

# LIGHT SOURCE SELECTION FOR A SOLAR SIMULATOR FOR THERMAL APPLICATIONS: A REVIEW

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## Abstract

Solar simulators are used to test components and systems under controlled and repeatable conditions, often in locations with unsuitable insolation for outdoor testing. The growth in renewable energy generation has led to an increased need to develop, manufacture and test components and subsystems for solar thermal, photovoltaic (PV), and concentrating optics for both thermal and electrical solar applications. At the heart of any solar simulator is the light source itself. This paper reviews the light sources available for both low and high-flux solar simulators used for thermal applications. Criteria considered include a comparison of the lamp wavelength spectrum with the solar spectrum, lamp intensity, cost, stability, durability, and any hazards associated with use. Four main lamp types are discussed in detail, namely argon arc, the metal halide, tungsten halogen lamp, and xenon arc lamps. In addition to describing the characteristics of each lamp type, the popularity of usage of each type over time is also indicated. This is followed by guidelines for selecting a suitable lamp, depending on the requirements of the user and the criteria applied for selection. The appropriate international standards are also addressed and discussed. The review shows that metal halide and xenon arc lamps predominate, since both provide a good spectral match to the solar output. The xenon lamp provides a more intense and stable output, but has the disadvantages of being a high-pressure component, requiring infrared filtering, and the need of a more complex and expensive power supply. As a result, many new solar simulators prefer metal halide lamps.

## Keywords

Solar simulator, sunlight, solar spectrum, CSP, metal halide, tungsten lamp

## 1 Introduction

The growing demand for energy, combined with issues of environmental pollution, climate change, and the rapid depletion of fossil fuels, have encouraged the research and development of cost effective renewable alternatives [1–3]. Solar electrical and thermal energy research groups have focused on developing novel technologies and on improving existing renewable solutions. In 2014, the global combined installed capacity of solar hot water and concentrating solar power (CSP) was 410.4 GW, representing 8% of the world's renewable energy sources [4].

The transient nature of solar energy represents a critical challenge for technologies testing. Outdoor experiments are carried out in real but uncontrollable environments. For example, incident solar energy levels are highly dependent on atmospheric conditions and sky clarity over time [5]. Therefore, achieving

the rapid and low-cost development of solar thermal and PV systems requires a controlled environment with key parameters that can be adjusted and monitored. Consequently, a range of solar simulators have been designed and used since the 1960's.

A solar simulator is a device with a light source which offers both an intensity level and a spectral composition close to that of natural sunlight [6]. It is used to simulate either extra-terrestrial or terrestrial radiation [7]. Early solar simulators were designed and built in the 1960's to be used in space applications research projects sponsored by the National Aeronautics and Space Administration (NASA) for spacecraft ground-testing by simulating environments at orbital altitudes [8–10]. More recently, research work has focused on terrestrial radiation simulators. These devices are used for a wide range of applications including testing, calibrating and characterising photovoltaic (PV) cells [11–14] and for the clinical testing of sunscreens [15–17]. The list of applications extends to the automotive industry for testing dashboards, steering wheels and air bags [18–20]; PV materials ageing tests [21–24]; studying the effects of light on the growth of plants and algae [25–27] and testing of thermal/thermo-chemical devices for use in the chemical reforming and production of chemical elements [28–30]. This paper deals with solar simulators built for thermal applications, although they are also relevant to PV and concentrating PV (CPV) testing [31–35]. More applications are covered in section 3. Such simulators have output fluxes ranging from a few suns (1 sun = 1 kW/m<sup>2</sup> [36–38]), to more than 30 suns, which are classified as low and high-flux solar simulators, respectively [39]. Those simulators consist of three main parts: a light source, a power supply and an optical component. Each part is selected to obtain a controlled output conforming to specific requirements. The current work focuses on the selection of a suitable light source, which is critical to ensure simulated solar radiation quality and reliability [40].

## 2 Standard Solar Spectrum

### 2.1 Blackbody radiator spectrum

A blackbody is an idealised object which is a perfect radiation emitter and absorber [41]. A blackbody radiator has the maximum possible spectral radiance for a heated body at a particular specified temperature. Therefore, this temperature is usually used as a convenient baseline for comparison with real radiation sources [42]. The sun can be considered as a blackbody radiator at a temperature of 5777K, which can be approximated to 5800K [43–46]. Spectral radiance of a blackbody can be determined, in W.m<sup>-3</sup>.sr<sup>-1</sup>, by applying Planck's law [47]:

$$E_{\lambda} = (2hc^2/\lambda^5)(e^{hc/\lambda kT} - 1)^{-1} \quad (1)$$

Where  $h$  is Planck's constant (6.6262×10<sup>-34</sup> J.s),  $c$  is the velocity of light (2.9979×10<sup>8</sup> m/s),  $\lambda$  is the wavelength (m),  $k$  is the Boltzmann's constant (1.3806×10<sup>-23</sup> J/K), and  $T$  is absolute temperature (K).

### 2.2 Solar spectrum

The actual solar spectrum differs from a blackbody radiance at 5800K because of absorption in the cool peripheral solar gas (Fraunhofer lines) [72, 73]. While passing through the Earth's atmosphere, direct solar radiation is attenuated by scattering and absorption by gaseous molecules (i.e. nitrogen, oxygen, aerosols and water vapour) [50]. Therefore, an Air Mass (AM) coefficient has been defined to characterise the solar spectrum after the solar radiation has travelled through the atmosphere [51]. The

AM coefficient is defined as the ratio of the solar radiation path length through the atmosphere ( $L$ ), incident at a zenith angle ( $z$ ), and the atmosphere thickness in the zenith direction ( $L_0$ ) [52]:

$$AM = L/L_0 = 1/\cos z \quad (2)$$

Although this relation can be refined by modelling more accurate path thicknesses through the horizon [53–55], equation (2) remains commonly used to define standard conditions for solar applications. It is expressed using the syntax "AM" followed by its value [51]. The variation between different AM definitions (i.e. AM0, AM1.0 and AM1.5) is illustrated in Fig. 1.

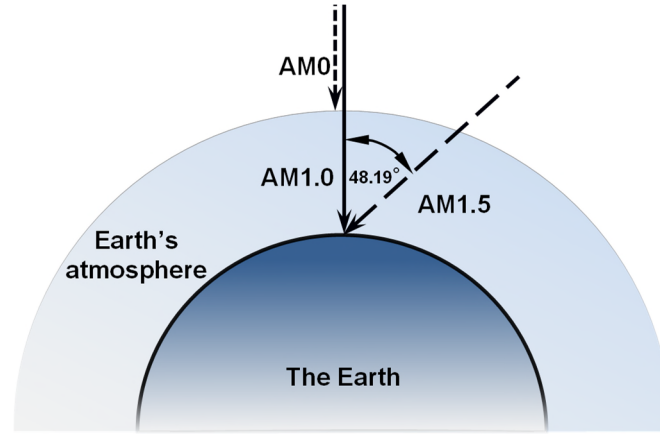


**Fig. 1. Air Mass (AM) definition (adapted from [56])**

The extra-terrestrial solar spectrum (**AM0**) is used to characterise PV panels used for space applications [57]. There are various solar irradiance spectra constructed from single and/or multiple measurement sets or models [58,59]. However, for space solar power applications, the standard ASTM E490 [60] is usually applied. The solar spectrum travelling through the atmosphere directly to sea level with a zenith angle of zero (**AM1.0**) is published by ASHRAE [61]. As solar panels and collectors operate at tilted angles, the solar radiation path is greater than one atmosphere's thickness [57]. Since the world's major solar installations and industry centres are located [62] at mid-latitudes, a specific AM number was defined for a zenith angle of 48.19°. Since the 1970s, **AM1.5** has been used for standardisation purposes [63–65] provided by ASTM G173–03 standard; previously ASTM G159-98 [66,67].

The solar spectrum is divided into three main regions: ultraviolet (UV), visible, and infrared (IR) with wavelength ranges of <400nm, 400–760nm, and >760nm respectively [68]. According to the International Commission on Illumination (CIE), the UV region can be defined in three bands: UV-A (315–400nm), UV-B (280–315nm) and UV-C (100–280nm) [69,70]. Fig. 2 shows a comparison between different solar spectra and the radiation spectrum of a blackbody at 5800K. The differences between the spectrum curves in Fig. 2 are attributed to the attenuation and transmission losses of sunlight over its optical path through the Earth's atmosphere. Therefore, the longer optical path shows the least spectral irradiance. However, data plotted in Fig. 2 confirms the assumption of treating the sun as a blackbody radiator at 5800K.

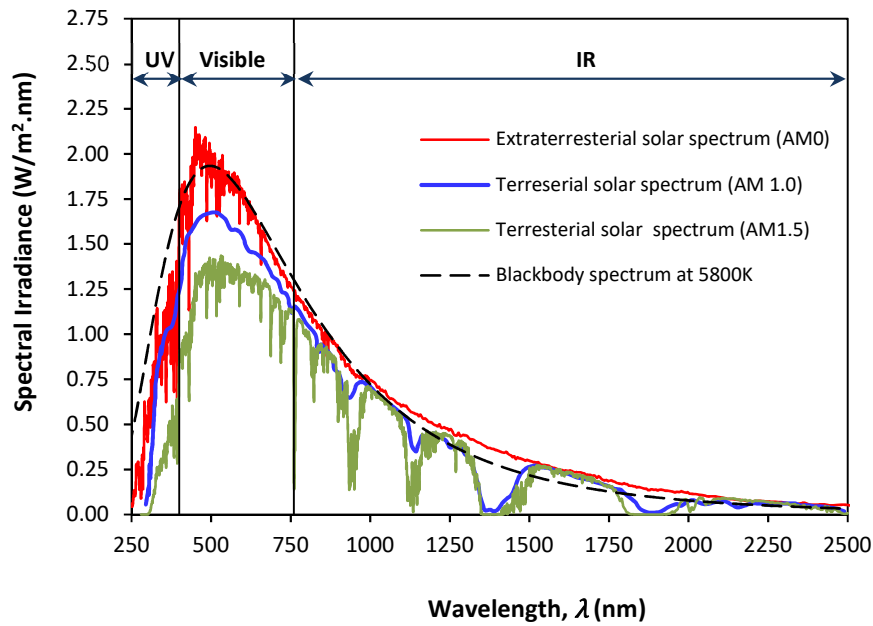


**Fig. 2. Comparison between solar spectra (AM0 [60], AM1.0 [61], AM1.5 [66]) and black body radiator spectrum [71]**

### 3 Light sources

Light source selection is the principal step in designing a solar simulator with suitable simulated solar radiation. This light source is required to meet several criteria: spectral quality, illumination uniformity, collimation, flux stability and a range of obtainable flux [72].

Various lamp types have been employed in solar simulators, including carbon arc, metal halide, tungsten halogen, xenon arc, mercury xenon, high pressure sodium vapour, argon arc and light-emitting diode lamps (LED) [33]. The choice can depend on the field of application of the solar simulator. For example, the optimum output current of a PV cell is generated when the incident spectrum matches with the spectral absorption properties of the semiconductor [107] and are more sensitive to the incident light spectrum below 1000nm for a silicon PV cell [33,73–76]. Multi-junction PV cells are more sensitive to the spectrum of the light source which affects their fill factor and short-circuit resistance [77]. Therefore, researchers tended to use multi-light source synthesis to improve the spectral matching for PV performance testing. These simulators employ either conventional light sources, such as xenon arc and tungsten lamps [78–80], or multiple LEDs with an adjustable emitted spectrum [81–83]. Due to this sensitivity, different classification standards of solar simulators for PV testing have been developed to classify solar simulators. These standards were developed by the International Electrotechnical Commission (i.e. IEC 60904-9), and also the American Society for Testing and Materials (i.e. ASTM E927, ASTM E948, ASTM E1036, ASTM E1362), and include Japanese Industrial Standards (i.e. JIS C 8912) and British Standards (i.e. EN 60904) [84–90].

For solar simulators used in terrestrial thermal applications, the principal parameters determined are: the peak flux, the total beam power and the flux density distribution [91]. They are less sensitive to the incident spectrum in the UV and visible compared to the IR spectrum part, as infrared represents most of the thermal radiation emitted by terrestrial objects [92–94]. Therefore, a mono-light source type is

usually employed with single or multiple lamp configurations. Moreover, the low sensitivity to the light source output spectrum minimises lamp's specifications requirements defined by standards related to solar thermal applications, including the International Standards (ISO 9806, ISO 19467) and British Standards (i.e. EN 12975-1, EN 12975-2, EN 12976-1 and EN 12976-2) [95–100].

For these simulators, the selected lamp types are usually argon arc, metal halide, tungsten halogen or xenon arc.

### 3.1 Argon arc lamp

The Argon arc lamp is a free-burning DC powered device [101]. The pressurised argon gas (with approximate pressure of 7–10 bar [102–104]) enters at the cathode end, swirls along the central core until it exits at the anode end. In order to cool the arc edge, a sheet of water is created by swirling a high flow rate water vortex along the inside quartz tube wall with pressure over 60 bar at the inlet [108, 110], as shown in Fig. 3.

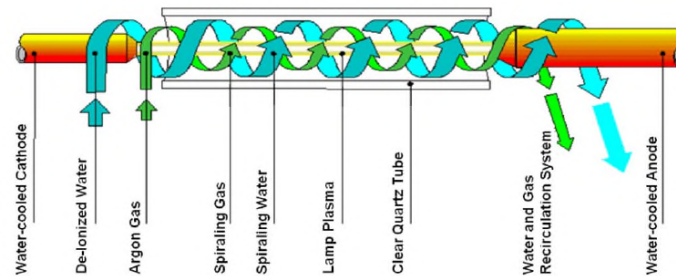


**Fig. 3. Schematic of vortex water-wall argon arc lamp [111, 112]**

These lamps have been used since the 1970s [108, 113–115] in the solar simulation field as well as in laser applications [111].

### 3.2 Metal halide lamp

In a metal halide lamp, the light is produced by an electric arc which is generated through a gaseous mixture of vaporized mercury and metal halide compounds under a high pressure ranging from 10 to 35 bar [112–114]. It is a type of high-intensity discharge (HID) gas lamp [115], as illustrated in Fig. 4.

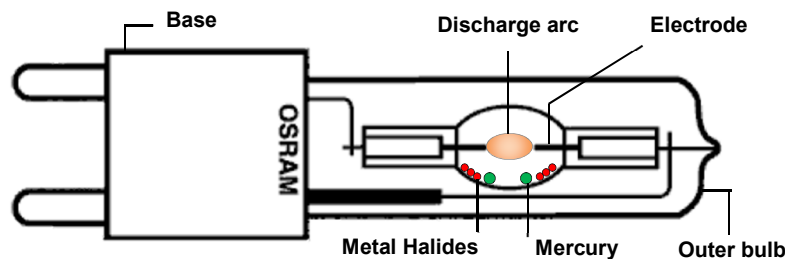


**Fig. 4. Metal halide lamp structure (adapted from [116,117])**

Metal halide lamps were introduced as a light source option for solar simulation after the development of compact source iodide (CSI) metal halide lamps [6]. Those CSI lamp types have high efficiency, a balanced spectral quality closely matching sunlight, long lifetime and relative low cost. Therefore, many researchers selected them for their simulators [31,118–126]. Other types of metal halide lamps have also been tested [7,39,72,127–137].

### 3.3 Tungsten halogen lamp

A Tungsten halogen lamp is a type of incandescent lamp which contains a halogen in the form of bromine or iodine surrounding a tungsten filament heated by an electric current [138,139], as shown in Fig. 5.

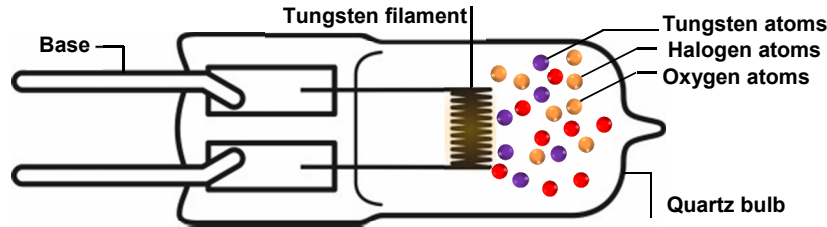


**Fig. 5. Tungsten halogen lamp structure (adapted from [140,141])**

While incandescent lamps have a maximum colour temperature of 3400K [142], according to the Wien displacement law [143], these lamps radiate weaker in the ultraviolet and stronger in the infrared regions compared to the solar spectrum with its colour temperature of 5800K [44–46]. Despite this disadvantage, tungsten halogen lamps have been utilised in solar simulation [123, 129, 150–157]. This may be attributed to their excellent light output and relatively low cost [152]. They are widely used in less spectrum-sensitive applications such as concentrated solar collector testing and as an infrared light source in multi-source solar simulators [6].

### 3.4 Xenon arc lamp

The Xenon arc lamp is a type of HID gas discharge lamp in which light is produced by passing an electric arc through ionized xenon gas under high pressure ranging from 10 to 40 bar [6, 159, 160], as shown in Fig. 6.

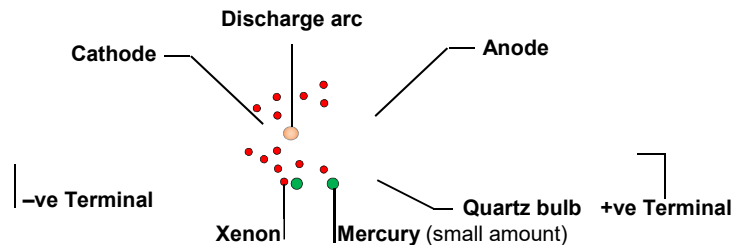


**Fig. 6. Xenon arc lamp structure (adapted from [155–157])**

These lamps are often preferred by manufacturers and researchers as a light source for solar simulators [6, 39, 40, 62, 98, 123, 164–179]. They benefit from an excellent quality and stable spectrum in the UV and visible bands. Their strong emission in the IR range can be filtered [142] if required. Moreover, a collimated high intensity light beam can be generated as a result of a brighter point source than other light sources [176]. However, operation of these lamps under high pressure creates an increased risk of explosion [177]. In addition, the UV radiation emitted by these lamps can generate ozone, which can create a respiratory hazard [178]. Besides health and safety concerns, their high cost and output sensitivity to power supply instabilities represent significant drawbacks that need to be carefully considered before using them in solar simulators [6,39,142,176].

### 3.5 Trends in using light sources

Table 1 summarises a list of thermal solar simulators details published in literature.

**Table 1. Comparison of different thermal solar simulators (chronological order)**

| Lamp type             | Lamp power (kW <sub>e</sub> ) | Number of lamps | Total output flux (kW <sub>r</sub> /m <sup>2</sup> ) | Spot dimensions (m) | Calculated conversion efficiency <sup>1</sup> (%) | Reference(s)       |
|-----------------------|-------------------------------|-----------------|------------------------------------------------------|---------------------|---------------------------------------------------|--------------------|
| Argon-arc lamp        | 400 DC                        | 2               | 1.21                                                 | 4.6x9.2             | 6.42                                              | [103]              |
|                       | 100 DC                        | 1               | 0.25–1.25                                            | 1.5x0.50            | 0.94                                              | [108]              |
|                       | 100 DC                        | 1               | 1                                                    | 1.5x0.50            | 0.75                                              | [109]              |
|                       | 150 DC                        | 1               | 6680                                                 | Ø0.01905            | 1.27                                              | [179,180]          |
|                       | 200 DC                        | 1               | 4250                                                 | Ø0.06               | 6.01                                              | [110,181]          |
| Metal halide lamp     | 1                             | 19              | 0.4–0.9                                              | Ø2.25               | 18.83                                             | [127–129]          |
|                       | 1                             | 36              | 0.2–1.1                                              | 2x2                 | 12.22                                             | [31,118]           |
|                       | 1                             | 36              | 1–1.2                                                | 1.2x2.4             | 9.60                                              | [118]              |
|                       | 1                             | 27              | 0.6–1                                                | 1.5x1.8             | 10.00                                             | [119]              |
|                       | 1                             | 55              | 0.865                                                | 2.5x2.3             | 9.04                                              | [120,121,126]      |
|                       | 1                             | 72              | 0.4–0.8                                              | 3x3                 | 10.00                                             | [122] <sup>2</sup> |
|                       | 1                             | 40              | 0.7–1                                                | 1.4x3               | 10.50                                             | [123]              |
|                       | 1                             | 28              | 0.983–1.188                                          | 1.06x1.06           | 4.77                                              | [124,125]          |
|                       | 1                             | 18              | –                                                    | –                   | –                                                 | [72,130]           |
|                       | 1.5                           | 7               | 60                                                   | Ø0.38               | 64.81                                             | [39,131]           |
|                       | 1.2                           | 1               | 0.8–1                                                | –                   | –                                                 | [132,133]          |
|                       | 0.4                           | 188             | 0.15–1.1                                             | 4.5x3.88            | 25.54                                             | [7]                |
|                       | 6                             | 1               | 112                                                  | 0.095x0.095         | 16.85                                             | [134]              |
|                       | 6                             | 7               | 927                                                  | Ø0.175              | 53.09                                             | [135]              |
|                       | 2.5                           | 6               | –                                                    | 50x0.4              | –                                                 | [136]              |
|                       | 1.2                           | 15              | 1                                                    | 2.5x1.5             | 20.83                                             | [32]               |
|                       | –                             | 35              | 0.8                                                  | –                   | –                                                 | [182]              |
|                       | 0.575                         | 35              | 1.2                                                  | 1.8x2.2             | 23.61                                             | [183,184]          |
|                       | 0.4                           | 88              | 0.15–1                                               | 1.6x1.6             | 7.27                                              | [185]              |
|                       | 1 & 2                         | 6x1kW & 6x2kW   | 0.1–1                                                | 2.8x 2.7            | 42.00                                             | [186]              |
|                       | 4                             | 32              | 1                                                    | 11x9.2              | 79.06                                             | [137]              |
| Tungsten halogen lamp | 0.3                           | 143             | 0.61–1.05                                            | 1.2x1.2             | 3.52                                              | [144–146]          |
|                       | 0.3                           | 12              | 0.102–0.55                                           | 1.2x1.2             | 22.00                                             |                    |
|                       | 0.3                           | 405             | 0.395–0.962                                          | 2x3                 | 4.75                                              |                    |
|                       | 0.3                           | 187             | 0.5–1.1                                              | 1.2x1.8             | 4.24                                              | [118]              |
|                       | 0.3                           | 200             | 0.5–1.46                                             | (1.6 m2)            | 3.89                                              | [118]              |
|                       | 0.15                          | 10              | 0.8                                                  | 0.12x0.50           | 3.20                                              | [148]              |
|                       | 0.15                          | 15              | 1.8                                                  | 0.40x0.60           | 19.20                                             |                    |
|                       | 0.3                           | 96              | 0.7–1                                                | 1.4x3               | 14.58                                             | [123]              |
|                       | 1                             | 14              | 0.4–1.5                                              | 1x1                 | 10.71                                             | [149]              |

<sup>1</sup> Energy conversion is defined and explained later in detail in section 4.5.

<sup>2</sup> Their measurements indicated that 143 klx is equivalent to 1kW/m<sup>2</sup>, while it was reported that 139 klx corresponds 1kW/m<sup>2</sup> [152].

| Lamp type      | Lamp power (kW <sub>e</sub> ) | Number of lamps    | Total output flux (kW <sub>r</sub> /m <sup>2</sup> ) | Spot dimensions (m) | Calculated conversion efficiency <sup>1</sup> (%) | Reference(s)      |
|----------------|-------------------------------|--------------------|------------------------------------------------------|---------------------|---------------------------------------------------|-------------------|
|                | 0.74                          | 6                  | 25                                                   | Ø0.1524             | 10.27                                             | [150]             |
|                | 0.3                           | 45                 | 0.6                                                  | 1.2x2.4             | 12.80                                             | [187]             |
|                | 0.3                           | 20                 | 0.5–0.645                                            | 2x0.46              | 9.89                                              | [188]             |
|                | 1                             | 4                  | 5.38–7.094                                           | –                   | –                                                 | [189,190]         |
|                | 0.3                           | 2                  | 0.425–0.918                                          | Ø0.12               | 1.73                                              | [191]             |
|                | 0.3 & 0.5                     | 4x0.3kW & 12x0.5kW | 0.63                                                 | 1.9x0.55            | 9.14                                              | [192]             |
|                | 0.4                           | 30                 | 0.2–1.2                                              | 1.45x1.6            | 23.20                                             | [151]             |
| Xenon-arc lamp | 20                            | 7                  | 0.135–2.95                                           | ~ Ø3.05             | 15.40                                             | [118]             |
|                | 6.5                           | 10                 | 0.1–1.7                                              | Ø1.6                | 5.26                                              | [118,159]         |
|                | 20                            | 1                  | 3,000                                                | Ø0.015              | 2.65                                              | [158]             |
|                | 6                             | 10                 | 4100                                                 | ~ Ø0.11             | 64.94                                             | [91,161,162]      |
|                | 30                            | 9                  | 1.7                                                  | Ø4.8                | 11.39                                             | [160,193]         |
|                | 15                            | 10                 | 6800                                                 | Ø0.06               | 12.82                                             | [163,164,194,195] |
|                | 15                            | 10                 | 11,000                                               | Ø0.003              | 0.05                                              |                   |
|                | 5                             | 1                  | 10                                                   | ~ Ø0.20             | 6.28                                              | [165]             |
|                | 6.5                           | 7                  | 3250–3700                                            | Ø0.06               | 22.99                                             | [166–168]         |
|                | 7                             | 1–12 <sup>3</sup>  | 54                                                   | Ø0.30               | 54.53                                             | [169]             |
|                | 6                             | 7                  | 4230                                                 | –                   | –                                                 | [170]             |
|                | 7                             | 12                 | 627                                                  | Ø0.20               | 23.45                                             | [171,175]         |
|                | 7                             | 1                  | 43.2                                                 | Ø0.11               | 5.86                                              | [33]              |
|                | 6                             | 7                  | 1860                                                 | Ø0.06               | 12.52                                             | [172,173]         |
|                | 7                             | 19                 | 735–1100                                             | Ø0.2                | 25.98                                             | [196]             |
|                | 7                             | 1                  | 329                                                  | 0.06x0.06           | 16.92                                             | [197]             |
|                | 3                             | 1                  | 100                                                  | 0.06x0.06           | 12.00                                             | [34,198–200]      |
|                | 3                             | 1                  | 1200                                                 | 0.005x0.005         | 1.00                                              |                   |
|                | 10                            | 1                  | 10,000                                               | Ø0.01               | 7.85                                              | [201,202]         |
|                | 1                             | 6                  | 0.05–0.8                                             | –                   | –                                                 | [203]             |
|                | 30                            | 9                  | 1.8                                                  | Ø4.79               | 12.01                                             | [204–207]         |
|                | 3                             | 1                  | 3.675                                                | Ø0.91               | 79.67                                             | [208]             |
|                | 5                             | 20                 | 18–24.3                                              | 0.4x0.07            | 0.68                                              | [174]             |

Using data listed in Table 1, solar simulators were categorised based on their year of construction (ten-year era) and the lamp type selected (Fig. 7).

<sup>3</sup> [169] carried out theoretical study based on 12 lamps, while experiments were reported on a single lamp.

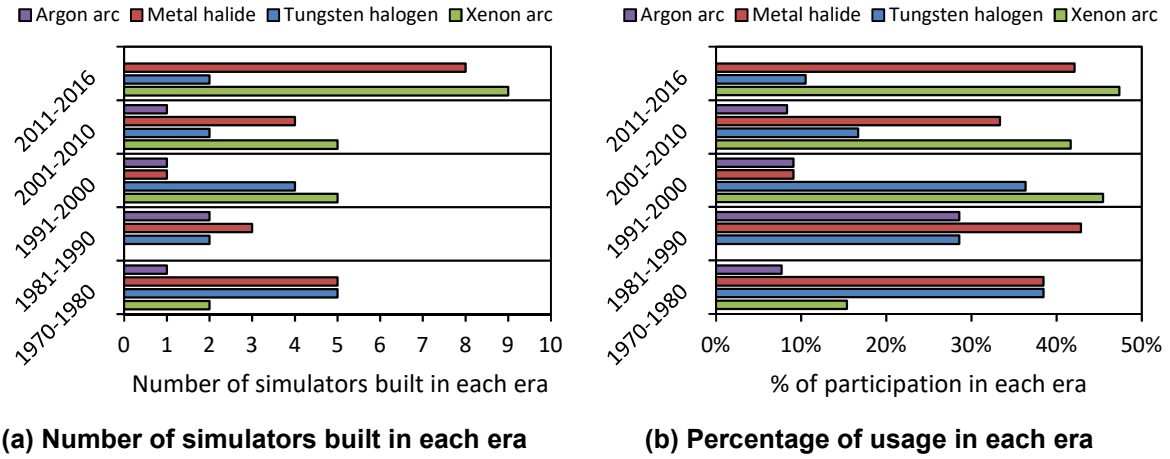


**Fig. 7 Light sources usage share in different eras**

The number of simulators built in each era and usage percentages per era are shown in Fig. 7a and Fig. 7b respectively. The participation share over the period from 1970 to 2016, based on 62 cases listed in Table 1, showed that the most popular lamp types are metal halide and xenon arc lamps with usage share of 34% each, while 24% of listed cases used tungsten halogen lamps. It can be observed that in 1970-80s, researchers used principally low-cost and available tungsten halogen and metal halide lamps rather than xenon or argon arc lamps. In 1990-2000s, xenon arc lamps competed with other types because of their excellent performance and high-quality output spectrum. From 2000s, metal halide lamps have made a resurgence compared to tungsten halogen lamps. This may be attributed to receding argon arc lamps usage since 2005 as a result of the acquisition of Vortek Industries Ltd., the main historical supplier of argon arc lamps [209].

#### 4 Guidelines for the selection of a light source

The design of a solar simulator can be divided into three major steps: 1) defining system output requirements, 2) reviewing different light sources with their characteristics and 3) processing data from previous steps to obtain the required design parameters needed to complete the final simulator design. A flowchart that can be used as a guideline is shown in Fig. 8.

First, the desired output flux, target area and the sensitivity to spectrum are defined. The light source output spectrum, availability, characteristics and requirements, cost and conversion efficiency are defined. Finally, a decision is made based on interactions between elements from the previous steps. The following subsections focus on the second step by reviewing each light source output spectrum, availability, characteristics and requirements, cost and conversion efficiency.

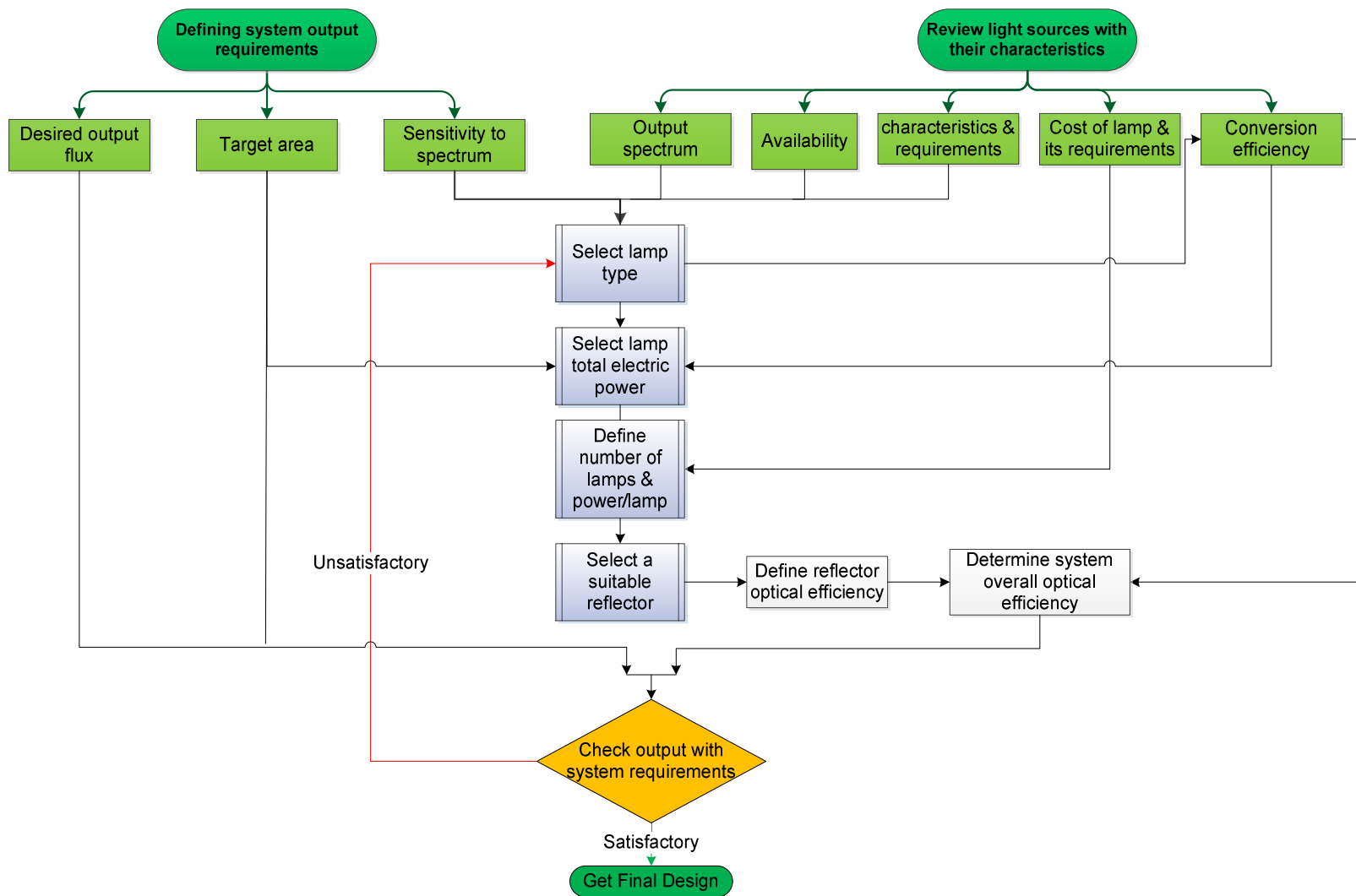


**Fig. 8 Flow chart of major steps of light source selection in the design of a solar simulator**

#### **4.1 Light sources standard requirements**

For light sources employed in solar simulators used for thermal applications, some parameters are required to meet the standard values listed in International and British Standards (ISO 9806, ISO 19467, EN 12975-1, EN 12975-2, EN 12976-1 and EN 12976-2) [95–100]. These parameters include spectral quality, collimation, flux magnitude and range of obtainable flux.

##### **4.1.1 Spectral quality**

The solar spectrum at optical air mass AM1.5 provided by the ASTM G173–03 standard [66] is used as a reference standard to compare the spectral distribution of the simulated solar radiation against that of the actual solar spectrum. The irradiance at a point on the tested specimen aperture area should not deviate from the mean irradiance over the gross area by more than  $\pm 15\%$  [95].

##### **4.1.2 Collimation**

Generally, the collimation condition of the simulated solar radiation is considered to be satisfied if at least 80% of the simulated solar irradiance received at any point on the tested specimen area has emanated from a region of the solar irradiance simulator contained within a subtended angle of  $60^\circ$  or less when viewed from any point [95]. However, these limits change in the case of measuring the incidence angle modifier (IAM)<sup>4</sup>. For this case, the collimation condition can be satisfied by at least 90% of the simulated solar radiation received at any point on the tested specimen area having emanated from a region of the solar irradiance simulator contained within a subtended angle of  $20^\circ$  or less. In other words, the maximum angle of irradiance to the test specimen in this case is required to be within  $20^\circ$  [95,96,99,100]

##### **4.1.3 Flux magnitude**

For the output irradiance magnitude, the light source is required to be capable of producing a mean irradiance over the plane of the tested specimen aperture greater than  $700\text{W/m}^2$  [95,97,98]. However, in some specialized tests, values of mean irradiance required may be in the range  $300\text{W/m}^2$  to  $1000\text{W/m}^2$ . The permitted deviation of measured global test solar irradiance from the mean value should be in the range of  $\pm 50\text{W/m}^2$  [95].

##### **4.1.4 Range of obtainable flux**

The effective irradiance width and height is required to be 100% or greater than each dimension of the test specimen width and height [96]. Table 2 summarises standard values and limits for the specified parameters.

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<sup>4</sup> The incidence angle modifier (IAM), represents the effect of the incidence angle on the optical efficiency and useful aperture area [245]. It corresponds to the decrease in the actual irradiance reaching the tested area with respect to irradiance under normal incidence, due to increasing reflection losses with the incidence angle [246].

**Table 2 Standard values and limits for different solar simulator parameters**

| Parameter               | Value limit                                                                                  | Standard(s)                                          | Reference(s)   |
|-------------------------|----------------------------------------------------------------------------------------------|------------------------------------------------------|----------------|
| <b>Spectral quality</b> | $\pm 15\%$ from the mean irradiance over the gross area                                      | ISO 9806                                             | [95]           |
| <b>Collimation</b>      | <b>General:</b> $\geq 80\%$ of simulated irradiance contained within an angle of $60^\circ$  | ISO 9806                                             | [95]           |
|                         | <b>IAM test:</b> $\geq 90\%$ of simulated irradiance contained within an angle of $20^\circ$ | ISO 9806,<br>ISO 19467,<br>EN 12976-1,<br>EN 12976-2 | [95,96,99,100] |
| <b>Flux magnitude</b>   | <b>Mean irradiance:</b> $\geq 700\text{W/m}^2$                                               | ISO 9806,<br>EN 12975-1,<br>EN 12975-2               | [95,97,98]     |
|                         | <b>Permitted deviation:</b> $\pm 50\text{W/m}^2$ from the mean global test solar irradiance  | ISO 9806                                             | [95]           |
| <b>Flux range</b>       | Effective irradiance area $\geq 100\%$ of tested specimen area                               | ISO 19467                                            | [96]           |

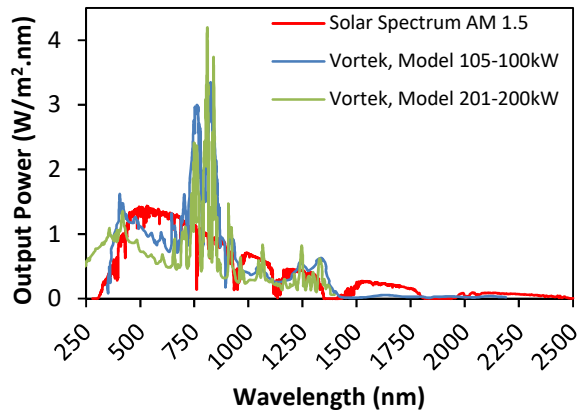
#### 4.2 Light sources spectra

Although thermal applications have a lower sensitivity to the light source spectrum than PV applications, a high spectral quality is preferable [212, 213]. The thermal response of a material varies with the incident radiation due to its spectral reflectance, transmittance, and absorption [214, 215]. A lamp can be characterised by its colour temperature. This value corresponds to a blackbody radiator temperature with a maximum irradiance which is obtained at the same wavelength as the light source [20, 216]. The colour temperatures of different light sources selected in thermal solar simulators (Table 1) are listed in Table 3.

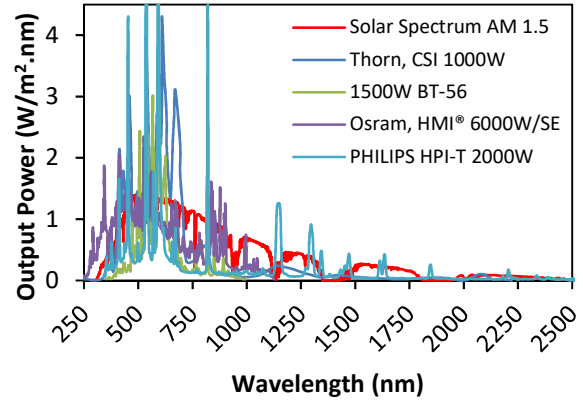
**Table 3 Colour temperatures of different light sources (based on available values)**

| Light source          | Colour temperature (K) | Reference(s)                              |
|-----------------------|------------------------|-------------------------------------------|
| Sun                   | 5777 (~5800)           | [43–46]                                   |
| Argon arc lamp        | 6500                   | [216]                                     |
| Metal halide lamp     | 4000–6000              | [55, 137–139, 141, 143]                   |
| Tungsten halogen lamp | 2100–3350              | [150–154, 157]                            |
| Xenon arc lamp        | 6000                   | [39, 62, 98, 166, 167, 171–173, 175, 218] |

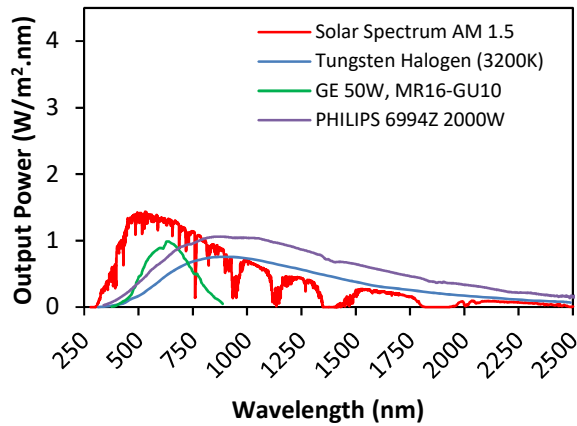
However, light sources with the same colour temperature can vary significantly in the emitted irradiance distribution [218]. The spectrum of each lamp type can be compared with the standard solar spectrum (AM1.5), as illustrated in Fig. 9.



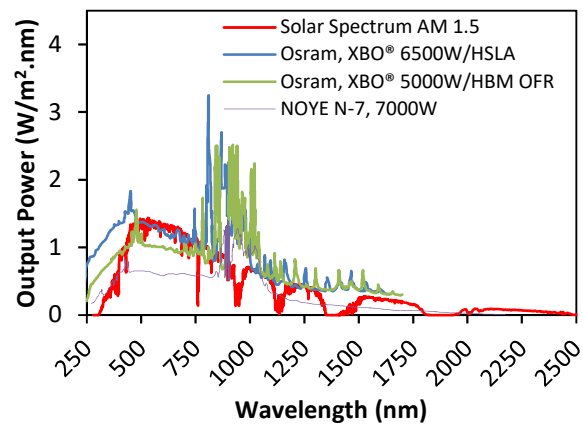
(a) Argon arc lamp [109,110]



(b) Metal halide lamp [39,118,167]



(c) Tungsten halogen lamp [219–221]



(d) Xenon arc lamp [165,167,171,175]

**Fig. 9 Different light sources spectra versus solar standard spectrum [66]**

Although argon arc lamps (Fig. 9a) do not emit in the IR wavelength over 1400nm, their “spectrum-matching” is closer than metal halide light sources. Metal halide lamps (Fig. 9b) emit a high quality spectrum distribution up to 900nm. The spectrum for wavelengths longer than 900nm tends to be a mismatch for the solar spectrum in the IR region. For tungsten halogen lamps (Fig. 9c), their low colour temperature is responsible for the mismatch of the output spectrum over 1000nm [222]. Finally, Fig. 9d shows that xenon arc lamps match a broader range of the solar spectrum. This can be improved further by filtering output spectra (i.e. Osram XBO® theatre lamps) [223].

From these comparisons, an important result is that each light source spectrum, from the same lamp type, varies significantly depending on the manufacturer. For example, some lamp manufacturers filter the output in the UV region, to block UV-B and UV-C radiations which have long term harmful effects on humans [224]. In addition, the data available can be limited as some lamp spectra are measured only over a specific range of wavelengths and for dedicated applications below 2500nm.

### 4.3 Light sources availability, characteristics and requirements

Additional aspects need to be considered as part of light source selection. Table 4 summarises other significant differences between different light sources including lifetime, additional requirements (e.g.

required ballast and igniters), internal pressure, average conversion efficiencies<sup>5</sup> and percentage of popularity<sup>6</sup>.

**Table 4 Summary of main characteristics of different light sources**

|                         | Argon arc lamp                          | Metal halide lamp   | Tungsten halogen lamp | Xenon arc lamp      | Reference(s)                       |
|-------------------------|-----------------------------------------|---------------------|-----------------------|---------------------|------------------------------------|
| Life time (hours)       | –                                       | 1000–6100           | 35–480                | 400–3500            | [123,211,225–231]                  |
| Additional requirements | DC power supply, rectifier and DC choke | Ballast and igniter | –                     | Ballast and igniter | [7,39,101,104,117,131,134,148,211] |
| Internal pressure (bar) | 7–10                                    | 10–35               | –                     | 10–40               | [6,102–104,112–114,153,154]        |

For example, in case of metal halide and xenon arc lamps, ballast and an igniter are required to power the lamp. If one of these elements is incompatible, this may lead to a shift in colour temperature, a dramatically lower lamp life expectancy, and an increased risk of lamp or system failure. Moreover, safety concerns should be evaluated before using certain light sources. For example precautions have to be taken for HID lamps which carry risks associated with retinal damage, UV hazards, or lamp explosion hazards due to their high internal pressures [232,233].

#### 4.4 Light source and components costs

A cost comparison of different light sources, and any additional components required, was addressed by selecting the same brand and lamp power. By checking lamp models used in solar simulators (Fig. 9), the Philips brand was found to be used twice with the same input power of 2kW<sub>e</sub>. The simulator used a metal halide lamp (HPI-T) whereas the second had a tungsten halogen lamp (6994Z). Therefore, a Philips xenon arc lamp with an input power of 2kW<sub>e</sub> was selected for comparison (LTIX). However, due to argon arc lamps being unavailable, no data was collected. Cost of lamps and any additional components are listed in Table 5.

**Table 5 Cost of different light sources and their requirements (in 2016)**

|                                  | Argon arc lamp | Metal halide lamp   | Tungsten halogen lamp | Xenon arc lamp       | Reference(s) |
|----------------------------------|----------------|---------------------|-----------------------|----------------------|--------------|
| Lamp model                       | –              | PHILIPS HPI-T 2000W | PHILIPS 6994Z 2000W   | PHILIPS LTIX-2000W/H | [234–236]    |
| Lamp cost (£)                    | –              | 96.07               | 32.65                 | 634.68               | [237–239]    |
| Additional requirements cost (£) | –              | 178.20              | 0.00                  | 2250                 | [240–242]    |
| Total Cost (£)                   | –              | 274.27              | 32.65                 | 2884.68              | –            |

<sup>5</sup> The average conversion efficiency from electric input power to radiative output power, based on different systems listed in Table 1.

<sup>6</sup> Participation share over the whole period from 1970 to 2016, based on 62 cases listed in Table 1.

Although costs listed in Table 5 fluctuate with time, power output and suppliers, this cost estimation can be used as an initial criterion in light source selection. According to this data, tungsten halogen lamps are the cheapest light source, while a xenon arc lamp is the most expensive option.

#### 4.5 Conversion efficiency

The energy conversion efficiency of a system is defined as the ratio between the useful output and the input [243]. A solar simulator can be considered as a system in which the electrical power supplying the light source is considered as input power, while the useful output power is represented by the radiative power reaching the target area, at which spot is detected. Hence, the energy conversion efficiency of a solar simulator,  $\eta_c$ , can be described by:

$$\eta_c = \text{Total output radiative power} / \text{Total electric power consumed by lamps} \quad (3)$$

By relating this definition to the target area, then it can be rewritten as:

$$\eta_c = \text{Total output flux} / (\text{number of lamps} * \text{lamp power} / \text{target area}) \quad (4)$$

The reflector optical efficiency, which is the ratio between the flux reaching the target and the emitted global flux [244], is already embedded in the energy conversion efficiency defined by Eq.(3) and Eq.(4). According to data listed in Table 1, the average conversion efficiencies of different light sources are shown in Table 6.

**Table 6 Average conversion efficiency of different light sources**

|                                         | Argon<br>arc lamp | Metal<br>halide<br>lamp | Tungsten<br>halogen lamp | Xenon<br>arc lamp | Reference(s)                        |
|-----------------------------------------|-------------------|-------------------------|--------------------------|-------------------|-------------------------------------|
| Average<br>conversion<br>efficiency (%) | 3.08              | 24.59                   | 10.21                    | 18.77             | All references listed<br>in Table 1 |

These values vary from the conversion efficiencies for the individual cases listed in Table 1. This can be attributed to the optical design of different simulators including; reflector designs, optical efficiencies and by using optical filters or transparent obstacles, i.e. lenses or protection glass panels. However, these averaged values can be used as a guideline for an initial estimation of the required electrical power for a specific type of light source.

## 5 Conclusions

A solar simulator device can approximately simulate the sun's radiation by using an artificial light source. In the 1970s, with the development of solar collectors, low-flux solar simulators were principally developed. Twenty years later, high-flux solar simulators were built for testing thermochemical and concentrated solar power components and PV cells. For thermal applications testing, four lamp types have been employed: argon arc, metal halide, tungsten halogen and xenon arc. Since the early 1970s, 37% and 33% of solar simulators were built using metal halide and xenon arc lamps respectively. Both

lamps are HID lamps with a colour temperature (4000–6000K) which is close to that of the sun (5800K). They possess an excellent output spectrum that closely matches that of natural sunlight. A xenon arc lamp has a more stable spectrum as well as a brighter point source, allowing the generation of a high intensity collimated light beam. However, this lamp type has complex and expensive requirements for its power supply, plus filtration requirements for its IR spectrum. Moreover, additional safety precautions have to be considered as its pressure can reach 40 bar during operation, which is five bar higher than the maximum metal halide working pressure. Therefore, metal halides lamps have been used as an alternative in many newly built sun simulators. Additional features have to be considered such conversion efficiency, long-term reliability, cost, additional requirements and life expectancy of each lamp.

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