INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 3, Issue 1, 2012 pp.9-18
Journal homepage: www.IJEE.IEEFoundation.org

Optimum sizing of steam turbines for concentrated solar power plants

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Abstract
In this work, a selection of the optimum steam turbine type and size for integration in concentrated solar power (CSP) plants is carried out. In particular, the optimum steam turbine input and output interfaces for a range of CSP plant capacity sizes are identified. Also, efficiency and electricity unit cost curves for various steam turbine capacities are estimated by using a combination of the Steam Pro software module of the Thermoflow Suite 18 package and the IPP v2.1 optimization software tool. The results indicate that the estimated efficiency and the expected specific capital cost of the power block are very important criteria in choosing the best steam turbine size of a CSP plant. For capacity sizes of 10kWe up to 50MWe, the steam turbine efficiency increases and the steam turbine expected specific capital cost of the power block decreases at a high rate, whereas for larger sizes they remain almost constant. Thus, there is significant efficiency gains to be realized and large cost savings in increasing the turbine size up to 50MWe. Finally, although the cost of electricity of a CSP plant with capacities greater than 1MWe is significantly reduced to less than 1US$/kWh, currently such technology can only become economically viable through supporting schemes.

Keywords: Steam turbines; Rankine cycle; Concentrated solar power; Power generation.

1. Introduction

Today, steam turbines with widely varying configurations, sizes and application purposes are used extensively in the electricity generation and process industries. These steam turbines represent a significant part of the capital and operating costs of most plants, and therefore optimizing their selection and sizing is of major economic importance for the viability of the plant. However, the selection of the optimum steam turbine based on type and size for any given new plant is not a simple process, since a number of criteria have to be examined and be satisfied. The main criteria, apart from the economic ones, include the actual plant steam operating conditions at the interfaces to the steam turbine, the existing power system capacity, the stability and reliability conditions and requirements that are in place to safeguard that the safe and reliable supply of electricity throughout the electricity network is not disrupted by the introduction of a new power plant.

In this work, a selection of the optimum steam turbine type and size for integration in concentrated solar power (CSP) plants is carried out. In particular, the CSP technologies that can be integrated with steam turbines to produce power are presented. Also, the optimum steam turbine input and output interfaces for a range of CSP plant capacity sizes are identified. Furthermore, optimum efficiency and electricity unit cost curves for various steam turbine capacities are estimated by using a combination of the Steam Pro software module of the Thermoflow Suite 18 package [1] and the IPP v2.1 optimization software tool [2]. The current work is part of an interdisciplinary collaboration between the Massachusetts Institute of Technology, the University of Illinois at Urbana Champaign, the Cyprus Institute and the Electricity Authority of Cyprus within the CSP-DSW project [3].

In section 2, a description of the existing CSP technologies that can be integrated with steam turbines for electricity generation is provided. In section 3, the input and output interfaces of the steam turbine cycle for various capacity sizes of CSP plants, as well as the estimation of efficiency and expected capital cost of the power block for various steam turbine capacities is carried out. The cost of electricity of CSP plants integrated with steam turbines is simulated in section 4. Finally, the conclusions are summarized in section 5.

2. CSP technologies

CSP technologies are suitable in areas with high solar irradiance. CSP plants offer a noticeable advantage when compared to photovoltaics (PVs), as large amounts of thermal energy can be stored easily with minimal losses and thus they can provide energy on demand (day and night). In this manner, CSP plants are capable of both reliably producing large quantities of power and, if they are part of a network with other renewable energies, compensating fluctuations of wind and PV energy. Hence they also contribute towards stabilizing the electricity grid. As a result, CSP plants allow greater use of fluctuating renewable energy sources (RES) within the electricity mix. A wide application of RES for electricity generation is envisaged in the Desertec project [4], where CSP systems, PV systems and wind parks would be spread over the Sahara desert. The main objective of Desertec project is the transmission of the produced RES electricity to European and African countries by a super grid of high-voltage direct current cables. The most important CSP technologies that could be integrated with steam turbines are (a) parabolic trough, (b) solar tower and (c) linear Fresnel.

2.1 Parabolic trough technology

A parabolic trough, which is the most commonly used CSP technology, is a long, trough-shaped reflector with a parabolic cross-section [5], as indicated in Figure 1. As a result of this cross-section, sunlight reflected within the trough is focused along a line running the length of the trough. In order to collect this heat, a pipe is positioned along the length of the trough at its focus and a heat collection fluid is pumped through it. The tube (or receiver) is designed to be able to absorb most of the energy focused onto it and must be able to withstand the resultant high temperature. Typical receivers for this purpose are made of steel tubing with a black coating and surrounded by a protective glass cover with the space between the two evacuated to reduce heat loss. An anti-reflective coating may be added to the outer glass surface to increase efficiency further.

The solar array of a parabolic trough power plant consists of several parallel rows of parabolic reflectors. The heat collecting fluid which is pumped through the pipes along the length of each solar trough is typically synthetic oil capable of operating at high temperature. During operation it is likely to reach temperatures between 300^oC and 400^oC. After circulating through the receivers the oil is passed through a heat exchanger where the heat it contains is extracted to raise steam in a separate sealed system and the steam is then used to drive a steam turbine generator to produce electricity. The heat collecting fluid is then cycled back through the solar collector field to collect more heat.

The parabolic troughs along which these tubular receivers run may be five to six meters wide, one or two meters deep and up to 150m in length. Many of these are required to collect sufficient energy to provide heat for a single power plant. As a consequence, these solar troughs form a physically large part of the solar plant and their cost can have a significant impact on plant economics.

Parabolic solar troughs are usually aligned with their long axes north south and they are mounted on supports that allow them to track the sun from east to west across the sky. In the first commercial plants the actual mirrors were made from 4mm glass which is both heavy and expensive. Modern developments aim to reduce the cost and weight by using new techniques and materials including polished aluminum instead of coated glass mirrors. Energy conversion efficiency is one of the keys to commercial success for solar thermal plants. The reflecting mirrors must be both accurately shaped, and accurately positioned in order to achieve maximum solar collection efficiency. Then the tracking system must ensure that each trough is in the optimum position, all day. Finally the tubular energy receivers must operate at the highest efficiency possible too.

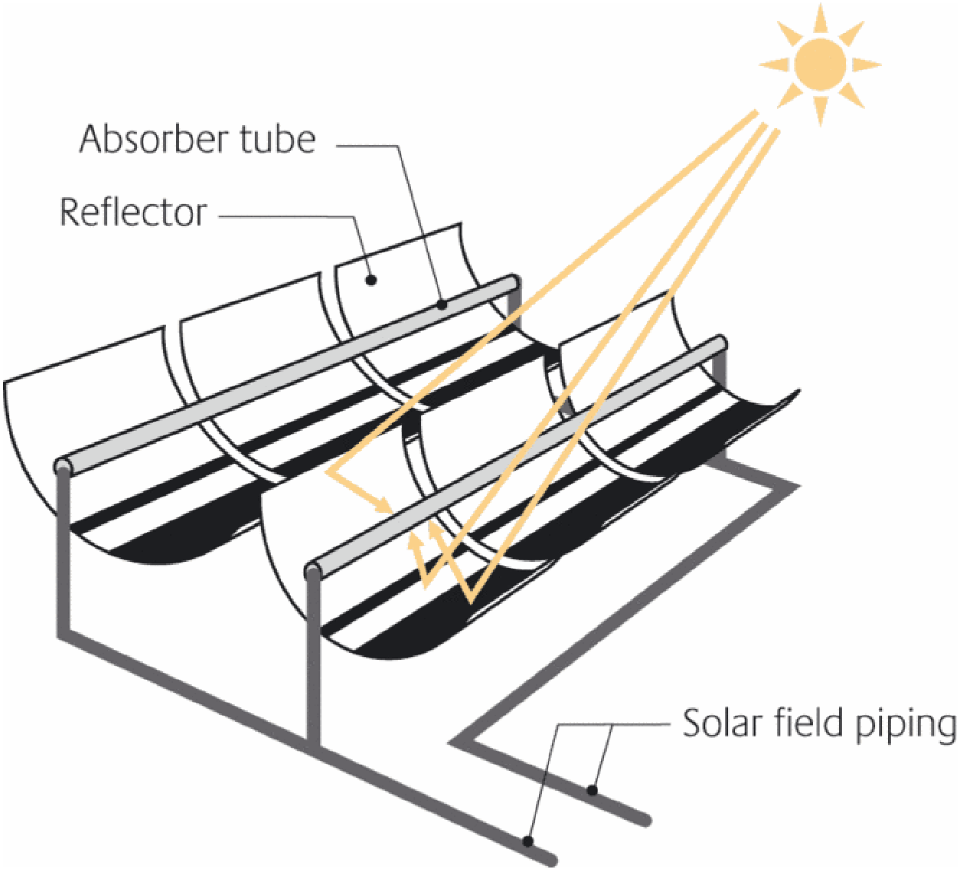

Figure 1. Principle of operation of parabolic trough system

2.2 Solar tower technology

Solar towers (often called solar central receiver power plants) offer an alternative method of exploiting the energy from the sun in a solar thermal power plant. In this case the collector field consists of an array of heliostats (mirrors) at the centre of which is a tower [5], as illustrated in Figure 2. At the top of the tower is a receiver designed to collect the heat from the sun.

In operation each heliostat has an individual tracking system and all are aligned so that the sunlight striking them is directed onto the receiver atop the central tower. As the sun moves across the sky, each mirror must be moved too if high collection efficiency is to be maintained. The receiver itself is designed to absorb the energy from the sunlight incident upon it and transfer it to a heat transfer fluid. Depending on system design, this heat transfer may be water, molten salt or air. Solar towers are normally designed with energy storage capability so that they can, in principle, operate 24 hours a day.

2.3 Linear Fresnel technology

Effectively, linear Fresnel reflector single axis tracking technology follows the principles of parabolic trough technology, but replaces the curved mirrors with long parallel lines of thin, shallow curvature (or even flat) mirrors or reflectors. These mirrors track the sunlight and are arranged in such way so that the direct solar irradiation is reflected and concentrated onto a stationary, single linear receiver (or absorber tube) located at a common focal point of the reflectors, several meters directly above them. The mirrors are capable of concentrating the sun’s energy to approximately 30 times its normal intensity. On top of the receiver, a small parabolic mirror can be attached (called secondary reflector) for further focusing the light [6], as shown in Figure 3. The receiver contains an absorber pipe where typically water is converted to steam in a process called direct steam generation, to drive a turbine to produce electricity. Typical steam conditions that can be generated by this technology at the steam turbine inlet of a Fresnel CSP plant are 270°C at 55bar. Optical efficiency of a typical linear Fresnel reflector system can reach 70%, and it is, however, still inferior to that of a parabolic trough system which is in the range of 75 – 80% [7, 8].

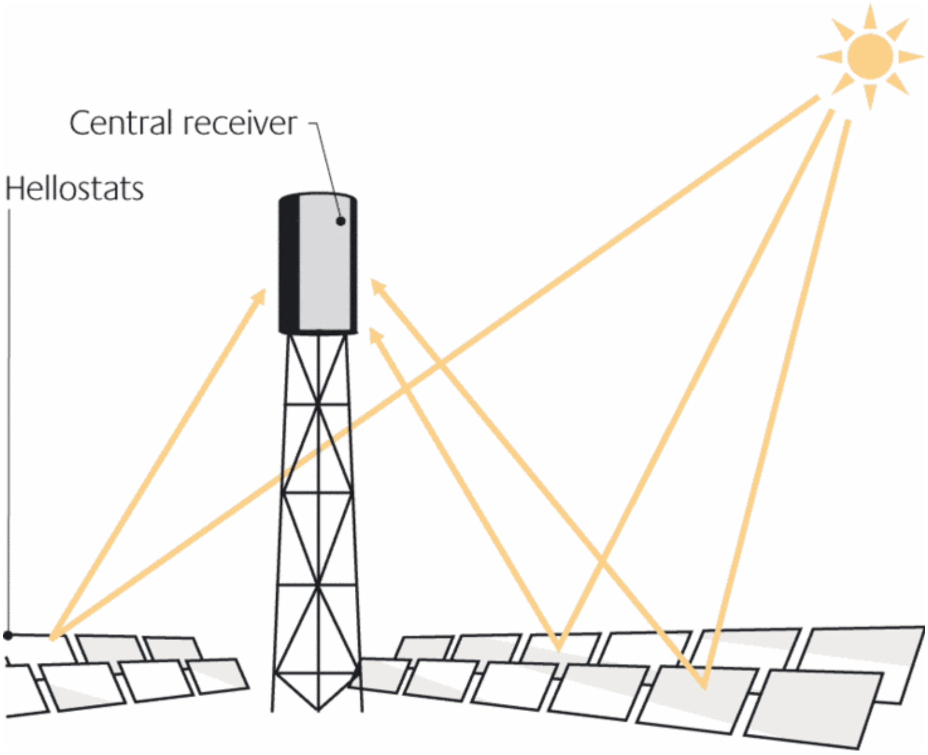

Figure 2. Principle of operation of solar tower system

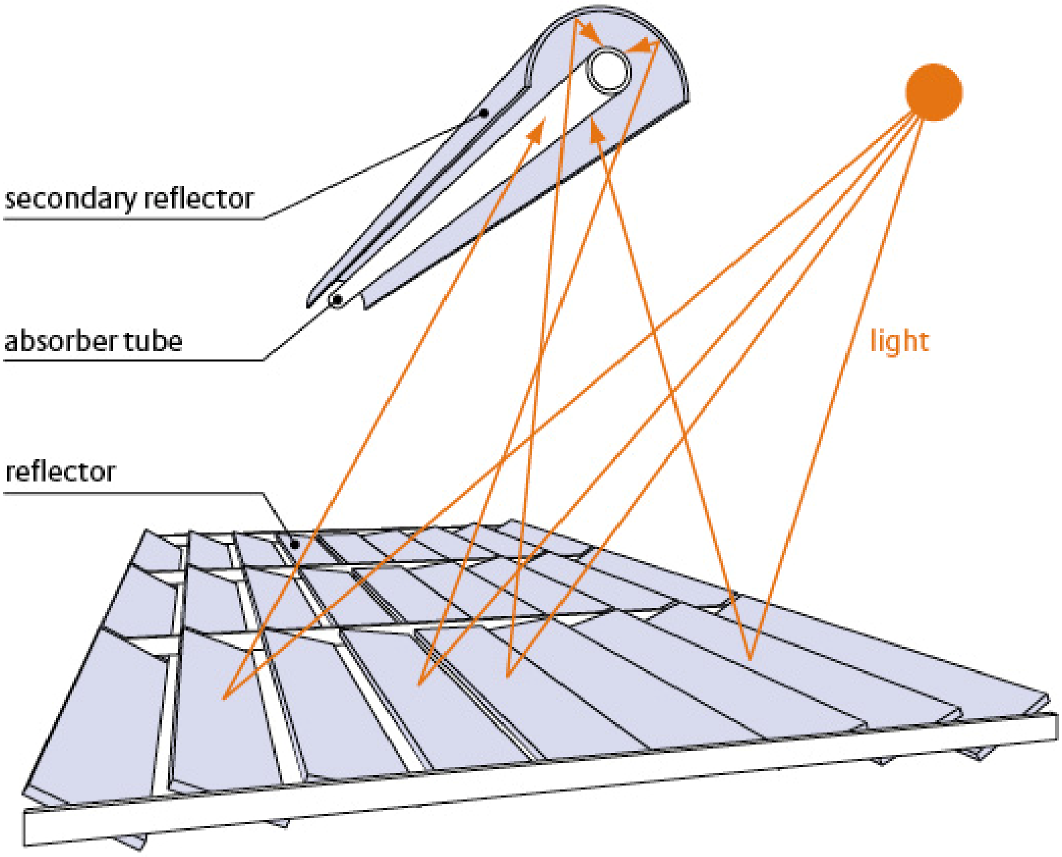

Figure 3. Principle of operation of linear Fresnel reflector solar system

A key component that makes all linear Fresnel reflector systems more advantageous than traditional parabolic trough mirror systems is the use of Fresnel reflectors. This greatly reduces the system's cost since curved glass parabolic reflectors are typically more expensive. Essentially, linear Fresnel technology systems aim to offer lower overall investment and operational costs, compared to parabolic trough technology.

A fundamental disadvantage of typical linear Fresnel reflector systems, apart from the lower plant efficiency, is that the receiver row is shared among several rows of mirrors. This can lead to the increased effect of shading of incoming solar radiation and blocking of reflected solar radiation by adjacent reflectors. The use of Compact Linear Fresnel Reflector (CLFR) technology, where the inclination of mirrors is alternated to focus solar energy on multiple linear reflectors, has been able to alternate this advantage and theoretically improve system efficiency.

3. Steam turbine optimum sizing

This analysis concerns the selection and the sizing of the optimum steam turbine to be integrated in various capacities of CSP plants. For the purpose of this analysis, the Steam Pro software module of the Thermoflow Suite 18 package [1] is used. The investigation covers all three major types of steam turbines, that is, condensing, back-pressure and extraction turbines, and also different power capacity sizes for the turbine, from 10kWe up to 100MWe. The extraction turbine was simulated for extraction pressures of 1, 2 and 6bar for designs up to 25MWe. For the 50MWe and 100MWe turbines the 6bar extraction pressure was reduced to 5.83bar, to avoid design modifications from the condensing turbine baseline design, which could possibly invalidate the comparison between the various parameters.

The results concerning the turbine inlet pressure are illustrated in Figure 4. It can be observed that by increasing the capacity of the plant, the inlet pressure of the steam into the turbine, at which maximum efficiency is obtained, also increases and for a capacity of the plant over 50MWe, the inlet pressure remains constant at 140bar. In the case of the inlet temperature, it is clear from Figure 5 that the inlet temperature of the steam into the turbine is constant at 540°C for all cases. From Figure 6, it is observed that the inlet steam flow into the turbine, at which maximum efficiency is obtained, increases linearly with the increase of the capacity of the plant. Particularly, for the case of condensing steam turbine, the exhaust pressure is at 50mbar, and the temperature at 33°C, which corresponds to steam quality of 0.85 at the turbine exhaust.

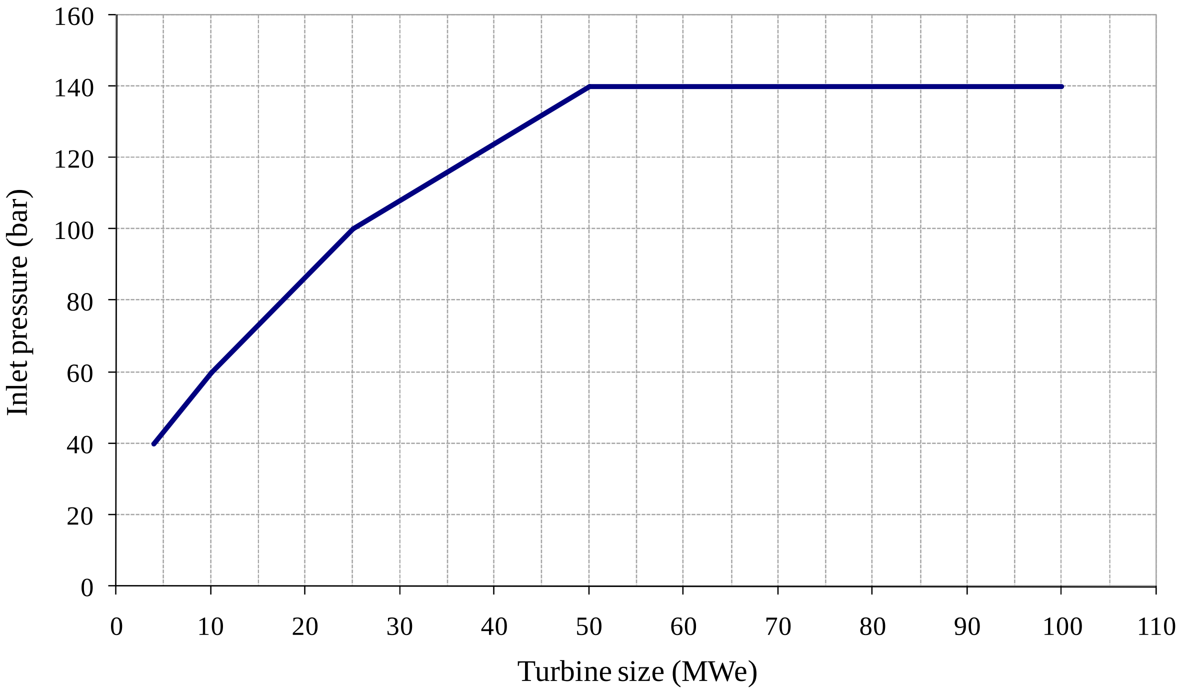

Figure 4. Inlet pressure of condensing, extraction and backpressure turbine

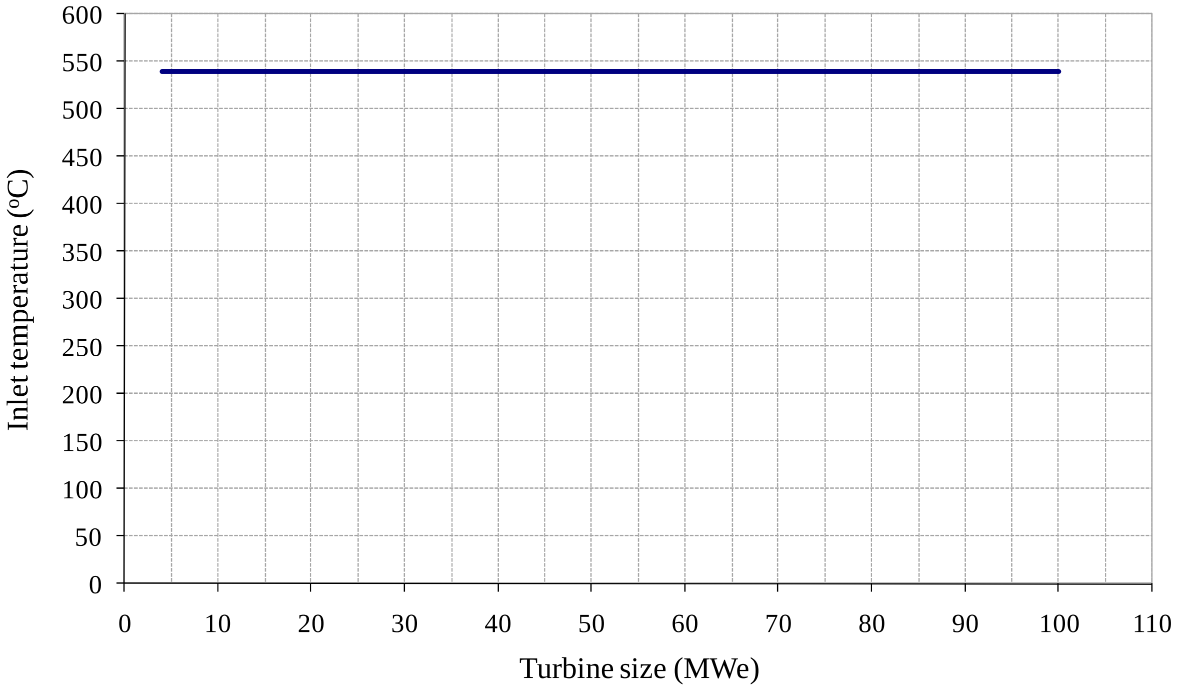

Figure 5. Inlet temperature of condensing, extraction and backpressure turbine

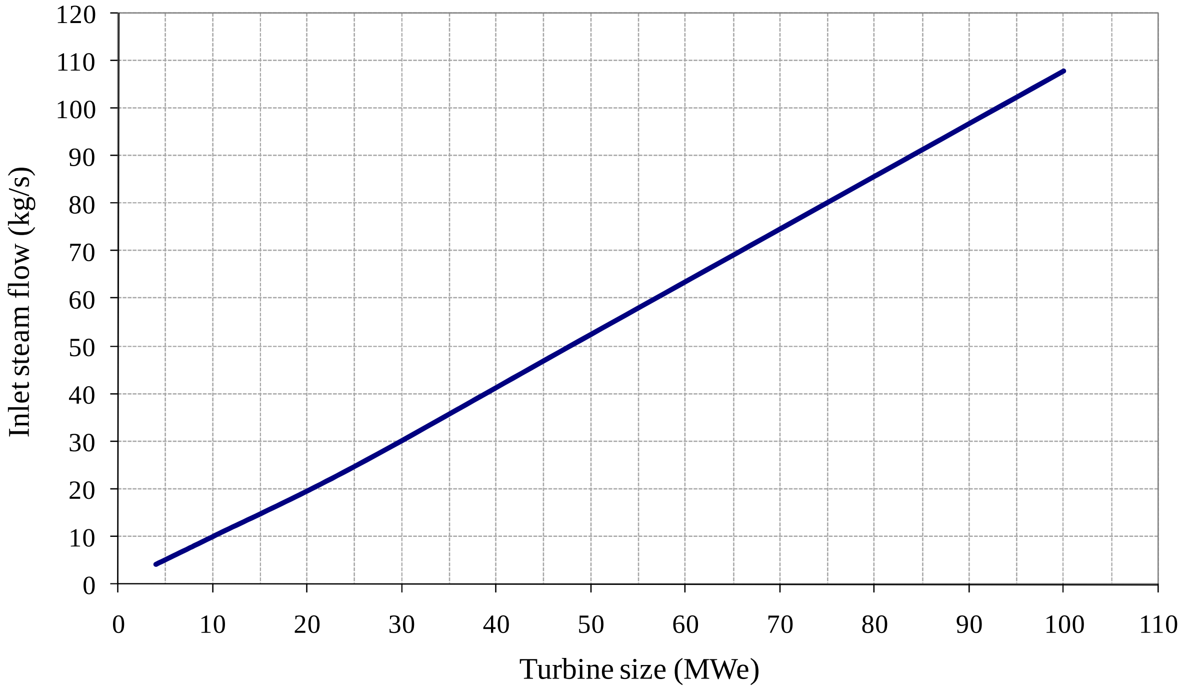

Figure 6. Inlet steam flow of condensing, extraction and backpressure turbine

The estimated maximum efficiency for different capacity sizes of steam turbines is tabulated in Table 1 and illustrated in Figure 7. For small to medium capacities up to 5MWe, it can be observed that the steam turbine efficiency increases at a relatively high rate. For larger capacities, the efficiency increases at lower rates. In fact, there is no significant gain if the power plant uses a steam turbine of 50MWe or 100MWe, there is however significant gain to be realized in increasing the turbine size up to 50 MWe.

Table 1. Optimum efficiency of various steam turbine sizes

Steam turbine size [kWe]	Maximum efficiency [%]
10	2.00
50	5.00
100	8.33
1000	22.25
10000	36.24
25000	39.22
50000	41.37
100000	42.92

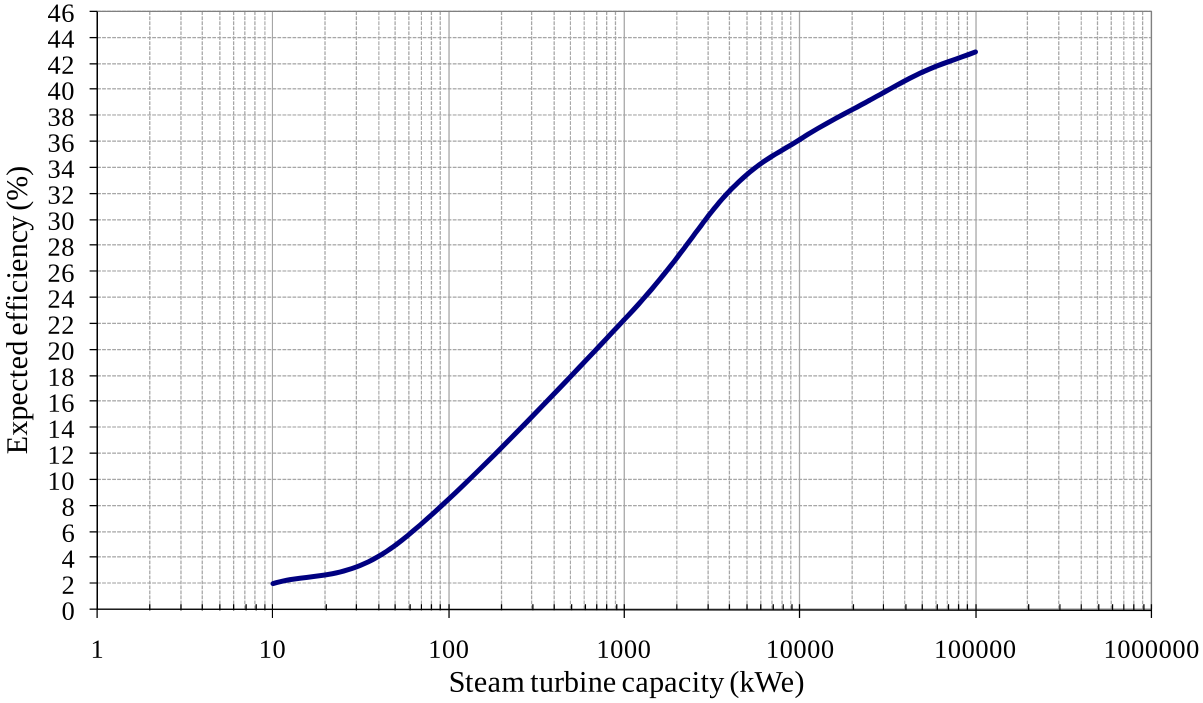

Figure 7. Maximum efficiency of the steam turbine

The expected specific capital cost of the power block, which includes the cost of the steam turbine, the condenser and the feed water heaters only, for different capacity sizes of steam turbines is illustrated in Figure 8. It can be observed that as the capacity of the steam turbine increases, the expected specific capital cost of the power block decreases with high rate, but for larger capacities it remains relatively constant at a minimum value. Thus, there is no significant difference in the expected specific capital cost of the power block if the size of the steam turbine is of 50MWe or 100MWe, but there are large cost savings in increasing the plant size up to50MWe.

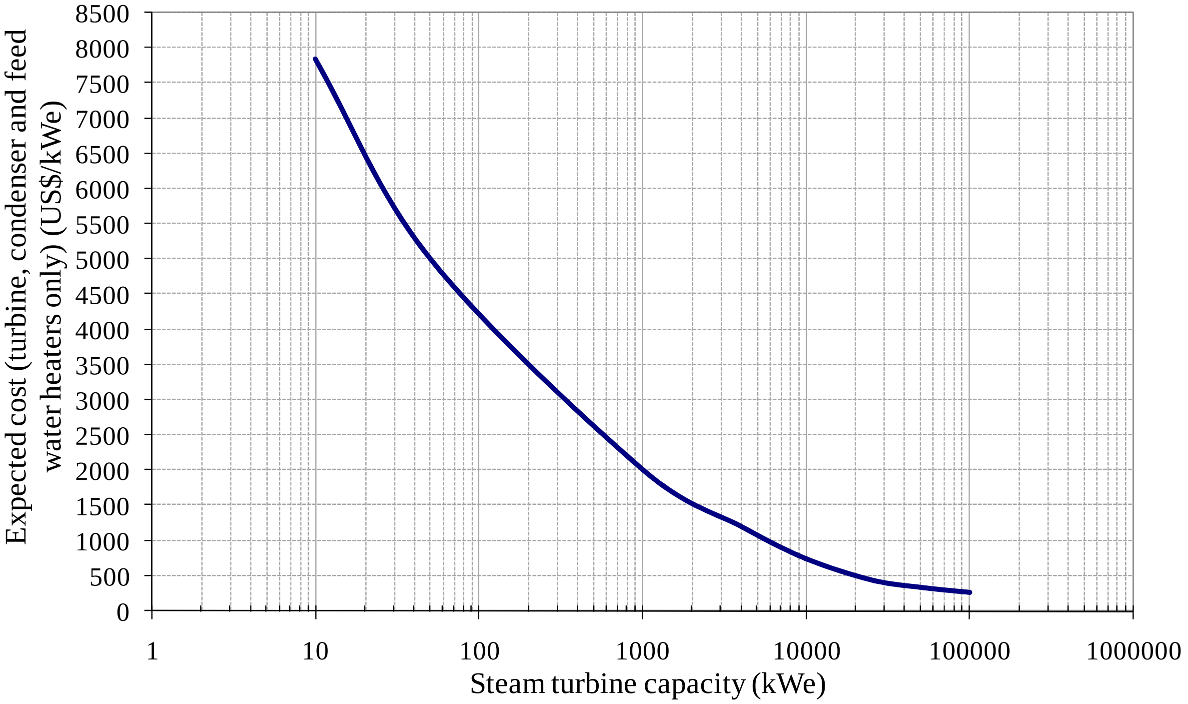

Figure 8. Expected capital cost of the power block (turbine, condenser and feed water heaters only)

4. Cost of electricity

In order to calculate the cost of electricity of a CSP plant, various capacity sizes, integrated with steam turbines are simulated by using the IPP v2.1 software tool [2, 9]. Throughout the simulations, a typical discount rate of 6% and an inflation rate of 2.5% are assumed. Also, the economic life of the CSP plants is assumed to be 20 years.

The results concerning the optimum cost of electricity of the different capacity sizes of CSP plants are tabulated in Table 2 and illustrated in Figure 9. It can be observed that the cost of electricity is reduced from 10kWe up to 1MWe, whereas for higher capacities it remains relatively constant at a minimum value. Although, for CSP plants greater than 1MWe the cost of electricity is below 1US$/kWh, with a minimum value of 0.42US$/kWh for 100MWe, this is still a very high cost for electricity generation compared to generation plants using conventional fuels. Therefore, adequate financial support schemes are necessary in order for CSP plants to become economically viable.

Table 2. Optimum electricity unit cost of various CSP capacities

CSP capacity [kWe]	Electricity unit cost [US$/kWh]
10	21.73
50	6.43
100	4.43
1000	1.04
10000	0.54
25000	0.48
50000	0.45
100000	0.42

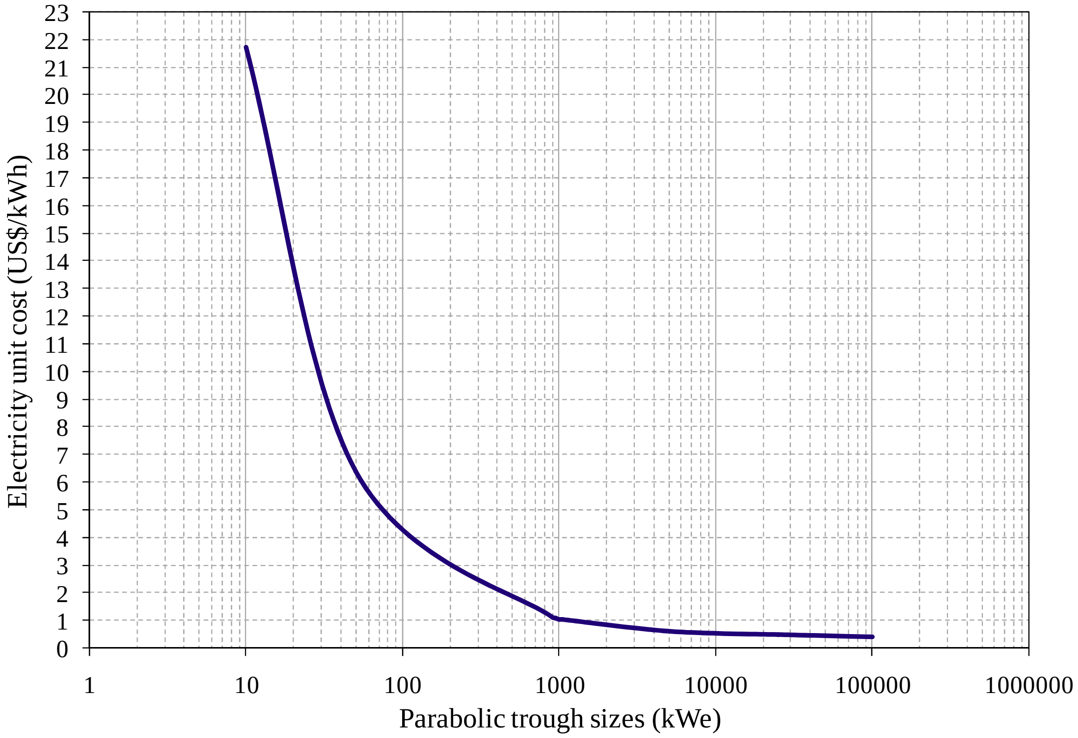

Figure 9. Optimum electricity unit cost of various CSP capacities

5. Conclusions

In this work, a selection of the optimum steam turbine type and size for integration in various capacity sizes of CSP plants has been carried out. The results indicate that by increasing the capacity of the plant, the steam inlet pressure of the turbine at which maximum efficiency can be obtained increases up to a capacity of 50MWe and then remains constant at 140bar. The steam inlet temperature of the turbine is constant at 540°C for all the examined types and sizes of steam turbines. Furthermore, the inlet steam flow into the turbine is linearly depended on the size of the turbine and therefore on the installed capacity of the CSP plant.

The estimated efficiency and the expected specific capital cost of the power block are very important criteria in choosing the optimum steam turbine size of the CSP plant. For capacity sizes of 10kWe up to 50MWe, the steam turbine efficiency increases and the steam turbine expected specific capital cost of the power block decreases with high rate, whereas for larger capacities they remain relatively constant. Thus, there is significant efficiency gains to be realized and large cost savings in increasing the turbine size above 50MWe. Finally, although the cost of electricity of a CSP plant with capacities greater than 1MWe is significantly reduced to less than 1US$/kWh, currently such technology can only become economically viable through supporting schemes.

Acknowledgements

The work presented in this paper is part of an interdisciplinary collaboration between the Massachusetts Institute of Technology, the University of Illinois at Urbana Champaign, the Cyprus Institute and the Electricity Authority of Cyprus. We would like to thank our colleagues in the project for the fruitful discussions.

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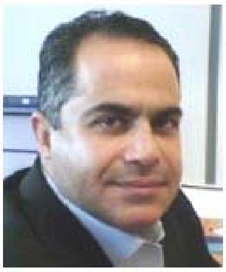

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