9th European Workshop on Structural Health Monitoring
July 10-13, 2018, Manchester, United Kingdom

SHM CASE STUDY: MOLTEN SALT TANK MONITORING FOR HIGHLY EFFICIENT CENTRALIZED SOLAR POWER PLANTS

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Abstract

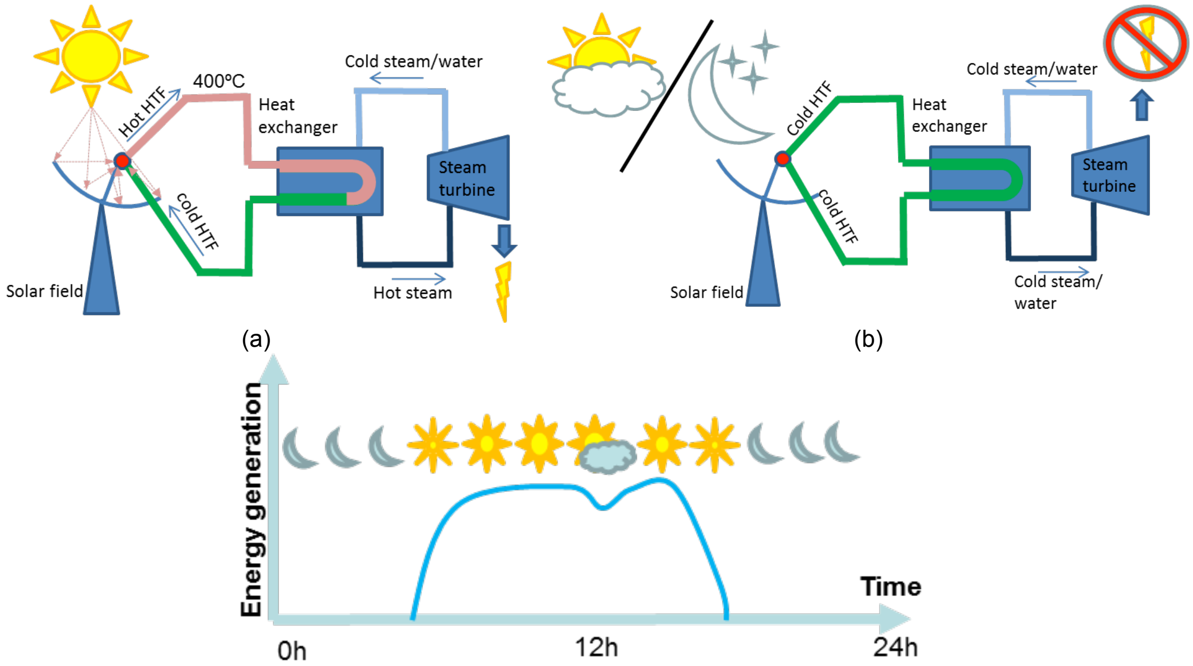
Centralized Solar Power has been acknowledged to play an important role in the energy mix of the future. However, some optimizations on designs and development in new materials are needed to obtain highly efficient thermal storage, a stepping stone to be a reliable technology. Thermal storage is done at temperatures that exceed 500ºC with highly corrosive molten salts, in infrastructures that include storage tanks. Therefore, ensuring safety and performance of the infrastructure and sysem through SHM and thermal performance is a key aspect for widespread adoption of the technology. In this paper the VoI implications of a fiber optic sensor-based monitoring system developed at NEWSOL project are discussed as a SHM case study.

1. Introduction

Concentrating solar power is a growing clean renewable energy source that helps address de global challenge of clean energy, climate change and sustainable development. As a matter of fact, it has been proposed as one of the most suited as energy source for the 21st century (1),(2), with an expected increase from 4GW in 2014 to 1000GW by 2050, carrying a big impact in CO2 emission lowering: 2.1GTon reduction (1).

The evidence of benefits CSP carries to the energy challenge field are clear, however, the actual CSP infrastructures are widely questioned service-life-wise. This is mainly given by the durability of functional materials used, which work on a far from optimized ratio regarding efficiency, durability and cost. A solution to help this balance is using thermal storage materials that keep the temperature of heat exchanger's and turbine's working regime so the energy generation intermittency due to solar radiation availability is eliminated: the performance of the plant is increased by constant steam production. Storage fluids based on Solar molten salts (SMS) are a proven solution that can keep a plant working during a complete night (3). The composition of SMS is usually KNO3 and NaNO3, so they are very corrosive, have a high melting point, usually above 200ºC, and can work at temperatures of up to 600ºC, depending on the mixture composition. There are two possible architectures for CSP using SMS: SMS are intermediate fluids or as the only heat transfer fluid (HTF). In the first case, SMS only store heat, and the main HTF is oil. The first case is depicted in figure 2 for the case of a parabolic solar trough facility. The HTF, is heated in the solar field with solar radiation and then is diverted toward two different heat exchangers: in the first heat exchanger, cold molten salt is heated from 300ºC to 400ºC (the maximum temperature the oil can operate). In the second heat exchanger hot

HTF heats steam that feeds the turbine. The cold SMS from both heat exchanger is redirected back to the solar field. When there is no solar radiation, at night or on cloudy days, the HTF does not go through the solar field and the flow directions on heat exchanger 1 are inverted: it is the hot SMS that heats up the HTF. Meanwhile the heat exchanger 2 remains the same, allowing generation of electricity on the turbine, since hot steam is still generated. When SMS is the only HTF, there is only a heat exchanger, the one heating steam, and the operating temperature of the system is higher: 600ºC or more depending on the SMS mixture used. The heated HTF is directed to a tank, and it is the tank which is directly connected to the heat exchanger to feed with hot HTF. Depending on the tank architecture, a two-tank system or a single thermocline system can be used, as it will be discussed in the following section.

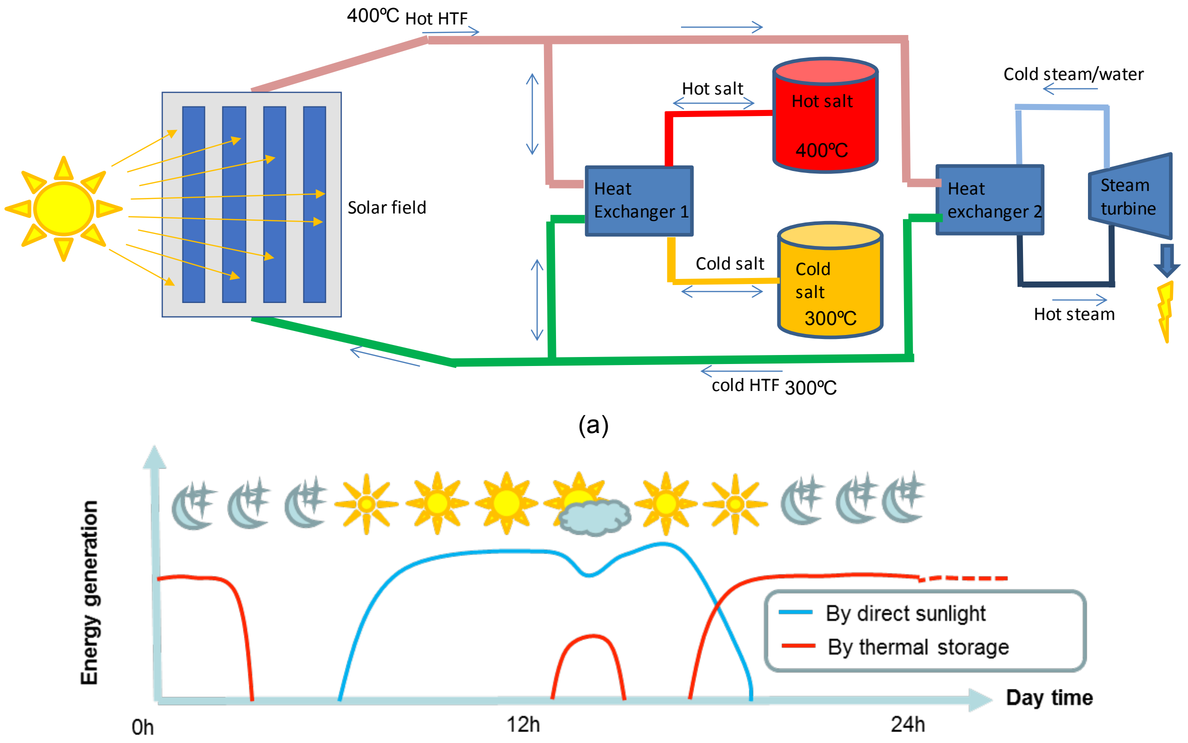


(a) (b)

(c)

Figure 1: Schematic of a CSP using HTF (a) with sunlight (b) without sunlight (c) and energy generation throughout the day.

Each of the configurations have their ups and downs. The HTF oil and SMS storage system can continue running if a problem occurs in the storage system, although only at daytime. SMS, being so corrosive have a big long-term stability impact in the materials of the infrastructure such as tanks and pipelines. However, the system where only SMS are used is more efficient, since higher temperatures are reached and a single heat exchanger is needed. In any case SMS should always operate at temperatures above their freezing points to avoid collapse of the plant. Therefore, SMSs deployment is a challenge due to the limitations they impose, although are a proven solution to increase efficiency and help widespread adoption of CSP (3).



(a)

(b)

Figure 2: (a) Schematic of a CSP using SMS (b) and energy generation throughout the day.

2. Advanced SMS tanks

Currently, SMS tanks are made of steel and must be carefully insulated to avoid any heat loss. Also, the current configurations need the deployment of two tanks: one for hot SMS and another one for cold SMS storage and great volumes of SMS. Therefore, a lot of research effort is conducted to optimize de Efficiency/Durability/Cost in the SMS storage tanks. Currently, in NEWSOL project (4), a solution based in novel materials for tank heat storage, advanced SMS, insulating materials, filler materials within the tank and advanced monitoring systems is being developed and demonstrated in a novel configuration: the thermocline tank. Figure 3 shows a CSP plant running only on SMS as HTF and storage fluid and the thermocline tank. The SMS, after heated in the solar field, is stored in the thermocline tank. The hot SMS, from the top of the tank is directed to the heat exchanger, where the steam is heated. Note the power block is the same as in the two-tank configuration. The cold SMS is then directed to the thermocline tank, where it is stored until it is heated in the solar field again. Note that the SMS input and output to and from the tank are at different height levels in the figure. This is to ensure that the fluids with different temperatures are placed at different parts of the tank to reduce heat transfer between them and isolate one from another. So, in the thermocline tank a vertical temperature gradient is observed, with an abrupt change in temperature between the hot and cold salt, called the thermocline. Therefore, when the tank is fully charged, the tank will be filled with hot SMS only, and when it is discharged, only cold SMS will be inside the tank. This way a lower volume of SMS is needed, and a single tank is needed for storage, reducing the cost of the system. The design consists of a single thermocline tank with concrete walls, instead of the classic 2–tank system with steel walls, containing filler materials inside the tank for sensible heat storage up to 550ºC. The new thermocline concrete tank will take advantage of the thermocline effect to combine both, the hot and the cold molten salt in the same tank by separating them through a thin layer of a high-temperature gradient. This thermocline tank will be filled with low cost solid filler materials that displace the more expensive molten salts and act as the primary thermal storage medium. These filler materials will be arranged in several layers along the tank height.

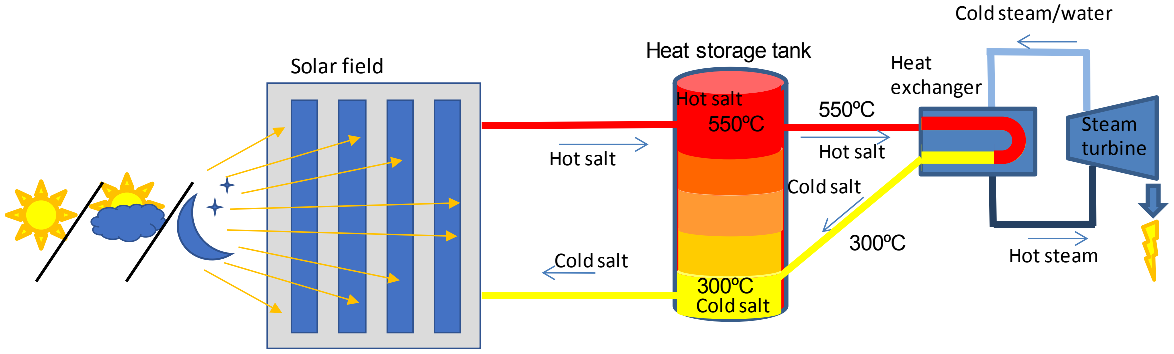


Figure 3: Thermocline SMS tank configuration on a CSP

3. Monitoring system and sensors for molten advanced SMS concrete tanks.

A solution to help widespread the adoption of SMS technology and thermocline concrete tanks, alongside with their benefits, is a monitoring technology that allows SHM and material performance assessment. Measuring and storing temperature data of the salt or the structural health of the tank is an important input and the sensing technologies applied are the key element for feasible and stable measurements. The most widely employed transducers are thermocouples for temperature monitoring, strain gages for strain monitoring and embedded or surface-bonded piezoelectric sensors for vibrations or acoustic emission (AE). However, these technologies present serious drawbacks for monitoring large structures at high temperature or corrosive environments. Thermocouples and strain gages are hard to multiplex and are subject to electric and magnetic disturbances. In the case of piezoelectric sensors, they lose the piezoelectric effect above temperature of Curie (300ºC) and exhibit degradation due to thermal cycling (5). Furthermore, they do not offer very good multiplexing capacities, and resistance to corrosion.

One promising alternative are the so called fiber optic sensors (FOS), in which the sensor and the communication channel are made of optical fiber. These sensors can measure different phenomena such as temperature, strain, vibrations or AE. Also, they exhibit properties such as immunity to electric and magnetic fields, are very small in size and light in weight, can be easily multiplexed, especially with Fiber Bragg Gratings. In the case of CSP storage, their properties regarding corrosion resistance and high temperature performance make the very well suited. some applications have already been studied using commercial FOS in SMS, however they have been discarded, mainly because the packaging used for the sensor protection is corroded by the SMS (6). A solution based on FBGs was presented by Grandal et al. (7), where a corrosion resistant package was employed to protect the FBG sensor from the salt and the temperature between 290 ºC and 550ºC was monitored. In NEWSOL this solution will be further developed (4) for monitoring at different locations of the tank within two scopes: 1. structural health monitoring of the tank and 2. assessment of thermal performance of the system. So, the monitoring system for the thermocline tank will consist of a fiber optic sensor network that will monitor input and outlet temperatures of salt, molten salt temperature in tank depth, concrete wall temperature, lateral wall temperature and base concrete temperature. Therefore, there will be two main groups of sensors: embedded sensors in the different concrete layers and temperature sensors immersed in molten salt. The sensors embedded in concrete layers will measure temperature and strain. The output of this monitoring system will consist on temperatures and strain in the different materials, structural parts and locations where the sensors are placed or embedded. So, the VoI analysis while rely in the information provided by this monitoring system.

4. Implementation of VoI analysis

As it has been explained, the information provided by the monitoring system developed for the tank will assess the structural health and the thermal performance of the system. Therefore, the VoI analysis will be indicated for both cases and the necessary simplifications are discussed below.

Decision maker: The decision maker will be the power plant operator, usually a private company.

Regulative constraints**:** In the case of the concrete SMS thermocline tank developed regulatory constraints are neglected, since the actual tank to be monitored is a demonstrator to proof the concept of the technology and material performance to a TRL level (8) equivalent of 7.

System temporal and spatial boundaries: A predesign of the demonstrator tank has already been performed. However, since the tank will be built during 2019 and some of the material solutions have not been completely developed yet, changes may be made to obtain the final design. Also note that the tank will operate during a three-month period, from September 2019 to January 2019, so the conclusions will be only available after this time.

Events of interest and the corresponding representation:

- Structural health:
    - Crack is generated or growing: the apparition of cracks is an event that must be detected and evaluated, since it can be an indicator for spalling or excessive load.
    - Thermal stress of materials is detected: Thermal stress can undermine properties of the materials and risk the structural health of the system.
    - Mechanical load is a given value: when applied loads are higher than the ultimate loads the structure was designed for, the structural integrity of the system is endangered.

- Thermal performance:
    - Temperature of the SMS at inlet or outlet is a given value: the temperature at inlets and outlets of the tank is an important parameter to estimate the charge and discharge rate of the tank.
    - The temperature gradients on tank depth is at a given height: will indicate the volume and place of hot and cold salt.
    - The tank is charged with a given capacity.
    - The electrical power demand is at a given value

Event consequences:

- Structural health:
    - Bad performance of the thermocline tank;
    - Collapse of the tank;
    - No thermal energy stored;
    - No electrical power generation
- Thermal performance:
    - More/less efficient energy generation;
    - Energy cost decrease/increase

Indicators (to observe):

- Structural health:
    - Loads, strains and cracks in the concrete
    - Temperature in materials and positions
- Thermal performance:
    - Current stored thermal energy in the tank
    - Electricity demand (not by monitoring system)
    - Sun radiation (not by monitoring system)

Decision alternatives – monitoring and/or inspection options:

- Cracks can also be detected by visual inspection but only if the cracks are in the outer part of the concrete tank, or if in the inner part during an outage (planned or emergency) and the tank is empty.
- Temperatures can also be measured with thermocouples but only at some given locations.

Decision alternatives – other measures, repair, replacement, etc.:

- Structural health:
    - Do nothing
    - Repair
    - Replace
- Thermal performance:
    - Do nothing
    - Charge tank at a given rate
    - Discharge tank at a given rate

This case study offers the possibility to perform a previous analysis, a model and to check it with a demonstrator. Being the tank constructed a demonstrator that will not be connected to a real CSP plant, there are some constraints related to the thermal performance's VoI analysis. Only some tests will be run during the operation of the tank, and these tests may not be indicative of the actual performance of a real tank. Also, there are factors related to energy generation cost that may change during the timeline of the project that would affect the VoI analysis related to thermal performance.

5. Conclusion

Efficient thermal storage is a key technology for widespread adoption of CSP, which is a challenge due to the high temperatures, above 500ºC, and corrosive molten salts. A monitoring system for SHM and thermal performance assessment further helps the viability of the materials and architectures and it is necessary at the current state of the development of infrastructure architectures and materials. In NEWSOL project, a monitoring solution based on fiber optic sensors is being developed. In this paper a case study based on the preliminary VoI implementation has been presented applied to the prototype in NEWSOL. The case study presented allows us to perform a previous analysis, a model and to feedback with a demonstrator. The VoI flowchart for concrete SMS thermocline tanks monitoring system is presented in figure 4. Note that the thermal performance related VoI is shown in grey while the SHM related is shown in black.

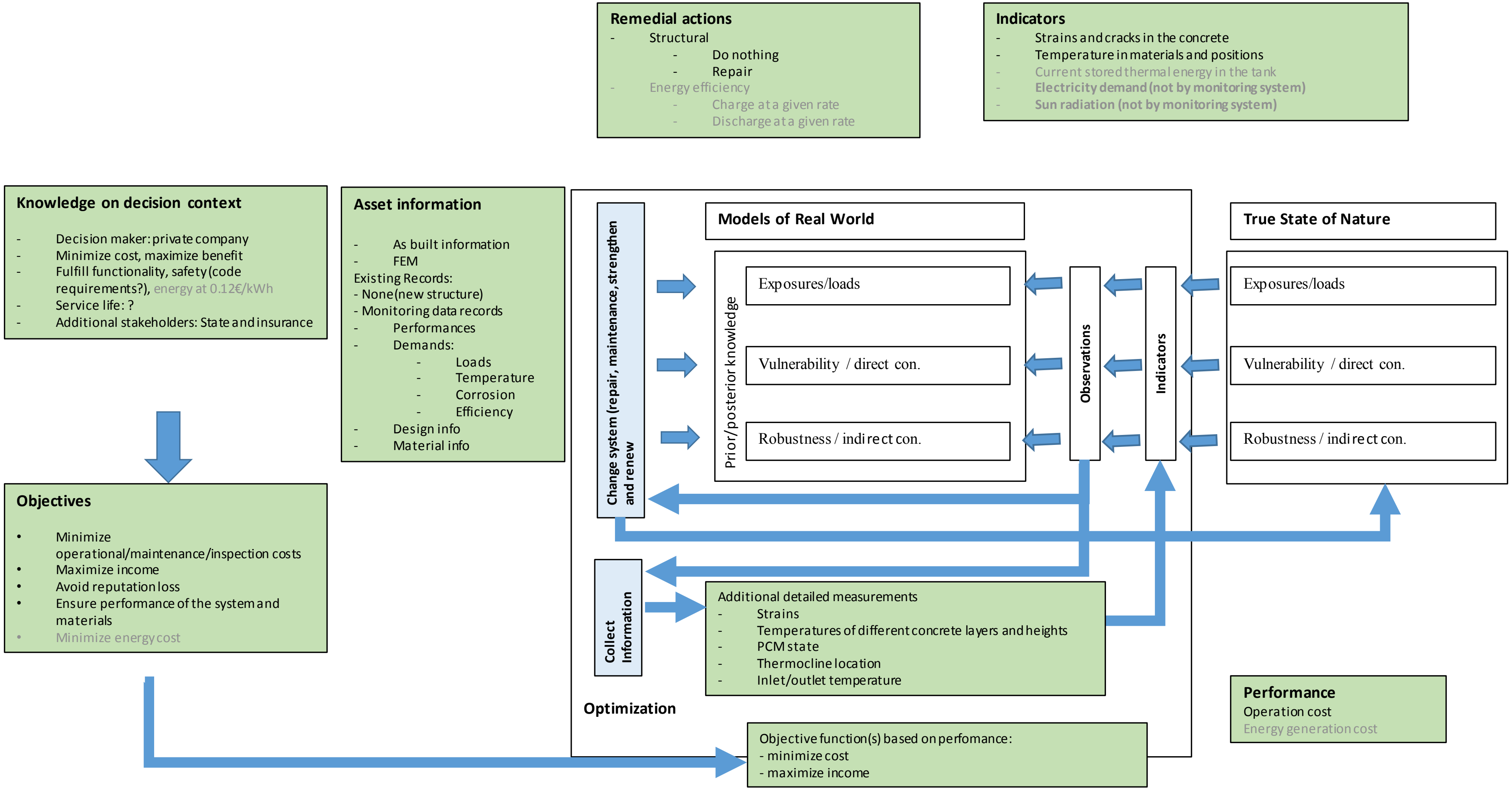


Figure 4: FlowChart for SMS concrete thermocline tanks.

Acknowledgements

This work has been carried out in the framework of NEWSOL project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 720985. The Cost action TU1402 is also acknowledged on the development of the case study.

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