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Corresponding Author: Mr. Marwan Mokhtar, BSc Eng.

Corresponding Author's Institution: Masdar Institute of Science and Technology

First Author: Marwan Mokhtar, BSc Eng.

Order of Authors: Marwan Mokhtar, BSc Eng.; Muhammad Tauha Ali; Rajab Khalilpour; Ali Abbas; Nilay Shah; Ahmed Al Hajaj; Peter Armstrong; Matteo Chiesa; Sgouris Sgouridis

Abstract: Solvent-based Post-combustion Capture (PCC) is one of the promising technologies for reducing CO2 emissions from existing fossil fuel power plants due to ease of retrofitting. A significant obstacle in widely deploying this technology is the power plant load reduction (output energy penalty - OEP) due to the energy intensive CO2 separation process. In this paper we propose and theoretically evaluate a system to reduce the OEP by providing part of the PCC energy input using solar thermal energy. It is hypothesized that reducing the OEP during the daytime coincides with peaks in wholesale electricity prices thus increasing the revenue stream for a solar-assisted PCC (SPCC) plant. The general framework for assessing and sizing a SPCC system is presented. A techno-economic assessment is performed as a case study for a 300 MWe pulverized coal power plant in New South Wales, Australia using actual weather and wholesale electricity price data. It is shown that the proposed technology can be economically viable for solar collector costs of US$100/m2 at current retail electricity prices for an optimal solar fraction, i.e. the portion of solvent regeneration energy provided by solar, of 22%. The convergence of increasing electricity prices and decreasing collector costs increases SPCC viability at higher solar load fractions.

Marwan Mokhtar
Masdar Institute of Science and Technology
P.O. 54224 Abu Dhabi, UAE
20-February-2011

Professor J .Yan
School of Chemical Science and Engineering
Div. of Energy Processes
Royal Institute of Technology
Kungl Tekniska Högskolan
SE-100 44 Stockholm, Sweden

Dear Professor Yan,

The authors would like to submit a paper for publication in *Applied Energy*. In the paper the authors propose propose a novel hybridization of solar thermal concentrators and solvent-based post-combustion capture of carbon dioxide from the flue gas of fossil-fuel power plants.

This work is a humble extension of the great work done in the field of carbon capture technologies and solar energy integration in industrial processes over the years. In this study we investigate the feasibility of applying such a system on coal-fired power plants in NSW Australia.

Title: “Solar-Assisted Post-Combustion Carbon Capture Feasibility Study”.

Authors: Marwan Mokhtar, Muhammad Tauha Ali, Rajab Khalilpour, Ali Abbas, Nilay Shah, Ahmed Al Hajaj, Peter Armstrong, Matteo Chiesa, Sgouris Sgouridis

Thank you for your time and consideration. I look forward to discussing our contribution in more details.

Yours Faithfully,

Marwan Mokhtar

Suggested Referees

1) Professor Olav Bolland
   NTNU Institutt for energi- og prosessteknikk
   olav.bolland@ntnu.no

2) Dr. Jens Hetland
   Research Scientist
   SINTEF Energy Research
   Jens.Hetland@sintef.no

3) Dr. Audun Aspelund
   Energy Consulting AS
   aspelund@energyconsulting.no
   Tel: +47 47 951 83 925

4) Dr. Hanne Marie Kvamsdal
   Senior Scientist
   SINTEF Materials and Chemistry
   Hanne.Kvamsdal@sintef.no
   Tel: +47 93059222

***Highlights**

>energy penalty is incurred due to post combustion carbon capture > it may reach 20% of total energy of a power plant > integration with solar energy reduces this penalty by supplying the needed heat for solvent regeneration > under certain conditions, this leads to yearly economical benefits > a case study is presented

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SOLAR-ASSISTED POST-COMBUSTION CARBON CAPTURE FEASIBILITY STUDY

Marwan Mokhtar*[1], Muhammad Tauha Ali[1], Rajab Khalilpour[2], Ali Abbas[2], Nilay Shah[3], Ahmed Al Hajaj[3], Peter Armstrong[1], Matteo Chiesa*[1], Sgouris Sgouridis*[1]

1 Laboratory for Energy and Nano-Science (LENS), Masdar Institute of Science and Technology, Abu Dhabi 54224, UAE

2 School of Chemical and Biomolecular Engineering, University of Sydney, Sydney, Australia

3 Department of Chemical Engineering, Imperial College, London, United Kingdom

Abstract

Solvent-based Post-combustion Capture (PCC) is one of the promising technologies for reducing CO_2 emissions from existing fossil fuel power plants due to ease of retrofitting. A significant obstacle in widely deploying this technology is the power plant load reduction (output energy penalty - OEP) due to the energy intensive CO_2 separation process. In this paper we propose and theoretically evaluate a system to reduce the OEP by providing part of the PCC energy input using solar thermal energy. It is hypothesized that reducing the OEP during the daytime coincides with peaks in wholesale electricity prices thus increasing the revenue stream for a solar-assisted PCC (SPCC) plant. The general framework for assessing and sizing a SPCC system is presented. A techno-economic assessment is performed as a case study for a 300 MW_e pulverized coal power plant in New South Wales, Australia using actual weather and wholesale electricity price data. It is shown that the proposed technology can be economically viable for solar collector costs of US\$100/m^2 at current retail electricity prices for an optimal solar fraction, i.e. the portion of solvent regeneration energy provided by solar, of 22%. The convergence of increasing electricity prices and decreasing collector costs increases SPCC viability at higher solar load fractions.

Keywords: Carbon Capture; Post Combustion; Solar Assisted; Solar Fraction; Energy Penalty; Coal Fired Plants

* Corresponding Authors: Tel.: +971 2 810 9156; fax: +971 2 810 9901. E-mail: addresses: mmoktar@masdar.ac.ae (M. Mokhtar), mchiesa@masdar.ac.ae (M. Chiesa), ssgouridis@masdar.ac.ae (S. Sgouridis)

1. Introduction

The majority of the world's primary energy consumption, about 86%, is still based on fossil fuels with their concomitant CO_2 emissions. According to the Intergovernmental Panel on Climate Change fossil fuel power plants contribute about 78.2% of CO_2 emissions from large stationary emission sources [1]. In US, over 40% of total CO_2 emissions are associated with the power sector while the contribution for Australia is greater than 50% [2], [3]. As a transition step towards low-carbon energy generation, Carbon Capture and Storage (CCS) is a key possible technology for reducing CO_2 emissions and stabilizing atmospheric concentrations of greenhouse gases. Another benefit of CCS can also be realized in terms of a CO_2 market as CO_2 is used in different industrial processes [4-6] especially for enhanced oil recovery (EOR) [4], [5].

There are three main approaches for CCS implementation in power plants; pre-combustion, oxyfuel combustion and post-combustion. Comprehensive descriptions of these processes can be found in [7], [8]. Though oxyfuel and pre-combustion technologies are studied extensively to be applied into new-build power plants, post-combustion (PCC) may be the most accessible option for retrofitting existing power plants [9] due to minimum changes required to the plant and represents the lower cost option per unit of carbon captured [10].

A number of PCC technologies are commercially available or at different research stages from conceptual study to pilot plant. These include solvent-based absorption-desorption, membrane [11], adsorption [12], [13] and mineralization [14]. However, solvent-based capture technology is mature and the 'best available technology' due to its prior application in EOR [15]. This has made it a widely considered approach for retrofitting of existing installations [4], [16].

Despite advances in solvent-based PCC, the implementation of this technology in a power plant introduces a notable energy penalty mainly due to solvent regeneration. The energy penalty value varies by the type of power plant and by different techno-economic studies ([1], [6], [17], [18]), and is estimated to be above 20% [18]. This results in serious reduction in power plant load (output energy penalty, OEP). The OEP is still a significant barrier in implementation of PCC in power plants.

This paper proposes a novel hybridization of solar thermal concentrators and solvent-based post-combustion capture (PCC) of carbon dioxide from the flue gas of fossil-fuel power plants and examines the potential of using solar energy for supplying part of the energy needed for solvent regeneration. The viability of such solar-assisted PCC (SPCC) is location specific as it depends on environmental conditions (solar irradiance), cost of electricity, land availability, etc. Regions with high insolation, long summers, air-conditioning demand, and a reliance on coal-fired power plants would be the most promising candidates for implementation of an SPCC system not only because of the availability of solar resource but also because of the correlation between high electricity demand with solar irradiance. New South Wales in Australia fit this profile and, in an initial screening, a promising apparent correlation was identified between high electricity spot prices and solar irradiance as shown in Figure 1 and the accompanying Table 1.

Figure 1 Hourly Electricity Price (EP) in 2009 vs. Hourly Global Horizontal Irradiance (GHI) for New South Wales, Australia (EP Source: [19]**, GHI Source:** [20]**)**

Table 1: Correlation of Hourly Electricity Prices and Solar Irradiance.

Based on the promising potential of reducing OEP using solar energy, the remainder of the paper we explore this idea further. Specifically, in Section 2 we review the CO_2 solvent extraction process currently considered for retrofitting a coal fired power plant and propose the integration of a solar-assisted solvent regeneration process. Section 3 presents a generalizable methodology used to assess the viability of an SPCC system. In Sections 4 we use the proposed assessment methodology to evaluate the feasibility of solar-assisted PCC for a realistic coal-fired power plant under actual Australian conditions and we then present and discuss the results of this study in Section 5.

2. Technical Overview of a Solar-assisted PCC System

In solvent-based PCC, the flue gas stream from the gas turbine/combustor is first cooled to 40-60°C [21]. It is then cleaned of soot and other impurities and sent to the absorber in which CO_2 is separated from the stream by chemical solvent scrubbing. CO_2 is absorbed into the solvent by reacting chemically with it to form a loosely bound compound. The CO_2 rich solvent is collected at the bottom of the scrubbing vessel. Subsequently, it is passed into a stripper column (the desorber) where the CO_2 rich solvent is heated by steam from the reboiler to reverse the CO_2 absorption reactions. CO_2 released in the desorber is compressed for transport and storage while the CO_2 lean solvent is recycled to the absorption vessel. Monoethanolamine (MEA) is widely used, though there are numerous other candidate solvents [6], [17]. For carbon capture by MEA scrubbing, the regeneration temperature requirements are in the range of 100°C –140°C [4], [17], [21]. The thermal energy for regeneration is sourced from the steam cycle by extracting high quality steam from the turbines. The resulting energy penalty for capturing 90% CO_2 using 30 wt% MEA from coal-fired plant is reported in the range of 19.4-39% based on different coal quality [6], [22]. The capture ratio, i.e. the desired percentage of CO_2 to be captured from the flue gas stream, is an influencing parameter for the capital costs of the facility and the associated OEP.

In order to reduce the OEP resulting from bleeding steam from the steam turbine circuit to heat the amine solution, solar energy can be used to fully or partially provide the solvent regeneration energy. Such a system was pointed out by [17] in a technical assessment of the issues pertaining to retrofitting PCC in Australian coal fired plants. Solar energy is a suitable option capable of providing the needed energy from a renewable resource and with an availability pattern that generally coincides with higher energy prices. The proposed SPCC system, shown in Figure 2, involves the hybridization of solar energy with the conventional method of supplying the regeneration energy, i.e. from the steam turbine circuit. Solar energy will supply the energy needed based on availability and the rest is supplied conventionally by bleeding steam from the steam turbine circuit. Since solar energy options are intermittent, thermal energy storage is included in the proposed system to buffer the fluctuations in the solar resource. Figure 2 provides a schematic of the proposed hybrid SPCC system and indicates its point of integration with a conventional PCC design.

Figure 2 Schematic diagram of the proposed integration of solar-assisted PCC in a Coal-Fired Power Plant (Modified from: [11])

3. Feasibility Assessment Methodology for Solar-Assisted PCC

The critical operational parameters guiding the design of an SPCC system are the CO_2 capture ratio (CR), solar fraction (SF) and thermal storage size (TS). With these parameters established in the basic design, the feasibility of the SPCC plant can be assessed based on key system variables that are region-dependent like solar resource, carbon price, fuel price, fuel carbon intensity, and post-capture costs. In Section 3.1 we present a general framework for assessing the benefits versus the costs of installing an SPCC system. Since there are a number of combinations of the design parameters e.g. CR, SF, TS, etc., an algorithm for exploring the design space is proposed in Section 3.2.

3.1 General SPCC Evaluation Framework

Equation 1 formulates the SPCC operational parameters and region-dependent variables into expected costs and revenues and calculates the expected revenue stream from its operation. The net revenue from a power plant fitted with an SPCC in the general case would consist of the generated electricity sold at price p_{elec} from which the following costs are subtracted: fuel, solar plant, CO_2 pumping and storage cost, and the carbon costs incurred from the CO_2 that is actually released. In the general case, the optimization problem for establishing the values of the operational design parameters under the constraints of the region-dependent variables for the SPCC system would intend to maximize the net revenues from electricity generation as calculated in Equation 1.

Eq-1

$$R = \int E_{elec}(t, SF(t)) \cdot p_{elec}(t)\, dt - \int FF(t) \cdot p_{fuel}(t) dt - P_{Solar}(A, TS) - P_{MEA}(CR) - \int E_{elec}(t, SF(t)) \cdot F_{CO2} \cdot CR(t) p_{stor} dt - \int E_{elec}(t, SF(t)) \cdot F_{CO2} \cdot [1 - CR(t)] \cdot p_{CO2}(t) dt$$

where:

R	: Net Revenue [$/yr]
E_{elec}	: Electricity generated [kWh]
p_{elec}	: Electricity price [$/kWh]
$FF(t) = \frac{E_{elec}(t)}{n(CR(t), SF(t))}$	: Amount of fossil fuel used [kg]
η	: Thermal to electricity conversion efficiency of the power plant [%]
CR	: Capture Ratio- the ratio of CO_2 captured from the effluent [%]
SF (t) = Y(Irr(t), A, TS)/D(t)	: Solar Fraction- the ratio of thermal energy yield (Y in kWh_{th}) provided by the solar field over total thermal energy requirement for regeneration (D) [%]
Irr	: Solar Irradiance [W/m^2]
A	: Solar field size [m^2]
TS	: Thermal Storage size [FLH[1]]
p_{fuel}	: cost of fuel [$/kg]
P_{Solar}	: levelized cost of the solar field and thermal storage unit including land costs [$/yr]
P_{MEA}	: levelized cost of MEA capture unit [$/yr]
F_{CO2}	: CO_2 intensity of the fuel [kg_{CO2}-eq/kWh_e]
p_{stor}	: cost of compressing, pumping and storing the captured CO2 [$]
p_{CO2}	: price of CO2 emitted in the atmosphere [$/$kg_{CO2}$]

In order to assess the feasibility of installing a solar-assisted PCC system rather than a conventional PCC, a techno-economic analysis for different combinations of operational parameters under region-dependent boundary conditions is needed. If the decision to retrofit a solvent-based PCC system is already taken on the merits of reducing carbon emissions impacts,

1 Full Load Hour, one full load hour of storage means that the storage has enough energy to allow reboiler operation for one hour at full load with no solar or other input. Since reboiler power at full load is 200MW, 1 FLH represent a storage size of 200MWh in the case described in Section 4.

it is possible to evaluate the decision on whether or not that unit should be solar-assisted by comparing the two cases:

- Case *A*: A PCC plant which continuously bleeds steam from the turbine circuit for solvent regeneration.
- Case *B*: An SPCC plant which uses both solar energy and turbine circuit steam for solvent regeneration, switching between them as necessary in real-time.

Equation 1 can be reformulated to reflect the difference between a typical PCC facility and a solar-assisted one by calculating the difference in the revenue of both cases as shown in Equation 2. The revenue difference of scenarios *A* and *B* could be obtained by subtracting the revenue equations of the two cases (R_A and R_B). Equation 2 simplifies the comparison by removing common terms under the assumption that operational parameters like the power plant fuel consumption and the capture ratio remain the same. For the SPCC to be feasible the revenue differential of Equation 2 should be positive.

Eq. 2

$$R_B - R_A = \int (E_{elec}(t, SF(t)) - E_{elec}(t)) \cdot \ p_{elec}(t)\,\mathrm{dt} - \mathrm{P_{solar}}(\mathrm{A, TS})$$

Eq-2 captures the differences between the two cases if the system boundary is drawn at the plant level. Yet it fails to capture an additional potential benefit of Case B which allows for higher levels of electricity generation that have lower carbon intensity. If the shortfall of Case A is supplied by a non-capturing conventional plant then, on a system level, there are additional emissions generated that come at an additional carbon cost as specified in Equation 3.

Eq. 3

$$R_{\mathrm{system}} = \int (\mathrm{E_{elec}}(\mathrm{t, SF(t)}) - \mathrm{E_{elec}}(\mathrm{t})) \ \cdot \mathrm{p_{elec}}(\mathrm{t})\,\mathrm{dt} + \int (\mathrm{E_{elec}}(\mathrm{t, SF(t)}) - \mathrm{E_{elec}}(\mathrm{t})) \ \cdot \mathrm{F_{CO2}}(1 - \mathrm{CR(t)}) \cdot \mathrm{p_{CO2}}(\mathrm{t})\,\mathrm{dt} - \mathrm{P_{solar}}(\mathrm{A, TS})$$

3.2 Simulation Methodology for SPCC Evaluation

Equations 1 and 2 indicate that the cost and relative effectiveness of SPCC are heavily dependent on the solar load fraction which is in itself dependent on solar field and thermal storage size. In order to investigate the different combinations we propose an algorithm for iteratively determining the size of the solar field and the thermal storage unit. Each feasible combination can then be evaluated for economic viability under varying boundary conditions including primary system design and monetary values of fuel, electricity prices and carbon prices.

The algorithm that we used in evaluating these options is outlined in the four following steps:

1. Specify system boundaries (output energy penalty, electricity prices, carbon prices, solar collectors cost, storage cost, financing conditions etc).

2. Initialize the iterative process by specifying a low initial value for solar field size. This value will be increased at each iteration of the simulation.
   2.1. Using performance parameters of the solar field, the amount of thermal energy generated by the solar field is calculated. This is done through an hourly simulation using weather and solar irradiation data of the specific site for a period of one year. For every simulated hour,
      2.1.1. a decision is made to supply regeneration energy from the solar circuit if the solar yield of that hour added to the energy in the storage is enough to satisfy the demand, otherwise the energy is supplied from the steam turbine circuit.
      2.1.2. in case the energy from the solar field exceeds the demand, the excess is stored in storage for later use, provided storage is not full. Once the storage is charged to its maximum capacity the solar collector operation stops.
      2.1.3. the storage content is logged at each hour to create a year-long profile, this profile which is used to select the required storage size. If the maximum storage size considered is 15 Full Load Hours (FLH), and the plant considered is a base load plant, then no daily carryover is expected.
      2.1.4. the amount of energy supplied by the solar field and by the turbine circuit is logged in order to determine the SF.
   2.2. Storage size is determined from the storage content profile created in Step 2.13 by taking the peak value of that profile. This would guarantee that the storage size is sufficient to use all the solar energy collected. The storage size however is limited to a maximum size. This is done since at higher solar load fractions the storage size will increase exponentially. For example, 150 FLH of storage is needed to achieve 70% SF compared

to only 15 FLH needed to achieve ~48% SF.[2] In our study the maximum limit on storage size is set to 15 FLH, which is a size normally used in solar power plants [23] [24].

2.3. At the end of the simulation year, the solar fraction is calculated by dividing the total solar energy contribution throughout the year by the total demand using the output of Step 2.1.4.

2.4. We then calculate net annual benefits as a result of supplying the required regeneration energy from solar power and avoiding using the steam the turbine network. These benefits are linearly related to the solar fraction calculated above in Step 2.3 through the energy penalty and electricity price as specified in Eq-2. In this step, we also calculate the carbon cost avoided on a system level as outlined in Eq-3.

2.5. The amortized cost of the system is calculated based on the cost of the solar field, storage, land and the financing conditions.

2.6. The selected solar field size is cost-effective if the revenues exceed the total amortized cost of the system in Equations 2 (plant level) and 3 (system level).

3. Enumerate the design parameters and repeat the simulation to populate the design space.

4. Iterate the process for several solar collector costs.

4. Case Study Assessment for a Solar-assisted PCC system under Realistic Boundary Conditions

In order to investigate the feasibility of an SPCC plant under realistic conditions we evaluate a case based on a conceptual installation in New South Wales, Australia. As noted in Section 1, the characteristics of the region fit the profile as potential area for installation of SPCC. In order to complete the analysis, we make certain simplifying but realistic technical and economic assumptions, described in Sections 4.1 and 4.2 respectively that allow a tractable exploration of the design space for this case study. The results of the assessment are presented in Section 4.3.

4.1 SPCC Assessment Technical Assumptions

[2] Solar Fractions in this example represent the SF that would be achieved at a certain field size if there were enough storage to store all the heat generated by the solar field.

The conceptual baseline plant for our case is a typical pulverized coal-fired power plant with a 300MW capacity operating in NSW, Australia. The thermal energy requirement for solvent regeneration for a capture ratio of 90% and CO_2 purity of 99% is estimated to be 200MW_{th} (3.12 GJ/tones CO_2)[11].

Firstly, we assume that the plant is operating at 100% capacity and shuts down for regular maintenance resulting in a capacity factor of 85%. As a result, the plant behaves as a base load plant. Operating as a based load plant implies that the power plant is a price-taker, i.e. it will not adjust its output in response to wholesale electricity price changes but it will continue to operate at capacity and its revenues will be a simple function of the price. Secondly, we assume a constant capture ratio of CO_2 from the flue gas – i.e. the capture system operates also at capacity with constant solvent quality. The capture ratio for this evaluation was set at 90% which is a common target for PCC projects [6]. Varying these assumptions could yield better overall system optimization but doing so introduces two more degrees of freedom that impact similarly a PCC and an SPCC plant. Thus, their inclusion was considered redundant as it does not elucidate the merits or lack thereof of the solar-assisted system that is the focus of this paper.

Thirdly, we assumed that the solar collector steam circuit is operating in a discrete fashion: either it is providing all steam necessary to operate the PCC plant or the collected solar energy is diverted to the energy storage if it is not enough. A bang-bang (on/off) control scheme is adopted for the purpose of switching between the two circuits because of its simplicity and ease of implementation. In other words, the steam turbine circuit cannot be used for partial load of the PCC and would provide the full PCC load when the solar circuit is off as shown in Figure 1. Such a choice is not expected to affect the performance of the system since thermal storage is used. As a result, the full electricity output energy penalty (OEP) is only incurred during those times that the steam is bled from the turbine circuit.

In order to produce realistic estimates of the solar potential, an hourly simulation of the solar field was performed for a full year of operation. This includes a thermal model of solar collector performance under historical direct solar irradiance, and the performance of the thermal storage system. (A lossless energy storage model is a reasonable assumption when the storage size is big, see [23]).

Among the different solar thermal technologies available, single axis tracking linear Fresnel concentrators offer relatively low cost, minimum structural requirements, low land area usage, and are capable of reaching the required operating temperatures [25], [26], and therefore are selected for this study. Currently Fresnel concentrator technologies can be installed at costs that range from ~300 to ~900 $\$/m^2$ [27].

The equation used for calculating the thermal energy yield of the Fresnel collector field is as follows:

Eq-4 $$Y = A \cdot [G \cdot \eta_o \cdot IAM - C_1 \cdot (T_a - T_m) - C_2 \cdot (T_a - T_m)^2]$$

Where:

Y: Average hourly heat output of the collector field [W]

G: Total irradiation on the surface of the collector (DNI) [W/m^2].

IAM: Incident angle modifier which is a result of collector system optical properties.

η_o: Optical efficiency of the collector at normal incidence.

C_1 and C_2: Performance constants of the collector supplied by the manufacturer [$W/(m^2.K)$], [$W/(m^2.K^2)$] respectively.

T_a: Ambient temperature[^oC].

T_m: Mean fluid temperature (average of inlet and outlet temperatures) [^oC].

A: Aperture area of the collector field [m^2].

Applying Eq-4 on an hourly basis for the whole year resulted in an average thermo-optical efficiency of 44.11% for the Fresnel collector field.

We assumed the use of solid sensible storage as the thermal energy storage medium used to buffer the solar resource fluctuations for SPCC applications. For carbon capture by MEA scrubbing, the regeneration temperature requirements are in the range of 100°C–140°C [4], [17], [21]. For these temperature ranges, solid sensible storage is sufficient using either sand-rock-mineral-oil or reinforced concrete with energy density ranging between 60-100 kWh_{th}/m^3 and medium cost in the range of 1-5 $\$/kWh_t$. The total cost of such a storage system excluding installation costs is typically between 20-25 $\$/kWh_{th}$ of which only 20% is associated with the cost of thermal storage media. The installation costs are estimated to be around 10% of total storage cost [28], [29].

4.2 SPCC Assessment Economic Assumptions

The capital costs of the solar field, thermal storage and land, in addition to maintenance costs of the solar field are amortized over the life time of the plant assumed to be 25 years. Eq-5 represents the annual levelized cost of the solar field (p_{solar}). The discount rate assumed is 6%. .

Eq-5

$$p_{solar} = \alpha \cdot \left[A \cdot \left(C + \frac{L}{U}\right) + S\right] + C \cdot A \cdot M \qquad \left[\frac{\$}{yr}\right]$$

Where:

α: Annuity $\frac{A}{P} = \left(\frac{i}{\left(1-\left(\frac{1}{(1+i)^n}\right)\right)}\right)$ [%]

A: Solar Field Area [m2]

C: Collector Specific Cost [$/m2]

L: Land Cost [$/m2]

U: Collector Land Utilization [%]

S: Storage Total Cost [$]

M: Maintenance [% of Capex]

Based on the technical and economic assumptions above, the general design parameter input values for SPCC comparative evaluation are summarized in Table 2. Applying Equations 4 and 5 to the revenue and operation equations 2 and 3, allows us to estimate the relative performance of SPCC against a conventional PCC installation under these assumptions and for a variety of configurations for solar-field/thermal energy storage sizes. Using the algorithm presented in Section 3.2, we investigate these combinations against realistic conditions. The results from these iterative simulations are presented in Section 4.3.

Table 2 SPCC Simulation Input Design Parameters.

4.3 Results of SPCC Feasibility Assessment

Using the assumptions from Sections 4.1 and 4.2, we performed annual simulations of the solar field performance for varying combinations of solar field and thermal energy storage. In addition, we varied the cost of the solar collectors and of the carbon price to establish at what ranges SPCC may be preferable to conventional PCC.

Figure 3 illustrates the relation between solar load fraction and solar field size. The linear region is an indication that the storage size is adequate to meet the fluctuations in supply and demand, thus an increase in the solar field size will be translated to a direct increase in the useful output of the plant. However, as we move further towards higher solar fractions, the storage size becomes a limitation and the curve starts to saturate.

Figure 3 Relation between solar field size and solar load fraction for a 300MW$_e$ coal fired power plant with capacity factor of 85% and 90% capture rate. Storage size is selected in during simulation for each design as explained in the algorithm in section 3.2 .

Figure 4 depicts the relationship between the solar load fraction and storage size. Similar to the field size, the required storage size will increase for higher solar load fractions. The relationship is almost linear in the region between 20% and 50%, however it can be seen from the figure that an exponential increase in storage size starts around SF=50%, which is why we limit the storage size to a maximum of 15 FLH. It can also be seen from Figure 4 that at low solar load fraction a small storage size is sufficient to meet the SPCC requirements.

Figure 4 Relation between solar load fraction (SF) and storage size in Full Load Hours (FLH). The curve shows the storage size required to achieve the corresponding solar load fraction.

Using the annual simulation runs for each combination of electricity price, carbon price, collector price and collector area described in Section 3, the relative economic performance of the SPCC against PCC is estimated. Figure 5 illustrates the relation between the net annual benefits (yearly revenue – yearly cost) and SF for different collector costs. Values of SF from 0 to >0.7 are obtained by varying collector area from 0 to ~ 1.5 km^2 in 0.03% increments. In Figure 5 the net benefits are plotted for representative values of electricity price, carbon price and collector costs.

Figure 5 shows that at zero carbon price and current electricity prices, the proposed system is only feasible at very low solar collector cost (~100 $/m^2$) and for low solar-fractions (30% or less) with an optimal solar load fraction in this case around 22% (collector area = 0.37 km^2) and yearly net benefits (additional revenue from using SPCC) around 2.0 M$.

Figure 5 Net benefit of Solar-assisted PCC for Different Solar Collector Costs (100-600 $/m^2$) and Varying Boundary Conditions; Carbon Prices (0-0.2 $/kg_{CO2}$) and Electricity Price Increments (EP_{inc}) (0-0.2 $/kWh).

The electricity pool price in NSW is relatively low (average of 4.43 cent/kWh [19]) compared to other countries (e.g. European average electricity prices can reach more than 20.0 €cents/ kWh (~27.36 $cent/kWh) in place like Denmark and Germany [31]). As electricity prices and/or carbon prices increase, SPCC installation becomes advantageous. It can be seen from Figure 5 that the proposed system is feasible at lower collector costs and that higher solar load fractions are also becoming feasible if a carbon tax is applied and/or if low-carbon electricity is sold at a premium price.

Table 3 summarizes the feasibility of SPCC at different combinations of carbon and electricity prices. The optimal solar fraction for each case is selected based on the maximum annual benefits when using SPCC as compared to PCC. For conditions that would fit a price regime close to that of Europe today (i.e. electricity price increment of $0.1/kWh and a carbon price of $0.05/kg CO_2 the $300/m^2$ collector available today would make economic sense with net benefits of $2.76 M annually.

Table 3 A summary of SPCC net annual benefits at varying carbon and electricity prices for a collector cost of (300 $/m^2$), optimal solar fraction corresponds to maximum annual net benefits.

5. Discussion and Conclusions

This paper proposes a novel hybridization of solar thermal concentrators and solvent-based post-combustion capture (PCC) of carbon dioxide from the flue gas of fossil-fuel power plants. The rationale for a solar-assisted PCC (SPCC) is based on the fact that solvent regeneration requires thermal energy of lower quality that can be provided relatively cost-effectively by a solar thermal plant thus leaving the higher quality steam to be used more efficiently for electricity generation. Furthermore, we hypothesized that since this mitigation of the output energy penalty (OEP) coincides with times when wholesale electricity prices peak thus resulting in increased plant revenues, a positive argument can be made for such a hybrid SPCC.

We develop a feasibility assessment methodology to evaluate the relative performance of combinations of solar field size and thermal energy storage under different cost and carbon price assumptions in Australian climatic and electricity market conditions. The case study plant was a typical 300 MW_e pulverized coal-fired power plant with installed carbon capture equipment with a PCC facility using 30 wt% monoethanolamine (MEA) solvent. The collector field used in the simulation was a Fresnel collector field. This type of concentrating solar collector is capable of generating adequate temperatures for solvent regeneration and is currently commercially available.

Since the temperature needed in this application is around 120^{o}C, less expensive non concentrating collectors or smaller and cheaper trough collectors might be available to provide these temperatures. The authors did not have enough information on the availability, technical performance or prices of these collectors and that is why different prices of solar collectors were shown in the results. The feasibility of the proposed system is expected to improve if we use non-concentrating collectors or low-concentration collectors (e.g. CPC), which are optimized for the required operating temperature.

Further, we assumed an ON/OFF control scheme for providing the reboiler energy either from the solar circuit or the steam turbine circuit. This choice might not be the optimal choice and higher utilization of the solar field might be achieved by combining both circuits in a more sophisticated control scheme.

In principle, solar-assisted post-combustion carbon capture is one of the most appealing points of integrating solar power into the power system; the relatively low operating temperature may allow for the use of cheaper collectors optimized for these temperatures. Through a consistent assessment of such an integrated system in the specific conditions of NSW Australia, it was found that only very low collector costs would make the system feasible at current conditions despite its environmental and energy generation benefits. As a result, broader acceptance of such a system is sensitive to the boundary conditions such as electricity prices, carbon taxes, financing conditions, cost of equipment, life time, energy PCC penalty etc. Since the assumption of PCC in any case is expected to raise electricity prices based on the opportunity cost of the avoided carbon emissions, the cost advantage of this technology will increase at higher electricity prices and higher carbon prices on a system-wide assessment.

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Figure1
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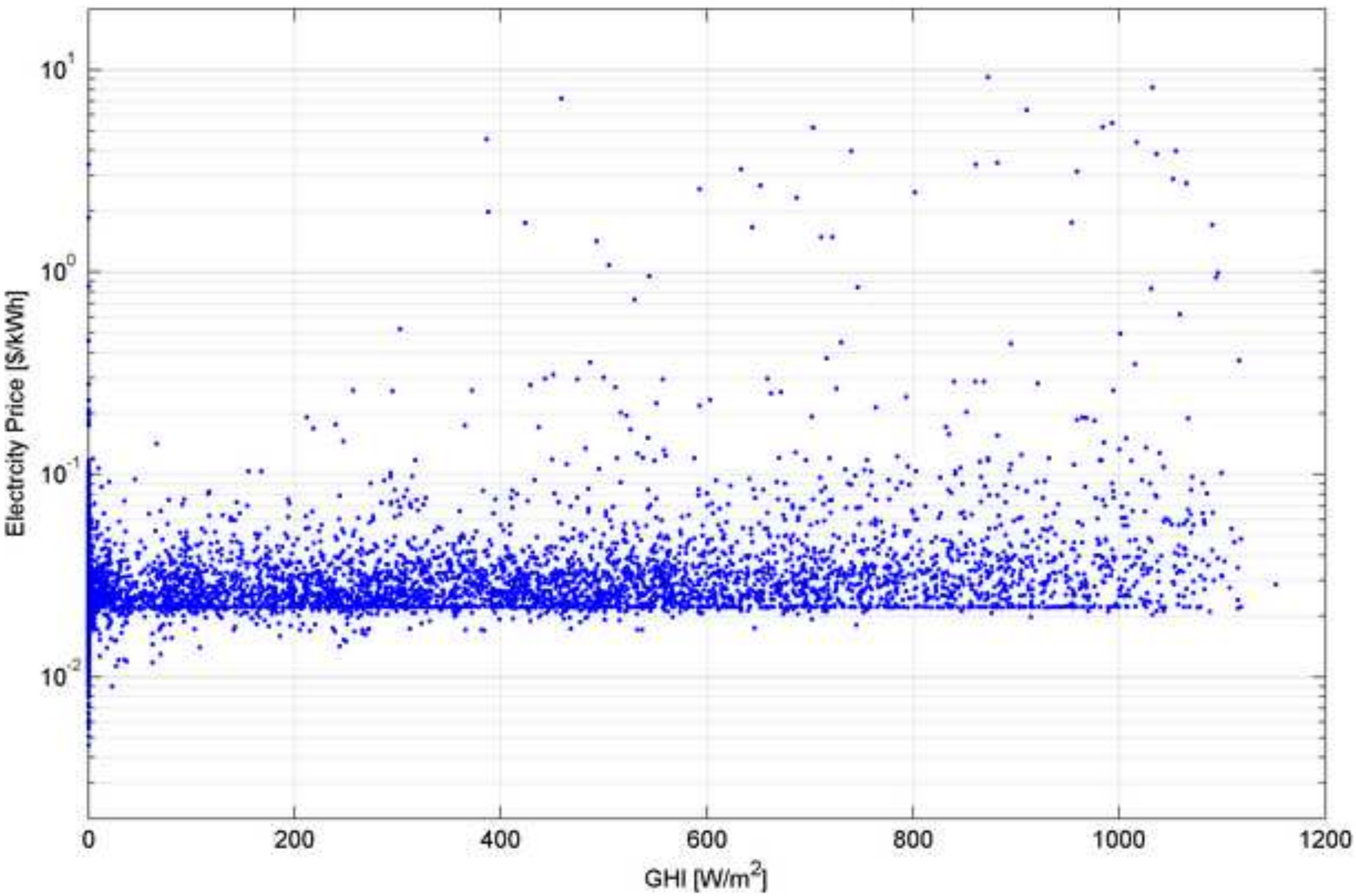
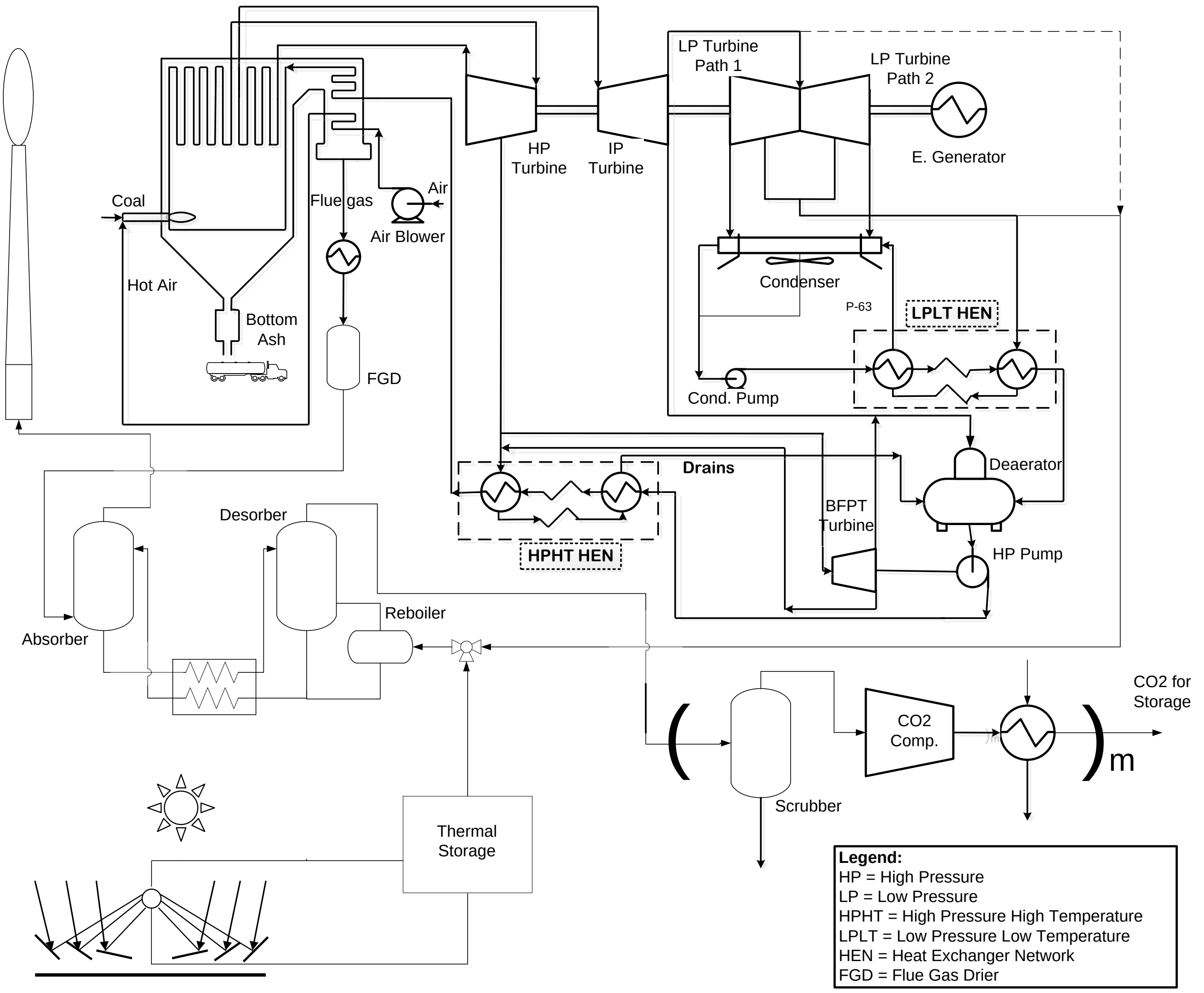


Figure2



LP Turbine Path 1
LP Turbine Path 2
HP Turbine
IP Turbine
E. Generator
Air
Coal
Flue gas
Air Blower
Hot Air
Bottom Ash
FGD
Condenser
P-63
LPLT HEN
Cond. Pump
Drains
Deaerator
BFPT Turbine
HP Pump
HPHT HEN
Desorber
Absorber
Reboiler
CO2 Comp.
CO2 for Storage
m
Scrubber
Thermal Storage
Legend:
HP = High Pressure
LP = Low Pressure
HPHT = High Pressure High Temperature
LPLT = Low Pressure Low Temperature
HEN = Heat Exchanger Network
FGD = Flue Gas Drier

Figure3
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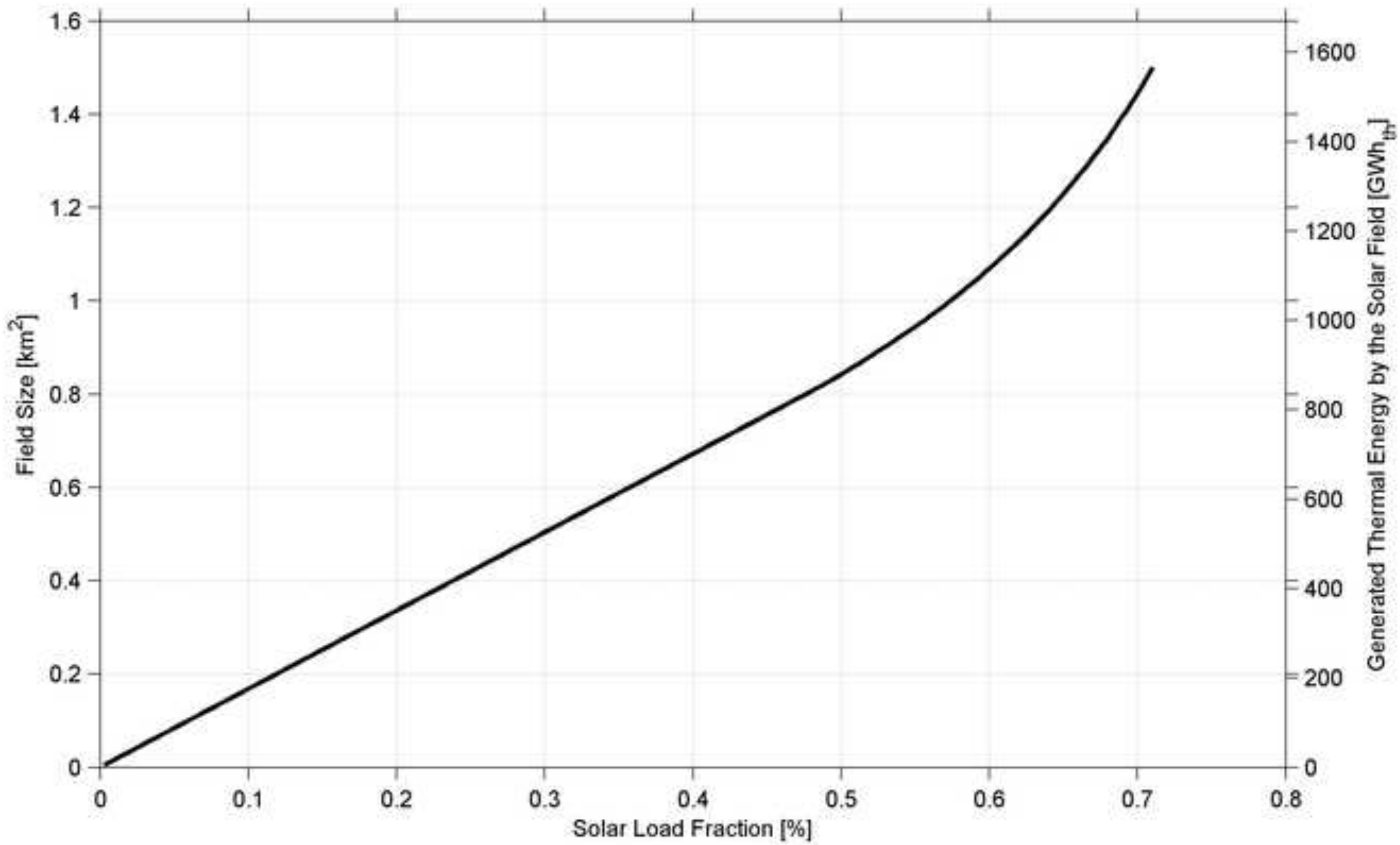

Figure4
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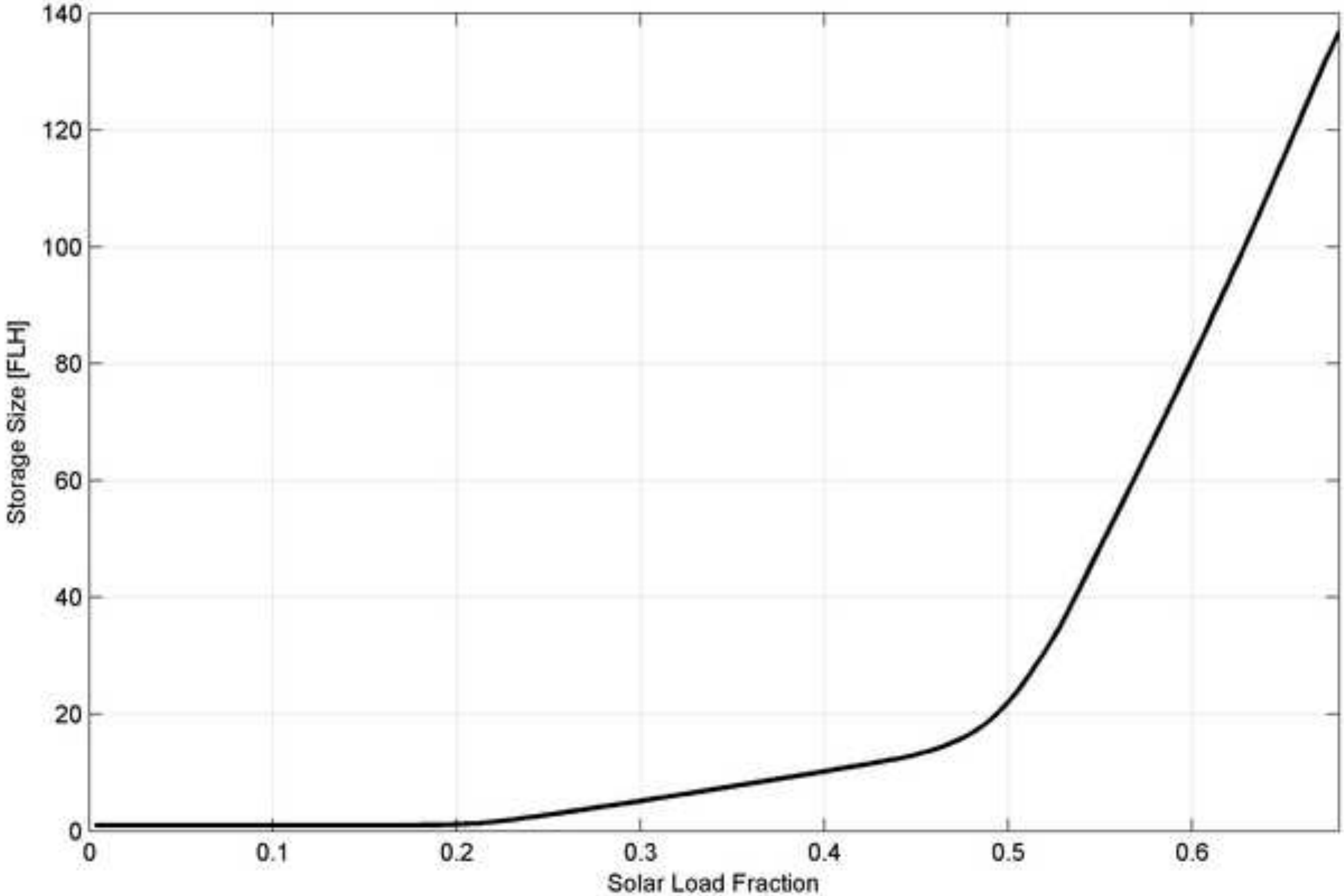
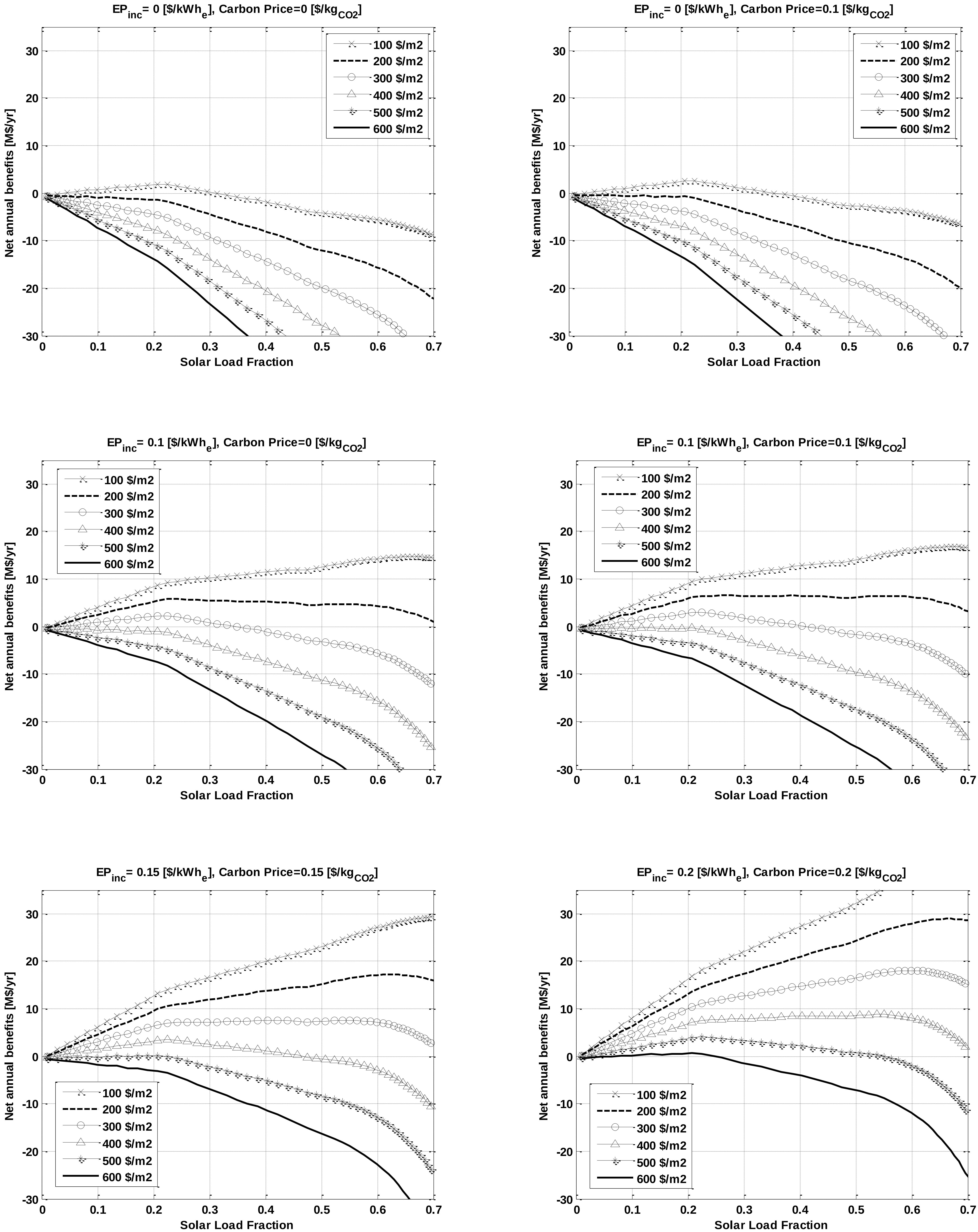


Figure5



EP$_{inc}$= 0 [$/kWh$_e$], Carbon Price=0 [$/kg$_{CO2}$]
EP$_{inc}$= 0 [$/kWh$_e$], Carbon Price=0.1 [$/kg$_{CO2}$]
EP$_{inc}$= 0.1 [$/kWh$_e$], Carbon Price=0 [$/kg$_{CO2}$]
EP$_{inc}$= 0.1 [$/kWh$_e$], Carbon Price=0.1 [$/kg$_{CO2}$]
EP$_{inc}$= 0.15 [$/kWh$_e$], Carbon Price=0.15 [$/kg$_{CO2}$]
EP$_{inc}$= 0.2 [$/kWh$_e$], Carbon Price=0.2 [$/kg$_{CO2}$]
Net annual benefits [M$/yr]
Solar Load Fraction
100 $/m2
200 $/m2
300 $/m2
400 $/m2
500 $/m2
600 $/m2

Table1

Table 1: Correlation of Hourly Electricity Prices and Solar Irradiance.

Hourly Solar Radiation (SR) Threshold	400 W/m^2	
Hourly Electricity Price Threshold (EPT) in $/kWh	EP > EPT & SR > 400 W/m^2	EP > EPT & SR < 400 W/m^2
0.0443 (Mean)	420 (70%)	182
0.05	340 (74%)	118
0.1	122 (87%)	18
1.0	29 (94%)	2
5.0	7 (100%)	0

Table2

Table 2 SPCC Simulation Input Design Parameters.

Parameter	Value	Parameter	Value
Storage Specific Cost [USD/kWh]	22	Plant Capacity Factor	85%
Simulation Time [h]	8760	Electricity Cost [USD/kWh]	Varying time series [19]
Simulation Resolution [h]	1	Plant Capacity [MWe]	300 [11]
Interest Rate	6%	Auxiliary electricity consumption (Pumps, blowers)[MWe]	17.1 [11]
Maximum Allocated Storage Capacity [FLH]	15 [23][24]	PCC auxiliaries (CO2 compression, flue gas blower, solvent pumps)[MWe]	17.2 [11]
Operating Temperature [^oC]	120	Power reduction due to reboiler energy consumption [MWe]	37.9 [11]
Life Time [yr]	25	Required reboiler heat [MW_{th}]	200 [11]
Coal Carbon Intensity [kg_{CO2-eq}/kWh_e]	941 [30]		

Table3

Table 3 A summary of SPCC net annual benefits at varying carbon and electricity prices for a collector cost of (300 $/m^2), optimal solar fraction corresponds to maximum annual net benefits.

Increment in Electricity Price [$/kWh$_e$]	Carbon Price [$/kg$_{CO2}$]	Optimal Solar Fraction [%]	Net annual benefits [M$]
0.00	0.00	0.30%	-0.45
0.05	0.00	0.30%	-0.40
0.10	0.00	21.73%	2.42
0.15	0.00	22.03%	6.04
0.20	0.00	58.74%	14.37
0.00	0.05	0.30%	-0.45
0.05	0.05	8.63%	-0.40
0.10	0.05	21.73%	2.76
0.15	0.05	26.50%	6.39
0.20	0.05	58.74%	15.29
0.00	0.10	0.30%	-0.44
0.05	0.10	8.63%	-0.26
0.10	0.10	21.73%	3.10
0.15	0.10	39.00%	6.93
0.20	0.10	58.74%	16.21
0.00	0.15	0.30%	-0.44
0.05	0.15	14.29%	-0.13
0.10	0.15	21.73%	3.44
0.15	0.15	54.79%	7.65
0.20	0.15	58.93%	17.13
0.00	0.20	0.30%	-0.43
0.05	0.20	21.43%	0.20
0.10	0.20	21.73%	3.78
0.15	0.20	55.02%	8.50
0.20	0.20	58.93%	18.05