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Life Cycle Assessment performance comparison of small solar thermal cooling systems with conventional plants assisted with photovoltaics

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Introduction

Development of renewable energy technologies is important for reducing fossil fuels consumption while contributing to climate change mitigation.

However, they cannot be considered totally clean because they have energy and environmental impacts that cannot be neglected during their life cycle.

Introduction

The LCA considers the environmental impact of a good/service while considering the primary and non renewable energy consumption, resources and materials use and emissions during the entire life cycle.

LCA is a powerful tool to compare different systems that provide the same service and also optimise processes and components in complex systems during several phases of their life cycle.

Introduction

In the IEA SHC Task 38 framework, a specific activity called the "LCA of solar cooling system" has been performed to, for the first time, apply this type of analysis to small size solar thermal H/C systems equipped with adsorption or absorption chillers.

Additionally, Task 48, "Quality assurance and support measures for Solar Cooling", started in October 2011, have embedded an extension of this activity that applies to a wider set of systems and applications.

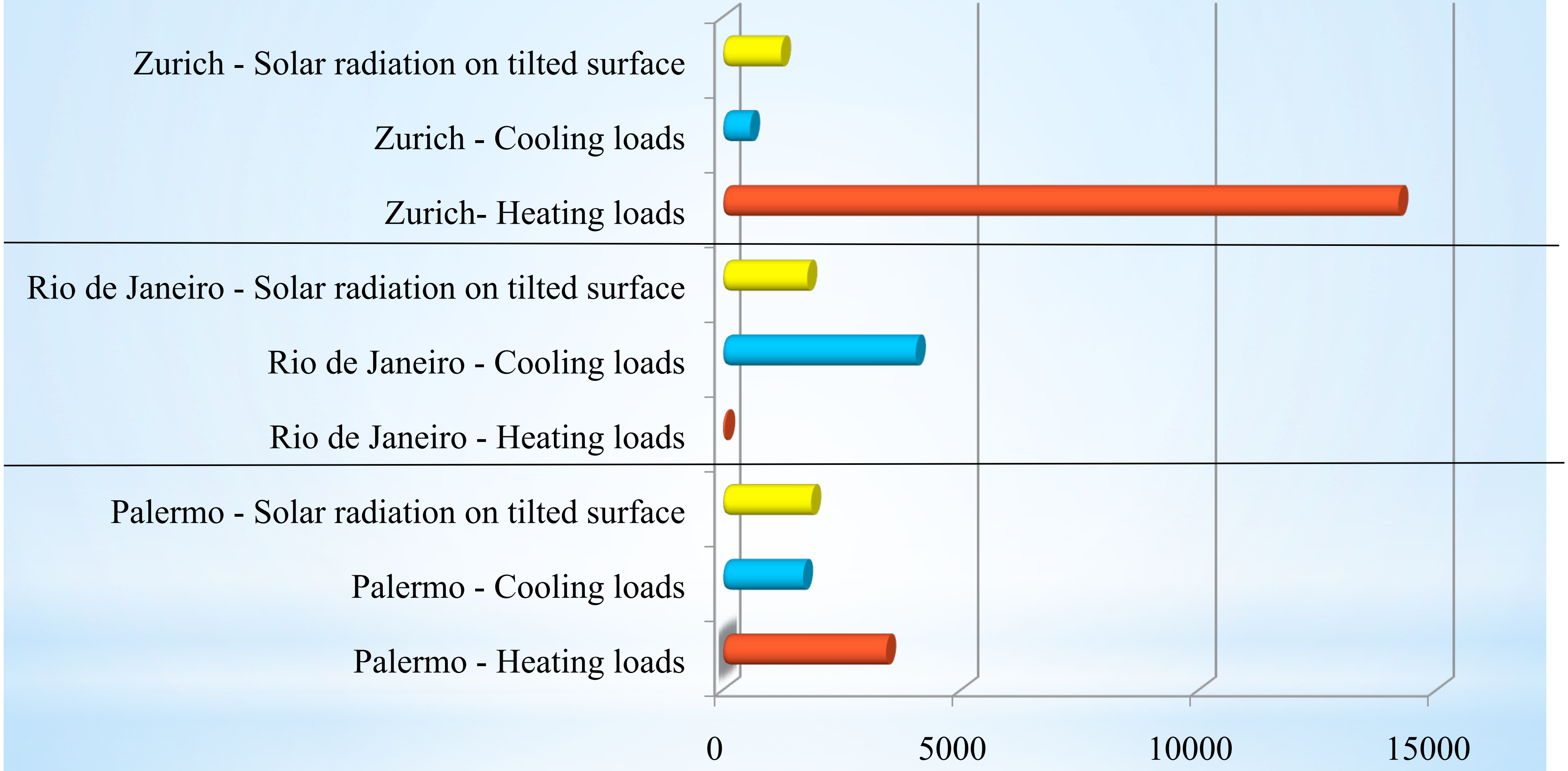
Starting from these outcomes, the application of LCA has been extended to other systems and climatic regions.

Objectives

This LCA study compares systems with small **(12 kW)** **absorption chillers** with systems with a **conventional compression chiller** assisted by a **photovoltaic plant** in three locations: Palermo (Italy), Zurich (CH), Rio de Janeiro (BR)

It aims to provide a more comprehensive investigation of the performances of these two families of solar assisted cooling systems, which is important for studies concerning effective systems to exploit solar energy for cooling purposes.

Characteristics of the locations chosen and case studies H/C loads



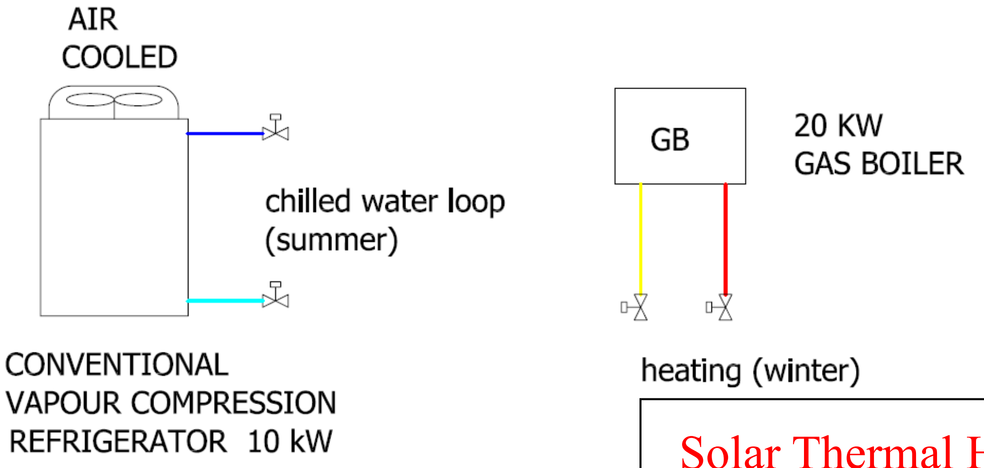
Annual solar radiation on tilted surface [kWh/m^2], cooling and heating loads [kWh] of the three chosen locations

Description of the systems

- **System 1**: **conventional** H/C equipment
- **System 2**: **conventional** H/C equipment, coupled with a **grid connected PV** plant
- **System 3**: **conventional** H/C equipment, coupled with a **stand alone PV** plant for **total cooling electricity load**
- **System 4**: **conventional** H/C equipment, coupled with a **stand alone PV** plant for **partial cooling electricity load**
- **System 5**: **solar thermal H/C**, with abs chiller and **hot** back-up
- **System 6**: **solar thermal H/C**, with abs chiller and **cold** back-up

Description of the systems

Conventional and PV assisted systems (1 to 4)

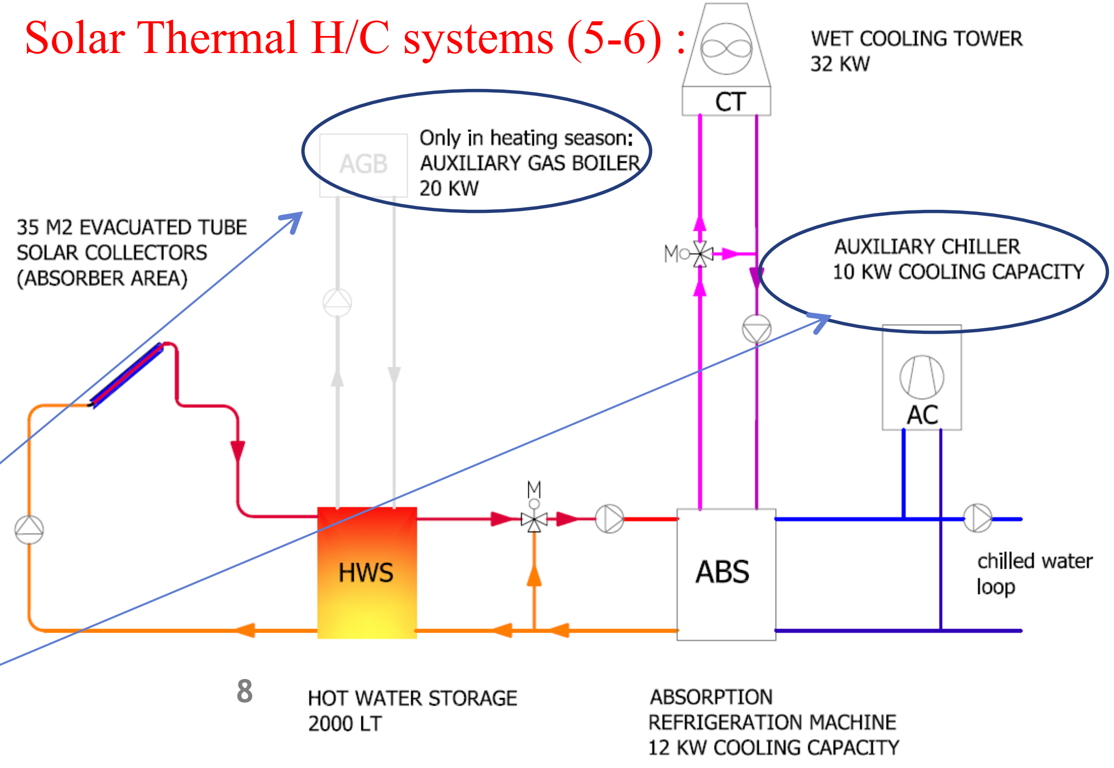


Heating is provided by a natural gas burner. Cooling is provided by a conventional compression chiller connected to the electricity grid. Electricity demand of systems 2, 3, 4 is filled by PV generation in different configurations and operations assumptions.

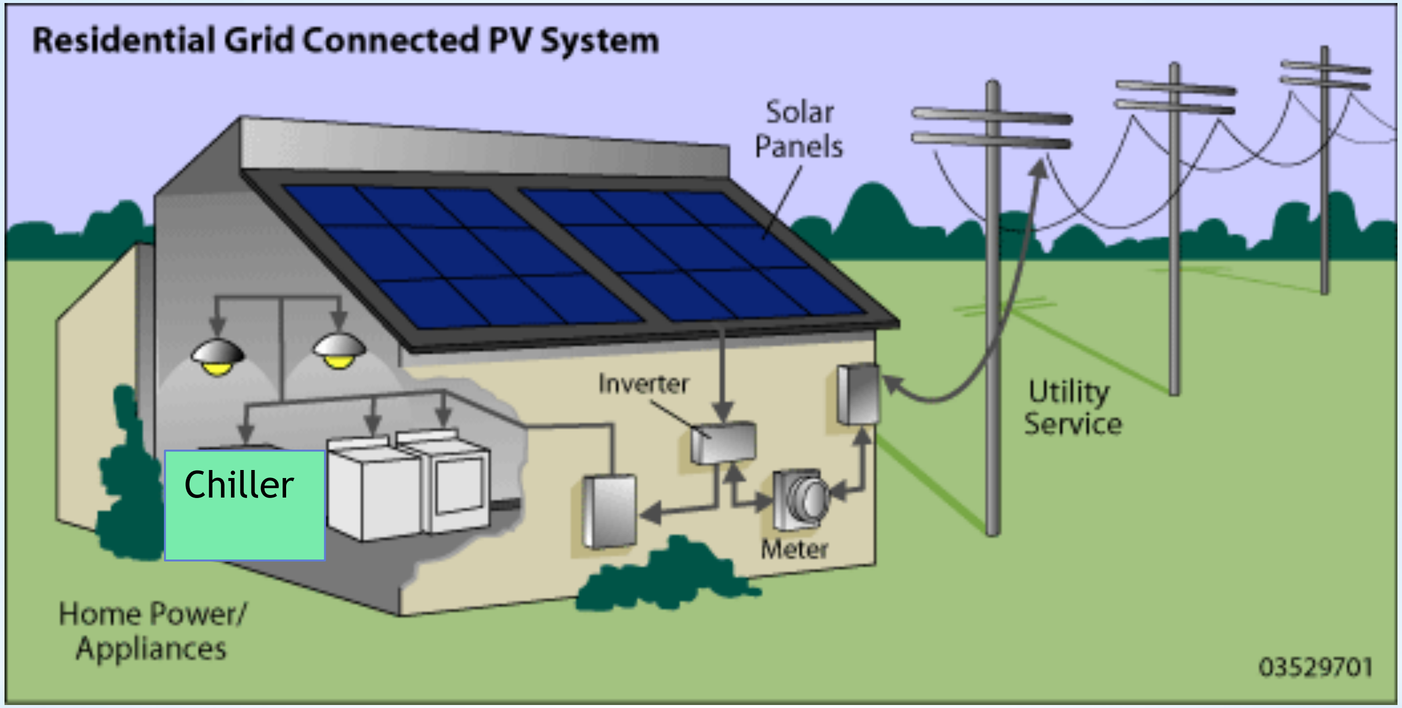
The solar thermal system (35m^2) warms-up water in the thermal storage tank (2m^3), and feeds the ABS chiller (12 kW), that is connected in a closed loop with the cooling tower. In winter, a gas burner integrates the production. Backup energy for the cooling operation is produced by:

- A gas burner (System 5)
- An auxiliary chiller (System 6)

Solar Thermal H/C systems (5-6) :



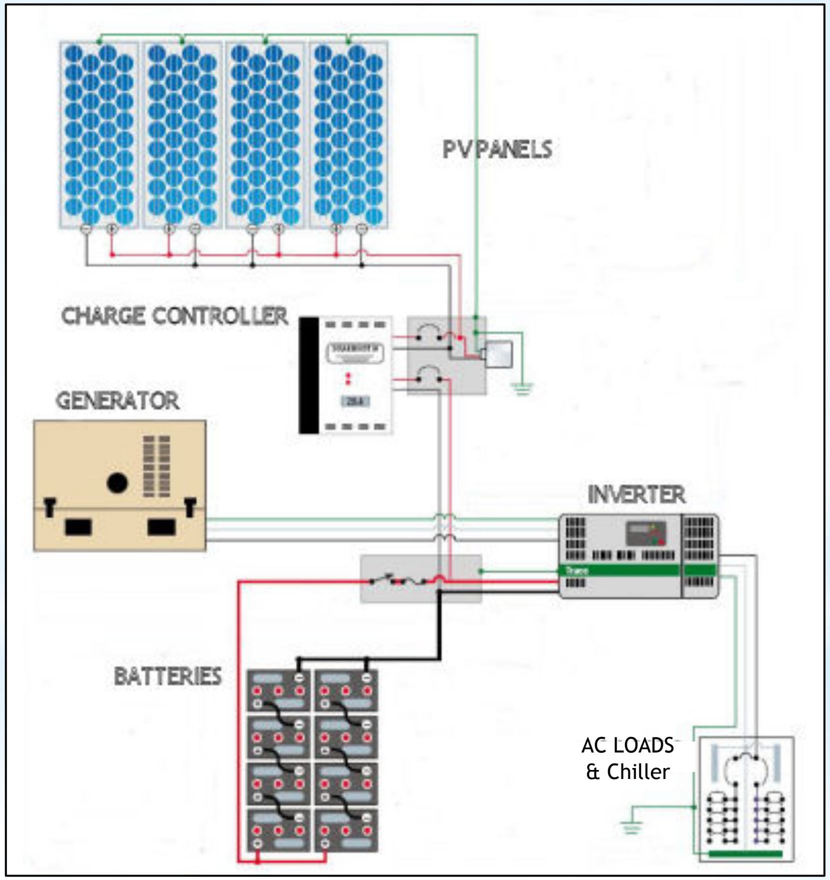
Description of the systems:
PV- Grid-connected (System 2)



For grid connected PV systems the designed peak power was calculated to produce all the electricity required by the chiller and the auxiliaries for one year of cooling system operation.

Description of the systems:
Photovoltaics – Stand-Alone

The stand alone systems have been built with two different considerations, which both include the average daily electricity load and the production in the months with cooling demand.



Description of the systems:
Photovoltaics – Stand-Alone

- **System 3**:
  - PV generators were built to meet the **maximum daily deficit** for the cooling months.
  - The electric storage ensures **three days of autonomy** in the cooling period.
  - There is an yearly **surplus** of electricity;
- **System 4**:
  - The generator peak power was determined so that the yearly production is equal to the **electricity saved through the operation of thermal SHC** systems with cold back-up.
  - The storage capacity still ensures **three days of autonomy** regarding this fraction of the load.
  - There is an yearly **deficit** of electricity;

Description of the systems: system data

	Palermo			Zurich			Rio de Janeiro		
	System 2 Grid Connected	System 3 Stand Alone Fulll Load	Ssystem 4 Stand Alone Partial Load	System 2 Grid Connected	System 3 Stand Alone Fulll Load	Ssystem 4 Stand Alone Partial Load	System 2 Grid Connected	System 3 Stand Alone Fulll Load	Ssystem 4 Stand Alone Partial Load
Peak power (kWp)	1.47	4.41	2.31	1.26	3.15	1.68	3.36	5.25	2.73
Battery capacity (Ah)	0	3,360	3,360	0	2,020	2,020	0	3,417	3,420

Description of the systems: system data

		Palermo		Zurich		Rio de Janeiro	
	[kWh]	Heating	Cooling	Heating	Cooling	Heating	Cooling
Conventional (System 1)	Electricity	0	1,995	0	1,046	0	4,542
PV grid-connected (System 2); PV stand alone, full load (Systems 3)	Electricity	0	0	0	0	0	0
PV stand alone, partial load (System 4)	Electricity	0	1,065	0	686	0	3,005
	Natural gas	2,754	0	14,951	0	103	0
Solar Th + Absorption Hot backup (System 5)	Electricity	52	937	81	655	74.4	2,062
	Natural gas	414	246	10,165	177	0	2,956
Solar Th + Absorption Cold Backup (System 6)	Electricity	52	1,065	81	686	74.4	3,005
	Natural gas	414	0	10,165	0	0	0

Life Cycle Assessment

The energy and environmental performances of the systems were assessed applying the **LCA methodology** (ISO 14040 series).

Functional Unit (FU): for each examined system the energy and environmental impacts were referred to the whole plant.

Life cycle of each system component was estimated to be 25 years, except for batteries (8,3 years), charge regulators (8,3 years) and inverters (12,5 years).

System boundaries:

- Production phase: including supplying raw materials, production/assembly maintenance/substitution of the main components of the plant;

- Use phase, including the life cycle of energy sources (electricity and natural gas) consumed (from the grid) during the useful life time of the plant;

- End-of- life phase, including the treatment of waste due to the components of the plant.

System boundaries:

Impacts not taken into account:

- transportation of plant components from their production sites to the plant;
- transportation of plant components from the plant to the disposal site at the end-of-life;
- installation and minor maintenance steps.

Databases and tools

- Data were implemented in the software Simapro
- Secondary data are referred to the environmental database Ecoinvent

Energy and environmental indexes:

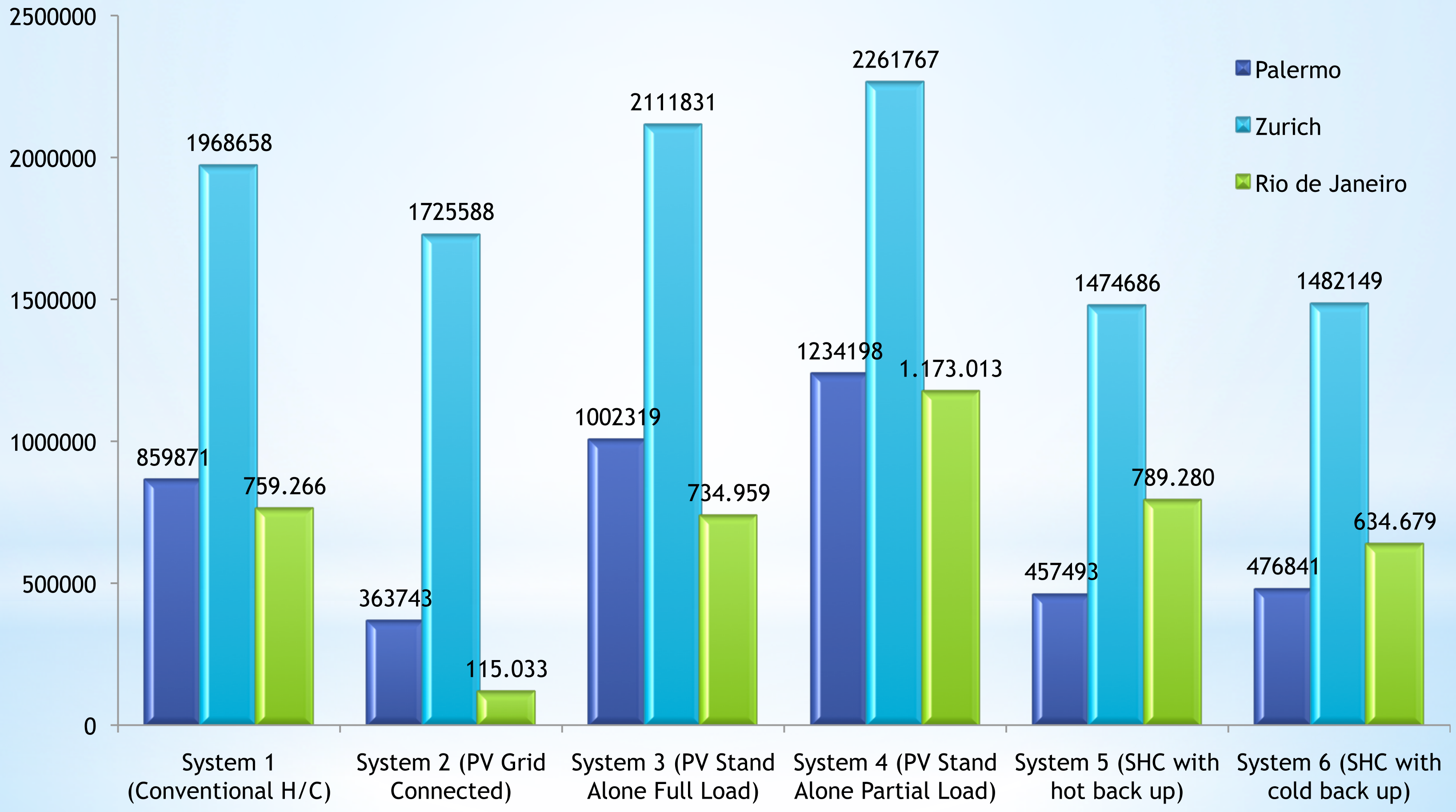
- Global Energy Requirement (GER), in MJ (method: Cumulative Energy Demand);
- Global Warming Potential (GWP), in kg CO_{2eq} (method: EPD 2008)

Energy and environmental Payback indexes:

- **Energy Payback Time (EPT)**: time (years) during which the system must work to harvest as much energy as is required for its production and disposal;
- **Emission Payback Time (EMPT)**: time (years) during which the cumulative avoided emissions are equal to those released during the life cycle of the plant itself (years).

Life Cycle Assessment

Global Energy Requirement (MJ)

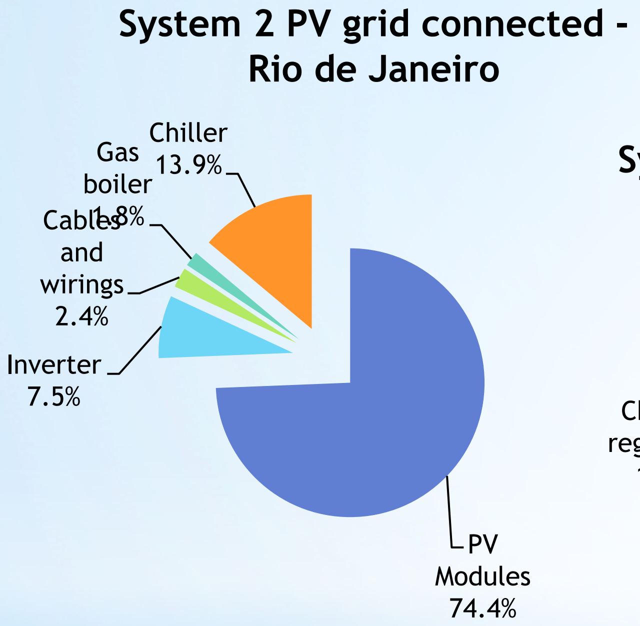


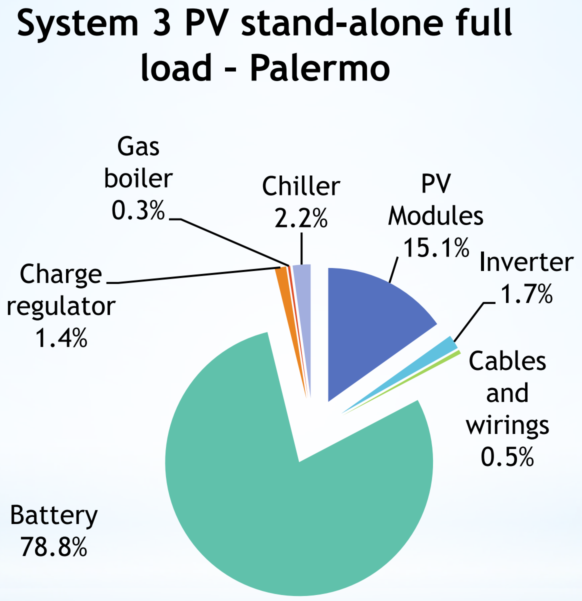
Life Cycle Assessment

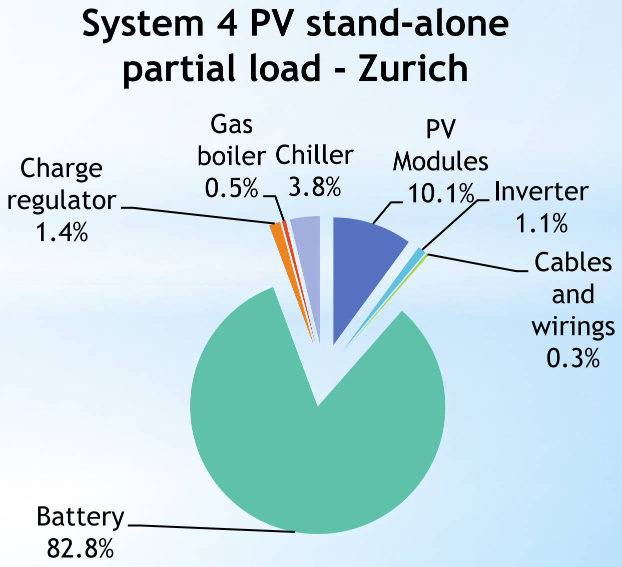
Global Energy Requirement

		System 1 Conventional H/C	System 2 PV Grid connected	System 3 PV Stand alone Full load	System 4 PV Stand alone Partial load	System 5 SHC with hot backup	System 6 SHC with cold backup
Palermo (MJ)	Production	14,357	55,048	661,380	609,317	117,000	129,505
	Operation	845,485	308,616	308,616	595,051	340,029	346,860
	End-of-life	29	78	26,649	26,614	464	476
	Total	859,871	363,743	1,002,319	1,234,198	457,493	476,841
Zurich (MJ)	Production	14,357	48,032	416,449	379,881	119,101	131,605
	Operation	1,954,272	1,675,426	1,675,426	1,863,795	1,355,121	1,350,068
	End-of-life	29	70	16,053	16,030	464	476
	Total	1,968,658	1,725,588	2,111,831	2,261,767	1,474,686	1,482,149
Rio de Janeiro (MJ)	Production	14,357	99,486	689,636	655,483	117,000	129,505
	Operation	744,880	11,543	11,543	516,241	671,815	504,699
	End-of-life	29	102	27,027	26,984	464	476
	Total	759,266	115,033	734,959	1,173,013	789,280	634,679

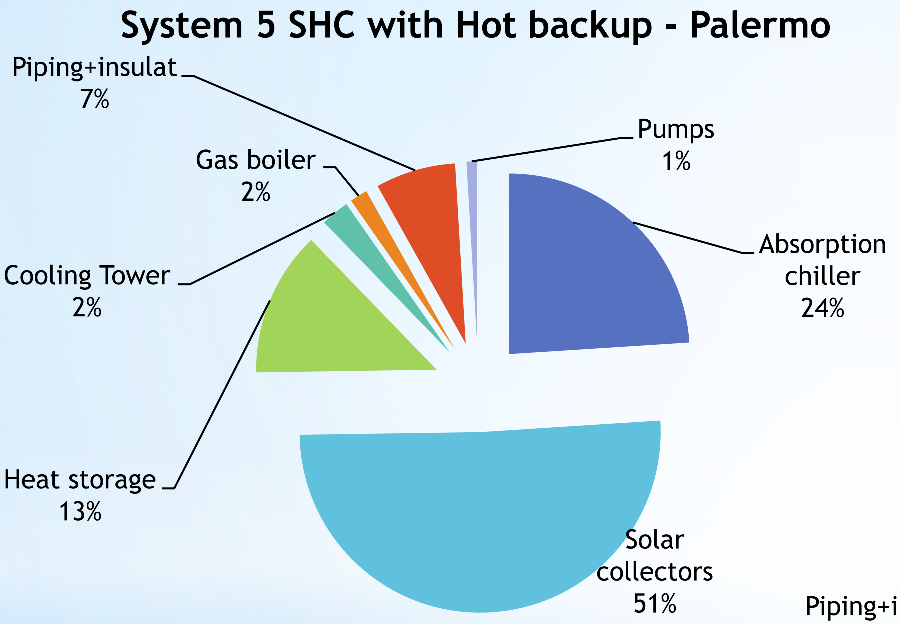
Production step: GER

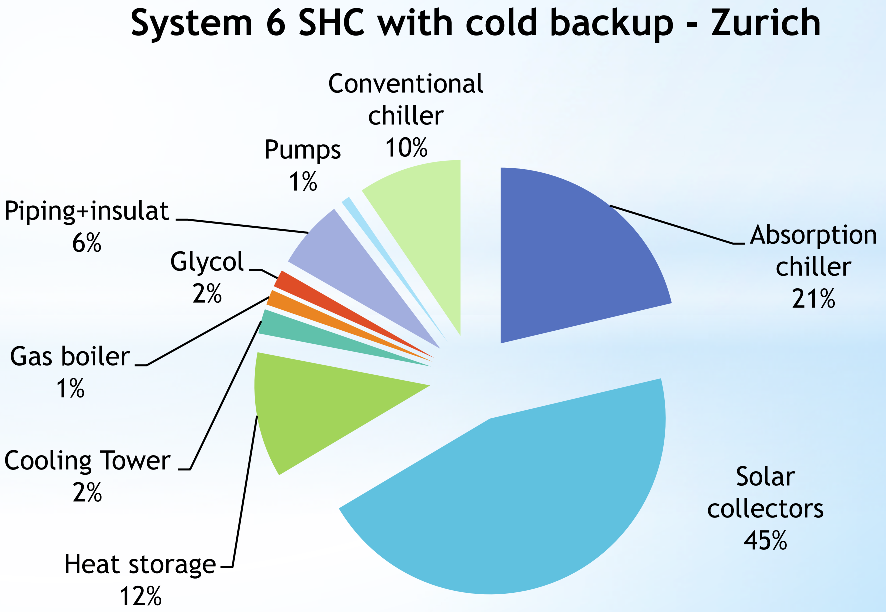




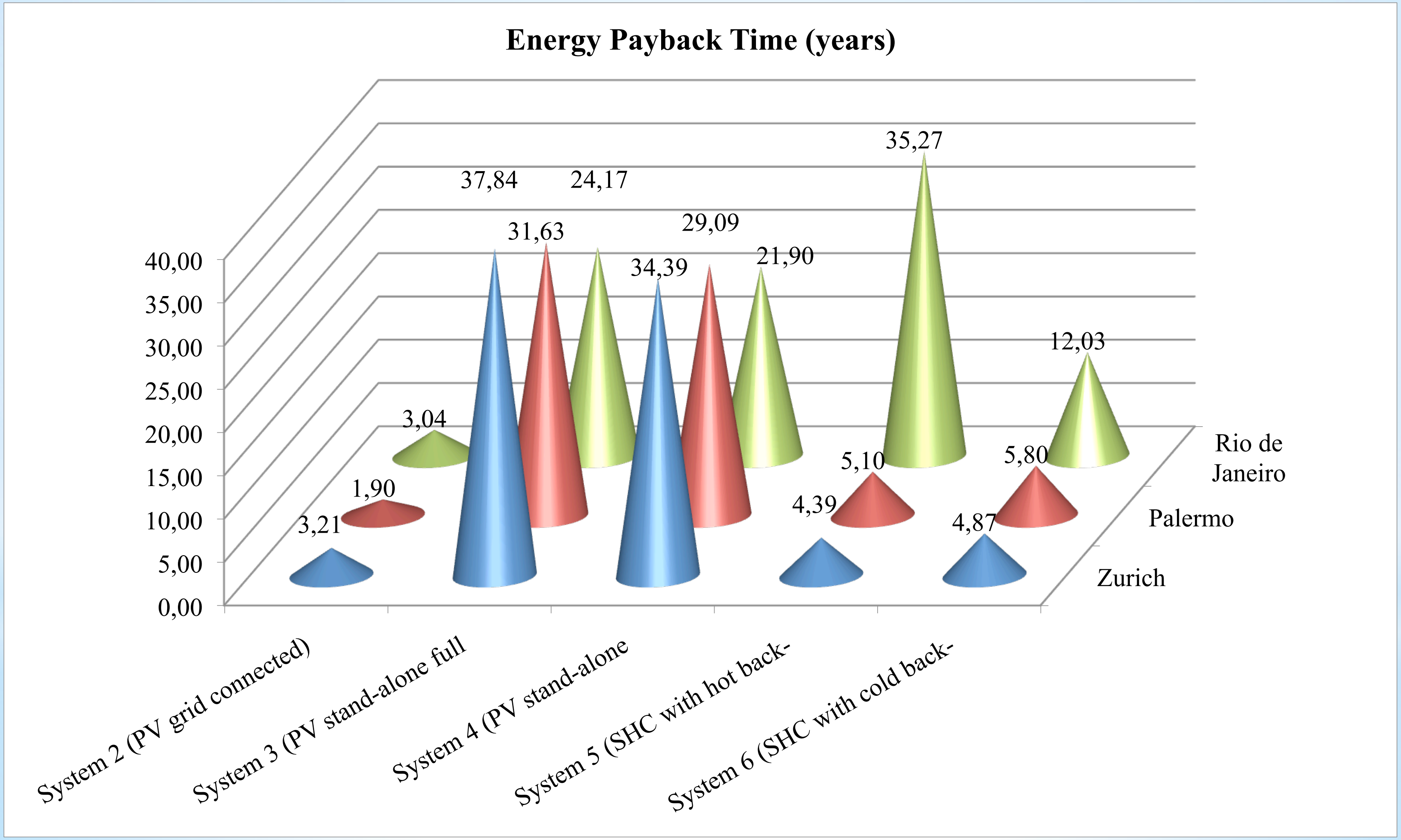


Production step: GER



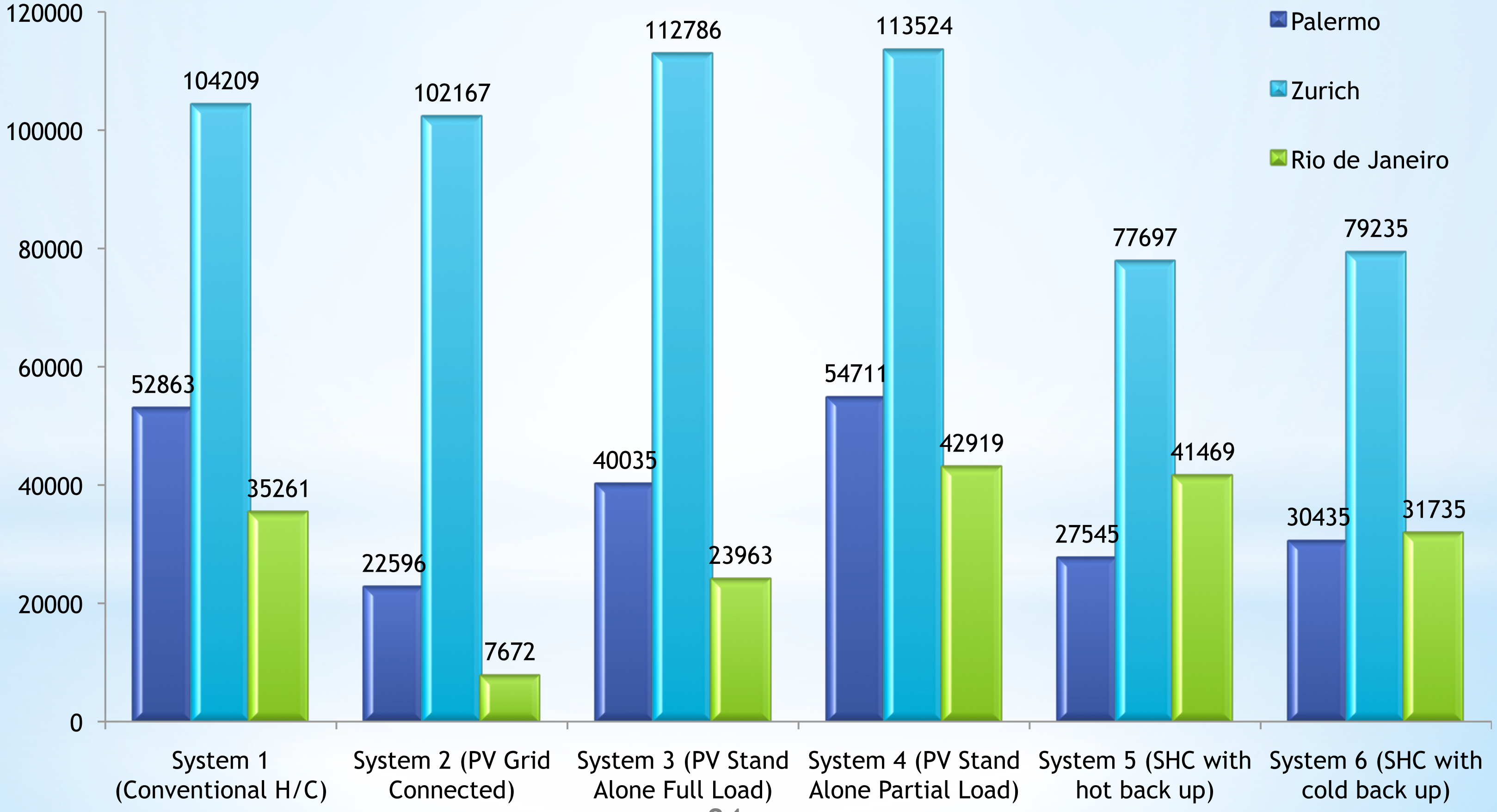


Life Cycle Assessment


Energy Payback Time (years)

Life Cycle Assessment

Global Warming Potential (kg CO_{2eq})



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Life Cycle Assessment

Global Warming Potential (kg CO_{2eq})

		System 1 Conventional H/C	System 2 PV Grid connected	System 3 PV Stand alone Full load	System 4 PV Stand alone Partial load	System 5 SHC with hot backup	System 6 SHC with cold backup
Palermo (kg CO_{eq})	Production	2,497	4,442	21,680	19,242	6,878	9,271
	Operation	50,322	18,025	18,025	35,248	20,322	20,779
	End-of-life	44	129	330	221	346	385
	Total	52,863	22,596	40,035	54,711	27,545	30,435
Zurich (kg CO_{eq})	Production	2,497	4,194	14,687	12,959	6,981	9,374
	Operation	101,669	97,855	97,855	100,392	70,370	69,476
	End-of-life	44	118	244	173	346	385
	Total	104,209	102,167	112,786	113,524	77,697	79,235
Rio de Janeiro (kg CO_{eq})	Production	2,497	6,773	22,915	19,924	6,878	9,271
	Operation	32,721	674	674	22,752	34,246	22,078
	End-of-life	44	225	374	243	346	385
	Total	35,261	7,672	23,963	42,919	41,469	31,735

Emission Payback Time

Location	System	EMPT (year)
Palermo	System 2 (PV grid connected)	1.57
	System 3 (PV stand-alone full load)	15.07
	System 4 (PV stand-alone partial load)	28.06
	System 5 (SHC with hot back-up)	3.90
	System 6 (SHC with cold back-up)	6.02
Zurich	System 2 (PV grid connected)	11.61
	System 3 (PV stand-alone full load)	81.21
	System 4 (PV stand-alone partial load)	207.32
	System 5 (SHC with hot back-up)	3.82
	System 6 (SHC with cold back-up)	5.61
Rio de Janeiro	System 2 (PV grid connected)	3.48
	System 3 (PV stand-alone full load)	16.19
	System 4 (PV stand-alone partial load)	44.21
	System 5 (SHC with hot back-up)	-76.77
	System 6 (SHC with cold back-up)	128.06

Conclusions

- In hot climates (**Palermo and Rio de Janeiro**), the systems with the **PV grid connected** plant (that not requires storage) performed best, as they have low GER and GWP values and payback times

- This plant-type is different than the other plants because it does not require storage due to free interaction with the grid. For these reasons, **a comparison of this system with the other systems is not meaningful** because the strength of the solar thermal H/C system is the ability to reduce the dependence from the electric grid and to avoid peaks, overloads and power quality variations

Conclusions

- The **PV systems with stand-alone** configuration performed worse than the PV grid connected systems and the solar thermal assisted systems in nearly all the analysed cases. The **impact of storage manufacturing** is large so only more efficient, durable and "green" technologies can overcome this impact.

- For the two **PV stand alone systems**, the system that provided the same electricity load that was avoided by the solar thermal systems performed worse than the system that was able to produce the total electricity demand (chiller plus auxiliary equipment). The **reduction in production resulted in the highest residual electricity** consumption

Conclusions

- Contradictory results were obtained for **Rio de Janeiro**, where there is a large cooling demand during all months, which is not adequately supported by solar radiation availability.

- the **large average national electricity conversion efficiency makes it difficult for solar thermal H/C plants to be competitive**, providing an opportunity for PV stand alone assisted systems.

- considering the GWP performances, being that electricity production characterised by a high use of renewable energy sources, in many cases, the **conventional systems were more convenient than the solar assisted ones**.

Conclusions

- In a cold climate (Zurich), **the opportunity to extend the use of the solar thermal system to meet the high heating load ensures good system performances**. This relationship is not true for PV assisted systems, which do not save on natural gas.

- The **results are sensitive to the data from the life cycle inventory for the PV systems**. Further investigating data sources are needed to produce a sensitivity analysis for the LCA results to improve the data quality.

Thank you