The University of Edinburgh

The School of Engineering

Civil and Environmental Engineering

Academic Year 2017 – 2018

A Study of the Required Spacing for Preventing Fire Spread Between Photovoltaic Arrays on Flat Roofs

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Master thesis submitted in the Erasmus+ Study Programme

International Master of Science in Fire Safety Engineering

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30/04/2018

Word count: 16484

Abstract

The fire spread under photovoltaic (PV) panels and the required spacing between PV arrays on flat roofs were studied experimentally in a custom-made set-up that represented a partial roofing segment. The roof segment was constructed by placing roof membrane on incombustible boards mounted on aluminum frames. A 10 cm by 10 cm by 6 cm wood crib was ignited under a PV panel in the experimental setup, providing a 7 kW to 10 kW ignition source. Heat flux values, heat release rate, fire spread, and temperatures were measured in the tests. Heat flux gauges were installed under and outside the PV panels to measure the fire risk under and away PV panels. The tests showed that the fire can burn stronger and grow faster under PV panels. For example, the fire under the PV panel could produce a 141-kW fire while only 5 kW was measured without panels. Nevertheless, the fire can burn less severe under burned PV panels, for instance, only 16 kW was measured under burned panels whereas 93 kW was observed under new panels, meaning the panel condition can influence the test outcome. The risk of fire spread between PV arrays is low on flat roofs when wind effects and roof orientation are not considered. The fire spread away the panels was little and the fire extinguished shortly after spreading outside the panels during the tests. The length of fire spread away panels remained small regardless the position of ignition source. Additionally, the risk of distant ignition was low based on the test results. The fire risk under PV panels can be mitigated by increasing the gap distance between panels and roofs. It was also found that the extraction flow of the exhaust hood can influence the burning under PV panels and the fire can be underestimated when testing with burned PV panels.

Abstract (Chinese)

本論文以實驗方式研究平面屋頂火災在太陽能光電板下的蔓延以及太陽能板所需的防火間隔。實驗設置係使用不燃材料隔板，隔板置放於訂製的鋁架上，並於隔板上鋪設屋頂防水膜以模擬局部平面屋頂。在屋頂膜上點燃一個10乘10乘6公分的木材堆來模擬火源。熱通量(HF)、熱釋放率(HRR)及火勢蔓延在實驗中被觀察及紀錄。熱通量計(HFG)安裝在太陽能板下及其外，以瞭解火災在太陽能板下及其外之危害。實驗顯示火在太陽板下燃燒更強大且成長更迅速，舉例來說，火在太陽能板下的熱釋放率是141 kW，而沒有太陽能板的時候卻只有5 kW。然而，若重複使用太陽能板於燃燒實驗，火勢則較使用新太陽能板為弱，例如重複使用太陽能板於燃燒實驗時，測得16 kW的熱釋放率，而使用新太陽能板於實驗時，卻測得93 kW的熱釋放率；代表太陽能板的條件可能影響實驗結果。在實驗中，火災在太陽能板覆蓋的範圍外僅蔓延數公分，並且在離開太陽能板覆蓋範圍後很快熄滅。即使移動火源位置，對太陽能板外的火災蔓延亦無影響。顯示在屏除風力影響下，火災在太陽能板間的蔓延危險性並不高。實驗結果亦顯示遠端引火之危險性低。然而，風力及屋頂傾斜角度對太陽能板火災的影響，仍待未來研究。根據實驗及文獻，增加太陽能板與屋頂間的距離可減輕太陽能板火災的危險性。此外，根據實驗經驗，排煙設備下的換氣氣流可能會影響在太陽能板下的燃燒現象；而重複使用同一太陽能板進行實驗所獲得的實驗結果，則可能低估火災在真實狀況下的強度。

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Chapter 1. Introduction

The installation of photovoltaic (PV) energy systems has been growing for more a decade. With the rapid increase after 2010, the total installation has reached 303 GW in 2016. And in 2016 only, more than 75 GW of solar energy systems was installed. What is more, 24 countries have installed at least 1 GW, and there is even more for leading countries, such as China (78.1 GW), Japan (42.8GW), and Germany (41.2 GW) (IEA PVPS, 2016). It shows that the installation of solar energy systems is a worldwide trend.

However, installing PV systems on existing constructions will put extra elements in the building, meaning the possibility of changing the fire dynamics, new source of ignition and extra fire loads. The risk of fire is then increased. In 2014, Italy recorded over 400 fires that were associated with PV systems (Fiorentini et al., 2016). In addition, 390 fires of the same kind in Germany in 2012 (Manzini et al., 2015a). However, the fire relate to solar energy systems could be much more since the fire statistics relating PV systems is still not provided in many countries (Casey C. Grant, 2014).

The stakeholders that are more interested to the fire safety of PV energy systems can be organizations doing inspection, codification, design, installation, and sales of PV energy systems, such as the fire and rescue service, manufactures, and standardization organizations.

1.1 Fire Risks for PV Systems

Installation of PV panels on the building introduces additional fire risks to the building, namely adding extra fire load, new source of ignition, influence to the operation of smoke and venting systems, intervening rescue actions, presenting the electrocution hazard for firefighting, and modify the fire behavior under PV panels (Fiorentini et al., 2016).

The total fire load of the construction will increase when new elements are added. Since flammable materials, such as electric cables, the back sheet of panels are included in the solar systems. Nevertheless, a previous research indicated that the fire load presented by PV panels is insignificant for roof constructions (Kristensen, 2015).

The solar energy systems can also be the source of ignition. As long as there is light, there will be electricity produced in the solar system. When electrical faults happened in the system, the electrical energy can be the source to provide the energy of ignition.

Furthermore, PV panels can be an obstacle of smoke and venting systems when it is not installed in a proper way. Some openings of smoke and heat control system are designed to be hidden in normal conditions to be stylish, while they might be neglected when installing PV panels and the venting can be blocked afterwards. Such inappropriate installation could lead to the failure of the smoke and heat control design.

In the other hand, the PV panels could be obstacles and present electrocution hazards during fire and rescue operation. The panels might interfere the movement of firefighters and the cables or panels can lead to stumbling hazard. Moreover, as long as there is light, the electricity is generated automatically, and it is very difficult to shut down the system completely. The continuous generation of electricity introduce the electrocution hazard for firefighting operations.

Besides, installation of the PV systems will change the fire dynamics under the PV panels. Installing PV panels is as “adding a roof” in the open space, which alters the conditions of heat transfer during fire. After installing the PV modules, the flame is then blocked by PV panels and more radiative heat is reflected to the roof elements. Relevant research showed that there is significant increase of heat flux to the roof construction after PV panels are installed (Kristensen, Merci and Jomaas, 2018). The increased heat flux is then making the fire burn stronger and faster under PV panels.

1.2 Previous Studies on PV Fire Safety

1.2.1 Impact of Construction Fire Safety after Installing PV Panels

Underwriters Laboratories has conducted a series of experiments to investigate the influence of PV panels to the fire on roof constructions. The experiments showed that the performance of fire resistance is deteriorated after installing PV panels. Higher temperatures and greater heat flux are received in the test when solar panels are installed. The level of effects can depend on the gap distance between panels and the roof, and the setback distance. The effect of PV panels is lessened when the gap or setback distance increases (Backstrom, Tabaddor and Gandhi, 2010). It is suggested that the roof assemblies should be tested in a combination with PV panels instead of tested separately (Backstrom and Sloan, 2012).

1.2.2 Preventing Ignition of Fire by Avoiding Electrical Faults

Prevention of the electrical faults could be the most well-studied field for preventing the fire in PV energy technology. Many research is done to mitigate the fire risk due to electrical faults, such as short-circuit and ground fault (e.g. (Zhao et al., 2013)), overcurrent (e.g. (Dhoke, Sharma and Saha, 2018)), or hot spots (e.g. (Aly, Jensen and Pedersen, 2017)) in solar modules. Nevertheless, prevention of electrical faults in solar energy systems lies in the scope of electrical engineering, thus it is out of the scope of this thesis.

1.2.3 New Testing Methods for PV Fire Safety

Some studies also suggest new testing methods for the solar modules in case of fire. Although several European standards for construction products are invoked for PV panels, these standards do not treat the specific characteristics of the PV modules properly. For example, the panels mounted on roof can be tested according to ISO 11925-2[1] as building components; however, such standard tests the panels in the conditions that are different from the materials or construction conditions when most PV systems are mounted, for example, the inclination angle during testing (Manzini et al., 2015a). In addition, studies also indicate deficiencies of invoking existing standards for PV elements, e.g. the inclination angle of panels, ignition intensity of flame, and ignition duration are not respected due to the outside installation. Experiments shows that a bigger inclination (e.g. a smaller angle) will cause more severe damage than vertical position configuration in the standard test (Manzini et al., 2015b). As a consequence, there is not yet suitable standards nor technical regulations for PV modules in case of fire safety, and testing methods for PV panels remain unvalidated. In addition, the fire rating of the roof will not remain the same after installation of PV panels, therefore, the roof and PV panel assemblies should be considered as a combination instead of only tested individually (Backstrom, Sloan and Gandhi, 2012a). However, the testing methods for PV panels are not discussed in this thesis.

1.2.4 Firefighting Safety on PV Fires

Several researches have done to investigate for mitigating the risk during firefighting or rescue operations for photovoltaic related fires. For instance, the research by Fire Protection Research Foundation provides the practice information, fire ground tactics, code development, and training suggestions for fire service commanders when dealing with structural fire equipped with solar energy systems (Casey C. Grant, 2010). Another research project carried out by Underwriters Laboratories (UL) investigate the electrical and casualty hazards for firefighting operations involving PV systems (Backstrom and Dini, 2012). Experiments also show that the electrocution risk can be avoided by keeping safety distances when using water jet for extinguishing PV fires (Tommasini et al., 2014)).

1.2.5 Regulations for PV Fire Safety

Some research discussed existing fire safety regulations about preventing the fire spread

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[1] ISO 11925-2: Ignitability of building products subjected to direct impingement of flame - Part 2: Single-flame source test

under PV modules. In Italian fire safety guidelines, the components of roofs or façades should be incombustible or a layer with EI 30 should be mounted between the elements and PV panels, when solar energy modules are installed. An alternative is to perform a risk assessment with respect to fire spread by considering the fire rating of construction elements and solar modules. Besides, a one-meter clearance between the arrays and skylights, natural smoke and heat exhaust ventilators (NSHEV), or wall/ceiling intersections[2] is required, to prevent the fire spreading under the PV arrays or to adjacent roof elements. The requirements are summarized in Figure 1 (Cancelliere, 2016).

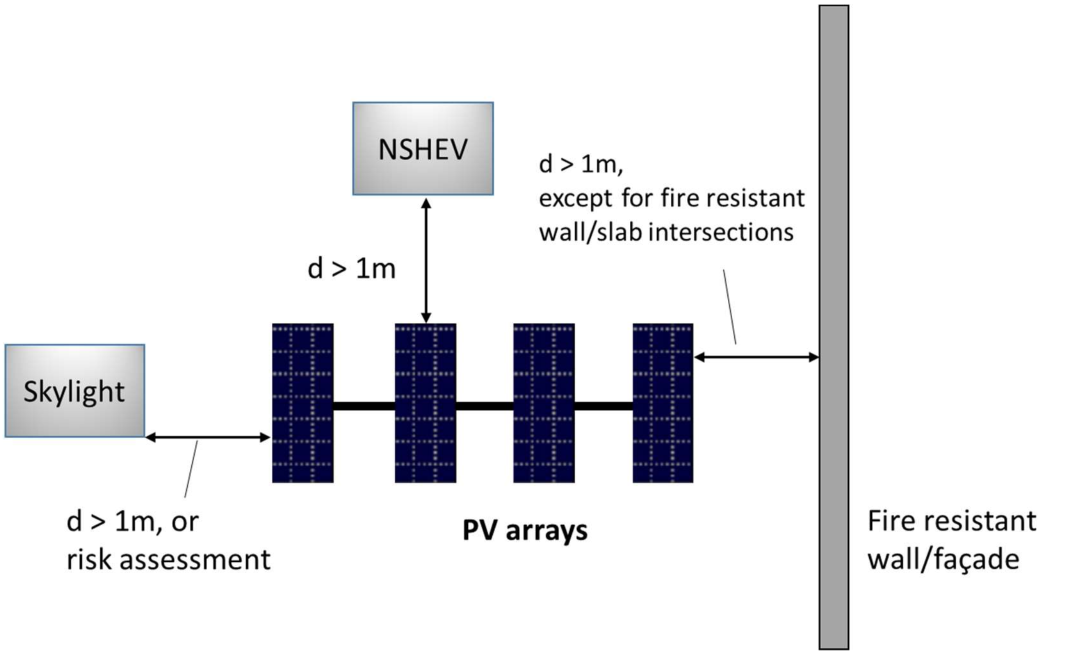


Figure 1 The summary of mitigating solutions of fire spread under PV panels in Italian fire safety guidelines. The construction elements should be incombustible or EI 30 on the roofs or façades, otherwise, risk assessment is required. In addition, a 1 m distance is required between PV arrays and Skylight, NSHEV, or wall/ceiling intersections (reproduced from Cancelliere, 2016)

1.2.6 Mitigating Methods for PV Fire

Several mitigation methods, such as setback distance, angled/vertical flashing, or fire screen, are tested to prevent the flame spread on roof assemblies by Underwriters Laboratories. The results showed that 36 inches (91 cm) setback distance was not enough for maintaining a Class A fire rating, if only the setback was used. On the other hand, a vertical flashing without gap hold the Class A rating even without setback distance (Backstrom, Tabaddor and Gandhi, 2009). It showed that the vertical flashing can be more effective for preventing the fire spread than a setback distance. In addition,

[2] The one-meter distance is not required if the wall or ceiling is constructed by fire resistant elements for the compartments.

more solar energy modules can be installed if less setback distance is required on the roof/façade.

In another set of experiments tested by UL 790 (ASTM E108) ignition source, Class A fire rating was not achieved at offsets at 1.3 m, when the PV panels are mounted with 0° inclination on low slope roofs. While the roof assembly passed the Class A with a 1.2 m offset, when PV panels were mounted with a 10° inclination (Backstrom, Sloan and Gandhi, 2012b). On the other hand, steep slope roofs passed the Class A rating with an offset of 0.91 m when PV panels are mounted parallelly. It showed that angled mounted PV-roof assemblies performed better than parallel mounted ones. This might due to the distance between panels are roofs increased when the PV panels are installed with inclinations. The reradiation heat from the panels was then weakened after the height increased. The tests also showed that steep slope roofs performed better than low slope roofs in the fire rating tests. However, it should be noted that the materials used for building steep and low slope roofs are different in UL 790 standard. The roof deck assemblies for steep slope roofs are constructed by 3-tab shingles over 19 mm plywood, while low slope roofs are built with 15 mm LSFR EPDM over 102 mm thick polyisocyanurate insulation boards. Some selected results of UL tests are listed in Appendix A.

A 5-inch (13 cm) gap was found to have highest risk of fire spread among 10, 5, or 2.5 inches (25 cm, 13 cm, and 6 cm) gap between PV panels and roofs in UL tests (Backstrom, Tabaddor and Gandhi, 2010). The temperature was elevated by the fire because of less entrained air in smaller gap of 5 inches. However, the temperature decreased when the gap reduced to 2.5 inches due to part of the testing flame impinged on the top of PV panels instead of burning under the PV panel completely.

It was also found that a 30 cm gap distance was able to hold Class A fire rating for steep slope roof assemblies, whereas 61 cm gap was not able to hold a Class A fire rating for low slope roofs (Backstrom, Sloan and Gandhi, 2012d). Although steep slope roofs performed better in the fire rating tests, it remains unknown whether it was because of the angle of roof installation or different element materials used. However, the tests implied raising the gap distance can be a possible solution for mitigating fire spread.

1.3 Aims and Objectives

Previous research already showed the hazard of fire spread under PV panels. However, it did not show the risk of fire spread from one cluster to another cluster of PV panels. And, is there a required spacing for preventing the fire spread?

The aim of this study is to show the risk of fire spread between PV panels by experiments and discuss if the required spacing between PV arrays and adjacent roof elements suggested by regulations would be sufficient based on the literature and tests. Therefore, experiments were performed by igniting the roof assemblies under PV panels and observe the fire spread under and outside the panels. Heat flux values, heat release rate, fire spread, and temperatures were measured in the tests. Furthermore, the risk of distant ignition was discussed based on the test results. Discussions and comparisons between previous research and this study were made to show the similarity and differences among different tests. In order to show how the burning underneath the panels can be influenced by the panel condition during tests, new and burned PV panels were both used in the tests. Another objective was to show if the position of ignition source would affect the fire spread, and what is more, to demonstrate how the fire could change when the gap distance between roofs and panels altered. Additionally, experimental suggestions should be given for future testing based on the experiment experience.

Chapter 2. Methodology

The experiments of this thesis were designed to investigate the risk of fire propagation to adjacent clusters or roof elements when a small fire occurs under PV panels on flat roofs. Roof membranes were placed on incombustible boards to present general flat roofs in the tests. One PV panel was on the West side of the roof with an ignition source under the panel. The ignition source was a 10 cm by 10 cm by 6 cm wood crib built by wood sticks and fire lighter. HRR, fire spread, and heat flux in several distances from the PV panels were measured. The heat flux measured in farther distances can be used to estimate the risk of distant ignition. In the second part of the tests, more HFGs and thermocouples were installed under PV panels to observe the heat flux underneath and temperature change.

New PV panels and burned PV panels are both used in the tests to show how the burning underneath the panels can influenced the fire under panels. Positions of ignition source were changed to show its influence to fire spread and the effects of gap distance change.

Two types of roof membrane of different sizes were used burned under the PV panel in the tests. The extraction flow of exhaust hood was increased after the significant production of smoke from the burning. Heat flux, heat release rate, and fire spread measured during the tests.

Critical heat flux (CHF) values for the roof membranes were tested in advance with cone calorimeter before the experiments. The CHF of membrane was 7 - 8 kW/m^2 for membrane A and 8 kW/m^2 for membrane B. The HRR of the wood crib was 8 to 10 kW when placed under the PV panel, which was high enough to ignite the roof membrane.

The tests started from smaller size of membrane due to safety perspectives and testing with wind was not possible for the risk of smoke spread in the lab. It was decided to use a 45 cm by 45 cm membrane in the first set of tests and 70 cm by 70 cm for the second set of tests under PV panels. The membrane under PV panels was connected was a 150 by 93 membrane outside the panels to observe the fire spread. Details of the experiment setup is discussed in the following sections, and the experiment matrix can be found in Table 2 of section 2.3.

2.1 Critical Heat Flux for Roof Membranes

Critical heat flux (CHF) is the incident radiant heat flux for the material to ignite. The tests were performed according ASTM E1354-17 with cone calorimeter and a spark ignition. The testing methods is an iterative procedure by igniting the samples with a range of heat flux. The tests start at high heat flux and reduced later. The first iteration starts at 10 kW/m^2, then 5 kW/m^2, and 2 kW/m^2, until the critical heat flux is found. The default exposure time is 20 min in the standard; however, the ignition time was also recorded if the membrane was ignited after 20 min.

2.2 Tests of Fire Spread under PV Panels

2.2.1 Experiment Set-up

It was of interests to show the fire spread under PV panels from a small fire, regardless the source of ignition. The fire can due to electrical faults, from another cluster of PV panels, or come from other roof elements. However, the source of fire was not discussed here, since the focus was the fire behavior change under PV panels.

The aim was to discuss the required spacing for PV arrays according to the fire spread. And the assumption was that the fire will keep spreading as long as it reaches the area under PV arrays. Therefore, the interests would be to observe how far the fire can spread on the membrane that is not covered by PV panels.

Solar energy systems are usually installed with an angle to receive the most sunlight in order to have efficient energy production. The panels can be installed in East-West orientation, facing south (for north globe), or parallel to roofs. In general, East-West mounted panels are usually mounted only with a small gap between the two panels, thus it is assumed when a fire occurs under one panel, it will burn the whole area under both panels. In this case, the spacing that matters will be the distance to adjacent cluster.

It was decided to place a PV panel on West side to represent both a single panel and a set of East-West panels. Placing two panels and adjusting the spacings in several tests was considered unnecessary, because by measuring the longest distance of fire spread already showed the distance under fire risks. Since the assumption was that the fire will spread all the way when it reaches the area under PV panels. Therefore, a single PV panel can represent an East-West oriented panels at the same time. The options of experimental setting and chosen option is in Figure 2.

The roof was built with incombustible boards supported by aluminum frames, with the roof membrane placed on the incombustible boards. On the West side of the setup is one PV panel placed in a 13° inclination. Three HFGs were placed on the East side of the setup away from the PV panels and three more HFGs were installed additionally under PV panels in the second part of tests. HRR was calculated afterwards and fire spread were measured after the tests. Two cameras are placed on the South West side and North East side during tests. After Test 19, the length of the setup was reduced to help the smoke extraction under the hood. The settings of the experiment are shown in Figure 3 to Figure 8, and detail of the experiment is shown in following sections.

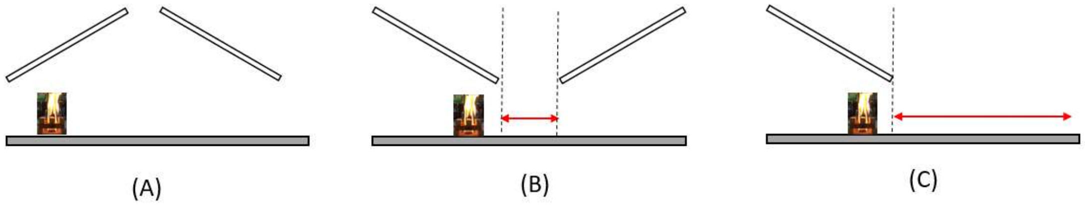


Figure 2 Options of experiment setup. It was assumed that a fire will spread as long as it reached the area membrane under PV panels. In this case, it was of interests to know how long fire can spread outside PV panels on roofs. Placing two panels and adjusting the spacings in several tests was considered unnecessary, because by measuring the longest distance of fire spread already showed the distance under fire risks. Therefore, design (C) was chosen to represent an East-West oriented panels or single inclined panels

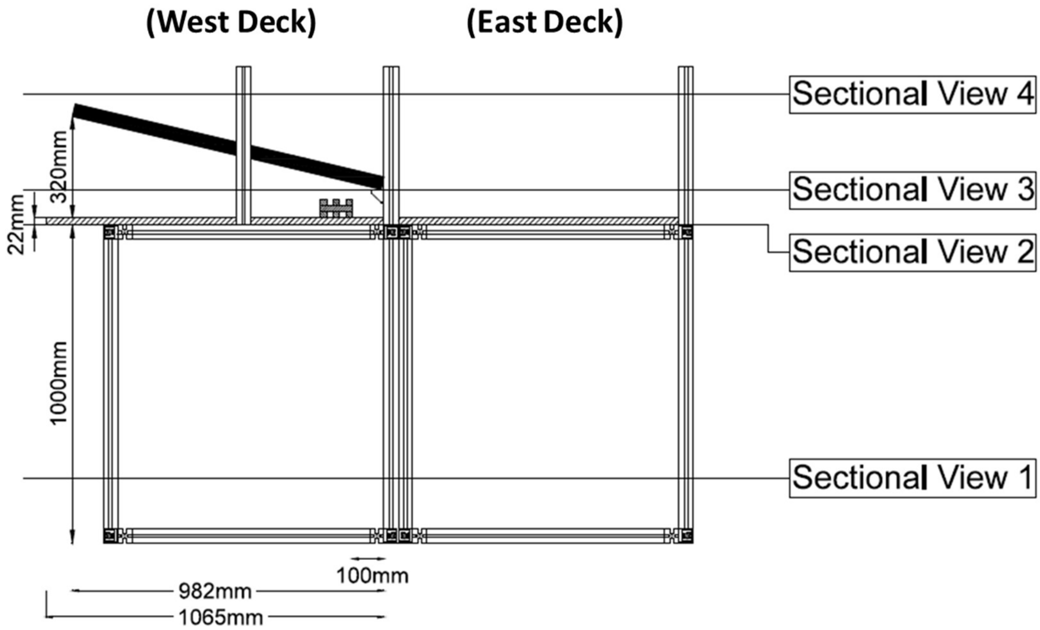


Figure 3 A schematic drawing of the experiment setup from side view. The setup was connected by two decks with incombustible boards on them. The height of the incombustible was 100 cm from floor. Two decks were placed together to form the whole setup. PV panels were placed on the left (west) deck. The length of the right (East) deck was reduced to help the smoke extraction after Test 19. The secntion views will be shown in the following figures to demonstrate the setup in detail from the upper view. The detail testing conditions can be found in the experiment matrix in Table 2 of section 2.3

Figure 4 A picture (side view) of the experimental setup under the hood

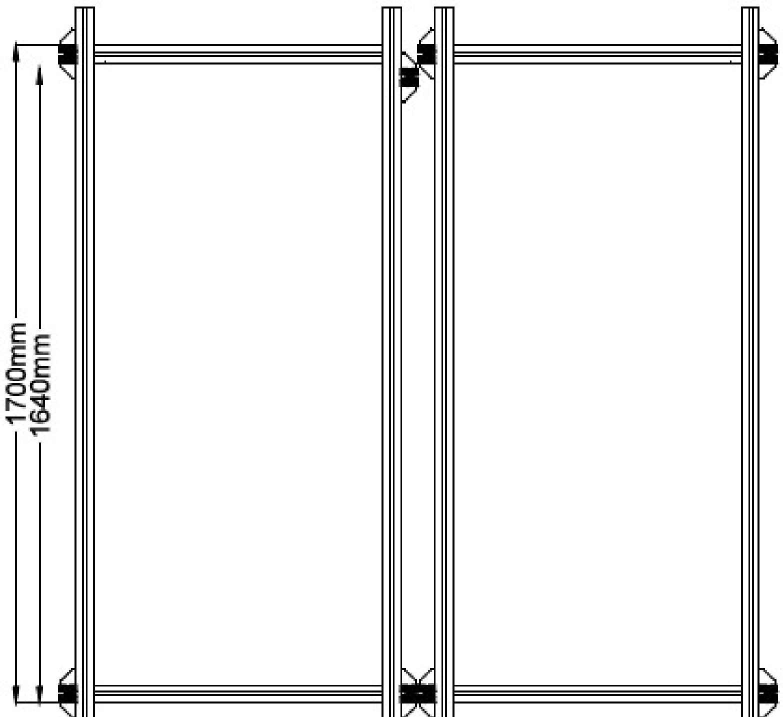


Figure 5 A schematic drawing of section view 1 of the experimental setup, showing the base of the setup

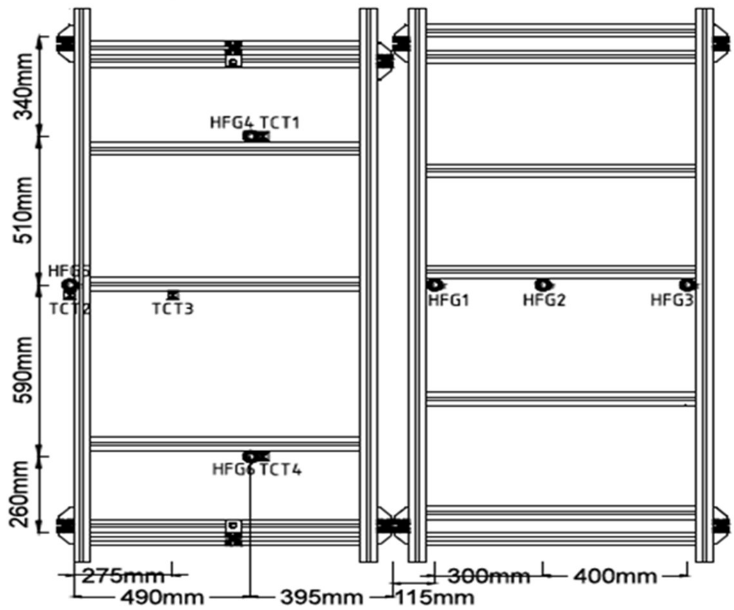


Figure 6 A schematic drawing of section view 2 of the experimental setup. It showed the positions of the HFGs and thermocouples. HFG-1, HFG-2, and HFG-3 was 30, 60, and 100 cm from the first board before Test 18. After Test 19, the distance was reduced to 11.5, 41.5, and 81.5 cm from the first deck. HFG-4, 5, and 6 were installed after Test 26, while it was 15 cm, 15 cm , and 24 cm for HFG-4, HFG-5, and HFG-6 from the membrane. Thermocouples were also installed next to HFG-4, 5, and 6 after Test 27

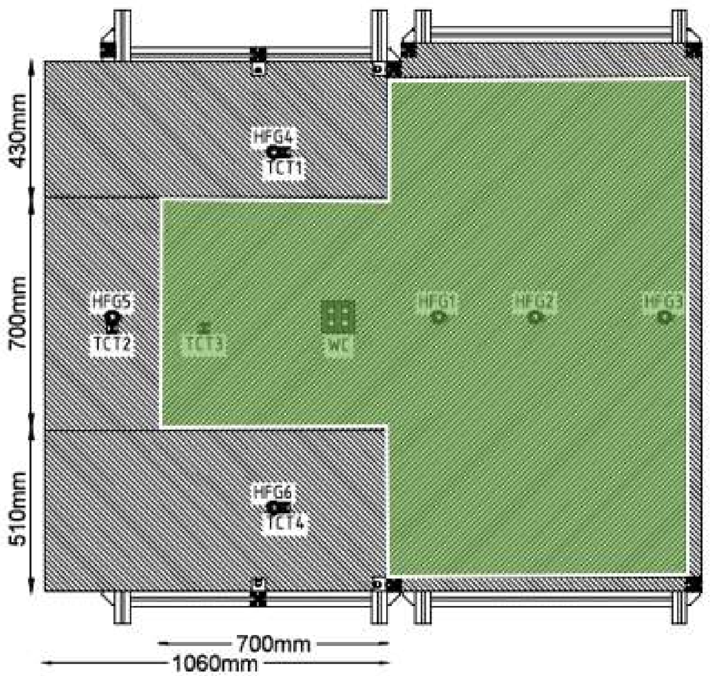


Figure 7 A schematic drawing of section view 3 of the experimental setup. The green area represents the are covered by the roof membrane when the membrane under PV panels was connected with membrane outside the panel

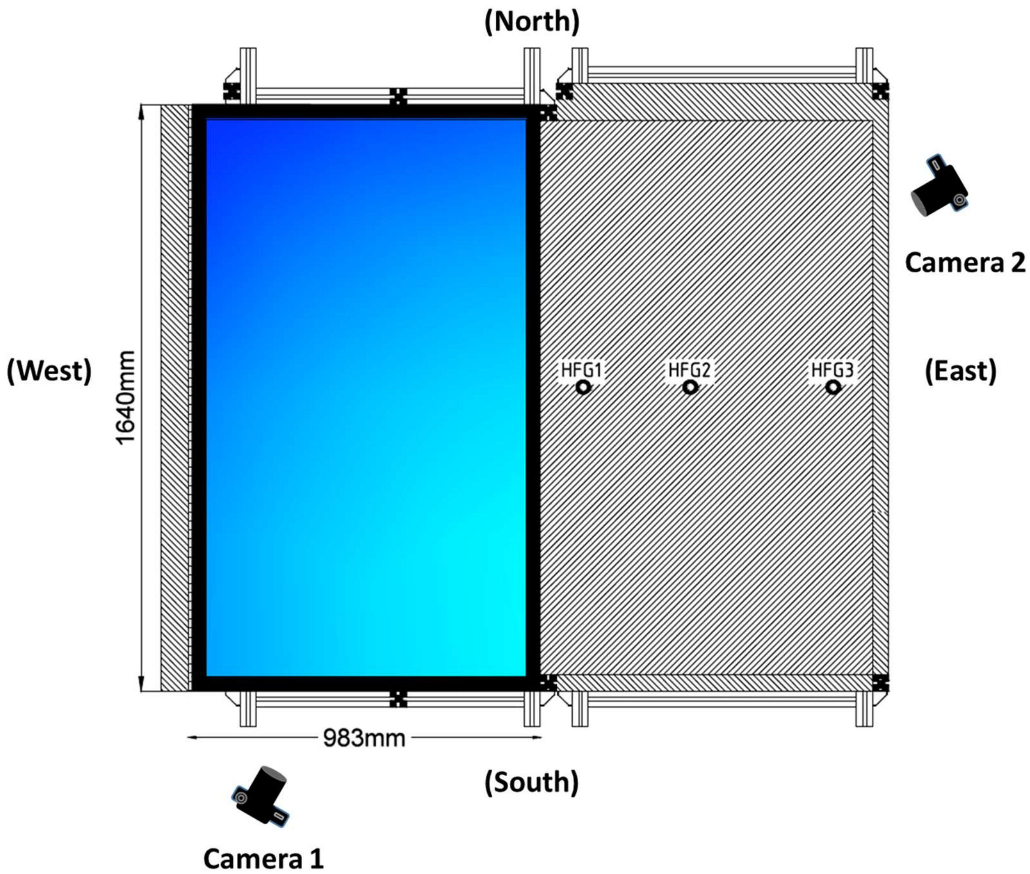


Figure 8 A schematic drawing of section view 4 of the experimental setup. The directions of the setup mentioned in the text are shown in this figure. PV panels were placed on the West side of roof assembilies. Camera 1 was placed on the South-West side and camera 2 was placed on the North-East side of the setup, as shown in figure

2.2.1.1 Heat Flux Gauges (HFGs)

The HFGs were placed in the same level as the roof membrane to make sure the heat fluxes measured are those received in roof level. The HFGs were cooled by tab water and they were installed in six positions. The model of HFGs were SBG01 heat flux meter produced by Hukseflux, and the measuring range was 100 kW/m^2 for HFG-1 and 2, 200 kW/m^2 for HFG-3, and 50 kW/s^2 for HFG-4, 5, and 6.

Three HFGs were placed in the first part of the tests and five HFGs in the second part of the tests. HFG-1, 2, and 3 were used in the first set of tests, while HFG-1, 2, 4, 5, and 6 were used in the second part.

HFGs were placed 30 cm, 60 cm, and 100 cm from the East half of the setup in first 18 tests. The distance was chosen for observing if there will be a risk for distant ignition for one-meter distance, since the Italian fire safety guideline suggests a one-meter clearance on PV panel and roof assemblies. From Test 19, the setup was reduced in length to create more space to help the smoke extraction. The distances to the East setup were reduced to 11.5 cm, 41.5 cm, and 81.5 cm accordingly, for HFG-1, HFG-2 and HFG-3. HFG-4, 5, and 6 were installed from Test 26, while HFG-3 was considered being too far to give valid readings based on previous tests, therefore, it was not installed afterwards. HFG-4 was installed in parallel with the center point of the membrane under PV panels with 15 cm distance away from the membrane, while HFG-6 was on the other side with 24 cm from membrane. HFG-5 was 14.5 cm from the end of the membrane. The 15 cm distance for HFG-4 and HFG-5 was chosen to compare with the readings from HFG-1, since the distance between HFG-1 and the PV panel was 15 cm. The distance of 24.5 cm was chosen also to compare with HFG-1, due to the distance from HFG-1 to the wood crib was around 25 cm. The measuring range of was 50 kW/m2 for HFG-4, 5, and 6 and 100 kW/m2 for HFG-1 and 2. The positions of HFGs are in shown in Figure 9.

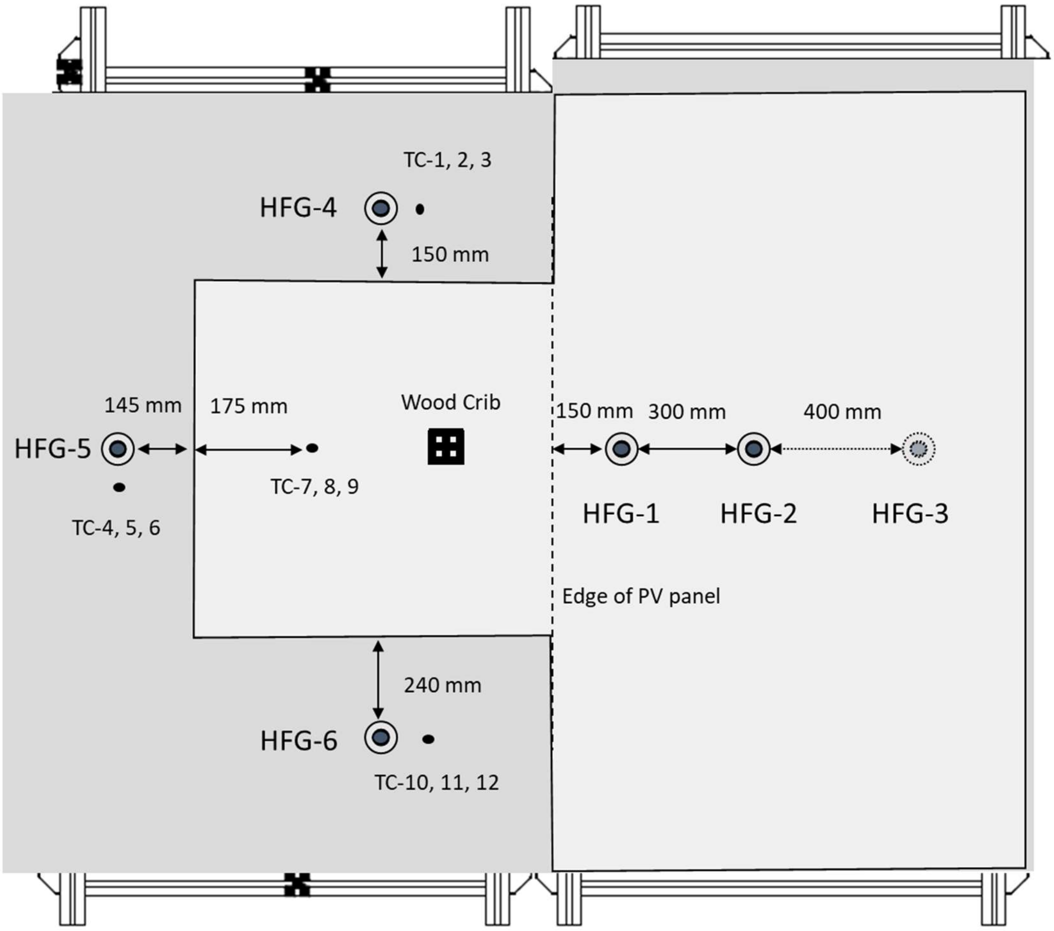


Figure 9 A schematic drawing of the positions of HFGs and thermocouples in second part of the tests. The measuring range of was 50 kW/m2 for HFG-4, 5, and 6, while it was 100 kW/m2 for HFG-1 and 2. HFG-3 was not installed due to not giving significant readings in a farther distance. The thermocouples were installed next to HFG-4, 5, 6, and in the middle of wood crib and HFG-5

2.2.1.2 Thermocouples (TC)

From Test 27, thermocouples were installed next to HFG-4, 5, 6, and in the middle of wood crib and HFG-5. Three thermocouples were installed in each position. TC1, 2, and 3 were placed next to HFG-4. TC 4, 5, and 6 were installed next to HFG-5 and TC 10, 11, 12 next to HFG-6. TC7, 8, and 9 were placed in the middle of wood crib and HFG-5. The position and height of each thermocouple is shown in Figure 9 and Figure 10.

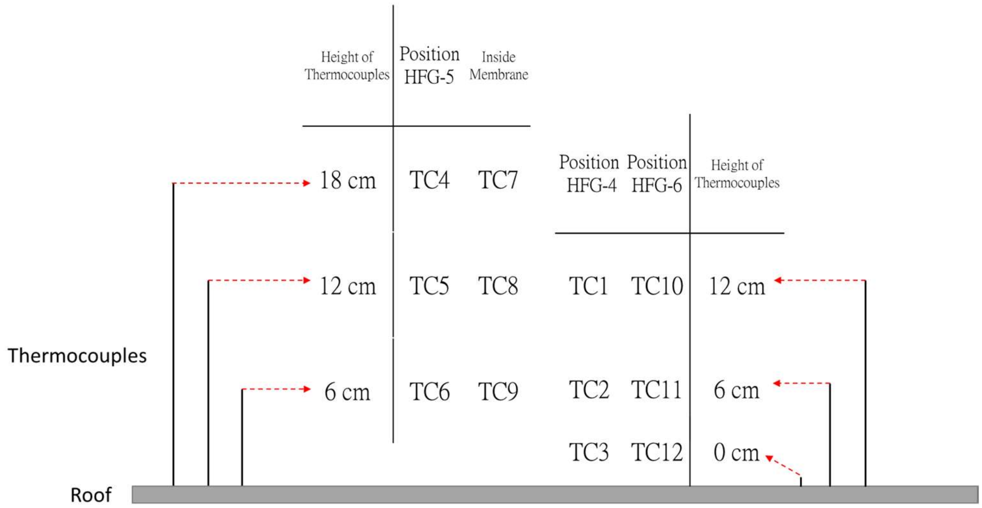


Figure 10 The drawing of thermocouple heights. There were three thermocouples in each position. The thermocouples next to HG-5 and 6 located in 18 cm, 12 cm, and 6 cm from the roof, while the thermocouples for HFG-4 and 6 located in 12 cm, 6 cm, and 0 cm from the roof

2.2.2 The Membrane Placed on the Flat Roof During the Tests

The tests performed by UL (Backstrom, Sloan and Gandhi, 2012d) showed that there is higher risk of fire propagation for flat roofs covered by membranes than a steep slope roofs covered by 3-tab shingles under PV panels. Therefore, the combinations of flat roof and membrane was chosen in the tests to present the worse scenario.

Two kinds of PVC roof membrane were placed on incombustible boards during the tests. The membranes are Class E fire rating membranes according to European standards. The characteristics of the membranes are shown in Table 1.

The size of membrane started from 20 cm by 20 cm and increased afterwards. The membrane size under PV panels was decided to use a 45 cm by 45 cm membrane in the first set of tests and 70 cm by 70 cm in the second, due to the safety concern in the lab. The membrane under the PV panels was then extended with a 150 cm by 93 cm (width x length) membrane away the PV panel. An example of membrane is shown in Figure 11.

Table 1 The membranes used in the experiments

	Membrane A	Membrane B
Material	PVC	PVC
Fire Rating (European)	Class E	Class E
Thickness	2 mm	1.5 mm
Density (per m^2)	2.60 kg/m^2	1.83 kg/m^2
Critical Heat Flux	7 - 8 kW/m^2	8 kW/m^2

The membrane width away from PV panels was reduced due to limited membrane available, in Tests 22 and 25. However, it was believed that the membrane size was enough for represent same test results as a 150 cm width membrane as in other tests, since the fire propagated much less than the membrane provided.

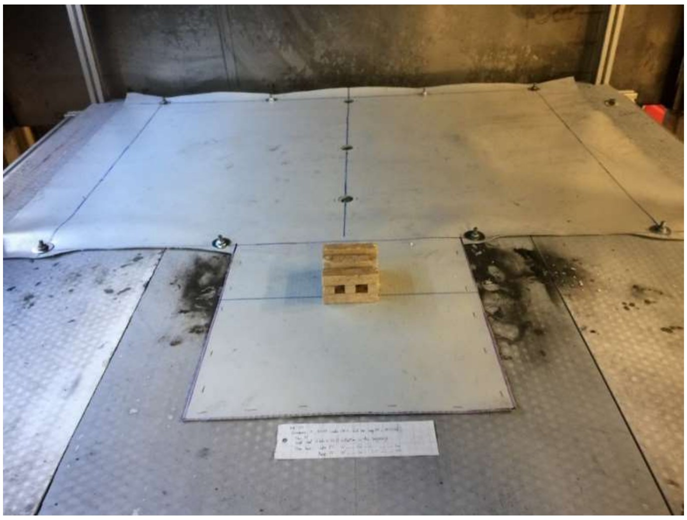


Figure 11 An example of 45 cm by 45 cm membrane placed under PV panels (1/2). The membrane under PV panels connected with 150 cm by 93 cm membrane outside the PV panel

Figure 12 An example of 45 cm by 45 cm membrane placed under PV panels (2/2). The membrane was connected with 150 cm by 93 cm membrane outside the PV panel

2.2.3 Ignition Source

A standard burning brand was considered before the testing, such as described in ASTM E108-17. However, the wood crib described in the standard was not meant to be used for testing fire spread or to be an ignition source. In addition, too much fuel might be added if a Class A or B brand was used, and a Class C brand might be too small. The conditioning process also take too much time for testing preparation. Since the wood crib was only for representing any ignition source possible, the experimenter decided to create a wood crib that can ignite the roof membrane but as small as possible.

A 10 cm by 10 cm by 6 cm wood crib with fire lighter was chosen to be the ignition source in the tests. The weight of wood crib is 190 $\pm$ 5 grams, and the fire lighter was around 10 grams. The wood crib was made by nine sticks of 2 cm by 2 cm by 10 cm wood. The wood sticks were placed in three layers with 3 sticks in each layer and the sticks were placed at right angles to the adjoining layers. The fire lighter was put in the gap of the wood sticks on the bottom layer. An example of the ignition source is shown in Figure 13.

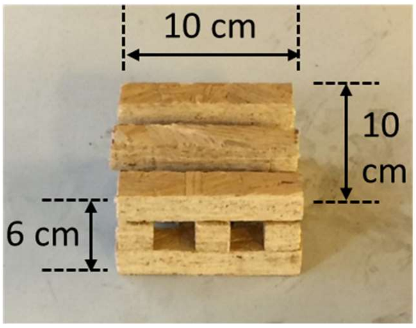


Figure 13 An example of ignition source (wood crib). The ignition source is made with nine 2 cm by 2 cm by 10 cm wood sticks, while solid fire lighter was placed in the bottom layer of the wood crib. All the wood sticks comes from the same piece of laminated wood

The wood crib was placed on the edge of membrane in first eight tests and in the center of membrane in Test 9. From Test 10, the wood crib was moved to 10 cm from the edge of membrane to observe the fire spread in another direction. In Test 9 and Test 30, the ignition source was placed 30 cm from the membrane. While in Test 28 and 29, the ignition source was placed at the edge of PV panel. The positions of the wood crib are shown in Figure 14.

2.2.4 Positioning the PV Panels

The dimension of the PV panel is 164 cm by 100 cm in width and length. PV panels were placed on the West side of the experiment setup. The cables of the PV panels were cut off because the burning of the cable will only affect the first test, while the PV panels were used repeatedly in most tests.

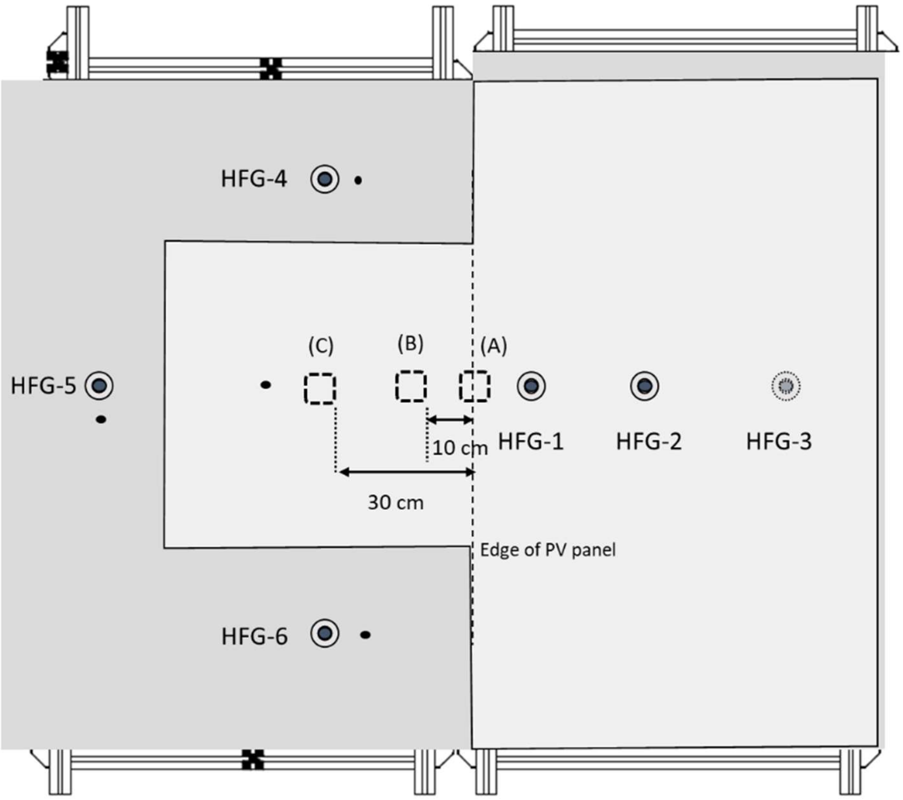


Figure 14 A schematic drawing showing the positions of the wood crib placed in the tests. From Test 10, the wood crib was placed 10 cm from the edge of membrane, as shown in position (B). In Test 9 and Test 30, the ignition source was placed 30 cm from the membrane, as position (C). While in Test 28 and 29, the ignition source was placed at the edge of PV panel, as shown in position (A)

2.2.4.1 Angle of Inclination

The best tilt angle for solar panels can depend on the orientation, latitude, season and the shading for the site while installing, to have the most energy production. When the sun light is perpendicular to the panels, the solar panels are most productive. In general, the panels should face to the south for northern hemisphere since the earth is a globe. The latitude and the season will also affect the angle of sunlight because there is a 23.5° inclination for the rotation axis of earth. The inclination angle for the solar panels should be larger during winter than summer period for receiving the most sunlight. In addition, the shading of adjacent constructions or plants will influence the production of solar energy.

As a result, the best inclination angle and orientation for the PV panels can vary significantly depending on the conditions of the host building. Tables for suggested installation angles range from 0° to 45° was provided for installing PV panels in UK (MCS, 2012). In the experiments performed by Manzini et al., several angles, such as 30°, 60°, 90° to the ground, are used for the test sample (Manzini et al., 2015a).

It was chosen to use a 13° angle for PV panels to compare with existing experiment data, while it also falls in the range of recommended PV installation angles.

2.2.4.2 Gap Distance

The gap distance was 9 cm at the lower side of the PV panel and the highest side was 32 cm from the roofs, since there was a 13° inclination for the panels. The 9 cm gap distance was chosen to be identical as previous tests done and thus the results can be compared.

In the tests performed by UL, a 13 cm gap between the PV panels and roofs represented the highest risk of fire spread. Since the gap was lower enough to have less entrained air but not too low to make the fire shifted to the upside of PV panels. However, the ignition sources in this study is different from what was used in UL tests. In UL tests, the ignition source was a gas burner with a 5.3 m/s air flow impinging from the side, while the ignition source in this thesis was a fire driven by buoyancy under PV panels. The fire in this study remained under PV panels during the tests. Therefore, even the gap distance was smaller than 13 cm, the flame was not distracted, thus the fire was not weakened as the smaller gap in UL tests.

2.3 Experimental Matrix

The size of membrane started from 20 cm by 20 cm and increased afterwards. In the first part of the tests, it was decided to use a 45 cm by 45 cm membrane under PV panels due to the smoke extraction perspective. In the second part of tests, the membrane increased to 70 cm by 70 cm under PV panels, thanks for new methods for helping the smoke extraction, such as extra sealing and adjusting the position of the setup under exhaust hood. The membrane under PV panels was connected with 150 cm by 93 cm membrane outside the panels. In the second set of tests, two experiments were done with a 150 cm by 100 cm under PV panels and connected with 150 cm by 100 cm outside the panels. The testing matrix is shown in Table 2.

The membrane was placed 20 cm from the edge of the left deck in first eight tests. While the distance to the first deck was then reduced to 10 cm after Test 9 to observe the fire spread in another direction.

The wood crib was put at the edge of the membrane in first few tests. After Test 10, the ignition source was placed 10 cm from the edge of membrane. In Test 9 and Test 30, the ignition source was placed around 30 cm from the membrane to observe the effect of gap distance. In Test 28 and 29, the wood crib was placed at the edge of PV panel to observe the influence of ignition position for fire spread.

The membrane was ignited under and without PV panels to show the influence of PV panels for fire spread. In addition, new and burned PV panels were both used in the tests to show how if the burning on the backside of panels could influence the fire under PV arrays.

The extraction flow of the exhaust hood was used to prevent the smoke from spreading in the lab; however, it was found later that the extraction flow could influence the burning under PV panels.

Table 2 Experimental matrix

	Description	Wood	Membrane				PV
			Type	Under PV	Away PV	Configuration	
Test 1	N/A	N/A	A	~25*30	N/A	N/A	No
Test 2	Wood crib only	N/A	No	No	N/A	N/A	No
Test 3	Wood crib only.	N/A	No	No	N/A	N/A	Burned
Test 4	N/A	0 cm from membrane	A	20*20	N/A	20 cm from board.	Burned
Test 5	Setup = Test 4	= Test 4	A	30*30	N/A	= Test 4	Burned
Test 6	Setup = Test 4	= Test 4	A	40*40	N/A	= Test 4	Burned
Test 7	Wood crib only	20 cm from board	A	No	N/A	No	Burned
Test 8	Setup = Test 4	= Test 4	A	50*50	N/A	= Test 4	Burned
Test 9	N/A	29 cm from membrane.	A	70*70	N/A	10 cm from board.	New
Test 10	N/A	10 cm from membrane	A	70*70	N/A	10 cm from board	Burned
Test 11	Setup = Test 10	= Test 10	A	70*70	N/A	= Test 10	No
Test 12	Setup = Test 10	= Test 10	A	30*30	N/A	= Test 10	Burned
Test 13	Setup = Test 10	= Test 10	A	40*40	N/A	= Test 10	Burned
Test 14	Setup = Test 10	= Test 10	A	30*50	N/A	= Test 10	Burned
Test 15	Setup = Test 10	= Test 10	A	40*40	N/A	= Test 10	Burned
Test 16	Setup = Test 10	= Test 10	A	50*50	N/A	= Test 10	Burned
Test 17	Setup = Test 10	= Test 10	A	45*45	N/A	= Test 10	Burned
Test 18	N/A	= Test 19	B	45*45	150*93	= Test 19	Burned
Test 19	The length of second deck was reduced by 18.5 cm	10 cm from membrane	B	45*45	150*93	10 cm from board	Burned
Test 20	Setup = Test 19	= Test 19	B	60*35	150*93	= Test 19	Burned
Test 21	Setup = Test 19	= Test 19	B	75*30	150*93	= Test 19	Burned
Test 22	Setup = Test 19	= Test 19	B	75*30	75*93	= Test 19	Burned
Test 23	Setup = Test 19	= Test 19	B	45*45	150*93	= Test 19	New
Test 24	Setup = Test 19	= Test 19	B	45*45	150*93	= Test 19	New
Test 25	Setup = Test 19	= Test 19	B	45*45	100*93	= Test 19	Burned
Test 26	Extra tests	10 cm from membrane	A	70*70	150*93	Connected	New
Test 27	Extra tests	= Test 26	A	70*70	150*93	Connected	Burned
Test 28	Extra tests	wood at the edge of PV (half out)	A	70*70	150*93	Connected	New
Test 29	Extra tests	= Test 28	A	70*70	150*93	Connected	unburned side
Test 30	Extra tests	30 cm from membrane	A	150*100	150*100	Connected	Burned
Test 31	Extra tests	= Test 26	A	150*100	150*100	Connected	Burned

Chapter 3. Results

Two types of membrane were used in the experiments. The membranes are PVC based roof membranes with fire rating of Class E. The critical heat flux was 7 - 8 kW/m^2 for membrane A and 8 kW/m^2 for membrane B. The results of critical heat flux measured can be found in Appendix B.

In ASTM E1354, it is considered no ignition if the material is not ignited in 20 minutes. As the heat flux decreasing, the time required for ignition increased until the ignition time exceed more than 20 minutes. In addition, the ignition time started to fluctuate near critical heat flux. It is shown in Figure 15.

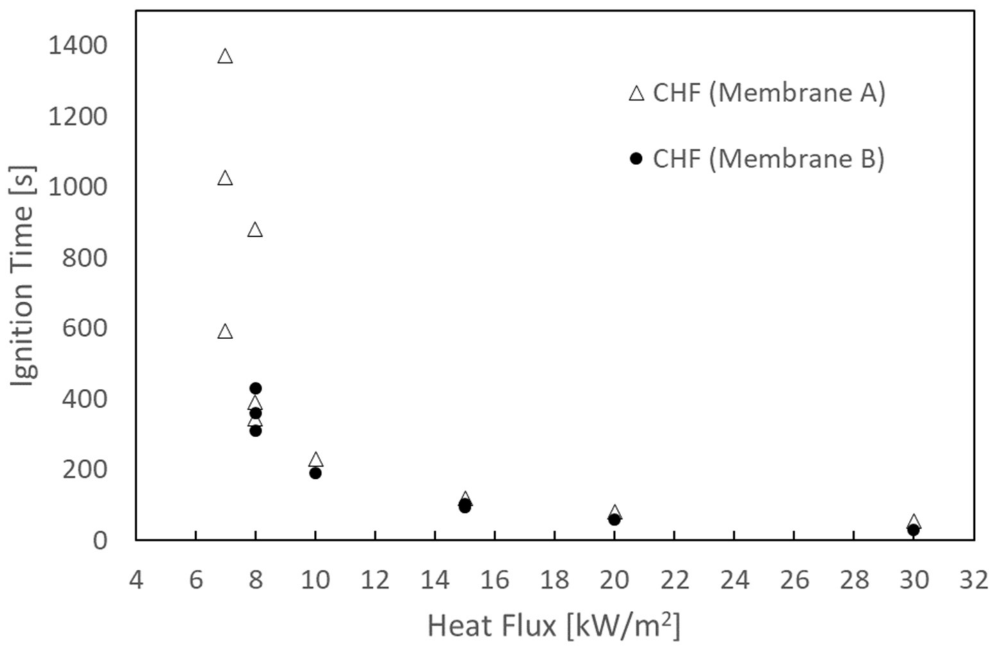


Figure 15 The ignition time over heat flux for critical heat flux tests. The tests show that the time for ignition increased when the heat flux decreased, and the ignition time fluctuated significantly at critical heat flux value

A plot for heat flux and ignition time was also made for membrane A and B in Figure 16. Linear extrapolation of CHF from the plot can be possible. However, in reality, the critical heat flux can be strongly influenced by convective heat, configurations, and boundary conditions.

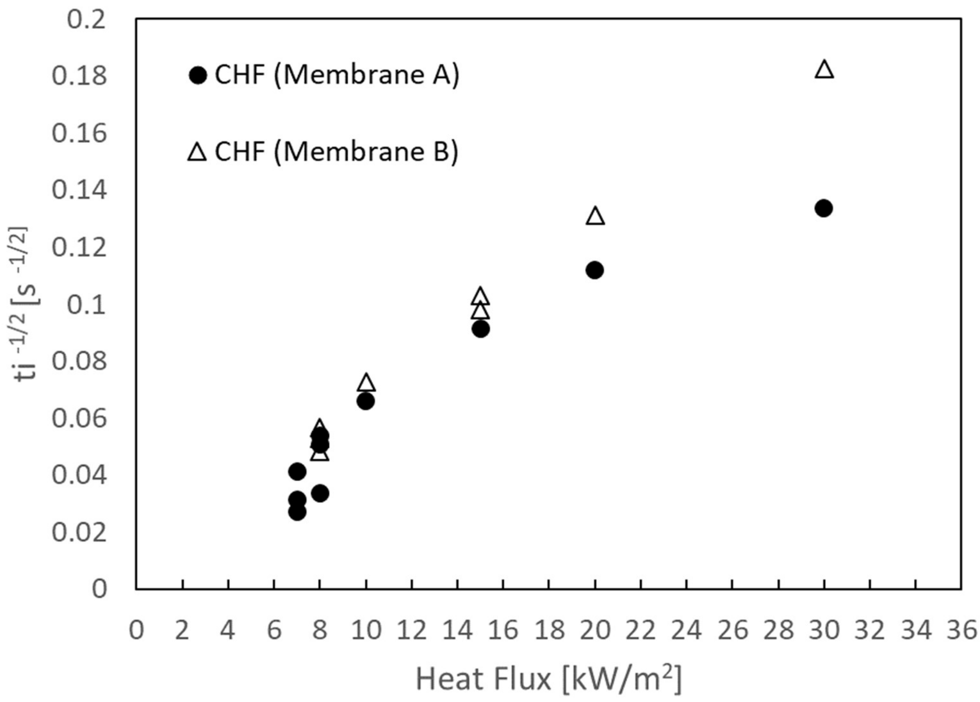


Figure 16 Heat flux over square roof of ignition time for membranes. Linear extrapolation of CHF from the plot will be possible. However, in reality, the critical heat flux can be strongly influenced by convective heat, configurations, boundary conditions

3.1 Qualitative Experimental Observations

A 45 cm by 45 cm membrane was placed under the PV panel and connected to a 150 cm wide membrane outside panel. The membrane was burned almost completely under the PV panel, but the fire did not spread much to the membrane area that was not covered by the PV panel (see Figure 17 and Figure 18).

The backside of the panel was flammable and the fire can extend more than the edge of the solar panel, when the flame started to spread on the its backside. Since the panel inclined in a 13° angle, the flame extended in the direction of the higher side of the panel due to the buoyance. A picture of the fire burning on the backside of PV panels is shown in Figure 19.

The solar panels were damaged after burning, and the level of damage was related to the scale of fire, in other words, the size of membrane burning underneath. Solar cells and wires underneath the panel fell down after the fire (Figure 18). Flammable dripping and cell falling was also observed when new panels were used in the experiments. The panel did not crack during the experiments; however, deformation of panels was observed during the tests.

Figure 17 The fire spread in Test 23. The fire did not propagate outside the panel, while the membrane under the PV panel burned completely. The panel did not crack during the experiments; however, deformation of panels was observed during the tests

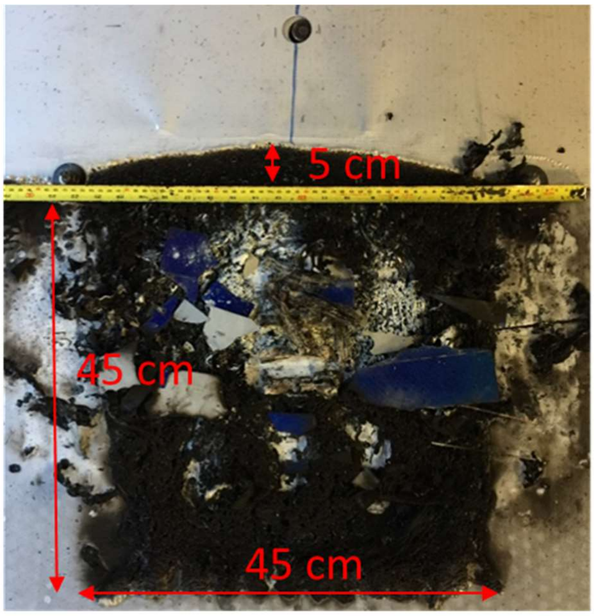


Figure 18 The fire spread under the PV panel in Test 23. The fire burned the whole 45 cm by 45 cm membrane under the PV panel. However, the fire only spread 5 cm out of the panel. The ruler represented the edge covered by the PV panel

New panels were used in Test 9, 23, 24, 26, and 28, while burned PV panels were used in other tests, due to the limited solar panel available. However, it should be noted the panels used in Test 10 and Test 29 were almost unburned.

The area burned underneath the panel was similar to the membrane size for Test 23 and Test 24, when new panels were used in the tests. Nevertheless, a larger area (around 125 cm by 80 cm) was damaged by the fire in Test 10. The reason was assumed to be higher extraction flow in Test10. The extraction flow was raised after the smoke production increased during the tests. The extraction flow increased to 1200 l/s in Test 10, while it only increased to 800 l/s in Test 23 and 24. The data also showed that the HRR can grow in exponentially than the membrane area. The area damaged by the fire on PV panels can be seen in Figure 20 and Figure 21.

Figure 19 A picture of the fire burning on the backside of PV panels (Test 24). The flame propagated on the backside of the PV panel. The flame extended longer much than the membrane size, and the fire spread rapidly on the backside. The fire also burned more severely when new PV panels were used in the tests

Figure 20 The damaged area of PV panels after the tests (front view). From left to right: tested repeatedly, Test 23, Test 24, and Test 10

Figure 21 The damaged area of PV panels after the tests (back view). From left to right: tested repeatedly, Test 23, Test 24, and Test 10

3.2 Heat Flux (HF) Measurements

The heat flux values measured were small due to the fire did not spread over the area shaded by the PV panel. Larger values were received for HFG-1 for the reason that it was closer to the fire burning under PV panels. As for HFG-2 and HFG-3, most of the values were smaller than 0.3 kW/m^2, which was considered negligible. All the heat flux values measured in the experiments were listed in Appendix C.

From Test 1 to Test 13 (except Test 10), The heat flux measured was ≦ 0.3 kW/m^2 in all HFGs. This can due to the fire did not spread much away the PV panel. The HF curve of Test 13 is shown as an example in Figure 22.

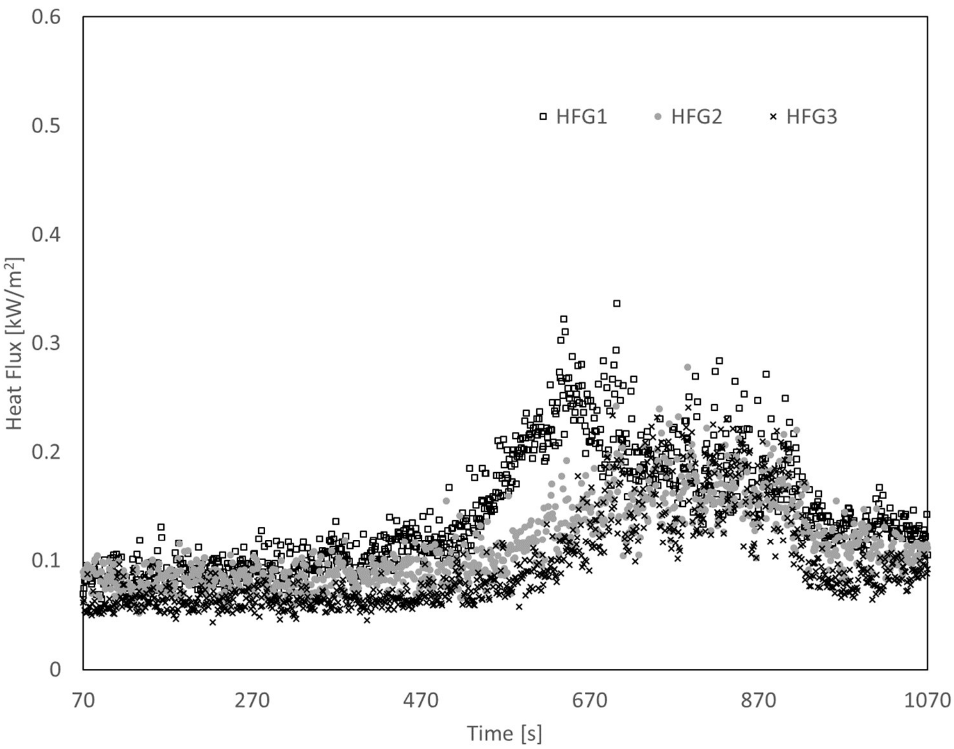


Figure 22 An example of heat flux curves for Test 1 to Test 13 (Test 13). The heat flux measured was ≦ 0.3 kW/m^2 in all HFGs from Test 1 to Test 13 (except Test 10). The figure shows the heat flux value from the time of wood crib was ignited

From Test 19, the incombustible board under the membrane was cut in order to move the experiment setup closer to the center of the exhaust hood, for improving the smoke exhausting. The heat flux values increased since the distance to the fire became closer. The HF curve is shown in Figure 23.

The heat flux value larger than 0.3 kW/m^2 for HFG-1 were plotted in Figure 24. The heat flux values increased significantly after the distance to the fire was reduced. The testing conditions for Test 15 and Test 16 were identical, while the membrane area of Test 16 was 1.6 times as Test 15; however, the heat flux value was almost the same for these two tests before the distance of HFG was reduced. Nevertheless, the heat flux was more than doubled when the area came to 0.49 m^2 under the PV panel, comparing Test 10 and Test 16.

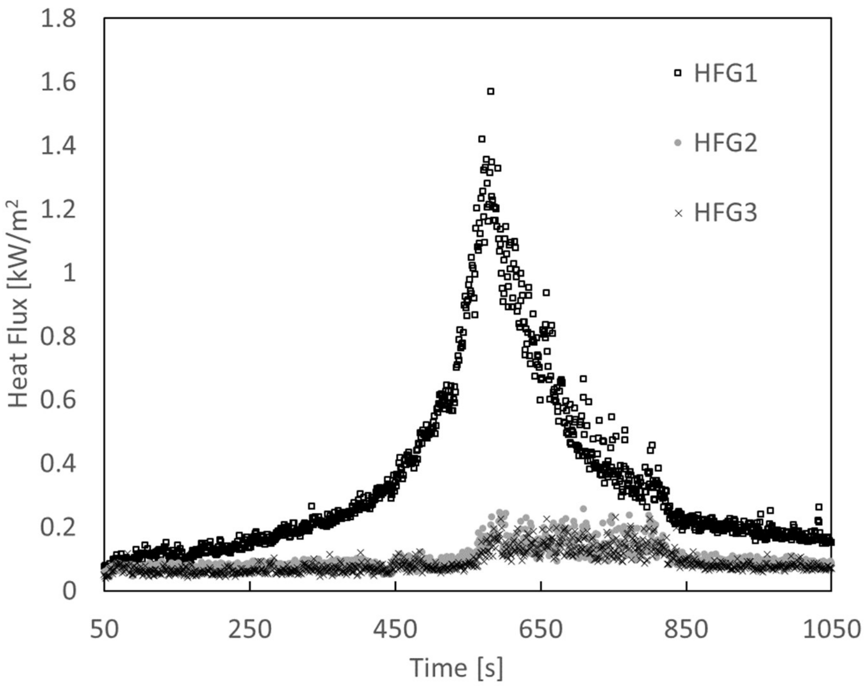


Figure 23 The HF curve of Test 19. Test 19 was the first test after the distance to fire was reduced. The distance for HFG-1, 2, and 3 are 11.5 cm, 41.5 cm, and 81.5 cm to the West deck. It is obvious that the heat flux in HFG-1 increased essentially. The heat flux measured in HFG-2 and HFG-3 was almost the same, and it can be assumed that the heat flux was almost negligible for these two HFGs

Test 19 and Test 25 are two tests with similar testing conditions and same membrane area (45 cm by 45 cm) under the PV panel, while the extraction flow was different for these two tests. The extraction flow of both tests started at 500 l/s. When the fire started to spread on the membrane and produced much smoke, the extraction flow was raised to prevent the smoke from escaping the hood. For Test 19, the flow was increased to 1000 l/s and remained to the end of test. While for Test 25, the flow was increased to 850 l/s for 100 seconds and reduced to 500 l/s later. It is assumed that higher extraction flow after fire spread can help the burning under PV panels, by bringing fresh air.

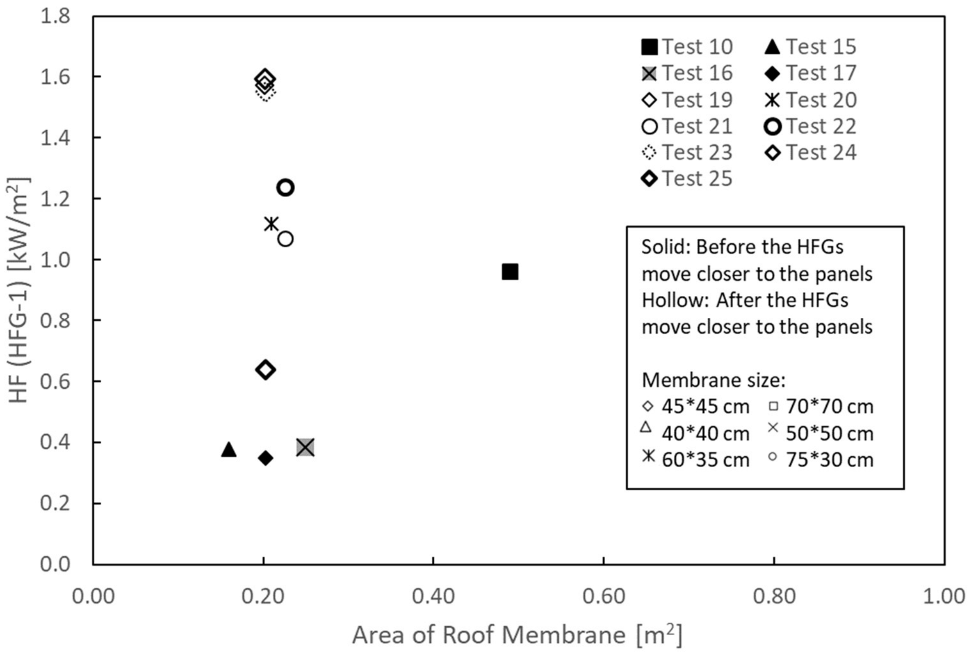


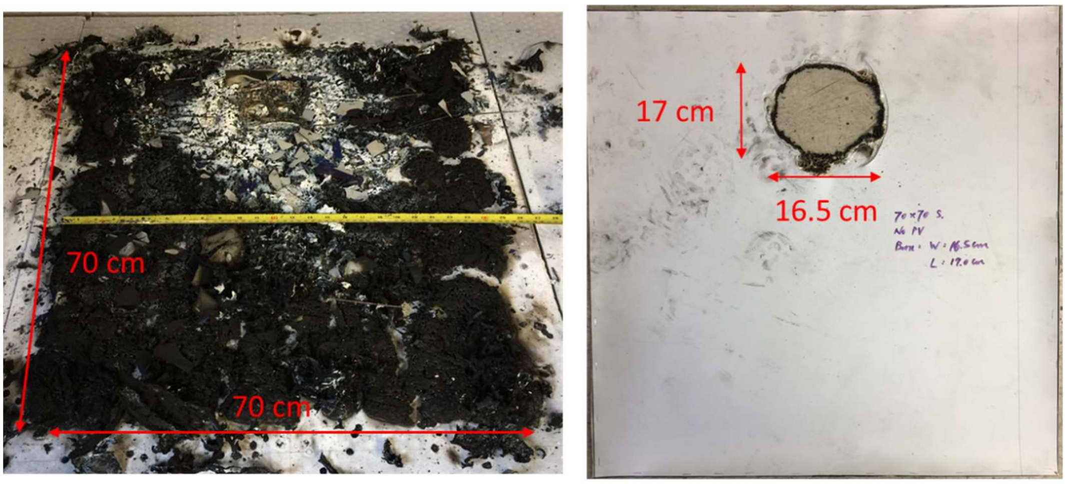
Figure 24 Heat flux values at HFG-1. The heat flux increased significantly when the distance from HFG to fire is reduced

3.3 Heat Release Rate (HRR)

The HRR values were calculated by both oxygen consumption calorimetry (OCC) and carbon dioxide and carbon monoxide generation (CDG) methods. The HRR values calculated by CDG method were chosen in this thesis. The reason for choosing CDG method was that the value calculated by CDG method were more stable than from OCC method, while the HRR value calculated by OCC method fluctuated much more than the other one. An example of HRR curve for OCC and CDG is shown in Figure 26. The maximum HRR value of each tests are listed in Table 3.

The HRR of the wood crib were 7 kW (without PV panel), 8 kW (under a PV panel), and 10 kW (under a PV panel). The HRR was higher than the critical heat flux of the membranes when wood crib was placed under the solar panels.

The burning under PV panels or without panels was significantly different. The fire only spread around 17 cm in length and width when no PV panel was placed in Test 11, while the fire burned the whole 70 cm by 70 cm membrane under the PV panels in Test 10. The HRR produced was also very different. A peak HRR of 141 kW was measured when the PV panel was placed, while only 5 kW was measured without placing the panel. The fire spread of Test 10 and 11 is shown in Figure 25.



Test 10 **Test 11**

Figure 25 Comparison of fire spread when membrane was burned under or without PV panels. The fire burned whole 70 cm by 70 cm membrane under the PV panels, while it only burned around 17 cm in length and width when no PV panel was placed

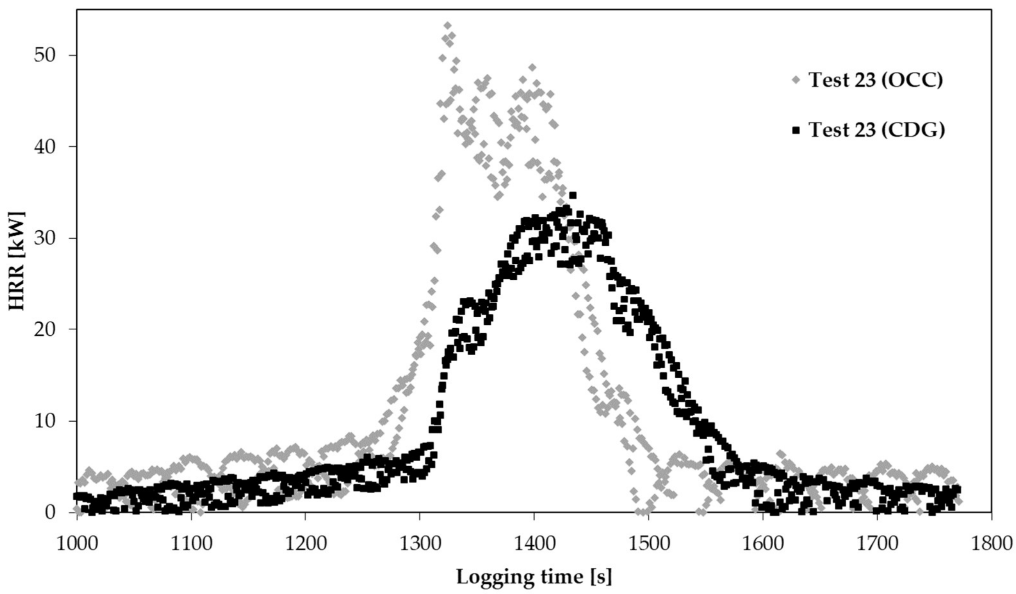


Figure 26 An example of HRR curves for OCC and CDG methods (Test 23). The HRR curve was more stable calculated by CDG method. Therefore, the values calculated by CDG method were chosen in the thesis

Table 3 HRR of the tests

	Peak HRR (CDG) [kw]	HRR/Area [kW/m²]	PV	Membrane under PV			
				Type	Width*Length [cm]	Area [m²]	% of Area Burned
Test 1	N/A	N/A	No	A	~25*30	0.075	N/A
Test 2	7	N/A	No	No	No	N/A	N/A
Test 3	10	N/A	Burned	No	No	N/A	N/A
Test 4	8	208	Burned	A	20*20	0.04	90%
Test 5	9	96	Burned	A	30*30	0.09	60%
Test 6	16	101	Burned	A	40*40	0.16	60%
Test 7	8	N/A	Burned	A	No	N/A	N/A
Test 8	9	37	Burned	A	50*50	0.25	50%
Test 9	10	20	New	A	70*70	0.49	20%
Test 10	141	288	Burned	A	70*70	0.49	100%
Test 11	5	11	No	A	70*70	0.49	20%
Test 12	Data Missing	N/A	Burned	A	30*30	0.09	80%
Test 13	27	167	Burned	A	40*40	0.16	80%
Test 14	21	142	Burned	A	30*50	0.15	60%
Test 15	18	111	Burned	A	40*40	0.16	80%
Test 16	26	103	Burned	A	50*50	0.25	80%
Test 17	22	107	Burned	A	45*45	0.20	80%
Test 18	Data Missing	N/A	Burned	B	45*45	0.20	80%
Test 19	Data Missing	N/A	Burned	B	45*45	0.20	90%
Test 20	30	144	Burned	B	60*35	0.21	90%
Test 21	19	86	Burned	B	75*30	0.23	60%
Test 22	20	89	Burned	B	75*30	0.23	90%
Test 23	35	171	New	B	45*45	0.20	100%
Test 24	35	175	New	B	45*45	0.20	100%
Test 25	22	110	Burned	A	45*45	0.20	70%

The HRR was higher when new panels are used. For instance, the HRR was 35 kW (Test 24) when new panels were used, while it was 22 kW (Test 25) when using a burned panel. Fire was observed that on the backside of PV panels, which should be the reason to cause the higher HRR in the tests that new panels were used. The figure of HRR and the area under the PV panel is shown in Figure 27. The tests showed that the HRR increased with membrane area burned.

High extraction flow seemed to obstruct the burning in the early stage of fire spread, making the burning for Test 8 and Test 9 weaker than other tests. For Test 8, the extraction flow was increased to 1200 l/s in the early stage of fire spread. While for Test 9, the extraction started at 1200 l/s.

For smaller size (0.15 m^2 to 0.25 m^2) of membrane burning under PV panels, the HRR produced did not change much according to the membrane size. For instance, the HRR was almost the same (26 kW/m^2 and 27 kW/m^2) for Test 16 and Test 13, while the membrane area of Test 16 (0.25 m^2) was 1.6 time as Test 13 (0.15 m^2). However, when the membrane area increased to 0.49 m^2 (Test 10), the fire grew much bigger. The HRR of Test 10 (141 kW/m^2) was 5.4 times than Test 16 (26 kW/m^2), while the membrane area was only 2 times larger. The reason might be the membrane ignited in Test 10 was big enough to create a fire that could ignite more membrane in the same period of time and induced a high HRR. The HRR/Time curve is plotted for Test 10 and Test 16 in Figure 28. Both Test 10 and Test 16 took around 150 seconds to reach its peak HRR from 8 kW. However, the gradient was much steep for Test 10. It is assumed that more membrane was ignited in same period of time for Test 10.

There was a trend that heat flux increased with area of membrane under the PV panel. However, the heat flux did not increase as significantly compared to the HRR as it was for Test 10 and Test 16. The heat flux measured for Test 10 was 1.0 kW/m^2, 2.5 times than Test 16 (0.4 kW/m^2), while it was 5.4 times for HRR. The reason might be the heat flux was blocked by the PV panel, when the fire burned underneath.

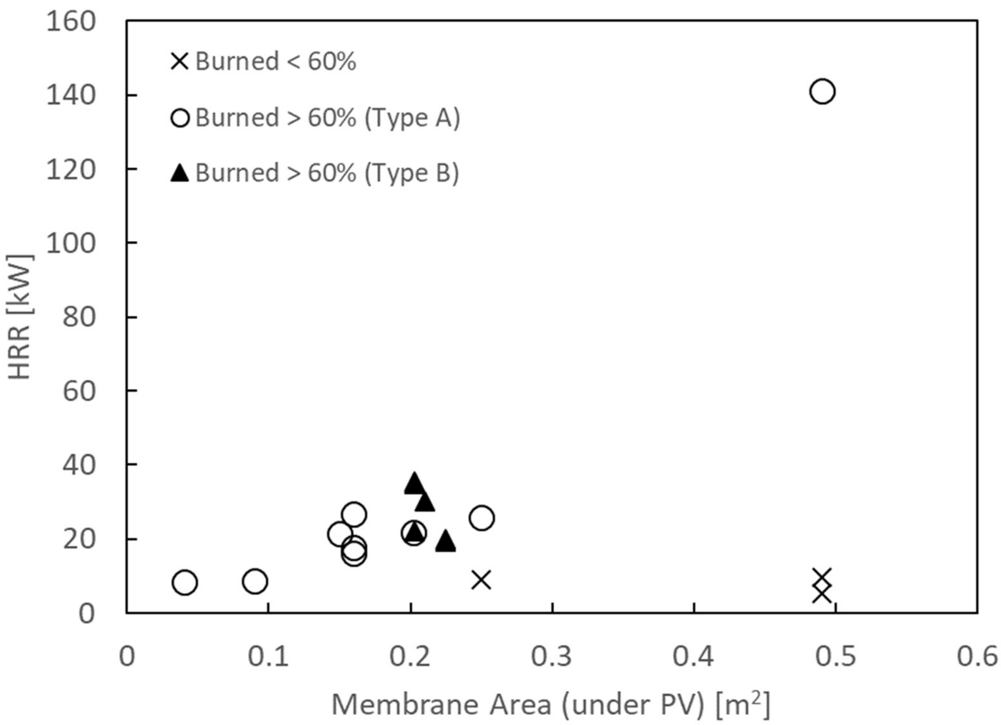


Figure 27 HRR over membrane area under PV panels. In general, the HRR increased with the area, but the increase of HRR was much more significant when the area reached 0.49 m^2

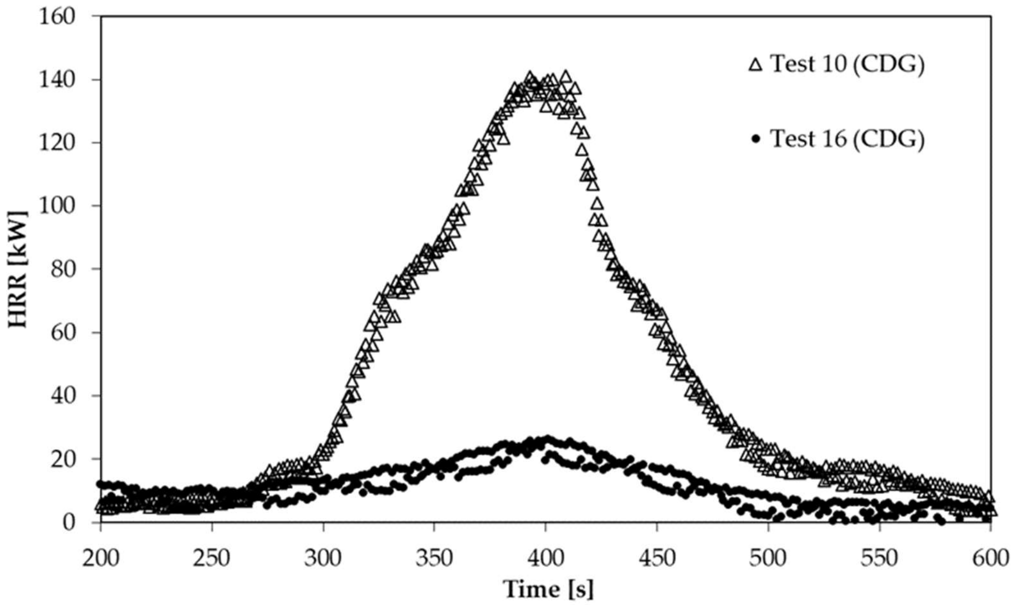


Figure 28 HRR/Time curve for Test 10 and Test 16. Both Test 10 and Test 16 took around 150 seconds to reach its peak HRR from 8 kW. However, the gradient was much steep for Test 10. It is assumed that more membrane was ignited in same period of time for Test 10

3.4 Fire Spread

The fire was much stronger when burning under the PV panel. As described in section 3.3, when the fire was ignited on the membrane without PV panels, the fire only burned 17 cm in length and width in Test 11. While a 70 cm by 70 cm membrane was burned completely with similar testing conditions when placed under PV panels in Test 10. The fire spread of Test 10 and Test 11 is shown in Figure 25.

Test 20, 22, 23 and 24 were tested in similar testing conditions, with the membrane placed under the PV panel extended away the panel. The tests were intended to investigate how far the fire can spread if there was no PV panel upon the roof membrane. The tests showed that the membrane burned almost completely under the PV panel, whereas the fire only spread most 5 cm away the PV panel when a 2 m^2 membrane burning under the PV panel. The maximum length and width of fire spread, under and away the PV panel, were recorded after the tests and the results are shown in Table 4.

The membrane area under the PV panel and the testing conditions are similar in Test 14 and 15, yet the width/length ratios were different among those tests. The dimension was 30 cm by 50 cm for Test 14 and 40 cm 40 cm for Test 15. The fire spread 76% (38 cm/50 cm) in length for Test 14, while the fire spread 90% (36.5 cm /40 cm) in length for Test 14. The picture of fire spread for Test 14 and 15 are shown in Figure 29 and Figure 30. It is assumed that the length of fire spread is related to the width of burning, since the heat received for a later ignited point depends on the area already burning during fire spread, which will be discussed in section 4.4.

Table 4 An overview of the extent of the fire spread on the roof membrane

	Extraction Flow [l/s]	Size of Membrane (W*L) [cm]		PV	Fire Spread [cm]			
					Under PV		Away PV	
		Under PV	Away PV		Length	Width	Length	Width
Test 1	N/A	~25*30	N/A	No	15	21	N/A	N/A
Test 2	500 to 300	No	N/A	No	N/A	N/A	N/A	N/A
Test 3	300 to 650	No	N/A	Burned	N/A	N/A	N/A	N/A
Test 4	630 to 850	20*20	N/A	Burned	18.5	20	N/A	N/A
Test 5	850 to 1200	30*30	N/A	Burned	22	30	N/A	N/A
Test 6	1200	40*40	N/A	Burned	34	36	N/A	N/A
Test 7	1200	No	N/A	Burned	N/A	N/A	N/A	N/A
Test 8	500 to 1200	50*50	N/A	Burned	24	31	N/A	N/A
Test 9	1200 to 750	70*70	N/A	New	17	20	N/A	N/A
Test 10	500 to 1200	70*70	N/A	Burned	70	70	N/A	N/A
Test 11	500	70*70	N/A	No	17	16.5	N/A	N/A
Test 12	400 to 500	30*30	N/A	Burned	25	27	N/A	N/A
Test 13	500 to 1200	40*40	N/A	Burned	39	40	N/A	N/A
Test 14	500 to 1000	30*50	N/A	Burned	38	30	N/A	N/A
Test 15	500 to 1200	40*40	N/A	Burned	36.5	40	N/A	N/A
Test 16	500 to 1200	50*50	N/A	Burned	47	47	N/A	N/A
Test 17	500 to 1200	45*45	N/A	Burned	43	44	N/A	N/A
Test 18	500 →1200 (300s) →900	45*45	150*93	Burned	41.5	45	0	0
Test 19	500 to 1000	45*45	150*93	Burned	45	45	0	0
Test 20	500 →1000 (50s) →750	60*35	150*93	Burned	35	60	1.5	27
Test 21	750 to 850	75*30	150*93	Burned	28.5	53	0	0
Test 22	500 to 750	75*30	75*93	Burned	30	72.8	3	43
Test 23	500 to 800	45*45	150*93	New	45	45	5	69
Test 24	500 to 750	45*45	150*93	New	45	45	4.5	65
Test 25	500 →850(100s) →500	45*45	100*93	Burned	36.5	45	2	18.5

Figure 29 The fire spread in Test 14. The fire only spread 38.5 cm in all 50 cm length. It is assumed that the heat flux reduced when the fire spread to the end of membrane width, making the burning decreased in width at end side of fire spread. The spread of fire will be further discussed in Chapter 4

Figure 30 The fire spread in Test 15. The width was wide enough to support the fire spread until the end of the membrane length

3.5 Tests with Larger Membranes Burning under PV Panels

A 70 cm by 70 cm membrane was placed under PV panels and connected with 150 cm by 93 cm membrane outside the panel in Test 26 to Test 29. Although the membrane size was larger for Test 30 and 31, the fire did not burn more than 70 cm by 70 cm, so they were considered similar with the rest tests. The position of ignition source, PV panel condition, and extraction flow were controlled during the tests for comparison. It was found that these three parameters had significant influence for the burning under PV panels.

3.5.1 HF Measurements

The heat flux values measured depended on the magnitude of fire burning under underneath the PV panels, since the fire did not spread out of the PV panels much. HFG-4 and HFG-5 are 15 cm from the membrane, while the HF measured was higher for HFG-4 in all additional tests. This can show that the position that was closer to the backside of PV panel received higher heat flux. Since the distances from the HFGs to the membrane were identical, it was assumed that the re-radiation heat was much less when the membrane was further away from the PV panels. HFG-1 was 15 cm from the PV panel, while HFG-1 was out of PV panel. The HF measured was much less for HFG-1. This can due to there was no re-radiation from the upper side of HFG-1. It also showed that the HF was much less without a panel.

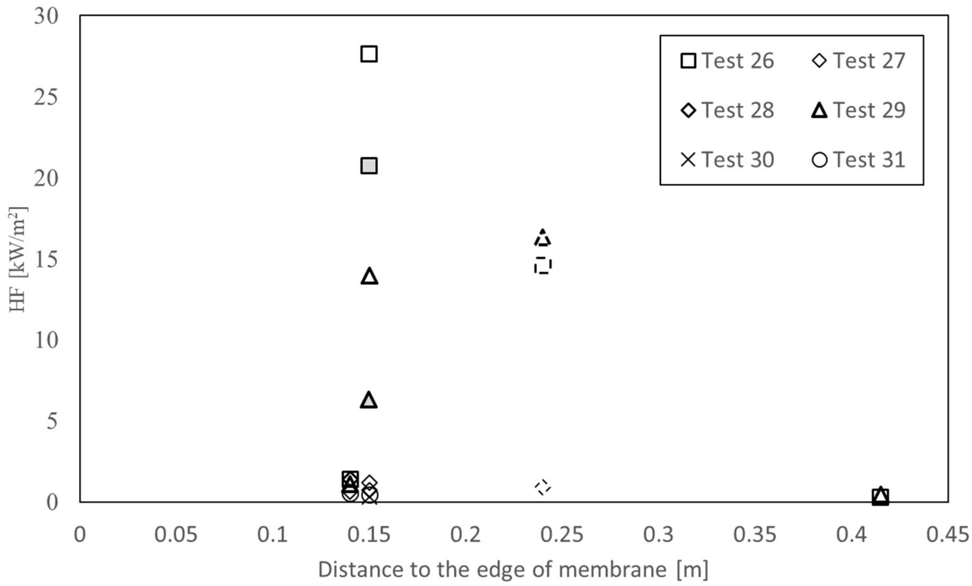


Figure 31 HF value over the distance between the roof membrane and HFGs. It showed that the HF was smaller when the distance to PV panel was larger. The HF under the PV panel was much higher than the HFG out of panels. (Legends for 0.15 m from the membrane: hollow: HFG-4, gray: HFG-5, sided: HFG-1)

The distance to PV panels was the same for HFG-6 and HFG-1, while the distance to the membrane was further for HFG-6. The HF measured was smaller for HFG-6 than HFG-1 in general. It is assumed that because the distance to the flame was longer. However, the HF measured in Test 29 was higher for HFG-6 than HFG-4. It was assumed the reason was that there was a faster burning on the backside of the PV panel in Test 29.

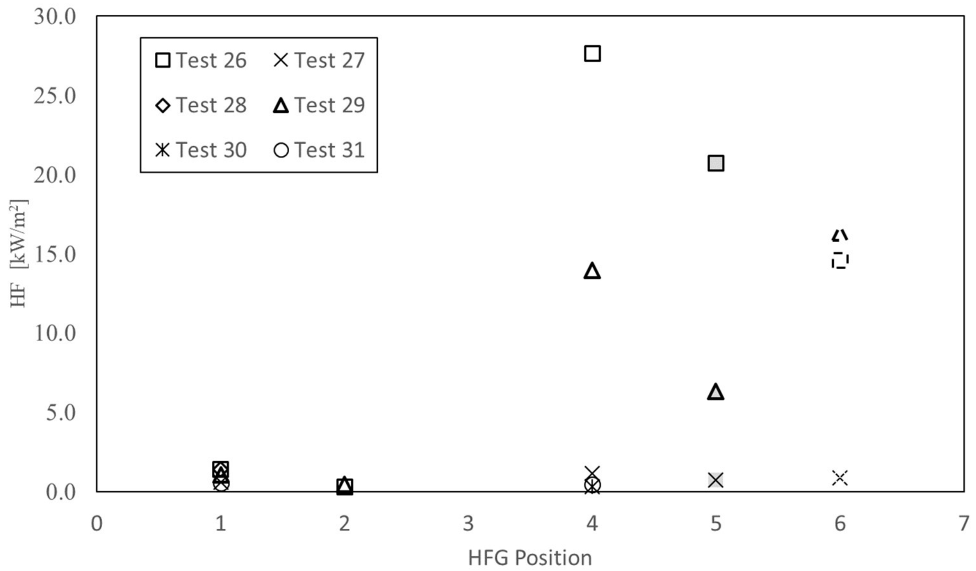


Figure 32 HF measured in different positions. It showed that the HF was smaller when the distance to PV panel was larger. The HF under the PV panel was much higher than the HFG out of panels. (Legends for 0.15 m from the membrane: hollow: HFG-4, gray: HFG-5, sided: HFG-1)

3.5.2 HRR Measurements

The tests showed that the panel conditions influence the burning significantly. New panels and burned panels are both used in the tests. The highest HRR showed in the tests burned under new PV panels, e.g. Test 26 (93 kW) and Test 29 (81 kW). The tests used burned PV panels show much smaller HRR, such as Test 27 (16 kW) and Test 31 (15 kW). It should be noted that the panel was considered almost unburned in Test 29, since the fire in Test 28 did not burned seriously and the unburned side was used in Test 29.

Similar HRR was measured for the same area burned was close to previous tests. However, the HRR measured in Test 10 was much higher than the other tests that the membrane was burned completely under PV panels. It is assumed that higher extraction flow after the fire spread in Test 10 helped the fire growing stronger. A figure of HRR and burned area is shown in Figure 33. The HRR curves in Figure 34 proved the assumption. The time required to reach the peak HRR was similar for Test 10 and Test 26, yet the peak value was higher for Test 10, meaning the burning was faster in Test 10.

The extraction flow has a significant influence on the burning as well. It was found in previous tests that higher extraction flow will have a negative influence for the burning in early stage. However, it was observed that when the fire started in a low extraction flow as 350 l/s under the hood, the fire became smaller, as shown in Test 28 (7 kW). On the other hand, it was assumed that the fire can grow faster when it was spreading on the membrane with a higher extraction flow, while the fire started to diminishing after increasing the extraction flow in Test 31 (15 kW). It is assumed that the hot smoke was extracted that reduced the heat flux on the membrane surface and make the burning became slower.

The position of ignition source influenced the burning obviously. When the ignition source was placed in a position that was further away from the backside of the PV panel, the fire reduced and almost not spreading. The HRR was also smaller in this case, as in Test 30 (5 kW) compared to Test 31 (15 kW). It showed that the distance between the PV panel and the roof can influence the fire spread notably. This can result in the re-radiation heat was reduced when the distance was further, thus the fire grew slower and smaller.

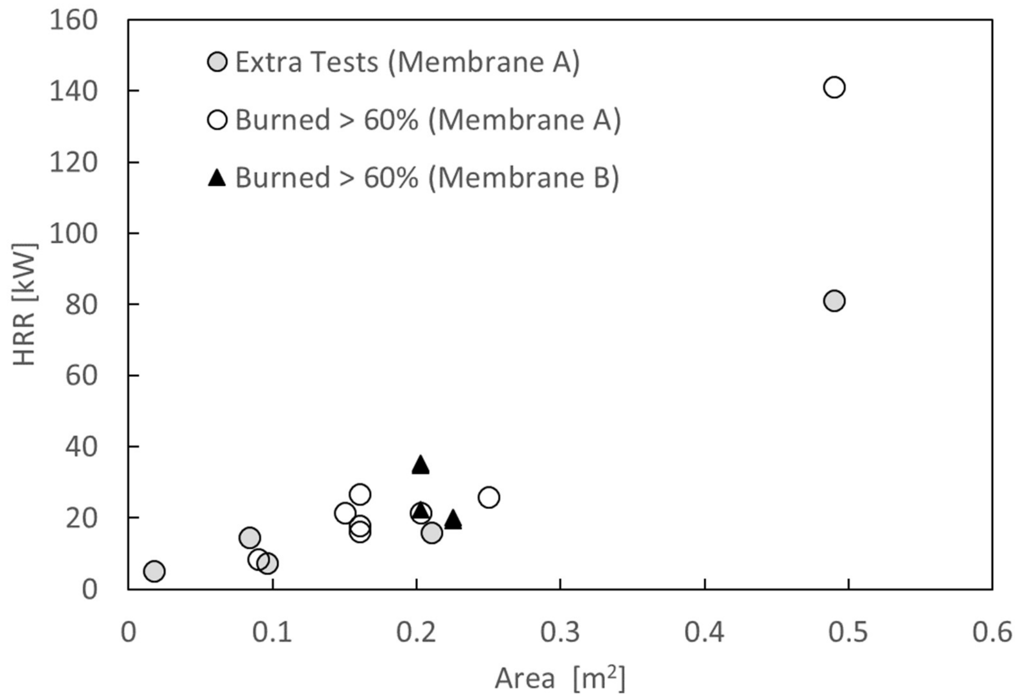


Figure 33 HRR over membrane area burned. Similar HRR was measured for the same area burned close to previous tests

In addition, when the ignition source was placed at the edge of PV panels, the fire grew slower in this case. It took around 860 seconds (Test 29) to reach the peak HRR from ignition for the test having the wood crib placed at the edge of panel, while it only took 630 seconds for Test 26 when the wood crib was placed 10 cm from the panel. However, it was assumed due to the fire from the ignition source was half way out of the panel.

Therefore, more heat was lost into the ambient air instead of feeding back the fire under PV panels. The HRR curves from ignition time for Test 26 and Test 29 are shown in Figure 34.

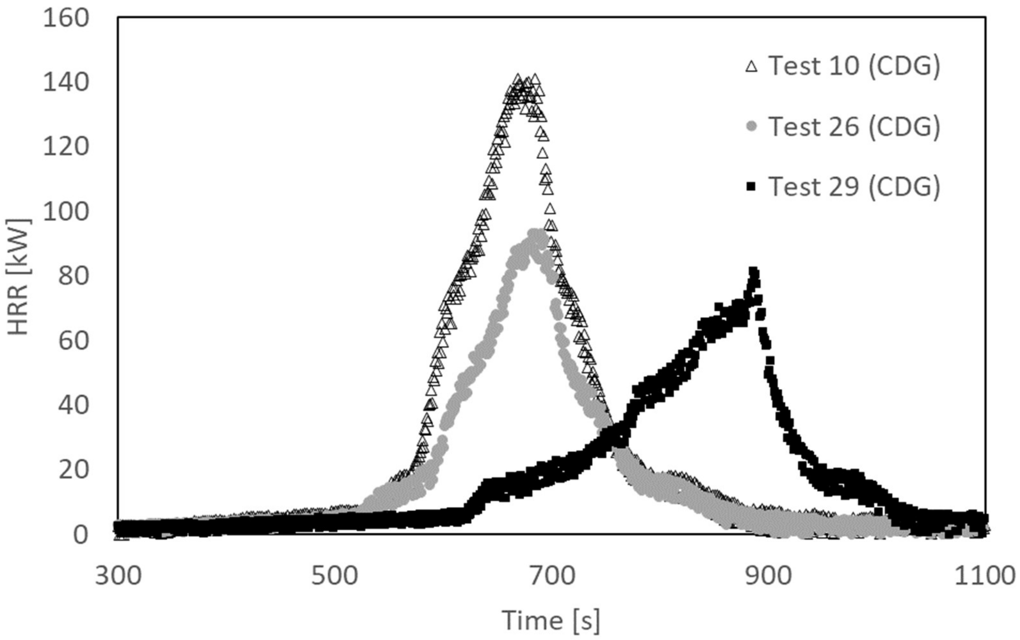


Figure 34 The HRR curves of Test 10, Test 26 and Test 29. (1) The time required to reach peak HRR was similar for Test 10 and Test 26, while the peak was higher for Test 10. It shows the burning was faster in Test 10. The reason was assumed to be the higher extraction flow. (2) It took more time for the test having the ignition source placed at the edge of the PV panel (860 s), while the time required (630 s) was less when the ignition source was placed 10 cm from the panel. It was assumed the reason was that the heat was lost in the ambient air when the flame was half way out of the panel

The heat release for PV panels was calculated by using the HRR curves. By integrating the HRR over time, the total heat release of the burning was then obtained. The heat release of the ignition source was around 2860 kJ, calculated by the same method from the tests that only wood cribs were burned. The heat of combustion of the roof membrane is 25 kJ/g, which was tested before this project. The combustion efficiency was 35.7% for PVC and 70% for wood (Drysdale, 2011). In this case, the heat release of burning one panel was estimated to be ranging from 6600 kJ (Test 26) to 16200 kJ (Test 29). It was assumed that the difference of heat release for panel films was due to the area burned was different during the tests.

3.5.3 Fire Spread

The fire spread had a positive correlation with the magnitude of fire burning under PV panels, the bigger the fire was the more fire spread. However, even the fire burned whole membrane under PV panels, the fire did not spread much out of panel. The furthest fire spread was only 6 cm in length, which was small compared to the 70 cm by 70 cm membrane burned under the panel. The tests showed that the fire spread away PV panels was very limited without the help of wind.

3.5.4 Thermocouples

The highest temperatures were measured in the position inside the membrane area, due to the location was closest to fire. Whereas in Test 29, the highest thermocouple next to HFG-6 measured a high temperature. It is assumed that the fire propagated on the backside of PV panel or the smoke layer led to the high temperature. The data also showed that the highest thermocouples measured higher temperatures. The reason might be the highest thermocouple was covered by the smoke layer under PV panels, which was observed in the video recordings. The measurements of thermocouples are shown in Table 5.

Table 5 Measurements from thermocouples

Distance from Roof [cm]	12	6	0	18	12	6	18	12	6	12	6	0
Thermo-couple	TC 01 [˚C]	TC 02 [˚C]	TC 03 [˚C]	TC 04 [˚C]	TC 05 [˚C]	TC 06 [˚C]	TC 07 [˚C]	TC 08 [˚C]	TC 09 [˚C]	TC 10 [˚C]	TC 11 [˚C]	TC 12 [˚C]
Test 27	99	< 80	< 80	< 80	< 80	< 80	268	113	125	147	80	74
Test 28	< 80	< 80	< 80	< 80	< 80	< 80	< 80	< 80	< 80	< 80	< 80	< 80
Test 29	488	279	320	484	279	296	650	794	794	706	316	365
Test 30	< 80	< 80	< 80	< 80	< 80	< 80	495	75	76	< 80	< 80	< 80
Test 31	< 80	< 80	< 80	< 80	< 80	< 80	313	76	70	< 80	< 80	< 80

3.6 The Extraction Flow and the Burning under PV Panels in the Tests

The extraction flow in most test started at 500 l/s and raised after the increase of smoke production when the fire started to spread on the roof membranes. The extraction flow under the exhaust hood was not tested in purpose during the tests; however, it was found that the extraction flow can influence the burning under the hood by comparing the results of the tests.

The tests showed that higher extraction flow can help the burning under PV panels after the fire spread. By comparing Test 19 and 25, higher heat flux values were measured in the test with higher extraction flow after the fire spreading on the membrane. It was assumed that high extraction flow brought more fresh air and help the growing of fire when the fire was already spreading on the roofs. However, in Test 31, the fire started to diminish after increasing the extraction flow. It was assumed that the fire was weakened after the hot smoke layer under the PV panel was extracted.

On the other hand, high extraction flow can also have a negative impact to the fire spread. When the extraction flow was started in a higher flow, say 750 l/s (Test 21), it was found that the fire spread was much less than the test started at 500 l/s (Test 22), as discussed in section 3.4. It is assumed that higher extraction flow would extract more pyrolyzed gas and obstruct the ignition in early stage of fire spread when the fire is not yet spreading significantly on the membrane. Furthermore, higher air flow also cooled down the fire and making the ignition more difficult. However, when the fire is already growing under the PV panel, increasing the extraction flow will help the burning process because it brings more fresh air to the fire, i.e. better ventilation condition.

In short, the extraction flow can influence the fire spread under PV panel in both positive and negative way in lab conditions. When the extraction flow is high in the early stage of fire propagation, the flow can influence the fire spread adversely. While in the period that the fire is already spreading on the roof membrane, the extraction flow will help the fire spread by creating better ventilation condition. The experimenters should bear this in mind when performing PV panel tests under the exhaust hood.

Table 6 Experiment results under different extraction flows

	Description	W*L [cm]		Extraction Flow [l/s]	Fire Spread [cm]				Max. HRR [kW] (CDG)	Max. HF [kW/m^2] (HFG-1)
					Under PV		Away PV			
		Under PV	Away PV		L	W	L	W		
Test 19	Similar testing conditions for Test 19 and Test 25	45*45	150*93	500 to 1000	45	45	0	0	N/A	1.6
Test 25		45*45	100*93	500 →850(100s) →500	36.5	45	2	18.5	22	0.6
Test 21	Similar testing conditions for Test 21 and Test 22	75*30	150*93	750 to 850	28.5	53	0	0	19	1.1
Test 22		75*30	75*93	500 to 750	30	72.8	3	43	20	1.2
Test 28	Similar testing conditions for Test 28 and Test 29	70*70	150*93	350 →1000(60s) →750	~15	~35	10	~10	7	1.4
Test 29		70*70	150*93	500 →1000 (120s) →1200	70	70	4	121	81	1.1
Test 27	Similar testing conditions for Test 28 and Test 29	70*70	150*93	500 to 1000	42.5	63	0	0	16	0.6
Test 31		150* 100	150* 100	500 →1000(65 s) →500	30.5	35	0	0	15	0.5

3.7 The Repeatability of the Tests

A 45 cm by 45 cm size membrane was chosen to perform tests with new PV panels in the first set of the tests. The test was repeated to prove the repeatability of the testing conditions, in Test 23 and 24.

The distance of fire spread was similar in these two tests. Both the membrane burned completely under the panels and similar propagating length away the panels. The fire spread of both tests are shown in Figure 35.

The peak heat flux for both tests are 1.6 kW/m^2 for HFG-1, while negligible heat flux values were measured for HFG-2 and HFG-3. The heat flux curves are quite alike for both tests as well. The heat flux curves are shown in Figure 36. The peak HRR values are 35 kW in both tests. The HRR curves calculated by OCC or CDG methods are similar between these two tests, which are shown in Figure 37. The results of fire spread, HF, and HRR were similar for these Test 23 and 24. Thus, the repeatability is reached among these two tests.

Figure 35 The fire spread on Test 23 (left) and 24 (right). The membrane burned completely under PV panels and the fire spread away panels are similar

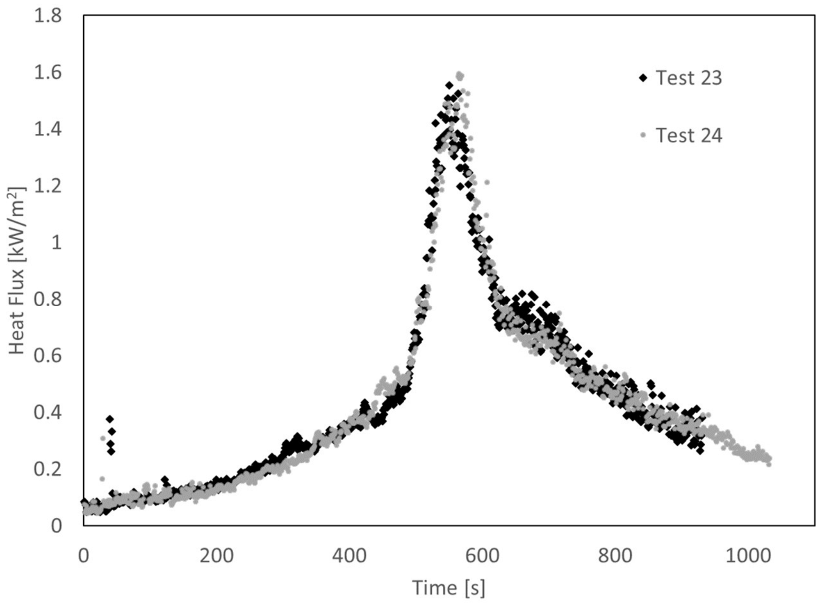


Figure 36 HF curves measured by HFG-1 for Test 23 and 24. The HF curves were similar for these two tests

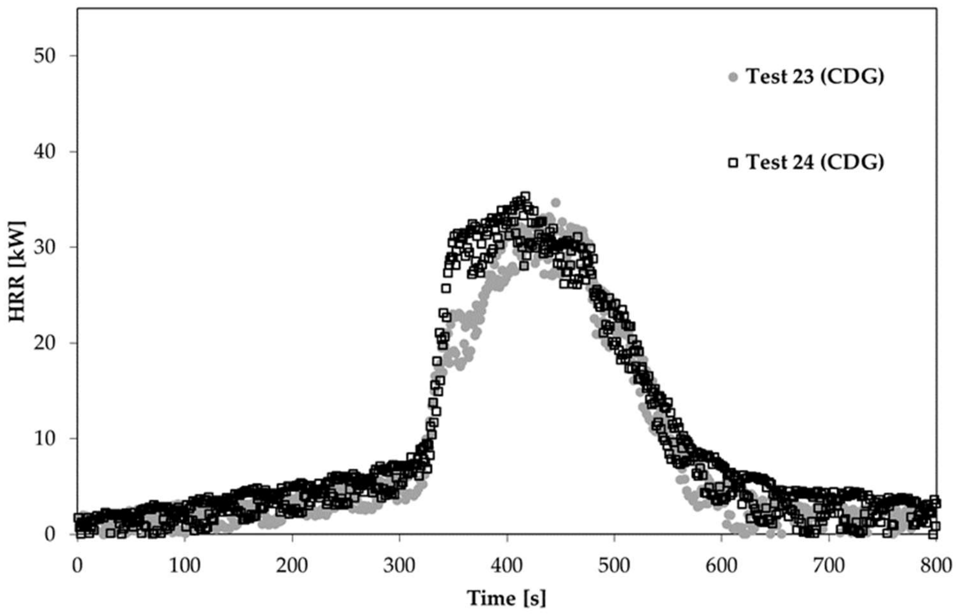


Figure 37 The HRR curves calculated by CDG method in Test 23 and 24. The HRR curves are quite similar for both tests

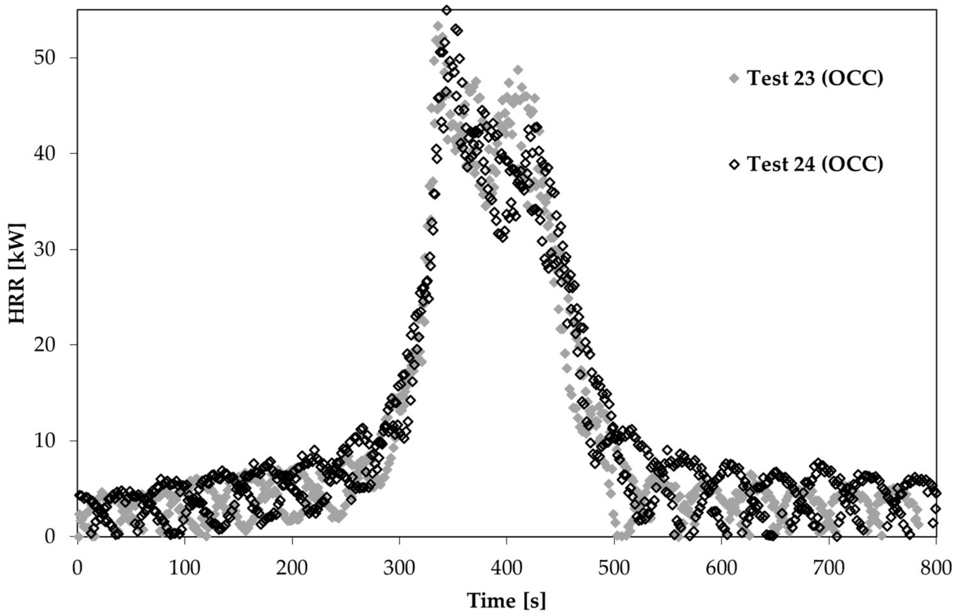


Figure 38 The HRR curves calculated by OCC method in Test 23 and 24. The HRR curves are quite similar for both tests. The HRR values used in this thesis were obtained from CDG method; however, OCC curves are shown here only for proving the similarity between two tests

Chapter 4. Discussion and Analysis

The burning under PV panels was much severe than burning without panels. The fire can burn the membrane completely under PV panels, while the fire only spread a few centimeters when no PV panels were placed. What is more, the peak HRR was 141 kW when a PV panel was placed upon the membrane in Test 10, while only 5 kW was measured without placing a PV panel in Test 11. Previous research also showed that installing PV panels on roof will deteriorate the fire rating, regardless the fire rating of the roof or PV panels (Backstrom, Tabaddor and Gandhi, 2009).

The reason that the fire spreading more severely under the PV panels is that the fire dynamics was changed. When PV panels are installed, the flame impinges the PV panel and extra heat flux is re-radiated by the panel, as adding roofs on the top of fuels. A significant increase for the heat flux was found after installation of PV panels. For example, the heat flux increased by 220% under PV panels when 7-kW gas burner fire measured in a 11 cm distance (Kristensen, Merci and Jomaas, 2018).

Although the fire becomes stronger when placed under PV panels, the tests also showed that the fire burned less severe when burned panels were used in the tests. The fire under new panels was more violent than burning under burned panels. For example, the HRR was 93 kW (Test 26) and 81 kW (Test 29) when burning under new panels, while it was only 16 kW (Test 27) and 15 kW (Test 31) when burned panels were used. This can due to the backside of the PV panels are flammable and the burning on the PV panels provided extra heat for the fire on the roofs.

Although the fire burning stronger and faster under PV panels, the fire spread away the panels was very limited in the tests. The fire only spread a few centimeters when a 70 cm by 70 cm membrane burned under the panels. The fire extinguished shortly after spreading outside the PV panels, in spite of the serious burning under PV panels. In addition, even when the ignition source was moved to the edge of the PV panel, i.e. closer to the other direction of fire spread, the fire only spread 4 cm in length out of the panel. Therefore, it is expected that the fire will not propagate long without the help of wind. The reason of the fire did not spread out of the PV panels can be that the heat diffused to the open air quickly and the absence of re-radiation when no PV panels were placed on the membrane. Although the risk of flame spread between PV arrays is low based on the results, the wind effects and roof orientation were not considered in the tests.

In Italian fire safety guidelines, an incombustible layer should be placed between the PV panels and the roof. In addition, a one-meter clear distance is required between the arrays and skylight, NSHEV, or wall/ceiling intersections. However, the fire spread more than 1.8 m under PV panels on flat roofs even a 1.3 m setback distance was set in UL tests. Therefore, a one-meter distance might not be sufficient to prevent the fire spread. Furthermore, more construction details, such as roof inclination and materials, and the installation details of PV panels, are necessary for determining the required spacing for PV arrays.

The chance of a distant ignition away PV panel is low according to the tests. Only 1.0 kW/m^2 heat flux was measured for a 141-kW fire in a close distance of 33 cm, from the PV panel. It is assumed that most heat flux was blocked by the PV panel. It showed that the risk of distant ignitions is low for the area extended from the lower side of PV panels.

4.1 Comparison with UL Tests

In the tests performed by UL, the roof-panel assemblies were tested with ASTM Class A fires. The Class A fire is a gas burner fire with a 5.3 $\pm$ 0.2 m/s air current, and the Class A fire rating is hold if the flame spread less than 1.83 m (6 ft). Mitigation methods for preventing the fire spread under PV panels were also tested.

However, the required spacing between PV arrays or roof elements were not discussed and only one test was performed relating to the spacing in UL tests. The experiment was done with two PV panels angled in 10°, with an 61 cm offset for the first panel and 30 cm spacing between the second. The test failed the Class A fire rating, meaning the fire propagated more than 30 cm between the panels with a Class A fire (Backstrom, Sloan and Gandhi, 2012d).

The ignition sources used in UL tests and in this thesis are different. In UL tests, the ignition source was a Class A burner fire impinging from one side of the PV panel. While in the tests of this thesis, the ignition source was put under the panels, to simulate a small ignition source under the panels. In addition, Class A fire was supported with air current, while the ignition source of this thesis was driven by buoyancy. The comparisons of the ignition source are shown in Table 7.

The fire spread at more than 30 cm in UL test, while the fire only propagated a few centimeters in this study. Nevertheless, it can due to the fire source was stronger in UL tests and supported with air current, which helped the fire propagation.

Although the testing conditions and objectives were different in UL tests and this thesis, both tests showed that the fire grew stronger and the risk of fire spread was higher after installing PV panels.

Table 7 The comparison of ignition sources between UL tests and this thesis

Ignition Source	UL Tests	Tests in the Thesis
Objective	The fire was used to simulate a fire came outside the panels to test the fire spread/ fire rating under PV panels	The fire was used to simulate a small ignition source under the panels and showed the risk of fire propagation. The purpose was to discuss the required spacing between PV arrays by tests
Magnitude	ASTM E108 Class A fire (Spread of Flame Test)	An 8-10 kW wood crib fire
Orientation	The fire came from the side of the roof assembly.	The burner was put under the PV panel and impinge directly upward.
Setback Distance	Experiments were performed with and without setback distance.	There was no setback distance from the ignition source. However, the ignition source was placed in different positions under PV panels

4.2 Comparison of Heat Flux Between Theory and Measurement

Equation (4.1) is used for calculating the theoretical heat flux to the HFGs. The equation can be used for calculating radiant heat flux when the distance from the center of fire the measuring point is more than two flame diameters (Quintiere, 1998).

$$\dot{q}" = \frac{X_r \dot{Q}}{4\pi c^2} \tag{4.1}$$

where $\dot{q}"$ is the heat flux, X_r is the fraction of radiative energy, $\dot{Q}$ is the HRR, and c is the distance from the center of flame to the measuring point. The assumptions are listed below:

(1) X_r = 0.209 for PVC (Drysdale, 2011).
(2) The values used for $\dot{Q}$ are the peak HRR measured during the tests.
(3) The point of flame is assumed be the center of the membrane under the PV panels.

The calculated heat flux values in the position of HFG-1 and HFG-2 are much higher than the measured heat flux. The reason can be that the heat flux was blocked the PV panel and the fire spread away the PV panel was very limited, so the heat flux measured was much lower than what was radiated by the fire. Moreover, the measuring range of HFG-1 and HFG-2 were 100 kW/m^2, which was much higher than the heat flux measured. The heat flux measured can be too small for the level of confidence. As for HFG-3, the calculated values are closer to the measurement; however, the values are very small and thus are negligible. The calculated heat flux values are shown in Table 8.

Table 8 Heat flux values by theoretical calculation and measurement

	Width * Length [cm]	Max. HRR (CDG) [kw]	HF [kW/m^2]					
			HFG1		HFG2		HFG3	
			Theory	Measurement	Theory	Measurement	Theory	Measurement
Test 1	~25*30	N/A	N/A	< 0.3	N/A	< 0.3	N/A	< 0.3
Test 2	No	7	0.7	< 0.3	0.2	< 0.3	0.1	< 0.3
Test 3	No	10	1.1	N/A	0.4	N/A	0.1	N/A
Test 4	20*20	8	0.9	< 0.3	0.3	< 0.3	0.1	< 0.3
Test 5	30*30	9	0.7	< 0.3	0.3	< 0.3	0.1	< 0.3
Test 6	40*40	16	1.1	< 0.3	0.4	< 0.3	0.2	< 0.3
Test 7	No	8	0.9	< 0.3	0.3	< 0.3	0.1	< 0.3
Test 8	50*50	9	0.5	< 0.3	0.2	< 0.3	0.1	< 0.3
Test 9	70*70	10	0.4	< 0.3	0.2	< 0.3	0.1	< 0.3
Test 10	70*70	141	5.6	1.0	2.6	0.5	1.3	0.48
Test 11	70*70	5	0.2	< 0.3	0.1	< 0.3	0.0	< 0.3
Test 12	30*30	N/A	N/A	< 0.3	N/A	< 0.3	N/A	< 0.3
Test 13	40*40	27	1.8	0.3	0.7	< 0.3	0.3	< 0.3
Test 14	30*50	21	1.2	< 0.3	0.5	< 0.3	0.2	< 0.3
Test 15	40*40	18	1.2	0.4	0.5	< 0.3	0.2	< 0.3
Test 16	50*50	26	1.4	0.4	0.6	< 0.3	0.3	0.3
Test 17	45*45	22	1.3	0.4	0.5	< 0.3	0.2	< 0.3
Test 18	45*45	N/A	N/A	< 0.3	N/A	< 0.3	N/A	< 0.3
Test 19	45*45	N/A	N/A	1.6	N/A	< 0.3	N/A	< 0.3
Test 20	60*35	30	6.0	1.1	1.4	< 0.3	0.5	< 0.3
Test 21	75*30	19	4.6	1.1	1.0	< 0.3	0.3	< 0.3
Test 22	75*30	20	4.7	1.2	1.0	< 0.3	0.4	< 0.3
Test 23	45*45	35	5.0	1.6	1.4	0.3	0.5	< 0.3
Test 24	45*45	35	5.1	1.6	1.4	< 0.3	0.5	< 0.3
Test 25	45*45	22	3.2	0.6	0.9	< 0.3	0.3	< 0.3

4.3 Heat Release Rate and Speed of Fire Spread under PV Panels

In general, the ignition time is shorter when heat flux is higher, as shown in the tests of critical heat flux in chapter 3. When larger membrane was burning under the PV panel, higher HRR was produced, meaning higher HF was generated under the PV panel. As a result, a faster and bigger fire.

Although the membrane size in Test 10 was more than double as Test 23, the required time for burning was similar. This suggests the burning in Test 10 was faster than in Test 23, where bigger area was burned and higher HRR was produced in similar amount of time. The tests showed that the fire can burn stronger and faster when the area of membrane is increased, while the HRR can increase exponentially with area. The HRR curves of Test 10, 16, and 23 are shown in Figure 39

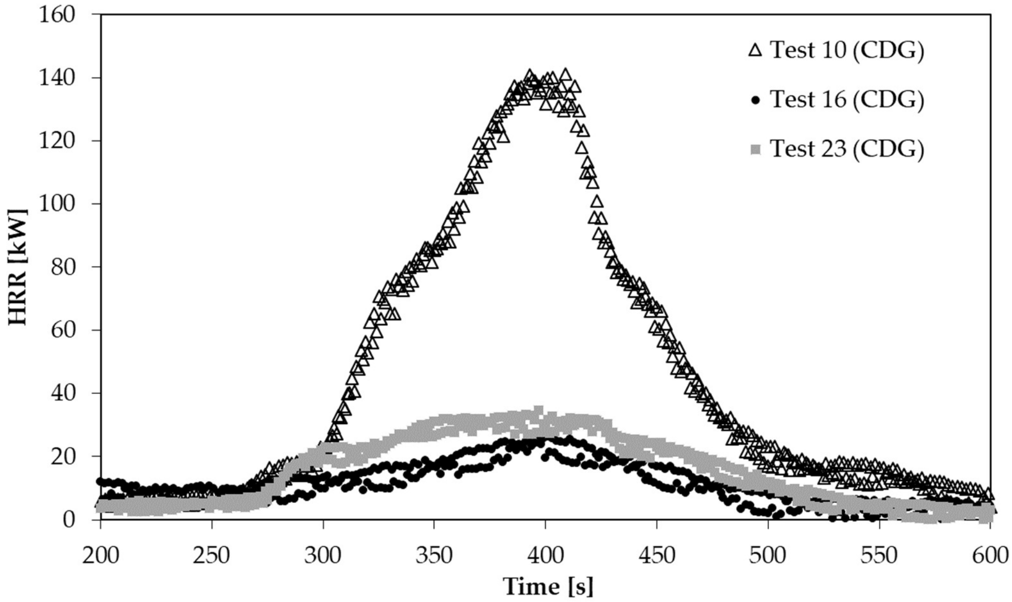


Figure 39 The HRR curves for Test 10, 16 and 23. The area was 0.49 m^2, 0.25 m^2, and 0.20 m^2, for Test 10, 16, and 23. The tests showed the time to reach peak HRR was close for burning the membrane under PV panels, even the size was different. It indicates that the fire can burn much stronger and faster when the membrane size is increased

4.4 Fire Spread on the Roof Membrane under PV Panels

Fire spread is a continuous ignition, the energy for later ignition is provided by the fuel burning at the moment. As the membrane was ignited on the membrane by the ignition source (wood crib), it could spread all over the whole membrane if the energy provided is enough to provide the ignition energy for the adjacent area, such as shown in Figure 40 (A).

When the fire propagated to the edge of membrane, it reached the end of fuel, meaning the last point of burning. The heat flux from the burning area decreased later, because the fire could not propagate beyond the boundary of membrane. In Figure 40 (B), point B is an unburned point that received heat flux from the burning area. However, the heat flux received was much less than point A.

When the heat flux was reduced, the unburned point did not receive enough heat flux for ignition. In this case, the burning line keep decreasing from both side of the membrane and finally stop at a point or a line. In the end, the burned area looked like an oval shape, such as shown in Figure 40 (C) and (D).

When the membrane is longer in length, such as Test 14, the fire spread described is more obvious. The fire spread in length was limited by the width burned. Therefore, the fire did not spread all over the membrane. In Test 14 (Figure 41), the fire only spread 38 cm on a 50 cm long membrane, while in most tests, the fire propagated more than 90% of the length (Figure 42).

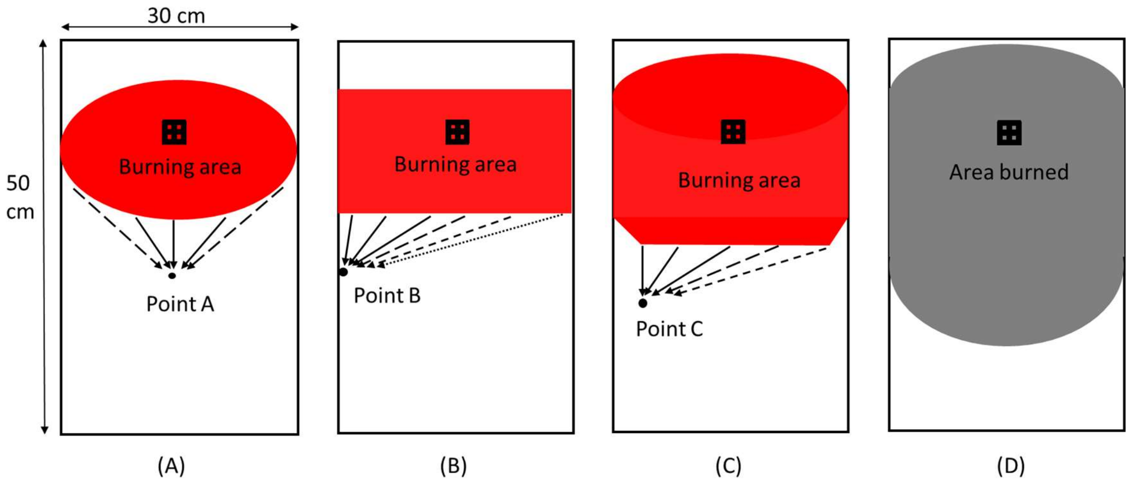


Figure 40 The fire spread on roof membrane during the tests. The black square represents the wood crib. Figure (A) shows the heat flux received from a burning area to an unburned point. Point A is in the center line of the membrane. Figure (B) shows the heat flux from the burning area to the point on the edge of membrane. Point B is on the edge of roof membrane. The solid lines are the heat flux provided by the burning area closer to point B. The dotted lines represent smaller heat flux coming the area that was further from the point. The heat flux received by point B was much less than point A. In figure (C), the burning line started to decrease from the edge of membrane on both side. Since there was no burning on the left side for point C, the burning line was then kept decreasing. In figure (D), the burning line kept decreasing from the edge of membrane and finally end in a line or a point and formed an oval shape

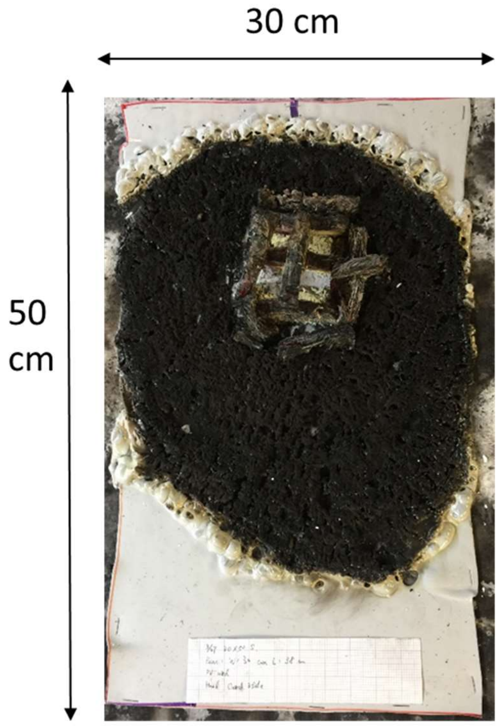


Figure 41 An example of fire spread on roof membrane (30 cm by 50 cm). The fire only spread 38.5 cm in all 50 cm length in Test 14. The fire spread in length was limited by the width burned. The fire spread was as an oval shape as described in Figure 40

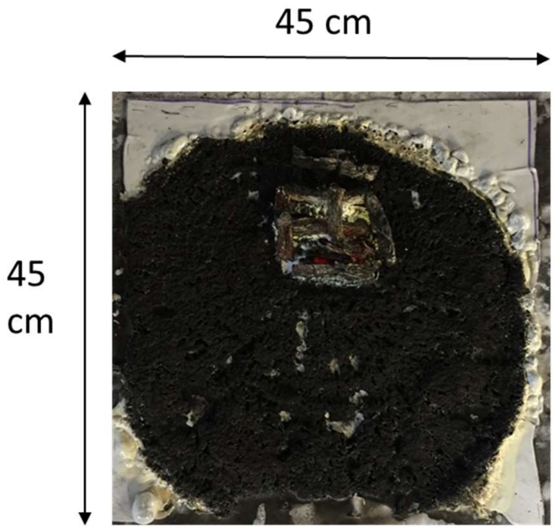


Figure 42 An example of fire spread on roof membrane (45 cm by 45 cm). When the width equals the width, the fire spread almost the whole length of the membrane

4.5 The Gap Distance and the Burning under PV Panels

PV panels are usually installed with a gap distance between the panels and the roof, whether they are installed parallel to the roof or with inclinations. During the tests, the fire spread and HRR was much smaller when the ignition source was placed in the position that was further from the backside of the PV panel, as in Test 9 or Test 30. Previous research also showed that the fire under PV panels can be influenced by the gap distance. A 12 inches (30.5 cm) gap was able to maintain the Class A fire rating on a steep slope shingled roof (Backstrom, Sloan and Gandhi, 2012d). On the other hand, when PV panels was mounted with a zero distance to the roof surface, a Class A fire rating was also maintained (Backstrom, Sloan and Gandhi, 2012c). The studies showed that the gap distance can be a way for mitigating the fire risk under PV panels.

When PV panels were raised, the amplification effect for fire seemed to be decreased. It can due to the re-radiation heat was reduced when the distance to PV panels increased. It suggests that the adjusting the gap distance can be a way for mitigating the fire risk under PV panels.

4.6 Experimental Suggestions

4.6.1 The Influence of Extraction Flow for Burning under PV Panels

The extraction flow was not tested in purpose during the tests but found to influence the burning under the exhaust hood. High extraction flow can obstruct the burning in early stage of fire spread, due to cooling effect from stronger air flow. While higher extraction flow can also help the burning under PV panels after the fire spread by bring more fresh air. However, the fire can also be weakened after the hot smoke layer being extracted under the PV panel. In short, the extraction flow can influence the fire spread under PV panel in both positive and negative way in lab conditions, as described in section 3.6. The experimenters could bear this in mind when performing PV panel tests under the exhaust hood.

4.6.2 The Influence of Burning on the Backside of PV Panels

The fire spread under PV panels is more severe due to the fire dynamics change under PV panels. In previous research, the heat flux measured under new or burned PV panels was similar on flat roofs by a gas burner fire (Kristensen, Merci and Jomaas, 2018). However, the fire was much severe when new PV panels were used in the tests. For example, 93 kW (Test 26) was measured with a new panel, while only 16 kW (Test 27) was observed with a burned panel, under similar testing conditions. It showed that the burning on the backside of the PV panels significantly influence the burning on the roof membrane.

In addition, the self-sustained flame was observed on the backside of PV panels and the fire extended further than the membrane size burned during the tests. Combustible drippings were observed from the backside of PV panels in the tests as well. In this case, there is a risk of fire spread from the backside of panels to adjacent elements, especially when installed on the façade.

Although the fire load was not tested due to the limited PV panels available, it was calculated from the total heat release minus the heat release of wood crib and membrane. The total heat release was estimated to range from 6600 kJ (Test 26) to 16200 kJ (Test 29), almost 140 to 350 g of propane. If a 10 m by 10 m roof with 70% of the area installed with PV panels, that can be a fire load equals 6 to14 kg of propane.

The fire can burn on the backside of PV panels and the flame on the fire can be enhanced by the heat released. The tests also showed that the fire burned more serious when new PV panels were used. Therefore, when PV panels are used repeatedly during the experiments, the experimenter should bear in mind that the test results might not show the worst case in reality.

Chapter 5. Conclusions

The fire spread under photovoltaic (PV) panels and the required spacing between PV arrays on flat roofs were studied experimentally in a custom-made set-up that represented a partial roofing segment. During the tests, heat flux values, heat release rate, fire spread, and temperatures were measured. The tests showed that the fire burned stronger and grew faster under PV panels. The whole roof membrane under PV modules was burned while the flame spread only a few centimeters without PV panels, under similar testing conditions. The literatures also showed that Class A fire ratings was not maintained after installing PV panels, regardless the fire rating of roof assemblies.

The fire dynamics changed after installing the PV panels. The flame and smoke are blocked and kept under the panels instead of spread to the surroundings. Extra heat is re-radiated by the panel, as if adding roofs on the top of fire. Previous study also showed that there is a significant increase heat flux on the roofs after installing PV panels. For example, the heat flux increased by 220% under PV panels when 7-kW gas burner fire measured in a 11 cm distance.

However, the tests also showed that the fire was less severe when using burned panels in the tests. The HRR and fire spread were much less when burned panels were used, for instance 16 kW was measured under a burned PV panels test, while 93 kW was produced with the fire under a new panel. This can due to the backsides of the PV panels are flammable and the burning under the PV panels is also fed by the fire on the backsides of panels.

The tests showed that the risk of fire spread between PV arrays is low on flat roofs in the absence of wind. Although the fire was stronger and grew faster under PV panels, the fire spread away the panels was very limited and it extinguished shortly after spreading outside the PV panels in the tests. The fire spread away panels remained small regardless where the positions of ignition source is. It is considered that the heat diffused to the open air quickly and short of the re-radiation from PV panels. In this case, the risk of fire spread out of panels is minor based on the test results. However, the effects from wind and roof orientation should be considered and tested in future studies.

Italian fire safety guideline suggests a one-meter clearance between the PV arrays and building elements with a layer of incombustible or EI 30 layer on the roofs or façade when PV modules are installed on roofs. Nevertheless, research showed that the fire can spread more than one meter from outside the PV panels in some tests, depending on the roof construction and PV installation methods. For example, the fire spread more than 1.8 m under PV panels on flat roofs even a 1.3 m setback distance was set in UL tests. Under this circumstance, more details for construction and PV installation are necessary to determine the required spacing for PV arrays.

The risk of a distant ignition away PV panel is low according to the tests. The heat flux on the lower side of PV panels was less than 1.6 kW/m^2, much lower than the critical heat flux (7 kW/m^2) of membrane. Moreover, the measurement of heat flux was fewer than theoretical calculation. It is assumed that most heat flux was blocked by the PV panel.

When the ignition source was placed at positions with higher gaps to the PV panels, the fire grew much smaller and the fire spread was much less in the tests. Previous research also showed that the fire rating was maintained after increasing the gap distance. On the other hand, when PV panels was mounted with a zero distance to the roof surface, the influence of PV installation was mitigated as well. The studies showed that the adjusting the gap distance can be a way for mitigating the fire risk under PV panels.

The testing conditions and objectives were different between UL tests and this thesis, but they both showed that the fire grew stronger and the risk of fire spread was higher under PV panels. On the other hand, the fire only spread a few centimeters out of panels in this study while the it spread more than 30 cm in UL test. However, the reason can due to the ignition source was stronger and it was supported by air current in UL tests.

It was found that the extraction flow can influence the burning under PV panels significantly, when performing PV fire tests in lab conditions. The tests showed that higher extraction flow can help the burning under PV panels after the fire spread. It was assumed that high extraction flow created a better ventilation condition for the fire growth. However, it also showed that the fire can diminish after increasing the extraction flow due to the smoke layer being extracted under the PV panels. Nevertheless, high extraction flow in the early stage of fire spread can reduce the size of fire because of cooling effect from the fresh air plus the pyrolyzed gas can be extracted.

Experimenters should also aware that the fire can burned less severe when burned PV panels are used repeatedly in the experiments. The backside of the PV panels is flammable and the fire on the backside helps the fire under PV panels. Therefore, the fire was much severe when burning under new PV panels. When using burned PV panels repeatedly during the experiments, the researchers should bear in mind that it might not show the worst case.

Although the fire burned much more severe under PV panels, the tests showed that the risk of fire spread between PV arrays and adjacent elements is low on flat roofs when the influence of wind was excluded. However, the literature showed that a severe fire supported by air current, merely a spacing between the PV arrays might not be sufficient to prevent the fire spread under solar panels. The research showed that the details of the construction and PV panel installation can have a significant impact for the fire spread. However, there is not yet standards how the PV panels should be installed for preventing fire spread underneath. More research will be required and it is necessary to raise the awareness of fire risk by the installers, manufacturers and standardization organizations.

The study showed the fire spread when a fire burning under PV panels and discuss the required spacing with the results. The testing results can be also used to compare with similar experiments or different testing conditions for future research.

5.1 Suggestions for Further Work

Although the tests showed that the risk of fire spread away the PV panel is low, the influence of wind and orientation were not studied in this research. In this case, the effects of wind and roof orientation for fire spread under PV panels can be studied in the future. In addition, the HRR can grow much bigger when larger area is burned under PV panels. Thus, full scale tests will be recommended to show the worst credible case.

Increasing the gap distance or installing PV panels with zero gap distance can reduce the influence for fire under PV panels. It will be interesting to show if there is a critical gap distance for PV panel installation which can minimize the influence of PV panels and also being economical.

PV panels are installed with different angles in different areas to produce the maximum energy, where the experiments in this study only tested one installation conditions. The installation angles can influence the fire growth under PV panels as well. Tests for showing the relationship of heat flux change under different installation angles can be done in the future.

Acknowledgements

I would like to thank Prof. Grunde Jomaas for his guidance through the whole study. He is always available when I need help and makes time for students under busy schedule. He responds fast and give good comments for the thesis writing and experiments. I also want to thank him for always pushing me forward and making me better. Very few professors are willing to get dirty for helping student's experiments, but Grunde is definitely one of them. He cares not only the research but also my life in Edinburgh. His guidance was not limited to academic training but also how to make a balanced life during study. For me, he is not only a great academic but also a great person.

I would like to thank PhD student Jens Steemann Kristensen, who is always generous and helpful. He shares precious experience and comments through the research and helped all experiments from the preparation stage. Jens is always patient and shows great sense of humor. From the first day I arrived, he gave me a warm welcome and share what he has, no matter the tools, knowledge, critical thoughts, or friendly smiles. He helped me to become familiar with the school and office, showed me how to use the equipments, and assisted me to get things that are necessary to continue the study. I really appreciate his help and kindness.

Chia-Lung (Farian) Wu, who is already my friend before I came to Edinburgh, also give me a big hand. He shared good experience of for thesis writing and showed me how to make beautiful figures with simple software, not to mention good advices for living in a new city. He also shares his interesting thoughts and research with me. Studying with him is much fun in Edinburgh.

I would like to thank Mohamed Beshir, Xu Dai, Simon Santamaria, and Bhisham Dhurandher who helped me to get necessary devices or places to work in the office. The thesis is written with much help of from the academics, staffs, and PhD students. Thank all of them for showing their interests and giving comments for my study. It is my pleasure to meet these friendly and intelligent people and I really enjoy studying with them.

Last but not least, I want to thank Sih-Yu Lai for sharing her interesting thoughts about my research. The discussions with her helped me organizing the ideas and inspired me in many ways through the whole research period.

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Appendix A: Table of Selected Tests from UL Experiments

Table 9 Table of selected tests from UL experiments

Roof Slope	PV Module[3]			Fire Rating (Class A)	Note
	Gap [cm]	Angle [°]	Setback [cm]		
Low	N/A	N/A	N/A	Pass	Baseline experiment No module installed
Low	13	0	122	Fail	
Low	13	0	122	Fail	
Low	13	0	132	Fail	
Low	13	10	122	Pass	
Steep	13	0	61	Fail	Shingle: manufacturer 2
Steep	13	0	91	Pass	Shingle: manufacturer 1
Steep	13	0	91	Pass	Shingle: manufacturer 1
Steep	13	0	91	Pass	Shingle: manufacturer 3
Steep	13	0	107	Pass	Shingle: manufacturer 3
Steep	13	0	0	Pass	Mitigation: vertical flashing without separation
Steep	13	0	8	Pass	Mitigation: vertical flashing without separation
Steep	13	0	30	Pass	Mitigation: vertical flashing without separation
Steep	13	0	61	Fail	Mitigation: small opening screen
Steep	13	0	61	Fail	Mitigation: angled flashing with 1-inch (2.5 cm) separation
Steep	13	0	91	Fail	Mitigation: small opening screen
Steep	13	0	91	Pass	Mitigation: angled flashing with 1-inch (2.5 cm) separation
Steep	13	0	91	Fail	Mitigation: setback only

[3] The length unit was transferred to centimeters from inches and round up to integers.

Appendix B: Table of Critical Heat Flux Tests

Table 10 Test of Critical Heat Flux (Membrane A)

	Heat Flux [kW/m²]	Time for Ignition [s]	Membrane Type	Note
Test 1	30	56	Membrane A	
Test 2	20	80	Membrane A	
Test 3	15	120	Membrane A	
Test 4	10	231	Membrane A	
Test 5	8	345	Membrane A	
Test 6	8	389	Membrane A	
Test 7	7	1028	Membrane A	
Test 8	8	882	Membrane A	
Test 9	7	591	Membrane A	
Test 10	6	No Ignition	Membrane A	There was no ignition and the test stopped after 22 minutes.
Test 11	7	1371	Membrane A	The membrane ignited after 20 minutes.
Test 12	7	No Ignition	Membrane A	There was no ignition and the test stopped after 22 minutes.

Table 11 Test of Critical Heat Flux (Membrane B)

	Heat Flux [kW/m²]	Time of Ignition [s]	Membrane Type	Note
Test 1	30	30	Membrane B	
Test 2	20	58	Membrane B	
Test 3	15	104	Membrane B	The membrane ignited at 84 s but extinguished after, and it reignited at 104 s.
Test 4	15	94	Membrane B	
Test 5	10	189	Membrane B	
Test 6	7	No Ignition	Membrane B	There was intermittent flame without sustained ignition. The test stopped after 22 minutes.
Test 7	8	430	Membrane B	
Test 8	8	360	Membrane B	
Test 9	7	No Ignition	Membrane B	There was intermittent flame (at 340 s) without sustained ignition. The test stopped after 22 minutes.
Test 10	8	310	Membrane B	

Appendix C: Heat Flux Values Measured in the Tests

Table 12 Heat flux values measured in the tests

	Membrane Size Under PV [cm]	Distance to the Ignition Source (HFG1) [cm]	Max. HF [kW/m2]		
			HFG1	HFG2	HFG3
Test 1	~25*30	N/A	< 0.3	< 0.3	< 0.3
Test 2	No	N/A	< 0.3	< 0.3	< 0.3
Test 3	No	N/A	N/A	N/A	N/A
Test 4	20*20	50	< 0.3	< 0.3	< 0.3
Test 5	30*30	50	< 0.3	< 0.3	< 0.3
Test 6	40*40	50	< 0.3	< 0.3	< 0.3
Test 7	No	50	< 0.3	< 0.3	< 0.3
Test 8	50*50	50	< 0.3	< 0.3	< 0.3
Test 9	70*70	69	< 0.3	< 0.3	< 0.3
Test 10	70*70	50	1.0	0.5	0.5
Test 11	70*70	50	< 0.3	< 0.3	< 0.3
Test 12	30*30	50	< 0.3	< 0.3	< 0.3
Test 13	40*40	50	0.3	< 0.3	< 0.3
Test 14	30*50	50	< 0.3	< 0.3	< 0.3
Test 15	40*40	50	0.4	< 0.3	< 0.3
Test 16	50*50	50	0.4	< 0.3	0.3
Test 17	45*45	50	0.4	< 0.3	< 0.3
Test 18	45*45	50	< 0.3	< 0.3	< 0.3
Test 19	45*45	50	1.6	< 0.3	< 0.3
Test 20	60*35	50	1.1	< 0.3	< 0.3
Test 21	75*30	50	1.1	< 0.3	< 0.3
Test 22	75*30	50	1.2	< 0.3	< 0.3
Test 23	45*45	50	1.6	0.3	< 0.3
Test 24	45*45	50	1.6	< 0.3	< 0.3
Test 25	45*45	50	0.6	< 0.3	< 0.3

Appendix D: Examples of Heat Flux Curves

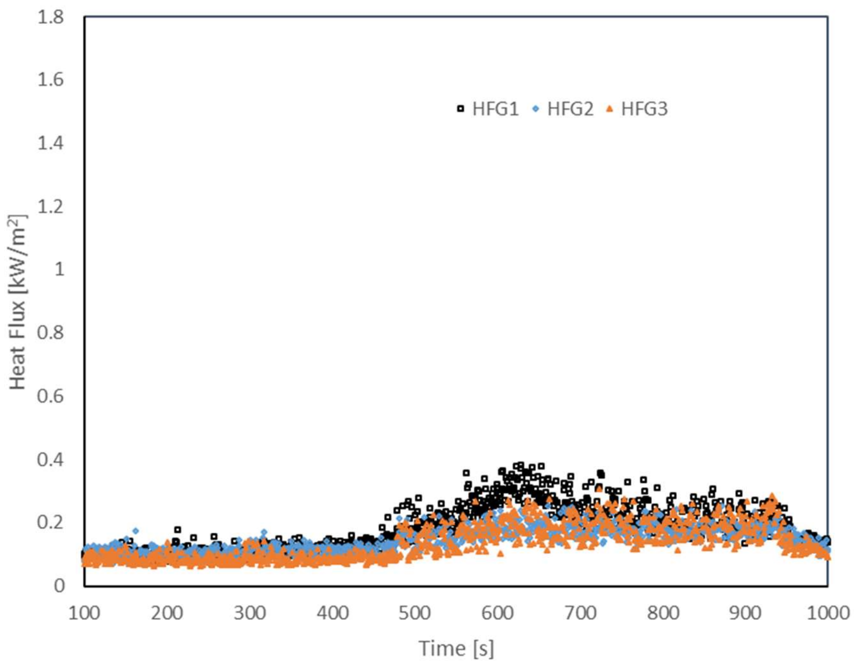

Figure 43 The HF curve of Test 16. It is shown as an example of HF curve for Tests from 15 to 18. From Test 15 to Test 18, the maximum HF measured was 0.4 kW/m^2

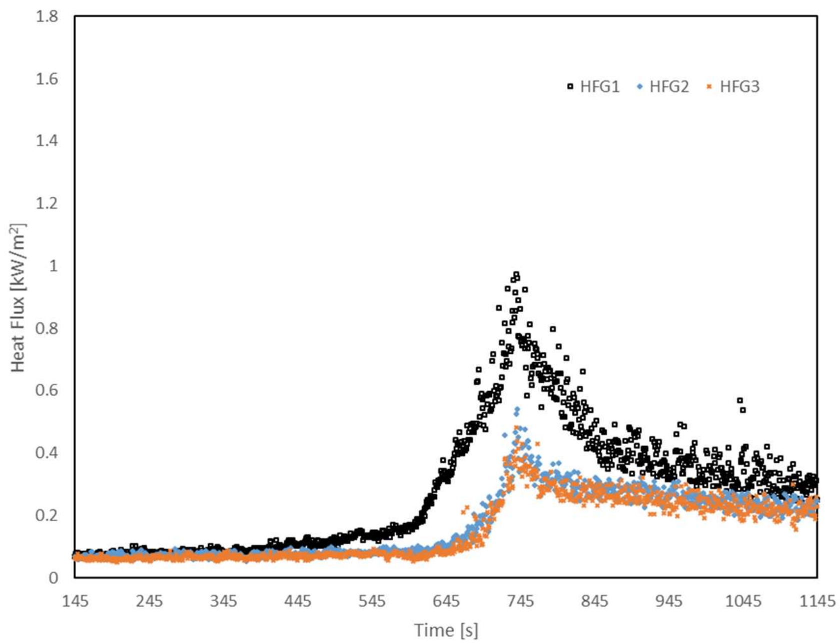

Figure 44 The HF curve of Test 10. Test 10 was burned with a 70 cm by 70 cm membrane. It was the largest fire in all tests. It can be seen that all three HFG measured significant heat flux. The heat flux measured was the largest before the distance between HFG and fire was shortened

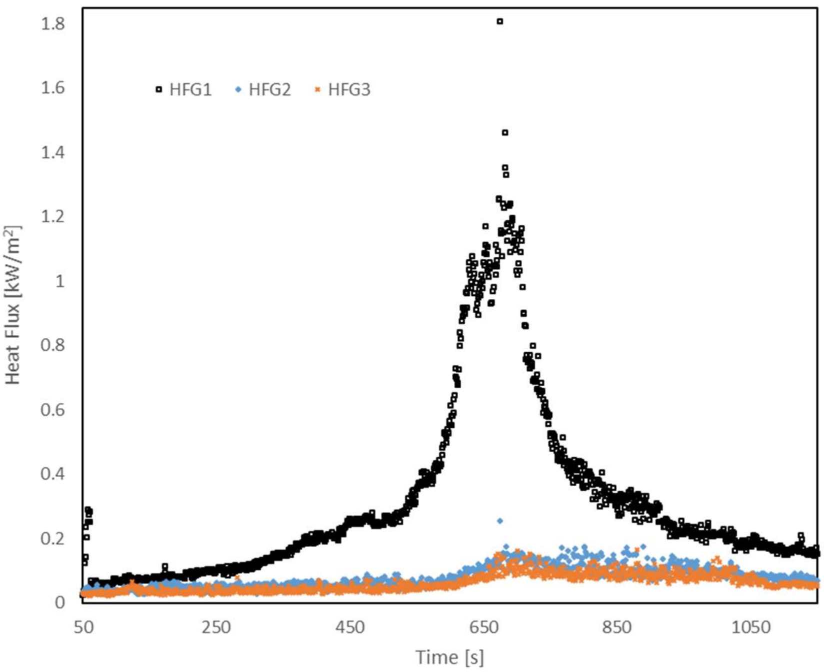

Figure 45 The HF curve of Test 22. It is a representative HF curve for Test 20, 21, and 22, when similar testing conditions conducted in these tests. Although the testing membrane size was larger in Test 20 to 22, the heat flux measured was smaller than a 45 cm by 45 cm size membrane, as in Test 19

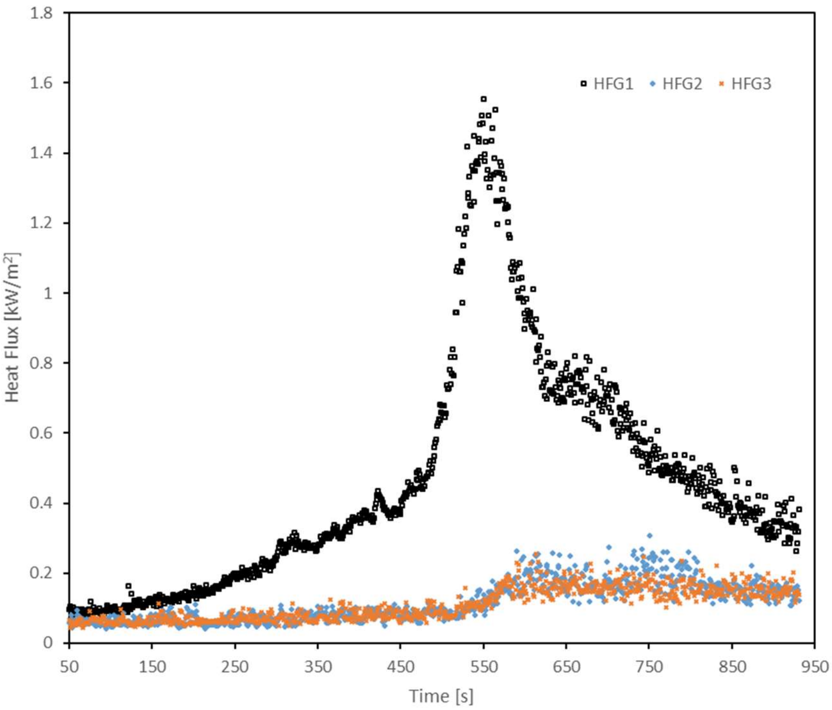

Figure 46 The HF curve of Test 23, a example of heat flux curve for Test 23 and 24. Test 23 and Test 24 were measured in a reduced distance with a 45 cm by 45 cm membrane burned under new PV panels. It was observed that the heat flux was higher for tests with new panels, by comparing Test 23, 24 and Test 25

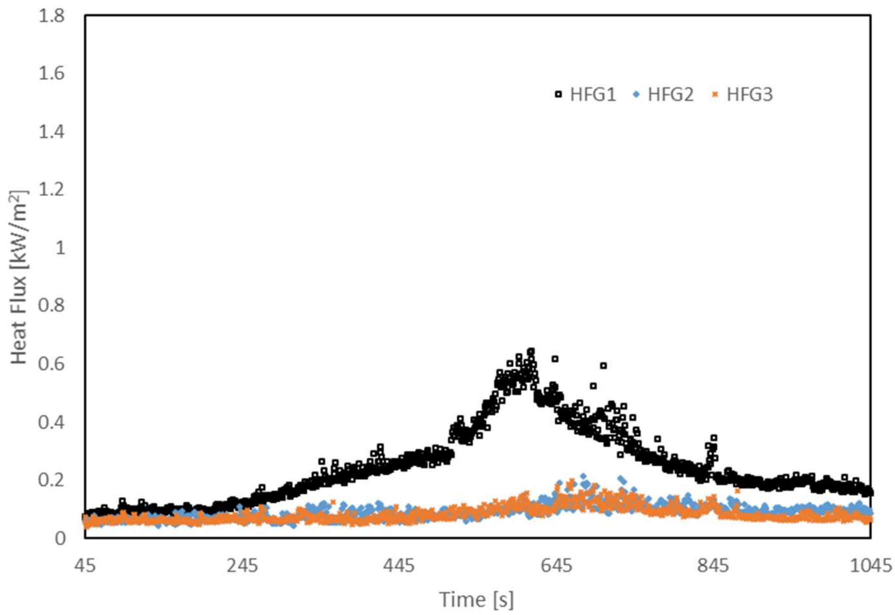

Figure 47 The HF curve of Test 25. The HF measured was much lower than 23,24. It was assumed due to using burned PV panel in the test