ULISSES 2.0 Solar Concentrator with mobile mirrors for use in fixed-tilt Solar Thermal Collectors or Photovoltaic Modules

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Abstract

ULISSES 2.0 is a new development for the solar thermal and photovoltaic generation market focused on large-scale solar heating and cooling plants for low and medium temperature industrial processes (50 - 150ºC). It is especially suited to mining processes such as electrowinning or electrorefining, or photovoltaic generation. In its thermal version, ULISSES 2.0 technology consists of large format solar thermal collectors aligned East-West (EW) or North-South (NS) depending on location and consumption eccentricity, with two tracking reflectors resulting in an increased aperture area. The moving reflectors not only increase the amount of solar radiation captured but also improve the safety of large-scale solar thermal plants, given that in an overheating situation the reflector can be moved to block the sun. Furthermore, this technology can also be used in large photovoltaic plants as solar radiation is homogeneously concentrated over the absorber surface. A TRNSYS parametric study was conducted using axis-tracking orientations, different global locations, and temperature levels as parameters, to evaluate the benefits of ULISSES 2.0 technology compared to BAU solar thermal technologies.

Keywords: Large-Scale, Solar Heating and Cooling, Industrial Processes, Mining, Electrowinning, Electrorefining, Solar Thermal, Photovoltaic, Concentrating Solar Power, Low and Medium Temperature, Drainback, Enhanced Safety Operation, Overheating, Stagnation, TRNSYS, ESCO

1. Introduction

ULISSES 2.0 is the next generation of a previous technology, ULISSES 1.0, which consisted of a single static reflector to boost generation and a large-scale drainback system to enhance operational safety in overheating or freezing events. This system was constructed and tested at a mining site in northern Chile in 2015 – 2016, the results of which encouraged further development of this technology.

Fig. 1: ULISSES 1.0 prototype (100 m^2 aperture area) consisting of a single static reflector

The basic concept of ULISSES is maintained in the 2.0 version: enhanced production and reliable low-cost operation to disrupt large-scale solar market. ULISSES is not only aimed at new solar thermal or photovoltaic plants, but also on existing ones, as its adaptability to the characteristics of existing frames and structures allow it to be coupled to existing thermal or photovoltaic solar collectors.

ULISSES 1.0 was upgraded to ULISSES 2.0 by incorporating a second reflector and adding the possibility of tracking both reflectors. Tracking can be conducted along two axis: North-South (NS) and East-West (EW) orientation.

- North-South (NS) orientation is intended for use at low latitudes. The absorber plane lies horizontal and mirrors track the sun from East to West.
- East-West (EW) orientation is best suited for use at high latitudes. The absorber plane has a tilt angle optimized for latitude and mirrors are oriented for tracking the solar altitude.

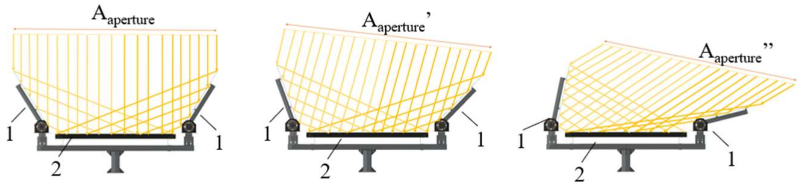

Fig. 2: Tracking concept for the NS orientation. 1 Reflector 2 Absorber. Concentration varies during the day, increasing for high incidence angles $A_{aperture} < A_{aperture}' < A_{aperture}''$

These developments resulted in ULISSES 2.0 technology that can be described as a non-focalizing truncated cone cross-section concentrator. Two tracking, flat reflectors are implemented that rotate on an axis perpendicular to the cross-section and having nominal low concentration levels (typically, $C \leq 2$), which vary during the tracking process.

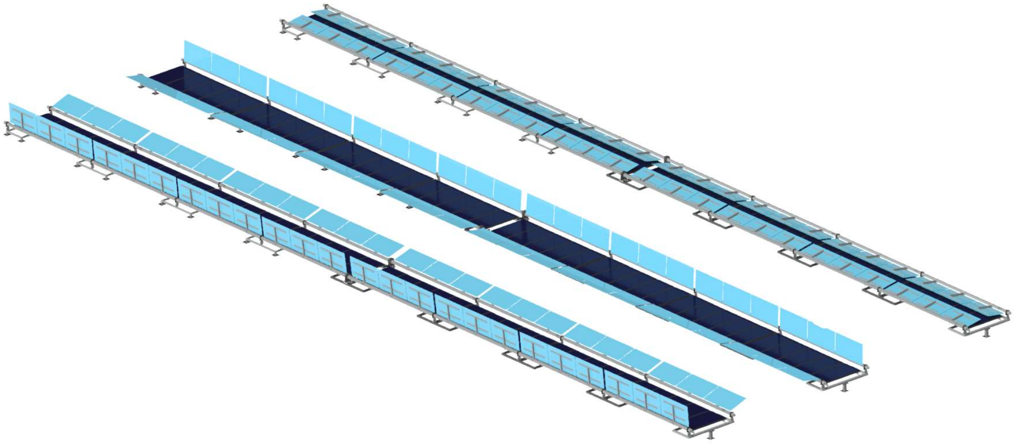

Fig. 3: General overview of ULISSES 2.0 Technology

The crucial feature of ULISSES 2.0 is the homogenous distribution of the concentrated radiation on the opening surface, absorber or photovoltaic modules. Importantly, this avoids the high local concentrations characteristic of other concentrators such as CPCs (Solar Cylindrical Collectors) and allows to be used in photovoltaic modules.

2. ULISSES Developments

Several adjustments have been made in ULISSES 2.0 to improve not only solar yield, but also to reduce capital and operational costs, and to increase the reliability of large-scale solar thermal systems.

A structural optimization study was conducted to reduce capital costs. Here, an integrated approach to unify solar collector and ULISSES concentrator structures were considered. Also, different anchoring-ballast systems were studied to reduce the civil engineering work commonly associated with large-scale solar field construction. Several solutions emerged from this study, which will be validated in the next prototype (see Section 5. Experimental Validation).

To reduce piping costs and ensure smooth operation (and consequently lower operational costs) in large-scale solar plants, an optimal hydraulic design for collector array interconnection of the large-scale solar field was implemented, similar to that of Phillip and Robert (2013). This included the optimal hydraulic configuration of the meander structure solar flat-plate collectors to be included in ULISSES concentrating arrays. As such, the absorber pipe and minimum manifold header pipe diameters were considered for the maximum collector array with low flow skewness factor and good emptying behaviour. Consequently, material and installation costs can be reduced given the lower total metal mass of array piping outside the collector.

Furthermore, the tracking system not only boosts solar production in applications that require heat at high temperatures but also ensures more reliable operation, as the mobile reflectors can block solar radiation from reaching the absorbers in situations close to overheating. This has the advantage of increasing the operational safety of large-scale solar thermal plants.

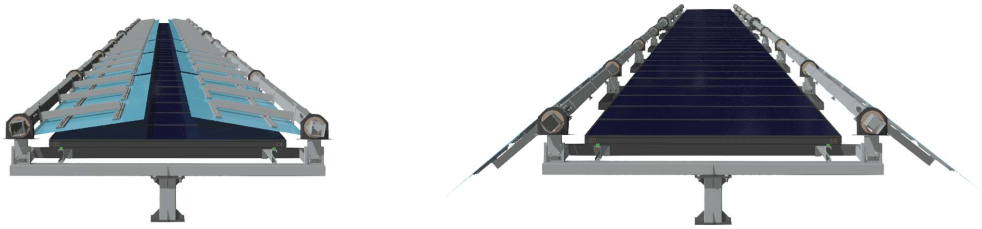

Fig. 4: "Overheating protection" position and "turtle protection" position against strong winds

When the solar system is close to overheating, the mirrors are folded so as to cover the absorber in an "overheating protection" position. This allows for the blocking of almost total solar radiation and maintains the solar field safe from over-heating. This position may also be useful at night, as covering the collectors protects the system against frost and cold radiation.

On the other hand, the tracking system allows wind loads over the collector to be reduced, whilst precluding the reflectors from high drag coefficient positions (normally close to 90º, vertical position in Figure 4). During strong winds events, the mirrors move to the most open "turtle position", which reduces the overall structure drag coefficient, and thereby the loads on the collector and concentrator.

The enhanced overheating and freezing protection reduce capital cost even further. In the absence of overheating scenarios, less expensive materials can be used in the primary loop, less antifreeze protection is required in the primary fluid flow loop, and even pure water could be considered as a primary heating fluid. This would also make the use of a heat exchanger (and secondary pump station) to mix the antifreeze fluid with water from secondary loop unnecessary.

Together, these improvements would result in an approximate 20% reduction of capital costs of a BAU (built-as-usual) large-scale solar thermal plants technology.

3. Methodology Analysis

To evaluate the benefits of ULISSES 2.0 technology compared to the BAU solar thermal technologies, a parametric study for different solar thermal ULISSES 2.0 concentrations and different axis-tracking orientations, various global locations, and temperature levels was conducted. The following parameters were analyzed:

- Different solar thermal technologies: BAU technology for Flat Plate Collector (FPC) and Evacuated Tube Collector (ETC) technologies used in large-scale plants were compared to ULISSES solar concentrator C=2.0 technology.
- Different ULISSES 2.0 axis-tracking orientations: East-West (EW) or North-South (NS).
- Different locations: Calama (Chile) -22.31º, Santiago (Chile) –33.47º, Seville (Spain) 37.42º, Kobenhavn (Denmark) 55 .67º, Beijing (China) 39.93º y Lhasa (Tibet) 29.65º. Locations were not only selected for potential markets, but also to evaluate the integration of ULISSES in existing large-scale thermal plants.
- Different return processes temperature levels (T_{ret}): 40ºC, 55ºC, 70ºC, 85ºC.

For the energy performance evaluation, a TRNSYS 17 by Klein et al. (2016) model was used.

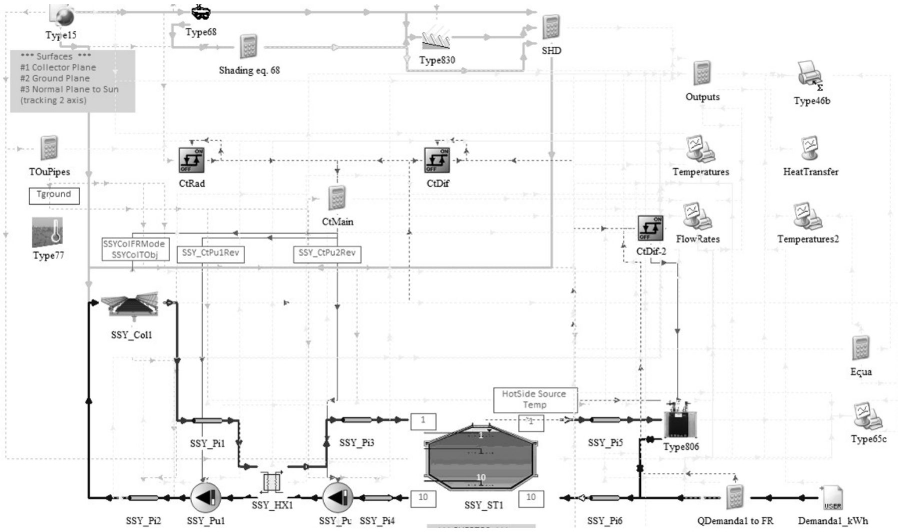

Fig. 5: TRNSYS 17 by Klein et al. (2016) model for ULISSES 2.0 performance evaluation

The TRNSYS model describes ULISSES 2.0 energy performance, considering the singularity of the double reflector incidence angle modifiers (IAMs), including accumulation and service. For the characterization of the ULISSES 2.0 technology, an IAMs study was previously conducted to characterize optical performance between the incident solar radiation and the radiation collected by the absorber.

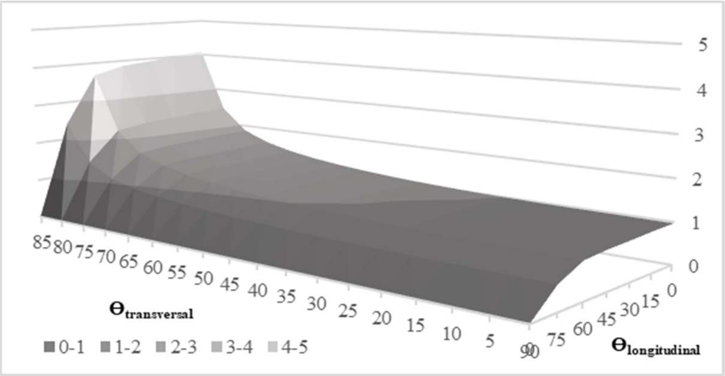

Fig. 6: Concentrating IAM used for ULISSES 2.0 C2 NS configuration performance evaluation

The following solar collector performance coefficients were considered for FPC BAU and ETC BAU technology:

Tab 1: Solar collector performance coefficients considered for FPC BAU and ETC BAU technology

Parameter	Unit	FPC BAU	ETC BAU
a_0	-	0.857	0.666
a_1	W/m·K	3.083	2.022
a_2	W/m·K^2	0.013	0.001
IAM (K50)	-	0.91	Bi-Axial

All cases (six technologies, six locations and four return temperatures) were simulated using a solar fraction objective of 33% so as not to affect eccentric solar thermal production versus constant demands.

Levelized cost of energy (LCOE) were calculated for a 20-year period considering a 3% inflation rate, an 8% discount rate and a 2% energy cost increase. The following capital costs were calculated for the different technologies:

Tab 2: Large-scale Solar Thermal capital costs [USD/m^2] by aperture area for different technologies for LCOE analysis

	Unit	FPC BAU	FPC C2EW	FPC C2NS	ETC BAU	ETC C2EW	ETC C2NS
Capital Costs	USD/m^2	355.67	369.64	366.35	366.39	375.00	371.72

Previous analysis have shown EW orientation costs to be higher than NS due to higher structural costs. Notably, the 20% ULISSES 2.0 technology reduction costs, regarding the hydraulics in the primary and secondary loop (listed in section 2. ULISSES Developments), were not considered in this analysis for a more conservative approach to ULISSES technology.

4. Results

The results of the TRNSYS simulations parametric study in terms of solar energy yields for FPC BAU and ETC BAU and its combination with ULISSES technologies, for the different locations and return process temperatures, are shown in following figures:

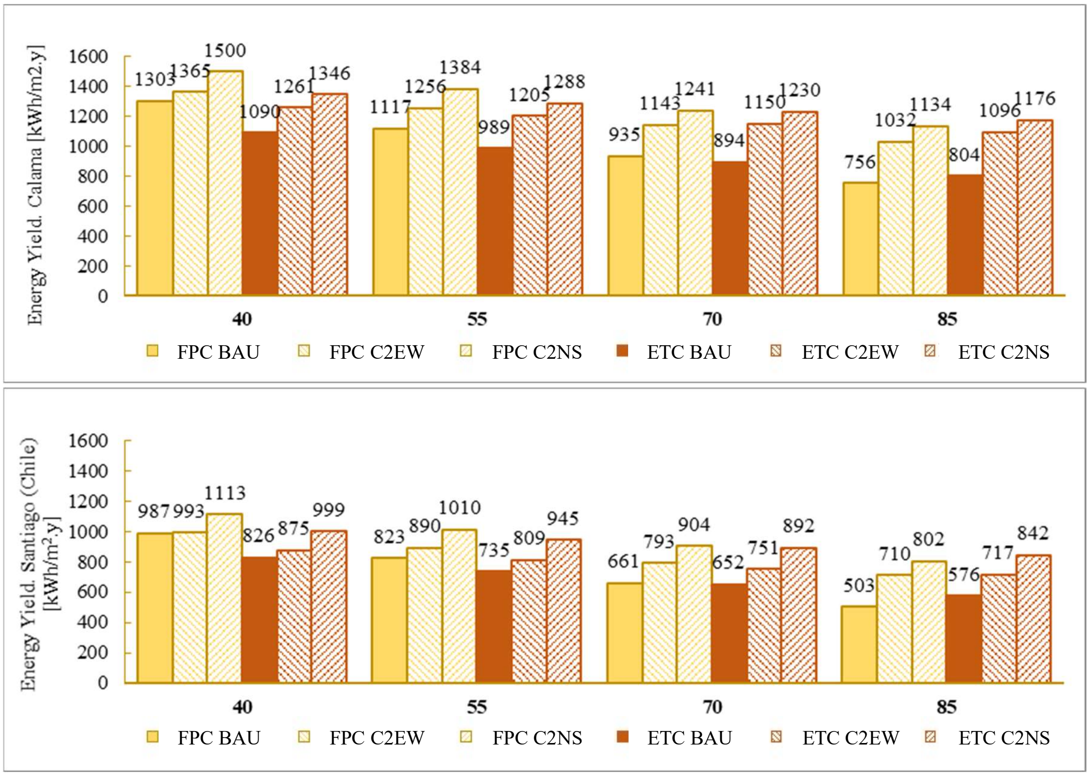

Fig. 7a: Energy yields [kWh/m^2] by aperture area for different solar thermal BAU and ULISSES technologies and return temperatures for Calama (Chile) and Santiago (Chile).

As shown in Figure 7a and 7b, ULISSES technologies outperform other technologies in locations with higher direct radiation (Calama, Santiago, Seville and Lhasa), at both lower and higher temperatures. In these locations, both North-South (NS) and East-West (EW) orientation improve solar yield production compared to BAU technologies. However, NS orientation is the optimal choice for solar fractions up to 40% due to eccentricity. For higher solar fractions or more eccentric demand, EW orientation would be the optimal. On the other hand, as shown in Figure 7b, in locations with more reduced direct solar radiation (Beijing), ULISSES outperforms other technologies only at higher return process temperatures and, given the location's latitude, mainly for EW orientation. In Kobenhavn, ULISSES outperforms other technologies in the EW orientation.

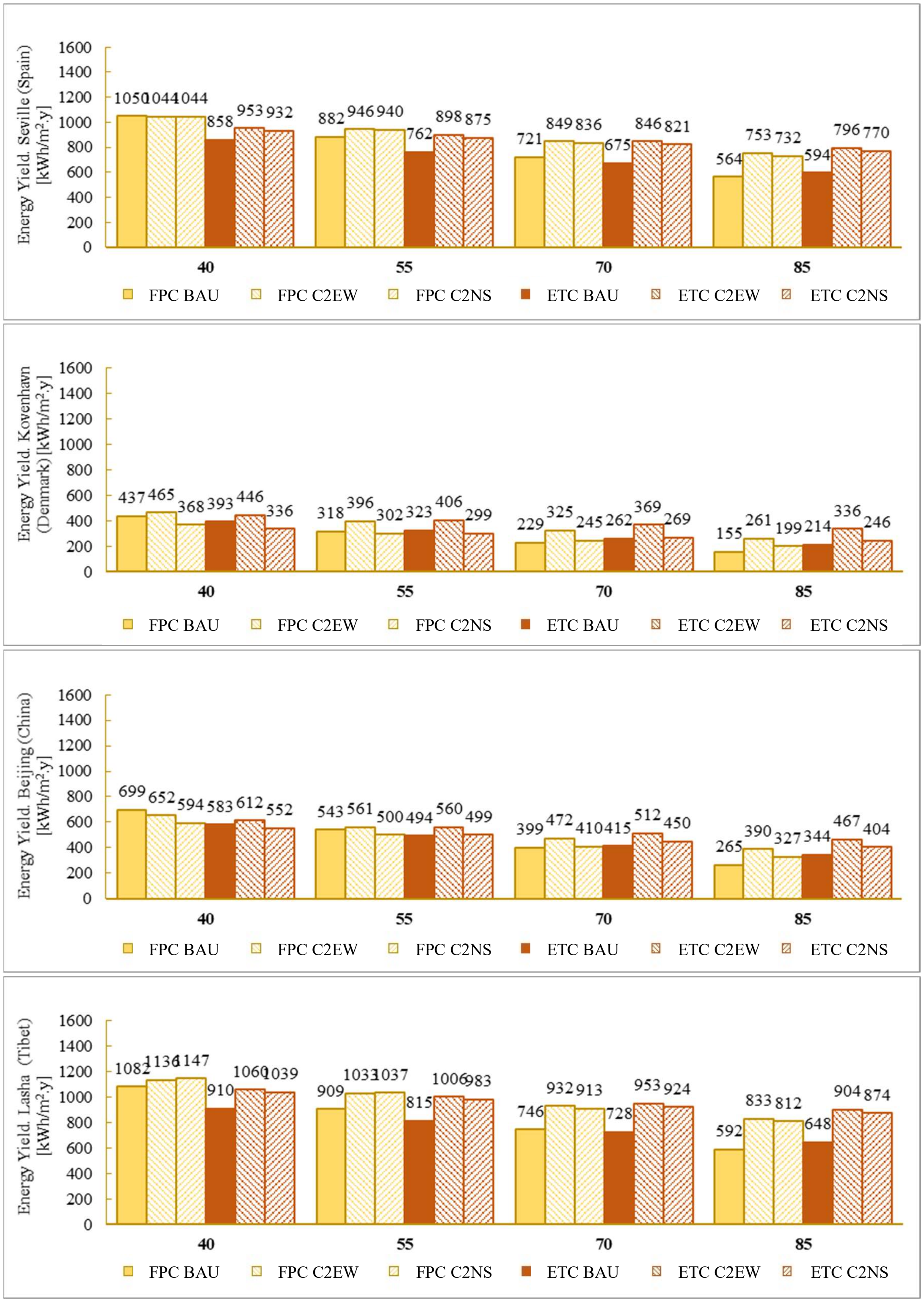

Fig. 7b: Energy yields [kWh/m^2] by aperture area for different solar thermal BAU and ULISSES technologies and return temperatures for Seville (Spain), Kobenhavn (Denmark), Beijing (China) and Lhasa (Tibet)

The following table summarizes the advantages of ULISSES over BAU FPC and ETC technologies in terms of solar yield production for different temperatures and locations.

Tab. 3: Changes of ULISSES solar yield production for different technologies, temperatures and locations. BEI Beijing, CAL Calama, KOB Kobenhavn, LHA Lhasa, SAN Santiago and SEV Seville. Red indicates disadvantage, black indicates advantage for ULISSES

	FPC - Flat Plate Collector							
	T_{ret} **40º**		T_{ret} **55º**		T_{ret} **70º**		T_{ret} **85º**	
	C2EW	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**
BEI	-7%	-15%	3%	-8%	18%	3%	47%	23%
CAL	5%	15%	12%	24%	22%	33%	36%	50%
KOB	6%	-16%	24%	-5%	42%	7%	68%	28%
LHA	5%	6%	14%	14%	25%	22%	41%	37%
SAN	1%	13%	8%	23%	20%	37%	41%	60%
SEV	-1%	-1%	7%	7%	18%	16%	34%	30%

	ETC - Evacuated Tube Collector							
	T_{ret} **40º**		T_{ret} **55º**		T_{ret} **70º**		T_{ret} **85º**	
	C2EW	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**
BEI	5%	-5%	13%	1%	23%	8%	36%	17%
CAL	16%	23%	22%	30%	29%	38%	36%	46%
KOB	13%	-15%	26%	-7%	41%	3%	57%	15%
LHA	16%	14%	23%	21%	31%	27%	40%	35%
SAN	6%	21%	10%	28%	15%	37%	25%	46%
SEV	11%	9%	18%	15%	25%	22%	34%	30%

It can be concluded that in the vast majority of locations and temperatures, the yield production of ULISSES is greater than any of the BAU. In locations with very low direct radiation (Beijing) or at very high latitudes (Kobenhavn), the advantages become evident at return temperatures (T_{ret}) >55ºC.

LCOE of FPC BAU and ETC BAU and their combination with ULISSES technologies were assessed using TRNSYS simulations as well as capital and operational costs. As illustrated in Figures 8a and 8b, ULISSES' LCOE reductions are greater for all return temperatures tested in locations with high direct radiation (Calama, Santiago, Sevilla and Lhasa). Reduced LCOE, or higher potential ESCO benefits, are proportional to process temperature. In these locations, the additional structure cost associated with EW orientations (referred in the cost structure description, see Section 3. Methodology Analysis) result in NS orientations being most advantageous. In locations with lower direct solar radiation (Beijing), ULISSES production only becomes advantageous at higher process temperatures and, due to location's latitude, mainly in the EW orientation. In Kobenhavn, it is mainly the EW orientation in which ULISSES is advantageous. This would make it possible to repower existing solar thermal plants that are already aligned in this orientation.

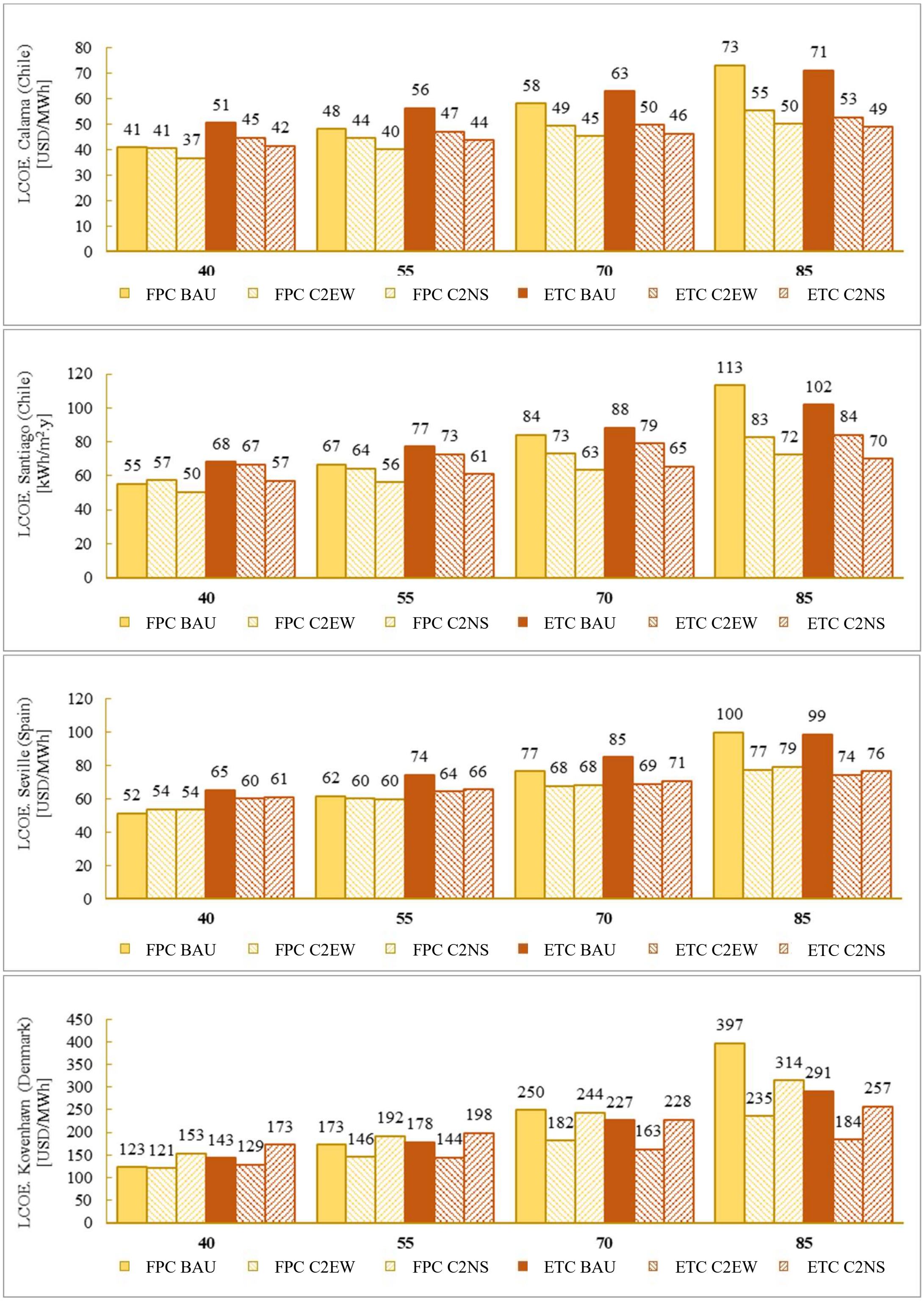

Fig. 8a: LCOE [USD/kWh] for different solar thermal BAU and ULISSES technologies and return temperatures for Calama (Chile), Santiago (Chile), Seville (Spain) and Kobenhavn (Denmark).

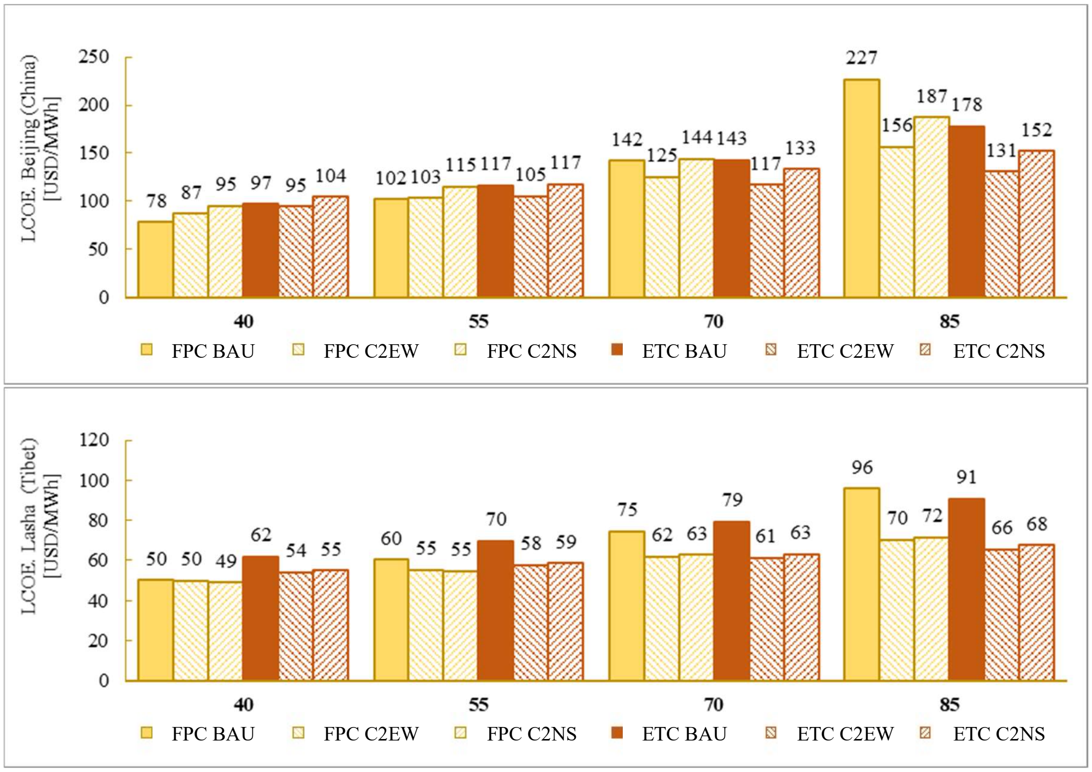

Fig. 8b: LCOE [USD/kWh] for different solar thermal BAU and ULISSES technologies and return temperatures for Beijing (China) and Lhasa (Tibet)

The following table summarizes the advantage of ULISSES in terms of LCOE:

Tab 4: Reduction of ULISSES LCOE for different technologies, temperatures and locations. BEI Beijing, CAL Calama, KOB Kobenhavn, LHA Lhasa, SAN Santiago and SEV Seville. Red indicates disadvantage, black indicates advantage for ULISSES.

	FPC – Flat Plate Collector							
	T_{ret} **40º**		T_{ret} **55º**		T_{ret} **70º**		T_{ret} **85º**	
	C2EW	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**
BEI	12%	22%	1%	13%	-12%	1%	-31%	-17%
CAL	-1%	-10%	-8%	-16%	-15%	-22%	-24%	-32%
KOB	-2%	24%	-16%	11%	-27%	-2%	-41%	-21%
LHA	-1%	-3%	-8%	-9%	-17%	-16%	-27%	-25%
SAN	4%	-8%	-3%	-16%	-13%	-25%	-27%	-36%
SEV	5%	4%	-3%	-3%	-12%	-11%	-23%	-21%

	ETC – Evacuated Tube Collector							
	T_{ret} **40º**		T_{ret} **55º**		T_{ret} **70º**		T_{ret} **85º**	
	C2EW	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**	**C2EW**	**C2NS**
BEI	-2%	8%	-10%	1%	-18%	-7%	-26%	-14%
CAL	-12%	-18%	-16%	-22%	-21%	-27%	-26%	-31%
KOB	-10%	21%	-19%	11%	-28%	0%	-37%	-12%
LHA	-12%	-11%	-17%	-16%	-23%	-21%	-28%	-26%
SAN	-2%	-16%	-6%	-21%	-10%	-26%	-17%	-31%
SEV	-8%	-6%	-13%	-12%	-19%	-17%	-25%	-22%

Table 4 and Figure 9 illustrate ULISSES' potential in terms of LCOE, for different locations and temperatures. At return temperature processes above 55ºC, ULISSES outperforms all other technologies. At temperatures below 55ºC, ULISSES achieves significant LCOE reductions for ETC in both NS and EW orientations in all locations except Beijing. Beijing receives low direct radiation and thus achieves lower solar energy yields, consequently increasing LCOE.

Fig. 9: Reduction of ULISSES LCOE for different technologies, temperatures and locations. BEI Beijing, CAL Calama, KOB Kobenhavn, LHA Lhasa, SAN Santiago, and SEV Seville. Increased LCOE indicates disadvantage, decreased LCOE indicates advantage for ULISSES.

5. Experimental Validation

To verify results, a second prototype plant will be built in Chile in the second semester of 2019 using solar thermal FPC, ETC and photovoltaic ULISSES 2.0 technology. In this prototype plant, performance and operational tests will be conducted to validate previous models.

This prototype will consist of:

- 56 m^2 aperture area FPC C1.6NS ULISSES Technology
- 35 m2 aperture area ETC C1.6NS ULISSES Technology
- 0.75 kWp Photovoltaic ULISSES Technology

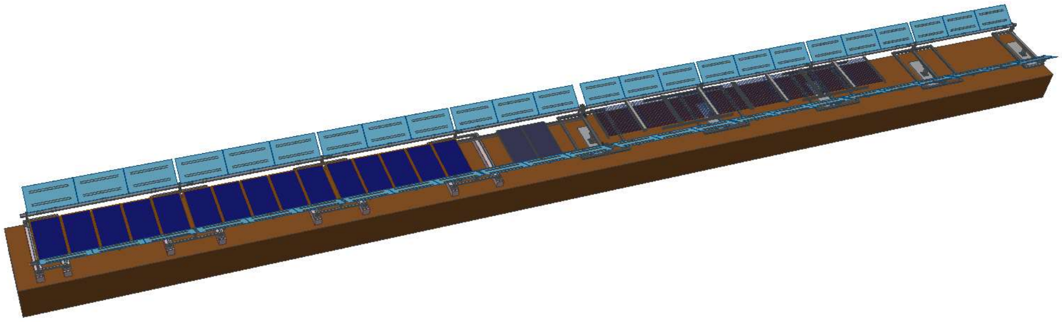

Fig. 10: ULISSES 2.0 Prototype to be constructed during second semester 2019

A detailed experimental analysis plan has been defined to test all operational modes. Performance figures of ULISSES technology will be obtained by installing a meteorological station with additional pyranometers for different measure planes, as well as heat and electricity meters. Cleaning operations will be part of the indicators to correlate with performance figures. First results are expected between the end of 2019 and the first trimester of 2020.

6. Conclusions

It can be concluded that ULISSES is a technology capable of not only of producing more energy by aperture area, but doing so more reliably, thereby enhancing the safety of large-scale solar thermal systems.

According to the parametric study, thermal energy production of ULISSES technology is 10 – 40 % higher in most locations and mainly dependent on process return temperature. For low temperatures, ETC C2EW technology performs best in terms of solar yield as a result of its better IAM. At $T_{ret} > 55$ºC an increased solar yield was obtained as a consequence of reduced thermal losses due to better IAM and concentration factors.

Regarding costs, it has been verified that the costs per unit area of the integrated FPC and ETC plus ULISSES technology are very similar to that of FPC or ETC BAU technologies. In addition, the enhanced safety operation due to the tracking protection positions, results in significantly reduced primary and secondary circuit costs by making the antifreeze in primary fluid or the heat exchanger superfluous. In the present analysis, these savings have not been considered to obtain more conservative technology penetration market scenarios.

In terms of LCOE energy price, ULISSES has almost total advantage at return temperature processes above 55ºC. Therefore, the potential market for ULISSES is very big, covering not only new solar thermal and photovoltaic systems but also existing ones. Hence, the repowering of existing large-scale solar thermal plants is considered as a prospective market. This further expands the potential target market of ULISSES, as the concentrator can be adapted to the characteristics of the existing frame.

ULISSES technology is patent pending in Chile, Europe, China, India and Israel.

7. Acknowledgments

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