The development and verification of a novel modular air cooled condenser for enhanced concentrated solar power generation

Final Report Summary - MACCSOL (The development and verification of a novel modular air cooled condenser for enhanced concentrated solar power generation)

Executive Summary:
Concentrated Solar Power (CSP) has the potential to make a substantial contribution to Europe’s electricity requirements. CSP plants require cooling to condense steam during the power generation cycle. Ideally water would be used to provide this cooling, however, in the locations where solar resources are most abundant, water supplies are scarce, and so condensers must be air cooled. Air Cooled Condensers (ACC) do exist, but plants which use ACC are known to have lower efficiency and higher power generation costs than plants whose condensers are water cooled. There is therefore a need for dry cooling technology which enables power plant performance levels which are comparable with plants which use water cooled condensers. The MACCSol project has developed such a technology – the Modular Air Cooled Condenser (MACC).
The MACCSol project commenced in 2010 and ran for 54 months. The consortium of project partners consists of three universities and six industrial partners. The universities are the University of Limerick in Ireland, the University of Erlangen in Germany, and the Universita Degli Studi di Perugia in Italy. The industrial partners involved are R&R Mechanical Ltd. in Ireland, Torresol Energy Investments Ltd. and Torresol Operations and Maintenance in Spain, AuBren Ltd. in Ireland, the Electricity Authority of Cyprus, and Vast Solar in Australia.

To develop the MACC, a variety of experimental, numerical and theoretical activities were pursued. To begin with, air side and steam side thermal and fluid characteristics of potential condenser tube designs were experimentally measured. From these measurements, correlations were developed which related the thermal and aerodynamic characteristics of various candidate MACC geometries to the MACC's fan power requirements. Using these correlations as an input, MACC design was optimised such that the power output of a CSP plant using the MACC was maximised, and the cost of electricity generation in such a plant was minimised. The experimental measurements which were performed also provided insights into the fundamental physics of flow and heat transfer within the condenser. Such insight was invaluable in the enhancement of the performance of the MACC.

The correlations which were developed from the experimental measurements were also used to develop speed control algorithms which continuously maintain optimum fan speed such that power plant output is continuously maximised. These correlations were also used to develop theoretical models to predict the effects of MACC design on power plant efficiency, power plant environmental impact and power generation costs. These models showed that a CSP plant using the MACC has up to 4% higher net power output than a plant which uses a conventional ACC. These models also showed that, when water consumption is considered, the MACC has a lower environmental impact than either the conventional ACC or a water cooled condenser. The electricity generation costs for a CSP plant were also seen to be favourable if a MACC is used rather than a conventional ACC.

To predict the effects of wind on MACC performance, a series of experiments and simulations were performed. These investigations showed the extent to which the wind can enhance the flow rate generated by a fan in favourable wind conditions, and the extent to which the wind can reduce the flow rate generated by a fan in unfavourable wind conditions. Simulations which were performed also showed that to optimise the orientation of the MACC in any given power plant, the site specific wind conditions for that plant must be considered, and hence the orientation must be optimised for each individual plant.

In order to validate the theoretical models which were used to benchmark the MACC against competing cooling technologies, an industrial scale MACC prototype was fabricated and erected in a 1.1MWe central tower CSP plant. Measurements which were performed on this prototype verified the accuracy of the theoretical models and thus verified the anticipated benefits of the MACC technology.

Project Context and Objectives:
In March 2007 the EU’s leaders signed up to a binding agreement to source 20% of Europe’s electricity needs from renewable sources by 2020. Concentrated Solar Power (CSP) has the potential to contribute significantly to this target. The European Industrial Initiative (EII) on Solar Energy – Concentrating Solar Power, outlines their ambition for CSP to contribute 3% of the EU’s electricity by 2020, with a potential for at least 10% by 2030. However, scarcity of water in the proposed CSP plant desert locations means that cooling the condensers of the CSP plants represents an obstacle to achieving these targets. According to the EU’s Strategic Energy Technology (SET) Plan, “Availability of water is an issue which has to be addressed for CSP development, as parabolic trough systems and central tower systems require cooling
Air cooling is recognised as an alternative to water cooling, and typically eliminates more than 90% of the CSP plant’s water requirement. However, according to the SET Plan, it can result in a 25% loss in a CSP plant on a very hot day. Therefore, in order to permit the targeted CSP deployment levels, enhanced air cooling methodologies must be developed, as water scarcity in the potential desert CSP locations, coupled with the inefficiency of conventional air cooling methodologies will prohibit these targeted power generation levels from being achieved. It is therefore a priority of the EU to develop these enhanced dry cooling technologies for CSP plants. It is in this context that the outputs of this project will have their biggest impact, in that they will remove one of the primary barriers to CSP reaching its full potential in contributing to the EU’s renewable energy target.

In recent years parabolic trough, central tower and linear Fresnel CSP plants have all been deployed commercially. Central tower plants have arguably shown the greatest promise. Figure 1 illustrates the configuration of a typical central tower CSP plant. In Figure 1, the plant is divided into the solar energy collection loop on the left and the steam cycle on the right.

Solar energy collection loop: In the configuration shown in Figure 1, a field of mirrors – also known as heliostats – are used to focus and concentrate solar radiation onto a solar receiver, resulting in high heat flux on the solar receiver. This heat is absorbed by a Heat Transfer Fluid (HTF) which is pumped through the receiver. The HTF enters the receiver at a temperature which is typically approximately 200°C, and due to the heat it absorbs, it leaves the receiver at a much higher temperature, up to 600°C. Some of this HTF may be pumped to a hot storage tank, for use at night time or during cloud cover, whilst the remainder is pumped to the steam generator. In the steam generator, the thermal energy within the HTF is transferred to the water flowing in the steam cycle to generate steam. The HTF is then pumped to the cold storage tank, after which it returns to the receiver and the cycle is repeated.

Steam cycle: As discussed in the previous paragraph, thermal energy from the HTF is used to create steam in the steam generator. This steam flows to the Steam Turbine (ST), where it expands and causes the ST shaft to rotate, thus turning the shaft of a generator, and generating electricity, which is transported to the electrical grid for distribution to the general public. The steam then flows to the condenser, where it changes phase from vapour to liquid. After leaving the condenser, the condensate is pumped back to the steam generator and the cycle is repeated.

As well as CSP plants, many other thermoelectric power plants, including coal and gas fuelled plants, incorporate a steam cycle. The cycle is fundamentally similar in each plant type, the only difference being the source of energy used to generate the steam. In CSP solar energy is used, whilst in a fossil fuelled plant, the energy comes from the combustion of the fuel.

In all steam cycles, the electrical power generated by the ST can be increased by increasing the pressure drop and hence the temperature drop across the ST. For a fixed temperature and pressure at the inlet to the ST, minimising the temperature and pressure at the outlet from the ST is therefore desirable. The equipment which is responsible for minimising this temperature and pressure is the condenser. Water cooled condensers (WCC) have traditionally been the preferred type of condenser for this purpose. The reason for this is that WCC can provide very low pressure and temperature at the outlet of the ST, whilst consuming very small amounts of power. However WCC consume huge volumes of water – thermoelectric power plants account for about 51% of fresh surface water use in Europe, and WCC are the primary consumers of this water. There is growing pressure to reduce the volume of water consumed in energy generation, and as a result, there is a great need for thermoelectric power plants to use condensers which do not consume water. In CSP plants, this need is even greater, as the locations where solar resources are most plentiful, typically do not have any cooling water available.
Air Cooled Condensers (ACC) may be used as a replacement for WCCs. As mentioned above, ACCs typically eliminate more than 90% of a CSP plant’s water requirement. A typical conventional ACC design is illustrated in Figure 2. In this arrangement, steam is transported from the ST to a bank of fined tubes which are mounted in an A frame configuration. Fans blow air through the finned tubes, thus cooling and condensing the steam within the tubes. The fans are usually 9-12m in diameter. As the deployment rate of ACC’s has grown, the shortcomings of the technology have become apparent to its end users. These shortcomings may be summarised as follows:

- The fans typically have very poor speed control, so optimisation of fan speed is not possible.
- The fans consume very large amounts of power, often up to 3% of the ST output.
- Ambient wind reduces the airflow through the fans, resulting in reduced ST power output.
- Air flow over the tubes is non-uniform, resulting in large uncooled regions.
- Due to the large size of the structures, assembly of the fans and tube bundles takes place on site, thus making this assembly task very expensive.

The high ambient temperatures which are typical of CSP plant locations exacerbate these shortcomings. This has provided the motivation for innovation in recent years in ACC technology. MACCSol has been at the forefront of this innovation.

In the MACCSol project, the technology which was developed was the Modular Air Cooled Condenser (MACC). In the MACC concept, the condenser is comprised of a number of MACC modules. Figure 3 (left) illustrates a single module while Figure 3 (right) shows a number of modules connected to a steam distribution duct. Steam is transported from the outlet of the ST to the modules. Each module measures approximately 2m wide by 8m long and consists of a bank of finned tubes which receive steam from the steam distribution duct and a bank of fans, each measuring approximately one meter in diameter. The fans force air over the bank of finned tubes, thus condensing the steam within the tubes. The condensate is collected in the condensate return line. In this design, the fan speed is fully controllable, resulting in improved power plant efficiency and the modules are assembled in a factory before shipping to the power plant site, thus making installation cheaper. A 30 MW ST would typically require approximately 150 MACC modules of the type illustrated in Figure 3.

In contrast to the conventional ACC, the MACC has the following features and benefits:

- Speed controllable fans which mean that fan speed is continuously optimised as ambient conditions and turbine load change.
- MACC modules, which are mounted in a manner which minimises the adverse effects of wind, and where possible, harnesses the wind to provide cooling of the finned tubes.
- The configuration of the fans relative to the finned tubes is such that a uniform air-flow is achieved and so uncooled regions of the finned tubes are eliminated.
- Because the MACC is modular, each module can be assembled in a factory. The only on-site assembly which will be required will be the attachment of the modules to the steam distribution ducts and the condensate return lines. This will result in significant savings in installation costs.

The objectives of the MACCSol project, as identified as the start of the project were as follows:

- Collection of power plant data on ACC fan power consumption, condensate temperature, turbine efficiency and ambient temperature and wind conditions. Thus, existing dry cooled CSP plant performance can be compared with the performance of the plant in which the MACC design is verified
- The development of a thermodynamic model which estimates the potential gains which can be made
through reduced fan power consumption, and the continuous operation of the condenser at optimum pressure, and which predicts the effects of various design options on plant net power output
- Validation of existing predictions of the performance of the conceptual MACC design through manufacture and test of physical prototypes
- Modification of MACC geometry based on prototype tests to optimise performance.
- Investigation of the capability for fan speed control to maintain condenser pressure at its optimum value irrespective of ambient temperature
- Investigation of the capability for fan speed control to eliminate the adverse effect of local wind speed on fan flow rate and hence condenser pressure, and thus maintain condenser pressure at its optimum value
- To investigate the feasibility of harnessing wind to assist fans in pumping air over the condenser tube bundles which are to be cooled
- To produce an industrial scale MACC solution, to experimentally characterise this solution, and provide a data set which proves to interested parties the benefits of the developed technology over conventional ACC designs
- The development of techno-economic models which quantify lifetime costs of various MACC design options, and allows these to be minimised.
- Provision of high-level knowledge on the design, operation and performance of ACCs to the European CSP industry to enable them to increase the power output from CSP power plants, and to minimise the cost of this power.
- To disseminate the project activities in a manner that results in a positive lasting project legacy.

Project Results:
This section presents a sample of the results which were achieved throughout the MACCSol project.
3.1 Air side characterisation of MACC prototypes and lab scale prototypes
In WP2 of the project, a large volume of measurements were performed to determine the air side heat transfer characteristics of numerous candidate heat exchanger finned tube geometries. A sample of the types of finned tubes which were investigated is shown in Figure 4. Measurements which were performed can be considered in two main categories:
- Measurements on 2m x 2m fan cooled MACC prototypes. These measurements were performed on three different prototype designs
- Wind tunnel measurements on 0.3m x 0.3m tube bundle samples
The aim of these measurements was to determine the accuracy of existing correlations for the prediction of the condensers' pressure loss and heat transfer characteristics, and where necessary, to generate new correlations. Once validated, these correlations could then be used in predicting the effects of condenser design on power plant performance. The availability of accurate correlations of this type is also vital to the design of a condenser for any power plant. Sample measurements from each of the three measurement categories and brief details of how they were performed are provide in the following paragraphs.
2m x 2m prototype measurements.
An example of a 2m x 2m MACC module prototype is illustrated in Figure 5. A sample set of measurements which were performed on this prototype are presented in Figure 6, in which pressure drop versus fan speed is plotted for an induced draft fan configuration, and a forced draft fan configuration with the fan to heat exchanger spacing (Z) at 700mm and 400mm. The measurements show that whilst existing correlations accurately predicted pressure drop for the induced draft configuration, it could not accurately predict pressure drop for the forced draft configurations. For this reason, it was necessary to generate new
correlations for the prediction of pressure drop for this design for the forced draft configuration. In the absence of such correlations, design of a condenser using this design would not be sufficiently accurate.

Wind tunnel measurements
In order to enable thermal and aerodynamic testing of a large number of finned tube geometries, a wind tunnel test facility was designed and fabricated. This facility is illustrated schematically in Figure 7, where the steam supply which was used to heat the tubes and thus enable thermal measurements is also presented. Figure 8 presents a plot of the heat transfer measurements for various finned tube designs in terms of a dimensionless heat transfer coefficient $StPr^{2/3}$, and compares these measurements with the correlations available in the literature. In the extreme cases the maximum deviation from the published correlations is of the magnitude 10-18%. Such deviations can be attributed to various circumstances such as fin to tube contact quality, data reduction methods and experimental error. For improved design accuracy a new set of correlations based on the measured data were created.

3.2 Steam side characterisation of MACC prototypes
In an air cooled condenser such as the MACC, heat is transported from the steam within the tubes, into the tube walls, through the external fins and into the cooling air stream. Section 3.1 presented the MACC’s characteristics in terms of the ability to transfer heat from the external fins to the cooling air stream. However, the way in which heat is transported from the steam in the tube to the tube wall also has a large impact on the performance of the condenser. Investigations into the characteristics of this part of the heat transfer path are discussed in this section.

The measurements were carried out on a full-scale prototype MACC, which was shown in Figure 5 and is presented again in Figure 9 and accompanied by a schematic of the same layout in Figure 10. The MACC was instrumented with a series of thermistors, to measure steam temperature, and pressure transducers, to measure condenser pressure. The influence of fan speed on condenser conditions was evaluated by measuring the MACC temperature and pressure for a series of incremental fan speed settings. Steam was supplied by a boiler and the quality of the steam was controlled by a water injection valve. Realistic condenser conditions were maintained throughout testing through the use of a vacuum pump and dephlegmator. This arrangement ensured air leaks, which occur at sub-atmospheric pressures, were continually removed from the system. The condensed steam (condensate) was collected in a condensate tank where it’s mass was measured, allowing for the mass flow rate through the MACC to be inferred. The condensate was then returned to the boiler feedwater tank via a condensate pump which created a closed system. An illustration of this arrangement is given in Figure 11.

The set-up shown in Figure 11 was necessary to not only guarantee that air leaks were continually displaced but to also ensure backflow was eliminated. Backflow is a phenomenon inherent in multi-row ACC designs, whereby excess steam that has not been condensed accumulates in the condensate manifold and flows back into some of the tubes. This can lead to the formation of air pockets and can reduce the effective heat transfer area of a condenser and is a very undesirable feature of multi-row ACCs. An example of an air pocket formed during testing on the MACC is given in Figure 12, where its presence is indicated by a cold region in the infra-red image. It was only when the researchers were confident that this issue had been eliminated that steam-side measurements were commenced.

Figure 13 shows some results obtained from the MACC measurements. The variation of pressure with MACC fan speed was recorded for a number of steam mass flow rates which were deemed to be representative of actual flow rates expected in an operational scenario. The trend of MACC pressure decreasing as fan rotational speed increases is illustrative of the ability of the MACC fans to control
condenser conditions and hence, how the fans will be capable of controlling the pressure at the outlet of a
turbine in a power plant. Though this trend was expected, and indeed predicted through modelling efforts,
it was nevertheless a reassuring confirmation.

In a more comprehensive demonstration of the ability of the MACC to control steam turbine conditions,
some power-plant modelling was carried out. A characteristic curve for a 50MW steam turbine was
obtained from the Electric Authority of Cyprus. The output from this turbine was evaluated based on the
measured pressure values given in Figure 13. An example of the outcome from this modelling can be seen
in Figure 14. Here the importance of controlling fan speed can be clearly seen as the net plant output
peaks at a specific fan speed and deviation from this optimum speed will result in significant reductions in
plant power output.

Similar plots to those shown in Figure 14, which were generated for varying ambient temperature, have
shown that the optimum fan speed varies significantly with ambient temperature. Therefore, in order to
continuously optimise plant output, fan speed must be controlled as ambient temperature changes.
It is expected that further measurements will be carried out on different MACC heat exchanger geometries
in the near future. These geometries will be selected based on optimisation carried out in WP4. The
measurement procedure for new geometries will not deviate from the methods previously established and
the equipment such as vacuum pump, dephlegmator, etc. will still be necessary to facilitate testing.

3.3 Steam side characterisation of MACC lab scale prototypes
In the 2m x 2m MACC prototypes presented in section 3.2 temperature and pressure measurements were
obtained, but only on a global scale. Local measurements are often more desirable as they provide a more
detailed insight into the various phenomena which ultimately, improves understanding. Despite numerous
attempts, it proved quite difficult to obtain local measurements on the 2m x 2m prototypes of the MACC,
mainly due to difficulty in mounting sensors in appropriate locations. Air leakage into the MACC was
another issue, which is an unavoidable and undesirable feature of all condensers which are operating
under vacuum. The main problem with the air leakage was an inability to control the amount of air leaking
into the condenser at any given time, which meant a controlled operating environment could not be
maintained. Therefore, due to these issues, a lab-scale condensation facility was designed, fabricated and
commissioned to study the condensate-side characteristics on a local-scale and in a controlled manner.
The heat exchanger in the lab-scale facility consists of a single circular-finned tube, common to many
operational ACCs, cooled by a bank of axial fans as seen in Figure 15.

One of the main advantages of working on a smaller scale was the freedom to design and tailor the system
to accommodate specific requirements. The lab-scale condenser was designed to maintain vacuum
conditions without the need for a vacuum pump. Therefore, pure-vapour condensation could be achieved,
which was not a possibility on the 2m x 2m MACC prototypes, where air was continually leaking in when
under vacuum. This provided an opportunity to quantify the condensation characteristics in the absence of
air. Such results can be used as a benchmark for comparison with successive tests involving controlled
amounts of air present in the system.

To obtain local measurements, pairs of collinear thermistors were mounted at specific sites along the axial
length of the tube. Each thermistor pair consisted of a thermistor embedded within the tube wall and a
corresponding thermistor mounted in the center of the tube. A cross-sectional view of this arrangement is
shown in Figure 16. This arrangement allowed the temperature difference between the steam core and
wall to be measured.

A series of experiments were carried out to characterise the facility and ensure parameters such as steam
quality, Reynolds number and air-side heat transfer coefficient (thermal boundary conditions) were of similar magnitude to those observed in the full-scale MACC prototype. Once these parameters had been established, a series of condensation experiments were carried out to investigate the various phenomena. One such experiment investigated the variation in condensate-side thermal resistance along the length of the tube. This was carried out for a range of flow rates, with the results presented in Figure 17. The thermal resistance was evaluated from equation 1:

$$dQ_i = \frac{T_(s,i) - T_(w,i)}{\frac{dQ_i}{dT}}$$

Where $T_(s,i)$ and $T_(w,i)$ are the steam core temperature and inside wall temperature, respectively, at the ith site location. $dQ_i$ is the local heat transfer rate.

It is immediately noticeable from Figure 17 that the thermal resistance increases with distance from the tube inlet. This resistance to heat transfer is solely attributed to the layer of condensate that forms as the vapour condenses. As the wall conductivity is very large and the thermistor site is located quite near to the inside of the wall, any resistance due to the wall is neglected. Coupled to this is the fact that little or no air is present in the heat exchanger and so the condensate film is the sole resistive path. An interesting feature of the results in Figure 17 is the reduction in thermal resistance as flow rate is reduced. It is hypothesised that this is occurring largely due to two reasons. Firstly, as the flow rate is decreased, the saturation temperature of the vapour decreases and the density reduces. This results in an increase in vapour velocity which tends to distribute the condensate film more evenly around the tube circumference and also tend to induce flow towards the tube exit. Also, as the flow rate is reduced, there is less mass in the system and inherently less condensate will form to inhibit heat transfer.

Currently, more experiments are being carried out to determine the effect of varying certain parameters on the condensate characteristics. Ultimately, the objective is to incorporate the relationships between certain parameters and the condensate characteristics into an improved model for predicting the performance of ACCs in a power-plant.

### 3.4 MACC optimisation

Using heat exchanger performance correlations which were generated from measurements such as those presented in sections 3.1, 3.2 and 3.3 coupled with fan performance characteristics, steam turbine performance characteristics and capital cost data, a theoretical model was built which was used as the basis for optimisation of the geometry of the MACC. Using the optimisation routine, MACC designs were identified which minimised CSP power generation costs. The results of this optimisation process are summarised in Figure 18 and Figure 19. Figure 18 shows how power plant annual power generation varies with condenser size for a range of condenser geometries, A to Q. This data was then used as an input to a techno-economic model, the results of which are presented in Figure 19, which shows the cost of electricity generation for each of the candidate geometries, when the optimum size version of that geometry is used. The results of this optimisation process were used as the basis for the selection of a geometry for the industrial scale prototype which was manufactured and tested in WP8 of the project.

### 3.5 Wind effects, on individual fans and at system level

Correct fan speed control in the MACC or any other air cooled condenser can significantly enhance the annual power output from a power plant. Operating the fans at too low a speed will cause excessive condenser temperature and pressure and hence impair steam turbine output. Whilst increasing fan speed will reduce condenser temperature, hence increasing steam turbine power output, if the speed of the fans is increased excessively, then any further increases in steam turbine output will be more than offset by
increased fan power consumption. Therefore, the speed of the fans must be continuously optimised to maximise plant output. Using the performance characteristics of the steam turbine and the fans allows this optimum speed to be determined over a range of ambient temperatures. However, if the performance of the fans is affected by ambient wind, then this optimum speed will be affected:

If the wind assists the flow through the fan, the power consumed by the fan to achieve a target flow rate will be reduced, and the optimum fan speed will decrease.

Conversely, if the wind opposes flow through the fan, then the power consumed by the fan to achieve a target flow rate will be increased, and the optimum fan speed will be increased.

Therefore, determining the optimum fan speed in the presence of wind requires that the effects of wind on fan performance be well understood. These effects of wind on fan performance have not previously been investigated in any depth. Such an investigation is the focus of the work which was undertaken by the Institute of Process Machinery and Systems Engineering at the University of Erlangen (UE). The wind influence at both the fan inlet and outlet are taken into consideration for condenser operation, in forced and induced draft configuration.

A fan test rig was designed and set up in the wind tunnel at UE, which enabled the measurement of fan pressure and flow rate at different wind velocities at different angles. Figure 20 shows a photo of the test rig. Pressure measurements are taken in a duct right behind the test fan, using an array Kiel probes. Kiel probes are used to measure total pressure in a fluid stream where the direction of flow is unknown or varies with operating conditions. The flow is then guided into a settling chamber, where the flow rate can be gauged.

The main purpose of this investigation was to investigate the influence of wind on the characteristic fan curve. This curve is defined by the different operating points of the test fan, consisting of fan pressure $dp_{static}$ and flow rate $V'$. Figure 21 shows the influence of 10 m/s wind attacking the fan inlet at different angles, on the characteristic fan curve. The numbers are given non-dimensionally with the characteristic numbers for the fan pressure and flow rate.

$\Psi$ and $\Phi$ are non-dimensional fan pressure rise and flow rate as defined in Equation 2 and Equation 3 respectively. Plotting fan performance curves using these non-dimensional parameters rather than dimensioned pressure rise and flow rate allows the characteristics of fans of different sizes and speeds to be compared. In Equation 2 and Equation 3, $n$ is rotational speed, $\rho$ is density, $D_o$ is the fan blade tip diameter and $D_i$ the hub diameter.

The black dashed line in Figure 21 shows the reference results without ambient wind. In comparison, the solid lines represent the results of experiments in 10 m/s wind environment at the fan inlet. Obviously, straight wind onflow (blue line) at the fan inlet supports fan performance, since the total pressure at the inlet is increased. For greater angles (67.5° and 90.0°), the cross wind yields smaller fan pressures $\Psi$ at given flow rates. The wind influence is more negative with increasing flow rate $\Phi$.

Experiments with the fan mounted in induced draft mode (i.e. wind effective at the fan outlet) have shown opposite effects. Even though direct (counter) wind at the fan outlet diminished fan performance, cross wind at larger angles tended to produce higher $\Psi$ at given $\Phi$. This is favourable, since it is easy to implement the fan in a way that wind always approaches at 90° (with the fan axis perpendicular to the ground), but the possibility of realizing direct on-flow at the fan inlet depends strongly on the wind direction. In addition to the integral pressure investigations, velocity measurements using optical technologies (Laser Doppler Anemometry, LDA) have been performed inside the duct behind the fan. For this, a glass section is mounted into the duct section and the cross section is probed with the LDA. Figure 22 illustrates the application and exemplary result of this measurement technique. Regions where the cross wind...
opposes the blade motion, show greater flow velocities. The axis-symmetry of the flow field was disturbed by the cross wind, although this effect decreased with larger flow rates. This may affect the performance of the connected condenser negatively.

Experiments with the fan mounted in induced draft mode at the condenser, i.e. wind influence at the fan outlet, have shown that the flow field pattern inside the duct is very uniform and not influenced by cross wind.

3.6 Wind effects at system level

As discussed above, one of the main obstacles to overcome when using air cooled condensers is the fact that they are susceptible to the local wind conditions present at the site of the power plant where they are installed. This issue is well documented in literature, with studies finding that both the wind's speed and direction play different roles in affecting the performance of the condenser. For example, high wind speeds and cross winds can significantly reduce the air flow rate in upwind condenser cells, while winds blowing along the condenser longitudinal axis leads to increased hot plume recirculation. It is therefore important to characterise these effects in the MACC design with the aim of producing an optimal configuration in order to mitigate against them.

To study the effects the wind has on the MACC performance at system level, a parametric analysis was carried out using numerical modelling. The three dimensional numerical model was built using simplified representations of the axial fans and heat exchanger finned tubes in order to keep the model size sensible. The wind was modelled by applying the atmospheric boundary layer profile at the edge of the numerical domain. Shown below in Figure 23 is an image of a typical result from the numerical modelling, showing a contour plot of the air temperature along with the velocity vector field. Wind is blowing from left to right. The air enters the MACC from underneath where it is entrained by the fans before passing over the heat exchanger and is then exhausted from the top. It can be clearly seen that the air temperature rises as it passes over the heat exchanger surfaces and this hot air is then carried away by the wind.

The parameters whose effects were studied include the wind speed and direction, as well as geometrical parameters, such as the condensers height from the ground, the A-frame angle, the spacing between condenser modules, and the direction it is built relative to the wind direction. Each of these parameters was varied in combination and the resulting change in MACC and power performance was determined. The results of the analysis showed that the optimal configuration design varies as a function of the local wind conditions at the site of the power plant. For example, it was found that for a location with high wind speeds and constant wind direction, the condenser should be built closer to the ground with a larger A-frame angle, whereas for a location with low wind speeds and variable wind direction the condenser should be built higher from the ground with a reduced A-frame angle. The results highlighted the benefits of tailoring the design of the MACC to individual power plants.

3.7 Results of thermodynamic modelling

Torresol Energy, the partner responsible for thermodynamic modelling, has produced the simulated environment of different solar thermal power plants and a combined cycle plant with different steam cycle cooling technologies. This simulation has been conducted using a combination of commercial software and in-house programming code.

The two solar thermal technologies selected have been, on the one hand, the tower power plants with heliostats and thermal storage and, on the other hand, parabolic troughs collectors. The part of the steam cycle has been modelled using standard software for commercial electrical generator plants design. The
solar concentration part, more specifically, the solar field and the solar receivers have been modelled using in-house programming code, in such a manner that these processes have become input blocks to the general thermodynamic cycle.

To model the MACC, Torresol used their thermodynamic models to generate steam turbine characteristics which quantify how steam turbine gross output varies with condenser temperature. The University of Limerick then integrated these characteristics into their MACC thermodynamic model to determine power plant net power output if the MACC is used as the steam cycle cooling technology for a range of temperatures.

Lastly, different geographical sites have been defined, analysing the solar resource in the area and defining high, medium and low radiative sites. The solar resource has been modelled as an incoming thermodynamic variable and put to the service of the simulations to be conducted.

Various alternatives have been simulated in the different scenarios:
Type of power plant: solar thermal power plant with tower (specifically, Gemasolar, tower power plant owned by Torresol), solar thermal power plant with Parabolic Trough Collector (PTC), combined cycle power plant.
Cooling system: cooling tower, air-cooled condenser and MACC.
Sites: America, South America, Europe (2), North Africa.

Once all the alternatives are available, work was carried out on the parameters affecting the working order of the MACC in each of the scenarios, in such a manner that results have been optimized and compared.

It is important to note that each of the cooling options shows strengths and weaknesses under different conditions and operational points, so that in order to conduct a full analysis, it is essential to take into account the boundary conditions for each of the options in specific sites. Thus, power calculations have been made for each option, at different loads and environmental conditions, simulating real operating conditions throughout the year; subsequently to this, the net annual production was analysed for a full analysis of each of the options.

Figure 25 illustrate a sample of comparative data from the analyses conducted, comparing net output from a central tower CSP plant using four different condenser designs: a conventional ACC, a cooling tower, and two different sized MACC condensers – one with 200 modules and the other with 300 modules. It is clear from Figure 25 that the MACC compares very favourably with both the ACC and the cooling tower.

3.8 Results of environmental modelling

A comparative Life Cycle Assessment (LCA) was carried out to compare the first MACC prototype with conventional Air Cooled and Water Cooled Condensers (ACC, WCC). A reference central tower 20 MW CSP plant operating in three different locations (see Table 1), was chosen for the comparison.

The aim of the analysis was to evaluate the environmental impact of the three condensers, depending on the location characteristics and, in particular, varying the DNI and water resources availability conditions. As a matter of fact, the freshwater consumption is one of the major environmental issues of the locations suitable for CSP plants operation. The parameter used to take into account of this issue and to weight the impact of condensers is the Scarcity Ratio (SR), defined as the share of gross consumption in the available renewable water resource:

$$\text{SR} = \frac{\text{water consumption}}{\text{available resource}}$$

Results presented in Figure 26 show that in a region with high DNI (2000 kWh/m2 x year) and medium stress condition (0.2 ≤ SR < 0.4) such as Spain, the WCC is the cooling solution with the highest impact; the impact of MACC is comparable with the impact of ACC. Moreover, varying the water stress conditions, the impact of WCC shows significantly higher than both ACC and MACC.
the impact of WCC varies significantly, while the air cooled condensers (ACC and MACC) are characterized by a smaller impact variation. It is also worth noting that the MACC has an impact lower than the conventional ACC in all the three locations considered. The LCA analysis carried out, definitely shows that the MACC condenser represent an attractive alternative to the conventional cooling solutions.

3.9 Results of lifetime cost modelling

A parametric optimization analysis of various MACC system configurations and sizes was performed in order to identify the optimum MACC system configuration and size to be used as the cooling system in a 50MWe parabolic trough CSP plant. The optimization analysis was conducted individually on a total of 17 different MACC system configurations with different geometries, namely MACC system configuration A through to configuration Q. Input data were provided for MACC sizes ranging from 200 to 1600 modules in steps of 200 modules (i.e. for a total of 8 different sizes/ scenarios) for each MACC system configuration. The optimum MACC system configuration and size was to be identified by investigating for each configuration the optimum trade-off between increased plant operating costs associated with high MACC system fan speeds and increased plant capital costs, associated with MACC system larger heat transfer area, which is proportional to the number of MACC modules. In order to perform the simulations required, the EAC’s IPP v2.1 software tool was employed.

In order to identify the gross output power and the associated condenser heat rejection requirements of a typical 50MWe steam power plant (in a 2000kWh/m2 DNI location), the Thermoflow 21 software package was used and specifically the Steam Pro 21 and the Steam Master 21 software. In order to provide a comprehensive analysis of the variability of turbine gross output power and condenser heat rejection requirements as a function of turbine outlet steam temperature, and therefore as a function of ambient temperature levels, the turbine outlet steam temperature was varied in 16 steps, across a temperature range of 33°C, i.e. between 32°C and 65°C. The results of the analysis are shown in Figure 27.

The results of the analysis concerning the electricity unit cost of the CSP plant as a function of MACC system (configurations A to Q) size are shown in Figure 28. Clearly, as the size of the MACC system increases, the cost of electricity of the plant decreases to reflect the increases in net electricity generation by the CSP plant. However, after a specific MACC size is reached, which is considered to be the optimum size, the electricity unit cost begins to rise reflecting the fact that the gains achieved in net electricity generation are now offset by the increases in MACC system capital cost. The optimum MACC system size is the size where the electricity unit cost of the CSP plant is minimum. By comparing across the various MACC system sizes, it is shown that configurations B and D exhibit the lowest electricity unit costs at sizes of 964 and 976 modules respectively. These are the optimum MACC configurations and module sizes. Finally, in the bubble chart depicted in Figure 29, a comparison of each configuration in terms of its (a) identified minimum CSP plant electricity unit cost (y-axis), (b) corresponding optimum MACC system size (x-axis) and (c) capital cost per module (indicated by the bubble size), is shown. It is clear that the configurations which can achieve low CSP plant electricity unit costs do so at larger optimum MACC system sizes ranging from 900-1000, as for example configurations D and B. In addition, these configurations have typically lower capital costs per module, illustrated by their smaller bubble size, compared to the configurations that have smaller optimum MACC system sizes.

3.10 Demonstrator installation and test results

Based on the outcomes of measurements performed on various MACC prototypes as described in sections 3.1 3.2 and 3.3 and subsequent optimisation activities as presented in section 3.4 and 3.6 a...
geometry was selected for the fabrication and installation of an industrial scale MACC prototype. This was installed in a CSP plant which was constructed by Vast Solar in Jemalong, New South Wales, Australia. This CSP plant has the thermal capacity of approximately 6MW. The prototype was designed by UL, R&R and AuBren, and was manufactured by R&R and AuBren in Ireland. After manufacture, the prototype was transported to Australia and was erected on the Vast Solar CSP plant. Images of the installation are presented in Figure 30.

Measurements which were performed on this prototype confirm verify the measurements which were previously performed on the 2mx 2m MACC prototypes, and thus confirm the predicted performance benefits of the MACC.

Potential Impact:

In this section, the technical results from MACCSol are first summarised. The intermediary steps which are required to bring about the desired impacts from these results are then described. Finally, the impact of these activities will be described.

4.1 Summary of technical results

Result 1: A modular, air cooled condenser technology for industrial scale concentrated solar power plants. Compared to conventional dry cooling methodologies, the MACC technology enables an increase in power plant efficiency of up to 4% for a given condenser footprint.

Lead users of this result:
- Designers of air cooled condensers for steam turbine turbine power generation plants, particularly concentrated solar power plants. The project partner representing this sector of lead user is R&D Mechanical Ltd.
- Designers, developers and operators of concentrated solar power plants. The partners representing this sector of lead user are Torresol Energy and Vast Solar.

Result 2: Pilot installation of the condenser in the Vast Solar plant. This installation consists of 8 MACC modules which condense the steam from a 1.2MWe steam turbine.

Lead users of pilot installation:
- Designers of air cooled condensers for steam turbine turbine power generation plants, particularly concentrated solar power plants. The project partner representing this sector of lead user is R&R Mechanical Ltd.
- Designers, developers and operators of concentrated solar power plants. The partners representing this sector of lead user are Torresol Energy and Vast Solar.

Result 3: Benchmarking of the MACCSol condenser with conventional water and air cooled condensers in terms of plant efficiency, environmental impact and electricity generation costs, over a range of climatic conditions.

Lead users of the benchmarking data:
- Designers of air cooled condensers for steam turbine power generation plants, particularly concentrated solar power plants. The project partner representing this sector of lead user is R&R Mechanical Ltd.
- Designers, developers and operators of concentrated solar power plants. The project partners representing this sector of lead user are Torresol Energy and Vast Solar.
- Manufacturers of steam turbines for the concentrated solar power sector (e.g. Siemens)
Result 4: Scientific Publications on the following topics:
- The means of minimising condenser parasitic losses using fan speed control.
- How to use wind conditions to assist cooling.
- Thermodynamic modelling and simulation of the implications of condenser design variations on plant level performance.
- Tecno economic modelling of the effects of condenser design on the lifetime cost of the condenser
- Modelling and prediction of the lifetime environmental impact associated with various condenser design options

Lead users of publications: Industrial and academic researchers in the fields of thermodynamics, thermal management, aerodynamics and power plant design.

Result 5: Design Specification of multi MW air cooled condensers for concentrated solar power plants.

Lead users of design specification:
- Designers and manufacturers of air cooled condensers for steam turbine power generation plants, particularly concentrated solar power plants. The project partner representing this sector of lead user is R&R Mechanical Ltd.
- Designers, developers and operators of concentrated solar power plants. The partners representing this sector of lead user are Torresol Energy and Vast Solar.

4.2 From expected research result to policy impact
Technology Commercialisation Phase

Although the outputs from the MACCSol project are of great scientific and technical quality and significance, as anticipated at the outset of the project, the technology is not yet commercially mature. Therefore, as outlined in the original project proposal, a further technology commercialisation project is required with duration of 18 to 24 months, to demonstrate the MACCSol technology at commercial scale, and to bring the technology to TRL 9. The main technical activities of the technology commercialisation phase will be to “debug” the MACCSol prototype, build a commercial grade demonstrator and perform long term measurements of the impact of this prototype on plant level performance. Reliability testing of the technology will also be performed. Documentation will also be required to define manufacturing standards, installation procedures and operating procedures. Safety standards will also be defined in the context of installation and operation. The outputs of this phase will be updated data benchmarking the MACCSol technology against conventional cooling technologies; reliability specification; safety, installation and manufacturing standards and documentation describing the operating guidelines.

4.3 Impact
CSP plants operable without cooling water

Steam power cycles – as are used in CSP plants rely on a condenser to return the steam at turbine outlet back to its liquid state. The condenser plays an important role in providing optimum conditions of pressure and temperature at turbine outlet and strongly influences turbine efficiency and hence power plant efficiency. Condensers are classified into two basic categories: wet cooled and dry cooled. Wet cooling the condensers of thermal power plants consumes large volumes of water. Evaporative water cooling schemes consume up to 2400 l/MWh whilst once through systems can consume up to 100,000 l/MWh. In fossil fuelled steam power plants this historically was not a problem due to the flexibility to locate the power
plant close to water supplies such as lakes and rivers, and the lack of regulation against the negative environmental impacts of returning heated water to waterways and the creation of plumes from cooling towers. However, environmental regulations coupled with water scarcity in locations suited to CSP generation make water cooling less attractive. In desert areas, where solar resources are in greatest supply, the cost of transporting water to the CSP plant site make this an excessively expensive option. As a result of the increase in efficiency and cost competitiveness of dry cooling which has been achieved through the MACCSol FP7 project, the subsequent MACCSol commercialisation phase, and the commercial launch of the MACCSol product, it will become cost effective for plant operators to construct plants which are dry cooled, thus eliminating the consumption of water in condenser cooling. This will facilitate the large scale deployment of CSP in the Mediterranean region’s richest solar locations, the deserts of North Africa and the Middle East.

High efficiency and cost competitiveness
Compared to liquid cooled condensers, current commercial dry cooled condensers result in lower power plant efficiencies and hence higher operating costs. Using conventional dry cooling, the annual output of a dry cooled plant is typically 5% lower than that of a wet cooled plant. Electricity generating costs are typically 2 – 10% higher for a plant using conventional dry cooling compared to a wet cooled plant with ample water supplies. The installation costs of a dry cooled plant are typically up to four times greater than those of a wet cooled plant. For these reasons, condensers in CSP plants, have historically been wet cooled. To facilitate the elimination of water consumption in CSP plants, dry cooling technology is required which can allow higher CSP plant efficiencies and lower electricity generation costs. This project is progressing towards achieving this impact through the following activities:
- Testing and modelling activities have optimised heat exchanger design so that the necessary heat removal can be achieved with the minimum of power consumption and with the smallest consumption of volume and material.
- Reduced power consumption will result in reduced operating cost and reduced environmental impact
- Reduced material consumption will result in reduced installation cost, manufacturing cost and environmental impact
- Development of a modular air cooled condenser which incorporates thermo-fluidically optimised heat exchanger design, steam and ambient temperature sensing capabilities, infinitely variable fan speed control and the development of design procedures which minimise adverse wind effects.
Compared to conventional air cooled condensers, the MACCSol technology has been shown to provide the following benefits:
- Efficiency increase of approximately 4%
- Annual increase in electricity output of approximately 4%
- Reduction of installation costs of 25 to 30%
- Reduction in electricity generation costs of 2 to 2.5%
- Reduced lifetime costs
- Reduced lifetime environmental impact

Massive deployment in desert areas
Every year, 630,000 terawatt hours of solar energy falls on the deserts of the Middle East and North Africa. In contrast, Europe consumes just 4,000 terawatt hours of energy a year, a mere 0.6 percent of the solar energy falling in this region. Figure 31 shows a map of the region which illustrates the magnitude of solar energy potential.
power which is available. Two squares are outlined in northern Africa labelled World and EU. These represent the respective areas onto which sufficient solar energy falls to provide the World and the EU with 100% of their electrical power if conversion technologies were 100% efficient. This emphasises the potential of utilising the solar resources of these regions to provide a significant portion of the EU’s electricity requirement. To exploit this potential, a number of initiatives have been set up, including the Desertec Industrial Initiative and the Union for the Mediterranean’s Mediterranean Solar Plan (MSP). However, as a direct result of the targeted areas of both initiatives being deserts, an obvious barrier to their success is the lack of water for CSP plant condenser cooling. Transporting water to these locations is clearly going to be prohibitively expensive, and so full realisation of the Desertec and Mediterranean Solar Plan initiatives relies on the availability of efficient and cost effective dry condenser cooling technologies. The ability of the technology which was developed in the MACCSol project to adapt to variations in ambient conditions will be particularly relevant to desert conditions where temperatures of over 40°C are common during the day, whilst night time temperatures drop below 10°C. It is therefore clear that the MACCSol project will have a major impact in removing barriers to the full exploitation of the solar resources of the deserts of the Middle East and North Africa.

Enabling CSP to emerge as major renewable electricity source

The EU has a commitment to producing 20% of its electricity from renewable sources by 2020. Based upon estimates from the SET Plan and from the Desertec Initiative, CSP could contribute almost a quarter of this target. However, as discussed in the SET Plan and as discussed above, the scarcity of water for condenser cooling, coupled with the inefficiency of existing dry cooling technologies impose a significant barrier to CSP deployment levels. It is in this context that the outputs of this project will have their biggest impact, in that they will remove one of the primary barriers to CSP reaching its full potential in contributing to the EU’s renewable energy target.

Other impacts, which will ensue from this project may be summarised as follows:
- Increased rates of deployment of CSP will lead to:
  - Reduced carbon emissions. Each GW hr generated by CSP reduces carbon dioxide emissions by approximately 273 tonnes using current cooling methodologies.
  - Economic growth. Widespread deployment of CSP has the potential to provide substantial economic growth. For example, a study commissioned by the U.S. National Renewable Energy Lab (NREL) showed that a 100MW CSP plant creates more than $600 million in impact to gross Californian state output, ten times that of a combined cycle fossil plant.
  - Creation of new jobs. According to a report issued by the Wuppertal Institute for Climate Environment and Energy, 580,000 jobs could be created in CSP by the middle of the century.
- Increased EU competitiveness in CSP component technologies. The United States Science Foundation in partnership with the US based Electrical Power Research Institute has recently initiated a research programme to advance the efficiency of dry cooled condensers for the power industry. Through this programme, a number of projects have been funded in both academia and industry in the US. The technologies being developed include methods to enhance the air side and steam side thermal performance of ACCs. The results of the MACCSol project will enable a monumental advancement in technology and as a result, will enable EU technology for dry cooling condensers to outperform the technology developed in the US.
- The condensing technology which was developed in this project is deployable in fossil fuelled steam
power plants. In this application, the benefits of the MACC over conventional ACC will also be significant, and will result in plant output increases of up to 4%. Significant reductions in carbon emissions from fossil fuelled plants will therefore ensue.

- The availability of fresh water is a growing concern across Europe. Thermoelectric power plants account for about 51% of fresh surface water use in Europe, and water cooled condensers are the primary consumers of this water. Successful development of the MACC technology will provide an efficient alternative to water cooled condensers, and thus facilitate a monumental reduction in Europe’s water consumption.

- In November 2014, an outbreak of Legionnaire’s disease began near Lisbon in Portugal. As of December 5th 2014, 336 people in were hospitalised, whilst 11 died as a result of the outbreak. Although the source of the outbreak was not confirmed in this case, Legionnaire’s disease is often caused by the emission into the atmosphere of water droplets from cooling towers such as those used in water cooled condensers in thermal power plants. The MACC will not release water droplets into the atmosphere, and so the replacement of condenser cooling towers by the MACC will prevent a large proportion of instances of Legionnaire’s disease.

Figure 32 illustrates the scientific and technological outputs from the MACCSol project, the activities which will be undertaken in the subsequent commercialisation phase, the outputs from the commercialisation phase, and the impacts which will result from these activities. The timeline on this figure illustrates that the full impact of the MACCSol will come about upon product launch, approximately six and a half to seven years after MACCSol launch. This is likely to be early to mid 2017. The availability of this product to the CSP industry in Europe at this time will give rise to the impacts listed above.

4.4 Dissemination

The plan for dissemination of project results was formulated with care given to the potential of dissemination activities to hamper exploitation due to potential disclosure of proprietary information. With this in mind, no project results were publicly disseminated without the prior notification and consent of all project partners. The results of the project were disseminated to various target groups as outlined below.

Dissemination within the consortium

Within the consortium information was be made available through the following media:
- Project website
- Workshops
- Teleconferencing
- Steering committee meetings
- Progress meetings

Successful dissemination within the group was critical as it enabled coherency in the activities of the partners. For example, presentation of the progress in optimisation of the MACC modules to MACC manufacturers and installers ensured that the designs which were developed were feasible to construct, whilst dissemination of details of the designs which were developed to the end users ensured that they meet with end user requirements. This level of communication within the consortium was critical to developing a product which is relevant to all parties, and thus increased the likelihood of the technology making the desired impact in terms of market penetration.

Dissemination to the scientific community

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Information was disseminated to the scientific community through scientific journals and conferences. These publications were targeted at scientific conferences such as the ASME International Mechanical Engineering Congress and Exposition, the Gas and Oil Exposition, SolarPACES and MENASOL, and journals such as the Journal of Applied Thermal Engineering, Energy and Life Cycle Analysis. Dissemination to this community gives the MACC technology credibility at a scientific and technical level, thus enhancing its likelihood of having commercial impact.

Dissemination to the power generation industry and energy policy makers

In order to publicise the MACC to the power generation industry two events were held on the premises of R&R Mechanical:

- The first of these coincided with the launch of the MACCSol project in September 2010, and was attended by the Irish Prime Minister, Mr Brian Cowen. The presence of the Prime Minister at the event attracted considerable attention from the Irish media, with articles appearing in national newspapers. The MACCSol project was also featured on Irish radio. This resulted in the creation of an awareness of the project amongst the general public in Ireland.

- Another event was hosted by R&R Mechanical in November 2013 to coincide with the completion of the fabrication of the MACCSol industrial scale prototype. Invitations to this events were sent to CSP industry leaders and policy makers. At this event, the attendees were able to see the prototype at first hand and were provided with explanations of the key features and benefits of the technology. The focus at this event was to get a more direct contact with the main players. The event also attracted considerable attention from Irish media.

Dissemination to general public

The MACCSol website contains pages which are used to give a more public-friendly face to the research by presenting the goals and achievements of the project in plain non-technical language, suitable for the general public. The aim of the website is to enhance the public’s understanding and appreciation of the importance of this collaboration and the impacts that it can bring.

List of Websites:
Project web site: www.drycoolcsp.eu
Coordinator: ronan.grimes@ul.ie

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