Reviewing the dysfunctions of large solar thermal system: a classification of sub-systems reliability

Gaëlle Faure[1,2], Mathieu Vallée[1,2], Cédric Paulus[1,2] and Tuan Quoc Tran[1,2]

1 Univ. Grenoble Alpes, INES, F-73375 Le Bourget du Lac, France

2 CEA, LITEN, 17 rue des Martyrs, F-38054 Grenoble, France

Abstract

All technical processes are subject to dysfunctions during their lifespan, and large solar thermal systems (LSTS) are no exception to this rule. In order to deal with them and minimize their impact, a good knowledge of dysfunctions affecting LSTS is a major issue. In this way, the return on investment can be increased and the competitiveness of solar thermal energy could be also improved.

This paper presents a study of the dysfunctions which can affect LSTS. We first conducted a literature review and found out that more studies are necessary to obtain some up-to-date reliability data on the dysfunctions. To complete the available information, our methodology combines a top-down approach based on a Failure Modes, Effects and Criticality Analysis (FMECA) with a bottom-up approach based on a survey for domain experts. Thanks to the merging of various sources, we propose a ranking of sub-systems reliability, showing in particular that the less reliable solar sub-systems are the controller (control and sensors) and the primary transport (hydraulic components of the primary loop). Other sub-systems are less prone to failure, but the status of solar collection is particularly interesting. While previous studies often point it out as a critical sub-system, our results tend to show that it is more reliable in recent LSTS.

Keywords: *Failure Modes Effects and Criticality Analysis, large solar thermal system.*

1. Introduction

Large solar thermal systems (LSTS) can provide renewable and low cost energy to district heating networks and industrial processes. Over the last 25 years, many of them have been developed mostly in Northern European countries. At the end of 2015, the total area of LSTS installations in operation in Europe reached 1 million m^2 (Mauthner et al., 2016). In France, the first two installations (about $800m^2$) started operating in 2014 (Renaude, 2016), and more installations are planned.

All technical processes are subject to dysfunctions during their lifespan, and large solar thermal systems (LSTS) are no exception to this rule. A dysfunction refers to the interruption of the system's ability to perform a required function under specific operating conditions. This interruption can be permanent or intermittent, abrupt or progressive. In any case, dysfunctions can entail a degradation of the production yields and/or additional maintenance costs. This can significantly hinder the return on investment and the competitiveness of solar thermal energy. Fortunately, the scaling increase of large systems enables more monitoring, which should be used to detect early and diagnose precisely many dysfunctions. However, few works have already been proposed to build fault detection and diagnosis (FDD) methods especially suited for LSTS (Ohnewein et al., 2006; Shahbazfar et al., 2012).

In order to develop a FDD method, a good overview of the type of dysfunctions that can affect the plant is a major prerequisite. In particular, FDD approaches can be developed with various aims, from short term detection of severe faults to long term detection of specific components wearing or fouling. Moreover, there is often a trade-off between detection of all possible faults (completeness) and precise diagnosis of the fault sources (resolution) (Venkatasubramanian et al., 2003). As a consequence, classifying the types of dysfunctions, their occurrence rate and their criticality provides useful information about which FDD method can give the most interesting results for LSTS systems.

In this paper, we present a study of dysfunctions of large-scale solar thermal systems (LSTS). Our methodology combines a top-down approach based on a Failure Modes, Effects and Criticality Analysis with a bottom-up approach based on a survey for domain experts, and provided us qualitative data about the main dysfunctions in LSTS. In section 2, we will first describe the state-of-the art of studies on dysfunctions in LSTS. In section 3, we introduce the methodology we adopted for this study. In section 4, we detail and discuss our results, from a

doi:10.18086/eurosun.2016.05.01 Available at http://proceedings.ises.org

global perspective to more precise results on the most frequent and critical dysfunctions. At last, section 5 summarizes our conclusions and opens perspectives on the development of new FDD methods.

2. State of the art

In this section, we introduce the current state of the art about dysfunctions of large scale solar systems. We first briefly present the system we consider, especially by defining the main relevant sub-systems (subsection 2.1). Please note that this description intends to be the most representative of LSTS configurations. We then report on our initial literature study (subsection 2.2).

2.1. System description

In this study, we consider LSTS with a total collector area above 500m², for the production of hot water at low and medium temperatures (80-120°C) with a focus on the production up to the feed-in. Other restrictions are applied in order to decrease the number of allowed layout while keeping the most common ones:

- Auxiliary heating: not studied ;
- System: pressurized, filled with water-glycol mixture ;
- Solar collector: no active tracking ;
- Storage: systems without storage are included. Only daily water, with passive stratification storages are taken account. Bi-energy storages are not considered in this study.

The remaining system is divided in five sub-systems to simplify the analysis as presented in Fig. 1:

- *Solar collection*: solar collectors, connections between collectors, fastening system.
- *Primary transport*: hydraulic components between solar field and first heat exchanger or storage (if no external heat exchanger).
- *Storage*: storage tank and internal heat exchangers if there are any.
- *External heat exchanger(s)*: if any.
- *Secondary transport*: hydraulic components between first heat exchanger or storage (if no external heat exchanger) and the feed-up.
- *Controller*: control-command components and sensors.

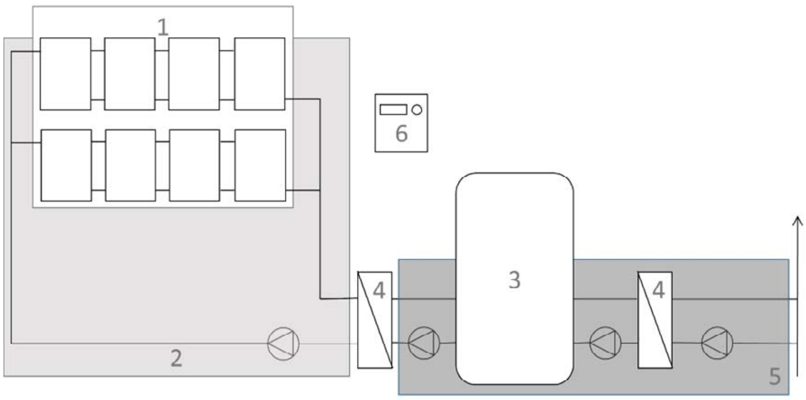


Fig. 1: Example of division of a LSTS plant in five sub-systems: solar collection (1), primary transport (2), storage (3), external heat exchanger(s) (4), secondary transport (5) and controller (6).

2.2. Literature review

Keeping in mind the characteristics of the system we have described in the previous section, we conducted a review of the literature dealing with the reliability of LSTS, with a specific focus on studies that provided data on the type and frequency of dysfunctions for each sub-system.

We can first notice that the most complete research studies on reliability of solar thermal systems date back from several decades ago (Chopra, 1980; Jorgensen, 1984). Some recent examples are the Solarthermie2000 and Solarthermie2000plus studies (Peuser et al., 2005), which are also based on solar systems in operation since the early 80's. Although these studies provide interesting inputs in terms of methodology, their results are difficult to exploit nowadays, since many of the considered technologies have been improved or are not in use anymore.

More recent studies are rather focused on small scale systems and solar domestic hot water (SDHW) system. They have especially been conducted in relation with governmental programs fostering the installation of solar thermal systems, and sometimes provide data based on monitoring results (ADEME, 2008; Cholin, 2011). Although some findings of these studies can be applied to LSTS, there are many differences in terms of size, kinds of sub-systems and overall installation and maintenance policies, which strongly affect the type and occurrence of potential dysfunctions. As an example, problems with the solar panels' fastening system are often reported in SDHW, but will likely be not as significant in LSTS due to the standardization of the components.

A main drawback of available studies is also the lack of feedback data about the actual occurrence rate of dysfunctions. Although one older study provides occurrence data for some defaults (Jorgensen, 1984), a similar study conducted 25 years later concluded in the lack of precision and reliability of available data (Menicucci, 2009). One important issue is the lack of consistency between databases, which often yields biases and contradictory results depending on the information source.

Despite the lack of recent and reliable data on dysfunctions in LSTS, we can highlight several important conclusions from this literature review:

- **Primary transport** consistently appears to be the most impacted sub-system. In particular, insulation is often lacking or not adequate, especially to resists UV rays and bird attacks. Leaks are a usual source of dysfunction, as well as pressure loss and air bubbles, which can also result from leaks. Finally, especially in large-scale installations, a bad hydraulic balancing between the solar subfields is sometimes reported.
- **Regulation and controllers** can have a high number of dysfunctions, often related to poor installation and parameter tuning, as well as wrong placement of sensors. Especially temperature sensors yielding wrong measurement strongly impact the performance of the system.
- **Solar collection** may have some dysfunction, but is less frequently cited. Moreover, some of the problems appearing in earlier studies have been fixed in more recent products.
- **Secondary transport and heat exchanger** appear to have much less dysfunctions, primarily because these are well-known, classical systems.
- **Storage** also appears to have few dysfunctions, for the same reasons. However, this could differ in large-scale systems with unusual storage sizing and technologies.

Based on this literature review, we decided to conduct a new study in order to better assess the type, occurrence rate and criticality of dysfunctions in LSTS.

3. Methodology

This part describes the methodology used to study the dysfunctions that can affect a LSTS. Subsection 3.1 gives a description of the chosen method: the Failure Modes, Effects and Criticality Analysis. In order to apply the procedure, we collected more data thanks to a survey (subsection 3.2). The last section presents the determination of an important figure, the Failure Risk Priority Number, based on the collected data. This number is a way to emphasize dysfunctions that are critical for the system.

3.1. Failure Modes, Effects and Criticality Analysis (FMECA)

In order to study the dysfunctions that can affect LSTS, we applied a standard methodology: the Failure Modes, Effects and Criticality Analysis (Isermann, 2006; Laronde, 2011; Villemeur, 1988). FMECA is a formalized method, developed in the 60's and commonly used in industry nowadays to evaluate the dysfunctions that can occur on a system. It consists of doing the inventory of the components, their functions and the ways they cannot perform these functions (failure modes). The analysis can be extended by adding possible causes of the failures and their effects on the whole system. Finally a Failure Risk Priority Number (FRPN) can be estimated to show the criticality of different failures. The results of this work is a large table as illustrated in Tab. 1.

Tab. 1: Extract of the resulting FMECA table.

<table>
<tr><th>Component</th><th>Function</th><th>Failure mode</th><th>Effects</th><th>Possible causes</th><th>Properties of the causes</th><th>Detection method</th><th>FRPN</th></tr>
<tr><td rowspan="2">Primary pump</td><td rowspan="2">Set the heat transfer fluid in motion</td><td rowspan="2">Never start</td><td>No energy production</td><td>Pump not connected</td><td>Installation error</td><td rowspan="2">No flow when sunshine and demand</td><td rowspan="2">25</td></tr>
<tr><td>Overheating of the primary loop</td><td>Electricity grid failure</td><td>Environment</td></tr>
</table>

In practice, we made a first analysis based on prior knowledge, discussions with local experts and the literature review presented in the previous section. However, the amount of collected information was insufficient to estimate the FRPN. In particular, no specific data about the failure occurrence rate was available. We then decided to conduct a survey with a larger panel of experts, as described in the following subsection.

3.2. Survey of domain experts

The survey was emailed to 23 experts in the field of LSTS. It was deliberately based on open-ended questions and consisted in:

- listing, for each sub-system, the dysfunctions that can affect it;
- giving a rough estimation of the occurrence rate for each listed dysfunction by choosing between “low”, “medium” and “high”;
- adding any significant information (cause, effect, detection…).

A sample of the survey form is given in Fig. 2. 90% of the surveyed experts returned an answer, and we collected results from a total of 21 experts from 7 countries and 20 different organizations (research institutes, consulting engineers, solar manufacturers, LSTS managers, training organizations). These additional information helped completing the FMECA and computing the FRPN as described in the next section.

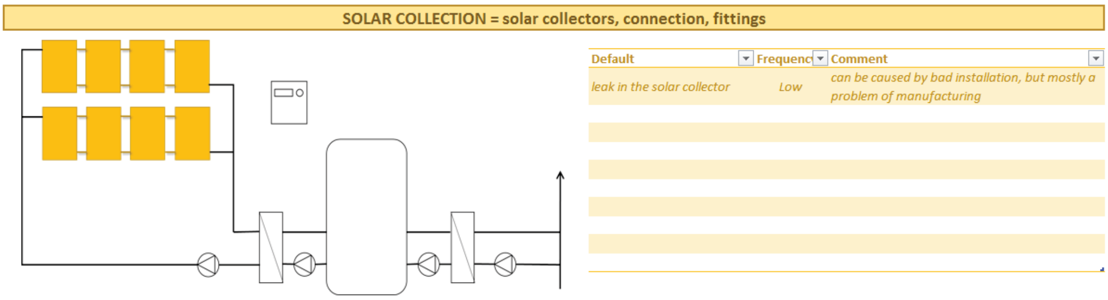


Fig. 2: Part of the survey concerning the solar collector sub-system. The same presentation is used for the other sub-systems.

3.3. Determination of the Failure Risk Priority Number (FRPN)

The Failure Risk Priority Number gives an indication of the criticality of a given failure mode for the system. It is computed for each failure i using equation *(eq. 1)*:

$$FRPN_i = ON_i \times EN_i \qquad (eq.\ 1)$$

where ON_i (Occurence Number) is a number representing the occurrence rate of failure i, EN_i (Effect Number) is a number describing the effects of failure i on the system. ON_i and EN_i are ranking values with a scale from 1 to 5. FRPN is itself a ranking number with a scale from 1 to 25, 1 standing for the less critical failure modes.

To compute ON_i we first derive a raw “occurrence rate” value O_i from the results of the survey and the state of the art using *(eq. 2)*:

$$O_i = 0{,}45 * N_i + 0{,}45 * \frac{3*Nhigh_i + 2*Nmed_i + Nlow_i}{6} + 0{,}1 * b_i \qquad (eq.\ 2)$$

N_i is the total number of citations of a failure i in the survey. $Nhigh_i$, $Nmed_i$ and $Nlow_i$ are respectively the number of “high”, “medium” or “low” frequency qualifications for this failure. b_i is a value ranked between 0 and 2 describing if the failure is often reported in the literature. We obtain ON_i by scaling O_i to an integer between 1 and 5 (the higher the number, the more probable the failure occurrence).

To compute EN_i, we estimated the effect of each failure based on its description and experts comments. Possible effect numbers are given in Tab. 1, and range from 1 (“No effect”) to 5 (“No more solar production”).

Tab. 1 : Criteria to estimate EN_i, the rank of a failure according to its effects on the system.

EN_i	Effect on the system
1	No effect - client does not notice anything
2	Slight and stable drop in yield
3	Progressing drop in yield
4	Significant drop in yield with immediate risk of substantial degradation of the system
5	No more solar production

The resulting FRPNs allow classifying the reported failure modes from the less critical ones, which have a low occurrence rate and no effect, to the most critical ones, which have both high occurrence rates and severe consequences on the system integrity. It has to be noticed that although the computation of the ONs and the FRPNs depend on the coefficients used in *(eq. 2)*, a sensitivity analysis showed that their value have a low impact on the results of the study. More specifically, using different sets of coefficients in *(eq. 2)* does not affect the ranking of failure modes along their FRPNs.

4. Results and discussion

We identified 130 possible failure modes or dysfunctions. One failure mode is the result of one or more causes, and leads to 392 independent causes or basic events. The main characteristics of these causes are presented in subsection 4.1. We also worked at the failure modes level, first by observing the distribution of the computed ranking values (subsection 4.2), then by focusing on the more critical failure modes (subsection 4.3).

4.1. Types of causes

This first subsection is dedicated to the study of the main causes of the failure modes. The causes that leads to failure modes with a very low occurrence rate are not taken into account. After this selection, 326 independent events remain. The literature concerning faults (Isermann, 2006; Villemeur, 1988) proposes different ways to describe and classify the failure modes and their causes:

(a). The sub-system affected by the cause.

(b). The origin of the cause, which can be a design fault, an installation error, a wrong operation (missing maintenance, wrong manipulation…) or the ageing of the components. Causes resulting from environment (weather conditions, power cut…) are also distinguished.

(c). The appearance's time, showing whether this cause is already existing during the commissioning stage or whether it appears during the operation.

(d). The time's dependency, distinguishing between abrupt (stepwise), progressive (drift-like, incipient) and intermittent causes, as defined by Isermann.

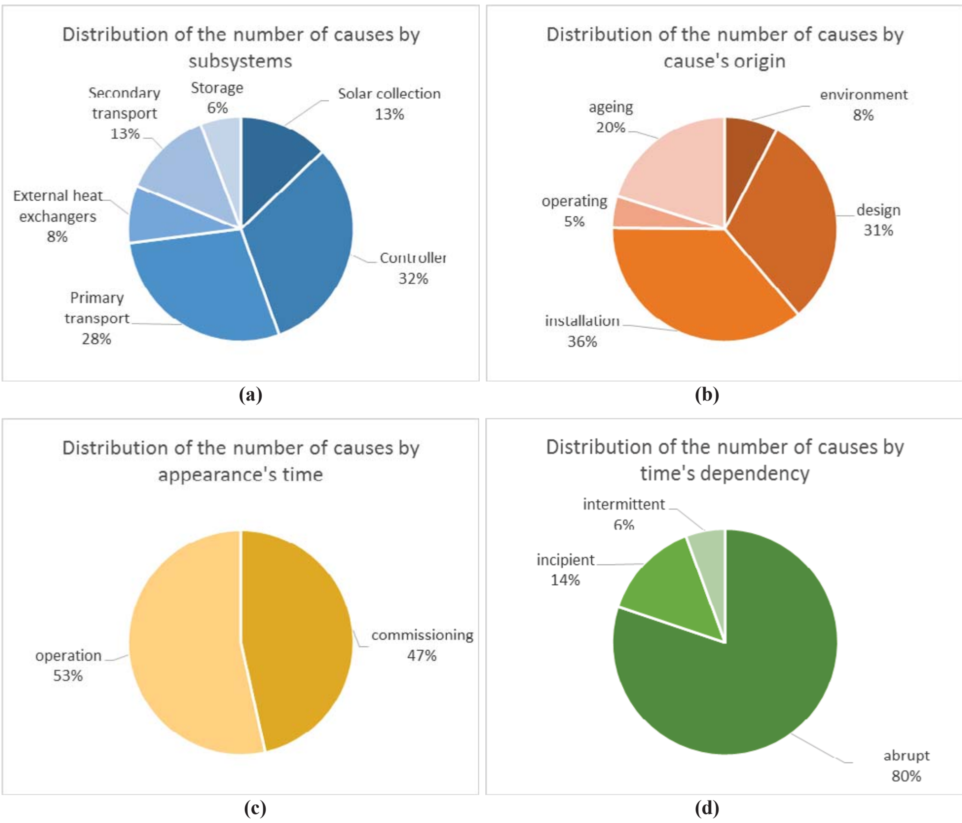


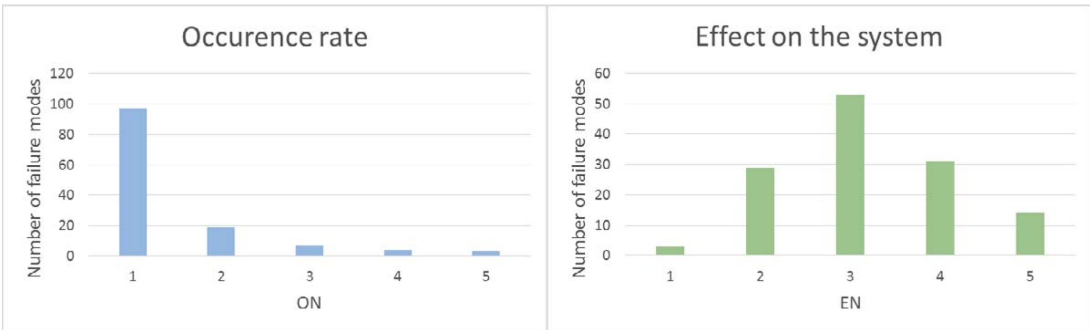
Fig. 3: Distribution of the number of found causes along some criteria: (a) sub-system, (b) cause's origin, (c) appearance's time, (d) time's dependency.

Fig. 3 presents the classification of the causes along these criteria. According to pie chart Fig. 3.a, controller and primary transport concentrate the largest number of causes of failure (60% together). Solar collection and secondary transport concerns both 13% of the inventoried causes. Storage and heat exchanger are less subject to failure. The results are in good agreement with the literature review of subsection 2.2. The pie chart Fig. 3.b shows that the main causes are design and installation problems (67%). Ageing is also a significant factor of failure. Operating and environment are less critical, in one hand because the system's environment is not extreme, and in other hand because the system is fully automatized and is designed to require few maintenance. Due to the high rate of design and installation dysfunctions, 47% of the causes are already present at the commissioning (Fig. 3.c). The pie chart Fig. 3.d teaches us that if mainly dysfunctions appears suddenly (80% of the causes), 14% are progressive, which is not negligible. The part of intermittent causes is quite low.

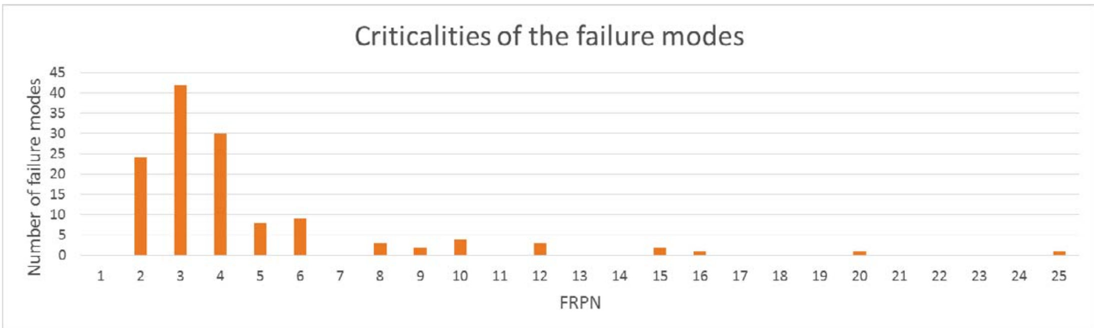
This first part does not take into account the criticality of the failure mode and the causes associated. It speaks about "what can happen". In the next parts, the criticality of the failure mode will be studied in order to work about "what is likely to happen".

4.2. Distribution of the failures along the key ranking numbers

Fig. 4 shows the distribution of the ranking number representing the occurrence rate (ON_i), the effect on the system (EN_i) and criticality ($FRPN_i$) of the failure modes or dysfunctions. The histogram plotted on Fig. 4.a reveals that there are few frequent failure modes. This is in accordance with some general commentaries made by experts when then reply to the survey: "defaults are rather occasional.", "a large scale solar thermal plant does not need much effort to secure an operation without failure", "we identified few defaults on solar plants". On the contrary, the impact of the failures on the global system is significant: histogram Fig. 4.b shows that more than 75% of the dysfunctions implies at least a progressing drop in solar yield ($EN_i \geq 3$), with a high risk of material degradation for almost 35% of them ($EN_i \geq 4$). Due to the low frequency of most of failure modes, the criticality is generally low (histogram Fig. 4.c). We can however show off one dysfunction with the maximal criticality ($FRPN_i = 25$). It will be detailed in the next sub-section.



(a) **(b)**



(c)

Fig. 4: Distribution of the failure modes along (a) their probability of occurrence, (b) their effect on the system, (c) their criticality.

Tab. 2 confirms that the distribution of the couples (ON_i, EN_i) follow the tendencies previously discussed: on the one hand, failure modes have in general a low probability of occurrence apart from their effect on the whole system; on the other hand the effect is mostly medium independently of their frequency.

Tab. 2: Distribution of the pairs (ON_i, EN_i).
The area delimited by a bold border includes the most critical failure modes which are studied afterwards.

		EN_i 1	2	3	4	5	Total
ON_i	1		22	42	25	8	97
	2	2	4	7	3	3	19
	3		2	2	1	2	7
	4	1		2	1		4
	5		1		1	1	3
	Total	3	29	53	31	14	130

4.3. Critical dysfunctions

Tab. 3 shows the most critical failure modes: those which have a Failure Risk Priority Number ($FRPN_i$) equal or above 8. This threshold represents the area delimited by a bold border in Tab. 2. This area is the lower-right corner of the table corresponding to the highest $FRPN_i$ without the pairs (1,5) which are less representative of a high criticality event, since an EN_i of 1 is "No effect - client does not notice anything" (see Tab. 1) and an ON_i of 1 can be achieved with only one citation. The failure modes are sorted along sub-systems, then along their $FRPN_i$. The most affected sub-systems are at the beginning of the table.

Tab. 3: Failure modes with a Failure Risk Priority Number equal or above 8.

Sub-system	Component	Failure mode	ON_i	EN_i	$FRPN_i$
Controller	Solar collector temperature sensor	Wrong measure	5	4	**20**
	Heat exchanger input/output temperature sensor	Wrong measure	4	4	**16**
	Solar collector temperature sensor	No more measure	3	5	**15**
	Heat exchanger input/output temperature sensor	No more measure	2	5	**10**
	Pyranometer	No more measure	2	5	**10**
	Controller	Breakdown	2	5	**10**
	Controller	Non-optimal control	3	3	**9**
Primary transport	Solar pump	Never starts	5	5	**25**
	Hydraulic connectors	Leak	4	3	**12**
	Heat transfer fluid (mixture of water and propylene- or ethylene-glycol)	Bubbles in the heat transfer fluid	3	4	**12**
	Pipes	Leak	3	3	**9**
	Pipes	Bad hydraulic balancing	2	4	**8**
	Expansion vessel	Too low pressure	2	4	**8**
	Solar pump	Too low flow	2	4	**8**
Secondary transport	Pumps	Never starts	3	5	**15**
Storage	Storage tank	Heats less than expected	4	3	**12**
Solar collection	Solar collector	Produces less energy than expected	5	2	**10**

These results have to be analyzed qualitatively more than quantitatively. Indeed, they are the results of a bibliography and a survey, which are far less accurate than an experimental test or the assembly of a large amount of representative data. For example, we can pick up on some bias on the reported occurrence rate (ON_i) for the failure mode "solar collector produces less energy than expected". ON_i is maximum for this dysfunction and seems overestimated, given the literature review (see subsection 2.2). Since the solar collector is the main component of a solar system, and one of the most complex, we can assume responders had a tendency to focus on reporting dysfunctions on this component first. Actually, additional interviews showed that the first quoted dysfunctions concerned the solar panels, even if the experts added later that these dysfunctions are uncommon. Moreover, solar collection appeared as the first item in the survey form, which could be an additional source of bias.

Generally, Tab. 3 is in line with the bibliography (subsection 2.2). Two sub-systems are more likely to fail: controller and primary transport with both 7 critical failure modes. Secondary transport, storage and solar collection have one critical failure mode each. External heat exchangers are not present in the results.

5. Conclusion and perspectives

In this paper, we report on a study concerning the dysfunctions that can affect large solar thermal systems (LSTS). We began with a review of the state of the art and noticed that there are few up-to-date information about large solar installations. Therefore, we performed a Failure Mode Effects and Criticality Analysis and completed it with an expert survey in order to obtain more elements. We finally presented the results of this analysis with a focus on the typology of the causes of failure and on the more critical dysfunctions. An important result is the fact at the commissioning almost half of the causes of the dysfunctions can already occurred. As a consequence, if a fault detection method is applied to a solar system, it cannot suppose that the plant works well at the beginning of the monitoring. As far as the risk of failure is concerned, although the majority of the dysfunctions is quite occasional, their impact on the efficiency and the degradation of the system is high. An automatic detection and a diagnosis of these problems are then of interest. In particular we demonstrated that two sub-systems are particularly subject to dysfunctions: the controller and the primary transport. Other sub-systems are less prone to failure, but the status of solar collection is particularly interesting. While previous studies often point it out as a critical sub-system, our results tend to show that it is more reliable in recent LSTS.

Based on the results of this study, our future work will focus on the development of FDD methods for specific sub-systems, starting with controllers, primary transport and solar collection. We can note that many available FDD methods work well for the controller part, but the two other sub-systems are less well covered. In particular, the detection, diagnosis and localization of dysfunctions on the primary transport sub-system and on solar collector are more complicated to perform, but are of prime importance due to the size of the solar field.

Additionally, we can mention that the study presented here could be a preliminary step for a complete reliability analysis of LSTS. A study like the one done by (Laronde, 2011) for the solar photovoltaic systems or the ANL Solar Reliability and Materials Program conducted by the Argonne laboratory in the late 70s (Chopra et al., 1978; Waite et al., 1979) could provide reliability data such as lifespan and failure rate of the main components of a LSTS. These data would be useful not only for the development of fault detection and diagnosis (FDD) algorithms but also for the design of the products and the optimization of the preventive maintenance.

6. Acknowledgement

This project has received support from the State Program "Investment for the Future" bearing the reference (ANR-10-ITE-0003). A special thanks goes to the experts who participated in the study. Their contribution was invaluable.

7. References

ADEME, 2008. Audit des installations de chauffe- eau solaires individuels - Principaux résultats et recommandations pour la mise en oeuvre des installations. ADEME.

Cholin, X., 2011. Retour d'expérience installations solaires thermiques - ASDER.

Chopra, P.S., 1980. Why do solar systems fail ? Sol. Eng. Mag. 14–21.

Chopra, P.S., Cheng, C.F., Wolosewicz, R.M., 1978. Preliminary Evaluation of Selected Reliability, Maintainability, and Material Problems in Solar Heating and Cooling Systems. Department of Energy, Energy and Environmental Systems Division.

Isermann, R., 2006. Fault-Diagnosis Systems - An Introduction from Fault Detection to Fault Tolerance.

Jorgensen, G.J., 1984. AN ASSESMENT OF HISTORICAL R&H DATA FOR SDHW SYSTEMS.

Laronde, R., 2011. Fiabilité et durabilité d'un système complexe dédié aux énergies renouvelables - Application à un système photovoltaïque. Institut des Sciences et Techniques de l'Ingénieur d'Angers.

Mauthner, F., Weiss, W., Spörk-Dür, M., 2016. Solar Heat Worldwide - Markets and Contribution to the Energy Supply 2014 (No. 2016 edition), Solar Heating and Cooling Programme. International Energy Agency.

Menicucci, D., 2009. Assembly and comparison of available solar hot water system reliability databases and information. Sandia Rep. SAND 2757, 2009.

Ohnewein, P., Dröscher, A., Schgaguler, K., Feichtner, F., Meißner, E., Luidolt, P., Köstinger, A., Heimrath, R., Jaindl, M., Streicher, W., 2006. IP-Solar: Development of a Web-Based Monitoring and Diagnostics Tool for Solar Thermal Systems, in: Eurosun 2006.

Peuser, F.-A., Remmers, K.-H., Schnauss, M., 2005. Installations solaires thermiques : Conception et mise en oeuvre. Le Moniteur Editions, Berlin, Allemagne : Paris.

Renaude, F., 2016. Monitoring results for the two firsts solar plants on district heating network in France: Balma Gramont and Juvignac. Presented at the 4th International Solar District Heating Conference, Billund, Denmark.

Shahbazfar, R., de Keizer, A.C., Kuethe, S., Jordan, U., Vajen, K., 2012. Fault detection and fault diagnosis for large scale solar thermal systems, in: Proc. of Eurosun 2012, Croatian Solar Energy Association. International Solar Energy Society (ISES), Rijeka, Croatie.

Venkatasubramanian, V., Rengaswamy, R., Yin, K., Kavuri, S.N., 2003. A review of process fault detection and diagnosis: Part I: Quantitative model-based methods. Comput. Chem. Eng. 27, 293–311. doi:10.1016/S0098-1354(02)00160-6

Villemeur, A., 1988. Sûreté de fonctionnement des systèmes industriels, Collection de la Direction des Etudes et Recherches d'Electricité de France. Eyrolles.

Waite, E., Patterson, D., Prucha, L., Singh, H., Wolosewicz, R., Chopra, P.S., 1979. Reliability and Maintainability Evaluation of Solar Control Systems (No. SOLAR/0903-79/70; ANL/SDP-TM-79-5). Argonne National Lab., IL (USA).