the monthly COP of conventional A/C varying from 2,2 to 3 (these values, also, consider the efficiency of regulation and distribution system).
The real discount rate of 3% (I), and the annual operation and maintenance costs 2% (m) of the initial cost. The lifetime of the system is assumed to be 25 years (n). The cost of electricity sold to the facility is 0.25 €/kWh.
We have, also, considered the public incentive for renewable electric power generation from CSP power plant, that, in our case, consist of 0.36 € per electric kWh.
Based on the data given in the above table and applying equations (1) and (6) respectively, and shown in Table 4.5.5 we obtain a Benefit Cost Ratio, as following:

$$BCR = \frac{B_A\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right]}{C_I\left[1 + m\left(\frac{(1+I)^n - 1}{I(1+I)^n}\right)\right]} = 0,72$$

4.5.5.3 Cyprus Pilot Project

As in the case of Jordan, the system erected in Cyprus is described in much more detail in other deliverables of the project. In summary, it consists of a Fresnel-lens based solar collecting array built on the roof a building that houses a school, opposite the premises of the Cyprus Institute. The rated thermal power of the system is 70 kW that uses thermal oil as the Heat Transfer Fluid, which though a heat exchanger heats up water, which in turn acts as the storage medium. Hot water from the storage tank circulates to an absorption chiller that's connected to the HVAC system of the adjacent Novel Technologies Laboratory building at the Athalassa campus of the Cyprus Institute.

Figure 1: The Fresnel lens based system at CyI

Any excess heat during the non-cooling months is either directly supplied to the HVAC (sidestepping the chiller) for heating, or is vented. To bolster the productivity of the available roof area, there are PV cells attached to the underside of the Fresnel lens rows that are utilised (via a custom made algorithm) intelligently for a mixture of isolated or combined reasons: when there are no cooling or heating load requirements, when the weather is unsuitable for concentred solar applications or when there is need to reduce the system temperature and/or internal pressure. The system costs are broken down in the table below:

Table 1: Breakdown of cost of pilot system in Cyprus

Sub System/Component	Size	Unit	Cost	% Share
Solar Field	70	kWth	€90,000	34.8%
Solar Cooling cycle (th)	35	kWth	€51,410	19.9%
PV cells	25.92	kWp	€22,378	8.6%
Integration	70	Kwth	€70,525	27.2%
Pyrheliometer			€13,636	5.3%
Thermal oil	1,096	litres	€10,960	4.2%

The 'integration' row in the table above combines the cost of several components, the most important of which are the hot water storage tank, the piping, wiring and all BOT costs, the electronic control systems and the commissioning costs. The 'solar cooling cycle' comprises of the absorption chiller and the cooling tower.

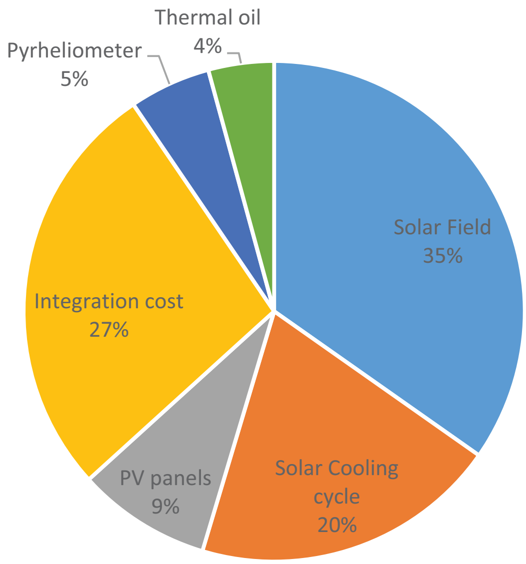

Figure 2: Cost composition for the system in Cyprus

System operation data

Since the system is not commissioned yet, there are no experimental data to use. To gauge how the system will perform, we've conducted a series of simulations using the TRNSYS simulation suite, the results of which are used to calculate the indices and projections below.

Table 2: Energy and finanial return from the CyI system

Sub System	**Quantity output/year**	**Unit**	**Tariff (€/kWh)**	**Annual Benefit**
Cooling	37,304	kWh_{th}	0.21	€7,834
Heating	42,633	kWh_{th}	0.21	€8,953
Electricity	27,712	kWh_{elec}	0.21	€5,820
Total	107,650			€22,606

There are more cooling days in Cyprus within a year than heating ones. In fact we assume here that there is cooling demand for 5 months and heating for 4, with the 3 remaining being transition seasons. The total energy produced by the solar system is 95,925 kWh in a year. The cooling share however needs to be multiplied by 0.7 (the COP of the abs. chiller), whereas the heating one comes intact as this mode bypasses the chiller completely.

There are no feed-in-tariffs for supplying a building with cooling or heating power from renewables in Cyprus at the time of writing[1]. The numbers shown in the 'Tariff' column for heating and cooling in the table correspond to the electricity saved which is charged at approximately 0.21 €/kWh as an annual average for 2015. The 'electricity' row assumes here that appropriate measures have been taken for self-consumption of the energy produced, since again there is no FiT in place for electricity produced by PV systems above 3 kWp.

To calculate equation (1), we use the following data:

Annual average DNI (beam radiation): 1,876 kWh/m^2
Aperture area of solar field: 184 m^2

And therefore
$\varepsilon = 0.312$

For equation (6), the following data assumptions are required:

Discount rate 2.0%
Lifetime 20
CAPEX €258,909
Annual O&M 2.0%

Substituting these in the equation we get in return:
BCR = 1.076

It's therefore assumed that there is – marginal – benefit in pursuing this. As however mentioned in the analysis in the introduction to this document, there are indicators not taken into account such as the

[1] There is, in fact, a support scheme for solar air-conditioning units for business which only contributes towards the capital expenditure of the investment. The CyI system however would not be eligible since it's a research-funded project.

reduction of greenhouse gas emissions, the employment benefits and the educational additionality. Moreover this is a research pilot project and should not be judged in the same context as a traditional commercial investment where the maximisation of these metrics is the priority.