2023

SUSTAINABLE ERGONOMICS FOR SOLAR INSTALLATIONS

Jesse Duroha
University of Rhode Island, jesse_duroha@uri.edu

SUSTAINABLE ERGONOMICS FOR SOLAR INSTALLATIONS

BY

JESSE CHUKWUNWIKE DUROHA

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

INDUSTRIAL & SYSTEMS ENGINEERING

UNIVERSITY OF RHODE ISLAND

2023

DOCTOR OF PHILOSOPHY DISSERTATION

OF

JESSE CHUKWUNWIKE DUROHA

APPROVED:

Dissertation Committee:

Major Professor Gretchen A. Macht

Valerie Maier Speredelozzi

Simona Trandafir

Corey Lang

Brenton DeBoef

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

2023

ABSTRACT

The demand for renewable energy resources has experienced significant growth over the past decade. Consequently, the solar installation workforce is growing rapidly to meet this need. The occupational safety risks associated with installations are an obstacle to the safety and well-being of solar installation workers. Although photovoltaic (PV) installers are known to experience some of the most significant and widespread construction-related occupational safety risks, PV installer accident investigation research, reporting, and verification are limited.

To contribute to this literature gap, this dissertation presents a systematic literature review of the occupational safety risks, mitigation measures, and current and potential safety research areas associated with PV installations. This dissertation also presents a survey study developed and administered to solar workers to understand their perceptions regarding a comprehensive list of installation safety risks (15 items). This dissertation explores how factors such as work experience, company longevity, and installation size influence the risk perception of solar workers. This dissertation also utilizes a Risk Significance Score (RSS) to rank the relative importance of safety risks to installers in the residential and meso or commercial setting. Then, based on the RSS this dissertation provides risk management recommendations to enhance the safety of installation work.

The findings of the systematic literature review in the Manuscript 1 and 2, show that the four major occupational safety risk categories associated with PV installations are: (1) electrical and fire risks, (2) heat stress, (3) manual handling risks, and (4) fall risks. Most of the available solar safety research focuses on electrical and fire safety. Fewer papers conducted risk mitigation research on fall accidents, manual handling risks, and heat

stress within the solar industry in detail. Within the sphere of manual handling, installers are exposed to musculoskeletal disorder risks, which is a relatively unexplored solar safety research area.

The findings from the safety risk perception survey study (*n* = 290) in Manuscript 3, revealed three types of solar installation workers based on risk perception (High, Moderate, and Low), with most installers having a Moderate perception of the Likelihood (ɣ = 77.38%) and Severity (ɣ = 76.22%) of safety risks. The proportion of membership in the High Likelihood/Severity class increased substantially as installation size decreased to residential and as company longevity and work experience increased. Manuscript 3 recommends a higher emphasis on safety during mentorship/apprenticeship programs, more exchange of safety knowledge between newer and more established solar companies, and a greater emphasis on safety education/certification especially for residential installers.

In Manuscript 4, the RSS resulting values were generally close to 0.30, suggesting that solar installation workers perceived the safety risks as manageable. Heat-related risks, falling from heights, and glare were the top concerns associated with residential work. Whereas, heat-related risks, along with struck-by-falling objects, and falling, slipping, or tripping, were the top concerns for meso or commercial work. Consequently, safety measures and training that should be prioritized for both residential and meso or commercial installations include work-rest schedules, early detection of heat-related illness, fall hazard identification, fall protection systems, electric shock and burn mitigation and clothing, and an organized site layout.

This research can aid solar installation companies, occupational safety professionals, and policy makers in understanding the safety risks and mitigation measures associated with PV installations. Moreover, this research clarifies the installers' risk perceptions, identifies areas where risk mitigation is needed, and provides valuable recommendations to enhance worker safety.

ACKNOWLEDGEMENTS

I want to thank my Ph.D. advisor, Dr. Gretchen Macht, for believing in me, supporting me, and mentoring me throughout the Ph.D. process. I learned so much from you about what it means to be a researcher, an educator, a leader, and a friend. I am so grateful for all your guidance.

Next, I want to extend my gratitude to the rest of my committee; Dr. Simona Trandafir, Dr. Valerie Maier Speredelozzi, Dr. Corey Lang, and Dr. Ryan Poling-Skutvik. You have been a strong source of inspiration and support for me throughout the research process. I would also like to thank everyone who contributed as a co-author or collaborator in the research articles included in this dissertation especially Dr. Simona Trandafir, and Dr. Corey Lang for their support, patience, and mentorship.

I want to thank Dr. Mehrsa Khaleghikarahrodi, Dr. Dominique Engome Tchupo, Dr. Nicholas Bernardo, Dr. Tim Jonas, James Houghton, Caroline Hammett, and the whole SIS Lab crew for their constant support. I want to thank Marsha Garcia and Dean Charles Watson for their support and mentorship. I would also like to thank the URI Catholic Center staff and students for being a faith community for me away from home and providing me the emotional and spiritual support I needed to focus and stay grounded during my time as a Ph.D. student.

Finally, I would like to thank my parents, Anya and Ifeoma Duroha, my siblings, Chidera, Brian, and Somfe Duroha for all their love and support. I couldn't have done it without you.

DEDICATION

Firstly, I would like to dedicate this work to my parents, who gave everything to provide me with an outstanding education. I will never forget all your love and sacrifice. Next, I would like to dedicate this work to solar workers. All the hard work you put in day and night to advance clean energy infrastructure hasn't gone unnoticed. I hope this work is evidence of that. But above all, I would like to dedicate this work to Jesus Christ, my God; you have truly been my strength and shield. Thank you.

PREFACE

This dissertation is written in manuscript form. The first manuscript, *Solar Installations & Their Occupational Risks,* is co-authored with Dr. Gretchen A. Macht and is published in the *Proceedings of the 2021 Human Factors and Ergonomics Society 65th International Annual Meeting*. The second manuscript, *Solar Installation Occupational Risks: A Systematic Review*, is co-authored with Dr. Gretchen A. Macht and was published in 2023 in the *Safety Science* journal. The third manuscript, *Solar Installation Safety Risk Perceptions: A Survey Study,* is co-authored by Dr. Gretchen A. Macht, Dr. Simona Trandafir, and Dr. Corey Lang and is being prepared for submission to the *Applied Ergonomics* journal. Finally, the fourth manuscript, *Ranking Solar Installation Safety Risk Perceptions: A Case of Installation Size,* is co-authored by Dr. Gretchen A. Macht, Dr. Simona Trandafir, and Dr. Corey Lang is being prepared for submission to the *Proceedings of the Human Factors and Ergonomics Society International Annual Meeting*.

The adoption of solar photovoltaic (PV) technology and infrastructure is increasing rapidly to meet the ever-growing global need for renewable energy sources. An obstacle to solar PV growth is the severity of the occupational safety risks associated with their installation. Although PV installers are known to experience some of the most significant and widespread construction-related occupational safety risks, PV installer accident investigation research, reporting, and verification are limited. Consequently, to address this research gap, the research outcomes of this work are to (1) *conduct* a systematic literature review that comprehensively details the health and safety risks, mitigation measures, current research, and potential research areas associated with PV installations; (2) *develop* and *administer* a survey study to understand PV installers' perception of the severity and likelihood of installation safety risks; (3) *rank* the relative importance of various safety risks to installers during residential and meso or commercial installations; (4) *provide* recommendations based on these results to enhance the safety of solar installation workers.

Manuscript 1, *Solar Installations & Their Occupational Risks Solar Installation Occupational Risks: A Systematic Review*, addresses Outcome 1 by providing a systematic literature review of the occupational safety risks utilizing the Scopus database as its main source. Manuscript 2, *Solar Installation Occupational Risks: A Systematic Review,* also addresses Outcome 1 by expanding the systematic literature review utilizing the Scopus, Web of Science, Science Direct, and PubMed databases and dives deeper into the mitigation measures, current and potential research areas associated with the installation occupational risks. Manuscript 3, *Solar Installation Safety Risk Perceptions: A Survey Study*, builds on Outcome 1 and utilizes its extensive literature review to develop and administer a survey for Outcome 2. This survey aims to understand installers' perception of the safety risks they experience and how these perceptions vary based on level of work experience, installation type, and company size. Manuscript 4, *Solar Installation Safety Training Perceptions*, fulfills Outcome 3 and ranks the relative importance of various safety risks to installers during residential and meso or commercial installations. Manuscripts 1- 4 fulfills Outcome 4 by providing recommendations, based on their results, regarding the risk mitigation measures and research needed to enhance solar worker safety.

This research contributes to the solar safety community by reviewing the occupational safety risks and understanding the perception of installers of the current state of safety associated with solar installations. Practically, this research can help safety professionals, researchers, installation companies, and policy makers better understand solar occupational safety risks, and inform the ongoing development of safety protocols, policies, and guidelines for PV installation work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

MANUSCRIPT 1: Solar Installations & Their Occupational Risks

Published in Proceedings of the 2021 Human Factors and Ergonomics Society 65th International Annual Meeting

Jesse C. Duroha[1] and Gretchen A. Macht, Ph. D.[1]

[1]*Department of Mechanical, Industrial & Systems Engineering, University of Rhode Island, Kingston, RI, USA*

ABSTRACT

With the solar industry's rapid growth, it is crucial to continuously review and assess the occupational risks associated with photovoltaic (PV) installations. PV installers are exposed to severe occupational risks, including but not limited to electrocution, heat stress, fall accidents, and manual handling risks. However, it is unclear what research is being done to mitigate these risks and where more research is required. Therefore, this paper performs a systematic literature review using the Scopus database to comprehensively review and identify: (1) the current knowledge available regarding the occupational risks associated with PV installations, (2) the health and safety effects these risks have on PV installers, (3) the research being done to mitigate them, and (4) the knowledge gaps for future research. This research can guide areas for future research concerning occupational safety and health in the PV installation sector.

1. INTRODUCTION

Keeping workers safe is crucial yet exceptionally challenging when solar installation companies are simply popping up and expanding at staggering rates across the country as a means to capitalize on the market. Within the last decade, solar energy has emerged as one of the fastest-growing energy sources in the country. Currently, solar accounts for 48% of all new electricity generating capacity in the US, with over 77 gigawatts (GW) of photovoltaics (PV) installed and 100 GW projected by 2025. With this growth, the solar industry's market worth exceeds $130 billion and, within the last decade alone, added 156,000 new jobs (Solar Energy Industries Associations, 2020; Gupta & Bais, 2019). A key component in the growth and success of the solar industry is the PV installation sector, which makes up 67% of all solar employment (The Solar Foundation, 2021). According to the US Bureau of Labor Statistics (2020), the fastest-growing occupation is a PV Installer at a rate of 63% in the next decade. Various states across the country are dedicating themselves to 100% Renewable Energy by specific year deadlines, such as Rhode Island, Hawaii, Virginia, and Washington, DC, aiming to significantly utilize PV systems to achieve this goal (National Resources Defense Council, 2020). This same level of growth is being experienced globally as well. In recent years, PV production has experienced the largest increase in net generating capacity amongst all the major energy sources (including wind, hydropower, and gas) (Solar Power Europe, 2019). With this commitment to increasing PV installations globally, the continuous development of a health and safety culture within the PV installation sector is essential.

The occupational risks experienced by PV installers are known to have a significant and widespread impact on the US workforce. According to the Occupational Safety and Health Administration (OSHA), PV installers are exposed to occupational risks including but not limited to: (i) Musculoskeletal disorder (MSD) risks from repetitive work at awkward postures, (ii) falls from elevated working surfaces, (iii) electrical risks and hazards (e.g., electric shock, burns, electrocution, and arc flash hazards), and (iv) heat stress from working for prolonged periods in hot temperatures (OSHA, n.d.; Solar Energy Industries Association [SEIA], 2006). In recent years work-related musculoskeletal injuries have accounted for approximately 30% of days-away-from-work cases in the US private industry (US Bureau of Labor Statistics, 2019; US Bureau of Labor Statistics, 2018; US Bureau of Labor Statistics, 2016). Fall accidents and electrocutions have historically been part of the construction industry's 'Fatal Four' (the four most frequent causes of fatalities in the construction industry) (Albert et al., 2020; OSHA, 2011; US Department of Labor, 1990). Additionally, over 600 people are killed from extreme heat annually (Center for Disease Control and Prevention, 2019), with workers in the construction industry historically being 13 times more likely to die from heat-related illnesses (HRIs) than other industries (Gubernot et al., 2015). Injuries resulting from these risks can lead to a loss of income, a decrease in productivity, an increase in workers' compensation premiums for employers, discomfort, pain, and death (Fatality Assessment and Control Evaluation Program [FACE], 2020; National Institute for Occupational Safety and Health [NIOSH], 2013; SEIA, 2006). Consequently, clear and transparent injury tracking and investigations of these risks within the PV installation sector can play an important role in developing strategies to improve worker safety.

There is a lack of official accident reports detailing the causes and effects of the various safety risks PV installers experience during installations. Over the years, available reports of PV installer accidents tend to focus on solar worker fall and electrocution injuries (OSHA 2020; OSHA 2018; FACE, 2019; FACE 2010; FACE 2009a; FACE 2009b), and rarely on other occupational risks, such as MSDs or HRIs that solar installers are likely to experience due to the nature of the work (OSHA, n.d.; Solar Energy Industries Association [SEIA], 2006). This lack of reporting indicates and contributes to a lack of awareness of the multitude of risk factors associated with installing PV systems. Additionally, the available PV installer accident reports point out that insufficient use of engineering controls (e.g., use of guardrails, skylight screens, covers, nets); administrative controls (e.g., job hazards analysis training, situational awareness training), and personal protective equipment (PPE) are significant causes of injuries and fatalities. Hence, more research is needed that reviews the safety risks and mitigation measures associated with PV installation work.

There is progress in the published literature regarding identifying the occupational risks PV installers face, however, more research is needed to comprehensively understand these risks and the best means to mitigate them. Although previous research has reviewed the hazards and aggravating factors associated with the industry, the work tends to be part of a larger study of the occupational risks present during the entire life-cycle of PV systems (Bakhiyi et al., 2014; Erten & Utlu, 2020; Hanson & Thatcher, 2020), thus, providing only a brief review PV installation occupational risks. Other more detailed literature reviews tend to focus on unique risks, and do not provide research solutions that consider the comprehensive effects of multiple risks (Aram et al., 2021; Lu et al., 2018; Wu et al., 2020), or lack information regarding the current research being done to mitigate these risks and the defining areas where more research is needed (Castañon et al., 2019). Therefore, this systematic literature review aims to comprehensively review: (1) the current knowledge available regarding the occupational risks associated with PV installations, (2) the health and safety effects these risks have on PV installers, (3) the research being done to mitigate them, and (4) the knowledge gaps for future research. This review can serve as a guide for future investigations into the occupational injuries associated with PV installations. Furthermore, it can help occupational safety, and health professionals develop safety protocols that improve the overall safety and productivity of PV installers.

2. METHODOLOGY

A systematic literature review was conducted to gather findings and identify research gaps regarding workers' health and safety during PV installations. The primary source of information for this literature review were journal articles. The Scopus database is one of the most extensively used databases for conducting literature reviews in construction and safety management (Varghese et al., 2018; Xia et al., 2020; Zhou et al., 2015) and was used to conduct the search. The literature search was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) checklist (Moher et al., 2009) using the keywords, and inclusion and exclusion criteria outlined in Table 1. First, articles whose titles were consistent with the inclusion and exclusion criteria were identified, and duplicate articles were removed. Then the article abstracts, and subsequently the full-text articles were screened. Finally, articles that matched the inclusion and exclusion criteria were included in the study.

Table 1 Systematic literature search guidelines

Steps	Description of Steps
Explicit Research Question	What are the occupational risks associated with PV installations and what research is being done to mitigate them?
Type of Literature	Journal articles
Database	Scopus
Keywords	Four groups of keywords were used and combined in multiple combinations in the search: Group 1 - Solar Energy: Solar, photovoltaic, PV Group 2 - Safety: Injury, hazard, risk, health, accident, safe Group 3 - Mode: Installation, construction, installer, install Group 4 - Specific risk terms: Heat stress, stress, fall, height, shock, burn, electrocution, wound, cut, laceration, fire, ergonomic, manual, repetitive, handling, awkward, posture
Inclusion and exclusion criteria	-The study deals with safety risks present during PV installations -The study is written in english -No limit was set for the time and location of the study

3. RESULTS

Initially, 148 articles were identified, based on their title, as consistent with the inclusion and exclusion criteria. Then after duplicate articles were removed, 95 articles remained. By screening the abstract of these 95 articles, only 52 articles were consistent with the inclusion and exclusion criteria. Next, the full-text articles were thoroughly screened, and as a result, 29 journal articles were selected as part of this review. Articles that were excluded during the abstract and full-text article screening mainly because: (1) the article did not contain specific information regarding PV installation worker safety risks; (2) the article solely focused on the environmental impact associated with PV occupational risks and did not focus on its impact on worker safety; (3) the article focused solely on occupational risk present during the manufacturing of PV panels. Table 2 shows a comprehensive breakdown of the contributions of the selected articles towards the occupational safety of PV installations. The main occupational risk/hazard categories presented in these studies are: falls from heights, falling objects, electric shock and burns, traffic accidents, struck by or against materials, ergonomic risks, wounds, lacerations, strains, sprains, thermal burns, and fire risks. For simplicity, the following sections will explore these risks in more detail under the headings: (i) electrical and fire hazards, (ii) heat stress, (iii) fall accidents, impact, and manual handling risks.

Table 2 Occupational risks, causes, and mitigation measures

Identified hazard/risk	Context/cause	Aggravating factors	Recommended controls and mitigation measures
Falling from heights, slips, and trip accidents	Installing photovoltaic panels on elevated surfaces such as rooftops	(1) Handling heavy and unwieldy objects near exposed edges (Dewlaney, 2012), slippery or brittle surfaces (Ho et al., 2020)	(1) Installing photovoltaic panels in solar garages (Rabbani et al., 2014) (2) Composite Shingles: Easier to lift and install and less slippery compared to metal or wooden roofs (Ho et al., 2020)
Electrical shock, electrocution, fire accidents	(1) Short circuit rupture, electrical fault, and arcing (Appiah et al., 2019; Moskowitz et al., 1983; Wybo, 2013)	(1) Presence of flammable materials on-site (Wybo, 2013) (2) Installations on the double-skin facade (Miao & Chow, 2019)	(1) Emergency shutdown device (Cancelliere et al., 2016; Wybo, 2013) (2) Utilizing fire-resistant material during installations (Cancelliere et al., 2016; Ju et al., 2019) (3) Ground or insulate dead metal parts, implement safety systems such as ground fault detectors and bypass diodes (Levins, 1986) (5) Design alleys in a PV system to aid circulation (Wu et al., 2020; Wybo, 2013) design frangible structures to make panel foldable in case of shock emergency (Wybo, 2013) (7) Increasing the PV tilt angle and panel-roof distance to reduce flame propagation (Ju et al., 2019; Kristensen et al., 2021) (8) Utilize refractory glass and Type II J-box design (Huang et al., 2018) (9) PV module backsheet fire-resistant design (Cancelliere et al., 2014) (10) Strategic placement of fire fighting equipment across the plant and in vehicles, clearing of fire breaks around site boundary (Guerin, 2017) (11) Arc Fault detection techniques and algorithms (Wu et al., 2020; Omran et al., 2020; Lu et al., 2018)
Heat Stress, heat injuries, dehydration, heat exhaustion, heatstroke (Samaniego-Rascón et al., 2019)	Working for prolonged periods in hot temperatures		(1) Unacclimatized workers with a work intensity of 400 kcal/h (heavy work) need to rest for 75% of each hour. (2) Unacclimatized workers with a work intensity of 300 kcal/h (moderate work) need to rest for 50% of each hour. (3) Acclimatized workers with a work intensity of 200 kcal/h (light work) may reach 100% of the work hour. (4) Acclimatized workers with work intensity of 500 kcal/h (very heavy work) may reach 50% of the work hour (Samaniego-Rascón et al., 2019)

3.2. Electrical and Fire Hazards

Electrical and fire hazards were the most prominently cited risks in the selected studies. The majority of the research currently being done to mitigate PV installation risks is about electrical and fire safety. Sreenath et al. (2020), Ranganath et al. (2020), and Guerin (2017) explore the hazards present in large-scale PV systems. Sreenath et al. (2020) performed a risk assessment to identify the risk of PV installations in airports on aviation safety. Their assessment identified electrical hazards as a significant risk to safety and provided preventive mitigation measures for them. They explain that electric shock risks may occur from vital electrical PV components coming into contact with workers. Since PV systems are challenging to de-energize once energized and exposed to sunlight (Levins, 1986; Wybo, 2013), they present shock risks to workers. Sreenath et al. (2020) also explain that short circuit ruptures in the string or combiner box can lead to fire outbreaks, especially around flammable materials (Wybo, 2013).

The remaining references focus on fire risks concerning rooftop PV installations. For example, multiple articles studied the effect of PV tilt angle and panel-roof distance on reducing the potential of fire outbreaks associated with PV installations (Ju et al., 2019; Kristensen et al., 2021; Kristensen & Jomaas, 2018). At the same time, other studies focused on improving the junction box design (Huang et al., 2018) or module backsheet design to reduce fire risks (Cancelliere et al., 2014).

In order to mitigate electrical and fire hazards, the use of underground electric cables, regular inspection of wires for short circuit signs, and materials near installations for flammability (Ju et al., 2019; Ranganath et al., 2020; Sreenath et al., 2020). Studies also recommended applying an internet of things (IoT) based panel maintenance system for remote monitoring and data sensing to improve the efficiency of fault detection (Appiah et al., 2019; Ranganath et al., 2020), however, this is an area for research focus. Ju et al. (2019) and Kristensen et al. (2021) also infer that increasing the panel tilt angle and panel-roof distance can reduce flame propagation in order to mitigate fires. Although these protocols are effective, it is essential to consider the effect of heat from sun exposure on installers.

3.2. Heat Stress

Heat stress was only identified by one of the studies as a risk during PV installations. Heat-related injuries such as dehydration, heat exhaustion, heatstroke can occur from working in hot temperatures for prolonged periods. Samaniego-Rascón et al. (2019) performed a risk assessment utilizing the wet-bulb globe temperature and work intensity (kcal/h) to determine a healthy work/rest schedule for solar workers. They indicate the importance of workers gradually acclimatizing to the heat and the workload.

As a guide, they conclude that for unacclimatized workers, when the work intensity is 400 kcal/h (heavy work), they need to rest for 75% of each hour, however, when the work intensity of 300 kcal/h (moderate work) need to rest for 50% of each hour. On the other hand, for acclimatized workers, when the work intensity is 200 kcal/h (light work), they can reach 100% of the work hour, however when the work intensity of 500 kcal/h (very heavy work) can reach 50% of the work per hour.

3.3. Fall Accidents, Impact, and Manual Handling Risks

Selected studies rarely identified falls, slips and trips, impact, and manual handling risks as hazards/risks during PV installations. Impact risks include traffic accidents on-site or being struck by or against objects (Bakhiyi et al., 2014). Ho et al. (2020) applied Prevention through Design (PtD) techniques to rooftop PV systems. Erten & Utlu (2020) also identifies falling from a height as a hazard and recommends using fall protection PPE to mitigate this risk. Ho et al. (2020) developed PtD for roofing materials, roof slopes, roof accessories, panel layouts, fall protection systems, and lifting methods. However, more research is needed to understand the manual handling risks PV installers are exposed to and the means to mitigate them.

4. CONCLUSION

This paper performs a systematic literature review to identify the current research knowledge and mitigation measures regarding the occupational risks associated with PV installations. After reviewing 29 articles, the occupational risks associated with PV installations were discovered as electrical and fire hazards, heat stress, fall accidents, impact, and manual handling risks. Based on the literature search, it is clear that most of the research done to mitigate the PV installation hazards are in the fire and electrical safety realm. Few papers address fall accidents, ergonomic and manual handling risks, and impact risks; however, extensive study is being done to apply PtD principles to mitigate fall risks in rooftop installations. In addition, more research is needed to understand the manual handling risks PV installers face. Other areas to be explored are the potential musculoskeletal disorders from extensive and large-bulk material handling, and visual stress from bright and reflective environments.

A key observation regarding this study is that the literature regarding occupational risks in the PV industry was fairly new, thus implying the start of a movement to quantify and understand how human factors and ergonomics can impact the worker occupational health and safety in a solar energy installation environment. A limitation of this study is that it utilizes only one database for the literature search. Future work can include using various relevant databases. Also, surveying PV installers to understand their perception of the occupational risks they experience and how this influences their safety and financial decisions. There is a recent trend to quantify and understand how human factors and ergonomics can assist in sustainability, let alone renewable energies. This paper contributes to this effort by outlining the current state of where we are as a society to help the significant influx of solar installers.

ACKNOWLEDGEMENTS

Thank you to the University of Rhode Island’s Sustainable Innovative Solutions (SIS) Lab for their unwavering support. A special thanks to the Penn State Solar Fab Collaborative and Dr. Frey Brownson for their guidance and encouragement.

REFERENCES (*Articles in Review)

*Appiah, A. Y., Zhang, X., Ayawli, B.B. K., & Kyeremeh, F. (2019). Review and Performance Evaluation of Photovoltaic Array Fault Detection and Diagnosis Techniques. International Journal of Photoenergy, 2019, 1–19.

*Bakhiyi, B., Labrèche, F., & Zayed, J. (2014). The photovoltaic industry on the path to a sustainable future — Environmental and occupational health issues. Environment International, 73, 224–234.

*Cancelliere, P. (2016). PV electrical plants fire risk assessment and mitigation according to the Italian national fire services guidelines. Fire and Materials, 40(3),355–367.

*Cancelliere, P., & Liciotti, C.(2016). Fire Behaviour and Performance of Photovoltaic Module Backsheets. Fire Technology, 52(2), 333–348.

*Cancelliere, P., Manzini, G., Traina, G., & Cavriani, M. G. (2021). PV modules on buildings – Outlines of PV roof samples fire rating assessment. Fire Safety Journal, 120, 103139.

Center for Disease Control and Prevention (2019, July 8). Extreme Heat. https://www.cdc.gov/disasters/extremeheat/index.html (Accessed: 15 July 2020)

*Chow, C. L., Han, S. S., & Ni, X. M. (2017). A study on fire behaviour of combustible components of two commonly used photovoltaic panels. Fire and Materials, 41(1), 65–83.

*Dewlaney, K. S., Hallowell, M. R., & Fortunato, B. R. (2012). Safety Risk Quantification for High Performance Sustainable Building Construction. Journal of Construction Engineering and Management, 138(8), 964–971.

Doan, D. R., & Derer, R. M. (2014). Arc Flash Calculations for a 1.3-MW Photovoltaic System.

*Erten,B., & Utlu, Z. (2020). Photovoltaic system configurations: an occupational health and safety assessment. Greenhouse Gases: Science and Technology, 10(4), 809–828.

Fatality Assessment and Control Evaluation Program (2009a) https://www.cdc.gov/niosh/face/pdfs/08CA006.pdf

Fatality Assessment and Control Evaluation Program (2009b) https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/OHB/FACE/Pages/09CA003.aspx

Fatality Assessment and Control Evaluation Program (2010) https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/OHB/FACE/Pages/09CA003.aspx

Fatality Assessment and Control Evaluation Program (2020, January 22). Preventing worker deaths in the solar industry. California Department of Public Health. https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/OHB/FACE/Pages/Solar.aspx (Accessed: 15 July 2020)

Fatality Assessment and Control Evaluation Program (2020) https://www.cdc.gov/niosh/face/pdfs/17ca005.pdf

*Fortunato, B. R., Hallowell, M. R., Behm, M., & Dewlaney, K. (2012). Identification of Safety Risks for High-Performance Sustainable Construction Projects. Journal of Construction Engineering and Management, 138(4), 499–508.

Gubernot, D. M., Anderson, G. B., & Hunting, K. L. (2015). Characterizing occupational heat-related mortality in the United States, 2000–2010: Analysis using the census of fatal occupational injuries database. American Journal of Industrial Medicine, 58(2), 203–211.

*Guerin, T. F. (2017). Evaluating expected and comparing with observed risks on a large-scale solar photovoltaic construction project: A case for reducing the regulatory burden. Renewable and Sustainable Energy Reviews, 74, 333–348.

Hanson, M., & Thatcher, A. (2020). Identifying Human Factors and Ergonomic Issues in Green Jobs: Facilitating Sustainable Green Jobs. In A. Thatcher, K. J. Zink & K. Fischer (Eds.), Human Factors for Sustainability: Theoretical Perspectives and Global Applications (pp. 171-192). CRC Press Taylor and Francis Group.

*Ho, C., Lee, H. W., & Gambatese, J. A. (2020). Application of Prevention through Design (PtD) to improve the safety of solar installations on small buildings. Safety Science, 125, 104633.

*Huang, Y.-C., Lee, S.-K., Chan, C.-C., & Wang, S.-J. (2017). Full-scale evaluation of fire-resistant building integrated photovoltaic systems with different installation positions of junction boxes. Indoor and Built Environment, 27(9), 1259–1271.

*Ju, X., Zhou, X., Gong, J., Zhao, K., Peng, Y., Zhang, C., Ren, X., & Yang, L. (2019). Impact of flat roof-integrated solar photovoltaic installation mode on building fire safety. Fire and Materials, 43(8), 936–948.

*Kamenopoulos, S. N., & Tsoutsos, T. (2015). Assessment of the safe operation and maintenance of photovoltaic systems. Energy, 93, 1633–1638.

*Kristensen, J. S., & Jomaas, G. (2018). Experimental Study of the Fire Behaviour on Flat Roof Constructions with Multiple Photovoltaic (PV) Panels. Fire Technology, 54(6), 1807–1828.

*Kristensen, J. S., Faudzi, F. B. M., & Jomaas, G. (2021). Experimental study of flame spread underneath photovoltaic (PV) modules. Fire Safety Journal, 120, 103027.

*Levins, A. (1987). Photovoltaic energy systems and consumer product safety. Solar Cells, 19(3–4), 325–332.

*Lu, S., Phung, B. T., & Zhang, D. (2018). A comprehensive review on DC arc faults and their diagnosis methods in photovoltaic systems. Renewable and Sustainable Energy Reviews, 89, 88–98.

*Miao, L., & Chow, C.-L. (2018). Investigation of burning photovoltaic panels on a double-skin facade with ejecting flame from an adjacent room fire. Indoor and Built Environment, 28(7), 938–949.

Miloua, H. (2019). Smart Energy Empowerment in Smart and Resilient Cities, Renewable Energy for Smart and Sustainable Cities. Lecture Notes in Networks and Systems, 462–469.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, T. P. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Medicine, 6(7), e1000097.

*Moskowitz, P. D., Coveney, E. A., Rabinowitz, S., & Barancik, J. I. (1983). Rooftop photovoltaic arrays: Electric shock and fire health hazards. Solar Cells, 9(4), 327–336.

National Institute for Occupational Safety and Health. (2013). Simple solutions for home building workers. https://www.cdc.gov/niosh/docs/2013-111/default.html (Accessed: 15 July 2020)

*Omran, A. H., Said, D. M., Hussin, S. M., Ahmad, N., & Samet, H. (2020). A novel intelligent detection schema of series arc fault in photovoltaic (PV) system based convolutional neural network.

OSHA (2018). https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=109537.015 (Accessed: 15 July 2020)

OSHA (2020). https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=124922.015 (Accessed: 15 July 2020)

*Rabbani, E. R. K., Lima, A. N. F. deSantos, F. J. B., Costa, V. A. de S., & Malafaya-Baptista, F. (2014). Sustainability Measures and Potential Impacts on Occupational Safety and Health: Brazilian Constructions.

*Ranganath, N., Sarkar, D., Patel, P., & Patel, S. (2020). Application of fuzzy TOPSIS method for risk evaluation in development and implementation of solar park in India. International Journal of Construction Management, 1–11.

*Samaniego-Rascón, D., Silva, M. C. G. da, Ferreira, A. D., & Cabanillas-Lopez, R. E. (2019). Solar energy industry workers under climate change: A risk assessment of the level of heat stress experienced by a worker based on measured data. Safety Science, 118, 33–47.

Solar Energy Industries Association. (2006) Solar Construction Safety. https://www.coshnetwork.org/sites/default/files/OSEIA_Solar_Safety_12-06.pdf (Accessed: 15 July 2020)

Solar Energy Industries Association. (2020) Solar Industry Research Data.https://www.seia.org/solar-industry-research-data (Accessed: 15 July 2020)

*Sreenath, S., Sudhakar, K., & Yusop, A. F. (2020). Solar photovoltaics in airport: Risk assessment and mitigation strategies. Environmental Impact Assessment Review, 84, 106418.

The Solar Foundation (2021). National Solar Job Census. https://www.thesolarfoundation.org/national/ (Accessed: 12 June 2021)

U.S Bureau of Labor Statistics. (2020, April 10). Solar Photovoltaic Installers - What Solar Photovoltaic Installers Do.https://www.bls.gov/ooh/construction-and-extraction/solar-photovoltaic-installers.htm#tab-2 (Accessed: 15 July 2020)

U.S. Bureau of Labor Statistics (2016, November 10). Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2015. https://www.bls.gov/news.release/pdf/osh2.pdf

U.S. Bureau of Labor Statistics (2018, August 28). Back Injuries Prominent in Work-related Musculoskeletal Disorder Cases in 2016.

U.S. Bureau of Labor Statistics (2019, November 7). 2018 Survey of Occupational Injuries and Illnesses. https://www.bls.gov/iif/soii-charts-2018.pdf (Accessed: 15 July 2020)

U.S. Department of Labor (1990, November) Analysis of Construction Fatalities-The OSHA Database 1985-1989.https://apps.dtic.mil/dtic/tr/fulltext/u2/a400187.pdf (Accessed: 15 July 2020)

Varghese, B. M., Hansen, A., Bi, P., & Pisaniello, D. (2018). Are workers at risk of occupational injuries due to heat exposure? A comprehensive literature review. Safety Science, 110, 380–392.

*Wu, Z., Hu, Y., Wen, J. X., Zhou, F., & Ye, X. (2020). A Review for Solar Panel Fire Accident Prevention in Large-Scale PV Applications. IEEE Access, 8, 132466–132480.

*Wybo, J.-L. (2013). Large-scale photovoltaic systems in airports areas: safety concerns. Renewable and Sustainable Energy Reviews, 21, 402–410.

Xia, N., Xie, Q., Griffin, M. A., Ye, G., & Yuan, J. (2020). Antecedents of safety behavior in construction: A literature review and an integrated conceptual framework. Accident Analysis & Prevention, 148, 105834.

*Zhao, G., Li, M., Jian, L., He, Z., Shuang, J., Yuping, S., Zhang, Q., & Zhongxian, L. (2018). Analysis of Fire Risk Associated with Photovoltaic Power Generation System. Advances in Civil Engineering, 2018, 1–7.

Zhou, Z., Goh, Y. M., & Li, Q. (2015). Overview and analysis of safety management studies in the construction industry. Safety Science, 72, 337–350

CHAPTER 2

MANUSCRIPT 2: Solar Installation Occupational Risks: A Systematic Review

Published in the Safety Science Journal

Jesse C. Duroha[1] and Gretchen A. Macht, Ph. D.[1]

[1]*Department of Mechanical, Industrial & Systems Engineering, University of Rhode Island, Kingston, RI, USA*

ABSTRACT

The adoption of solar photovoltaic (PV) technology and infrastructure are increasing rapidly to meet the ever-growing global need for renewable energy sources. An obstacle to solar PV growth is the severity of the occupational safety risks associated with their installation. Although PV installers are known to experience some of the most significant and widespread construction-related occupational safety risks, PV installer accident investigation research, reporting, and verification are limited. To contribute to this literature gap, this paper conducts a systematic literature review to understand and present the occupational safety risks, mitigation measures, and current and potential safety research areas associated with PV installations. A systematic literature search for relevant articles was conducted from October 2021 to January 2022 using the Scopus, Web of Science, Science Direct, and PubMed databases identifying 365 articles by their title. After screening these articles with various selection criteria, 31 articles were selected as relevant to the research questions of this study. These selected articles identified electrical and fire risks, heat stress, manual handling risks, and fall risks as the major occupational safety risk categories associated with PV installations. This study can aid solar installation companies, occupational safety professionals, and policy makers gain a deeper understanding of the safety risks and mitigation measures associated with PV installations as they develop protocols and guidelines to safely support the solar workforce's development.

1. Introduction

In order to support sustainability through renewable energy, the solar industry and its workforce, have grown significantly in the last decade (Interstate Renewable Energy Council, 2021a; Solar Power Europe, 2021). In recent years, solar production has experienced the largest global increase in net generating capacity, contributing over 35% of net power generating capacity (Solar Power Europe, 2019, 2021). In the United States (U.S.), solar has experienced an average annual growth of 42%, with over 100 Gigawatts of installed capacity (Solar Energy Industries Associations, 2020). This growth is likely to continue, especially with various states (e.g., Rhode Island, Hawaii, Virginia, California, and New Mexico) across the U.S. dedicating themselves to over 60% of renewable energy electricity generation by specific deadlines, aiming to significantly utilize solar photovoltaic (PV) systems to achieve this goal (National Resources Defense Council, 2020). Consequently, the U.S. solar workforce is projected to expand rapidly and is "on [the] trajectory to reach 400,000 solar jobs by 2030" (IREC, 2021b, p.3). A key component in the growth and success of the solar industry is the PV installation sector, which makes up 67% of all solar employment (IREC, 2021b). According to the U.S. Bureau of Labor Statistics (2021), "employment of solar photovoltaic installers is projected to grow 52 percent from 2020 to 2030, much faster than the average for all occupations." With this commitment to increasing PV installations, the continuous development of health and safety knowledge and culture within the PV installation sector is essential.

Photovoltaic installers are known to experience some of the most significant and widespread construction-related occupational safety risks (Occupational Safety and Health Administration [OSHA], 2011; U. S. Department of Labor, 2017a,b,c). These risks include:

(i) musculo- skeletal disorder (MSD) risks from repetitive work at awkward postures, (ii) falls from elevated working surfaces, (iii) electrical risks and hazards (e.g., electric shock, burns, electrocution, and arc flash hazards), and (iv) heat stress from working for prolonged periods in hot temperatures (Hanson & Thatcher, 2020; U.S. Department of Labor, 2017a). In recent years, work-related musculoskeletal injuries have accounted for approximately 30% of days-away-from-work cases in the U.S. private industry (U.S. Bureau of Labor Statistics, 2016, 2018, 2019). Furthermore, fall accidents and electrocutions have historically been part of the construction industry's 'Fatal Four,' also called the four most frequent causes of fatalities in the construction industry (Albert et al., 2020; OSHA, 2011). Additionally, over 600 people are killed from extreme heat annually on average (Centers for Disease Control and Prevention, 2019), with construction industry workers historically having the highest proportion (36.8%) of heat-related illness (HRI) deaths (Gubernot et al., 2015). Nevertheless, there is still a lack of formalized reporting and verification of solar worker accident data, frequency, cause, fatalities, and property damage associated with the impact of these risks in the solar industry (Sovacool et al., 2015).

Photovoltaic installer accident investigation reporting and verification are limited (Sovacool et al., 2015). Available reports of PV installer accidents over the years tend to focus on fall and electrocution injuries (California Fatality Assessment and Control Evaluation Program, 2020; OSHA, 2018, 2020) and rarely on other occupational risks (e.g., MSDs or HRIs) that workers are also likely to experience due to the nature of PV installation work (Oregon Solar Energy Industries Association, 2006; U. S. Department of Labor, 2017a,b,c). This lack of reporting indicates and contributes to a lack of awareness of the risk factors associated with installing PV systems. Additionally, available PV installer accident reports (California Fatality Assessment and Control Evaluation Program, 2020; OSHA, 2018, 2020) highlight insufficient use of engineering controls (e.g., use of guardrails, skylight screens, covers, nets); administrative controls (e.g., job hazards analysis training, situational awareness training), and personal protective equipment (PPE) as significant contributors to PV installer injuries and fatalities. Hence, reviewing the safety risks and controls or risk mitigation measures associated with PV installations is crucial to continuously educate PV installers regarding the most effective safety practices on-site.

Previous research in the solar safety realm that has explored safety risk detection and mitigation has mainly focused on mitigating fire risks (Aram et al., 2021; Lu et al., 2018a; Ong et al., 2022; Wang et al., 2021; Wu et al., 2020). For instance, Ong et al. (2022) attempted to understand if PV systems pose an additional fire risk to buildings during their operations. Through conducting a BowTie analysis of rooftop grid-connected PV systems, Ong et al. (2022) found that the main contributors to fire incidents during the operation of PV systems were arc faults and improper installation of PV systems. Wang et al. (2021) also utilized fault tree analysis, regression analysis, and machine learning to propose a photovoltaic failure probability model capable of providing early warning for fault occurrences in utility-scale solar systems, thereby mitigating fire risks. Safety risk mitigation research that explores other solar safety risks seems to be emerging.

There is progress in the published literature regarding identifying the various occupational risks associated with solar workers during PV installations. However, a comprehensive literature review that explores the risks, mitigation measures, and potential research areas associated with PV installation safety is lacking. Previous literature reviews have identified some risks and aggravating factors related to solar installation work (Bakhiyi et al., 2014; Erten & Utlu, 2020; Hanson & Thatcher, 2020). However, these works tend to be part of a larger study of the occupational risks present during the entire life-cycle of PV systems (Bakhiyi et al., 2014; Erten & Utlu, 2020; Hanson & Thatcher, 2020); thus, the works provide only a brief review of PV installation occupational risks. In addition, more detailed literature reviews have tended to only focus on unique risks, such as fire and electrical risks (Aram et al., 2021; Lu et al., 2018a; Wu et al., 2020), or have been geared towards a specific installation type, such as floating solar photovoltaic projects (Sen et al., 2021). Therefore, there is a lack of clarity regarding the relationships and comprehensive effects multiple risks have on PV installation safety in various contexts and settings and the research and safety measures needed to mitigate these risks.

This study performs a systematic literature review that aims to comprehensively answer the following research questions: (1) What are the occupational risks associated with PV installations?; (2) What health and safety effects do these risks have on PV installers?; (3) What research is being conducted to mitigate these risks?; and (4) What potential research areas need to be pursued? This review can serve as a guide for future investigations into the occupational injuries associated with PV installations. Moreover, it can aid occupational safety and health professionals along with various installation stakeholders (i.e., installation and insurance companies) as they develop safety protocols to improve PV installers' overall safety and productivity.

2. Methods

A systematic literature review was conducted to gather findings regarding occupational risks, health and safety effects, and current and potential safety research areas. A systematic literature review is a process that utilizes methodical and explicit techniques to select, review, and analyze literature based on a pre-formulated research question (Moher et al., 2010). A systematic review is distinct from a *meta*-analysis because it refers to the entire process of searching, selecting, evaluating, and synthesizing findings from various literature (Ahn & Kang, 2018). A *meta*-analysis is usually a step in the systematic review process that involves using a statistical approach to analyze data and information from various research articles to attain a pooled outcome (Haidich, 2010). A *meta*-analysis requires the articles being analyzed to possess heterogeneity (i.e., the articles being analyzed have sufficiently similar methods and outcomes; Ahn & Kang, 2018; Lorenc et al., 2016). This systematic review does not conduct a *meta*-analysis because it is open to articles that possess a wide variety of methods (e.g., literature review, experiment, risk assessment) and outcomes. However, this systematic review follows the detailed process of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009; Moher et al., 2010) with an awareness of how current systematic reviews have applied these techniques (Ayodele et al., 2020; Garrisson et al., 2021; Xia et al., 2018, 2020). Figure 1 illustrates the systematic review process that was conducted in this study. Since systematic reviews can vary based on the research question, type of study (qualitative or quantitative), and field of study, there is no clear minimal requirement for the number of studies that can be included in a systematic review (Moher et al., 2009; Moher et al., 2010). This systematic review was conducted in three phases:

planning and computer search, eligibility evaluation, and content analysis to comprehensively answer the research questions.

The planning and computer search phase (Section 2.1) involved selecting the most relevant databases, inclusion and exclusion criteria, and keywords (Table 3) to search for literature that could answer the research questions. Then during the eligibility evaluation phase (Section 2.2), a literature search was conducted using relevant keywords and databases. The identified literature was then screened and was either accepted or rejected based on its consistency with the inclusion and exclusion criteria. Finally, during the content analysis phase (Section 2.3), each article was reviewed in detail, and key information from each article was extracted manually and coded into ten categories in a spreadsheet (see Table 4). Then the coded articles' information was grouped according to the occupational safety risks they addressed (Figure 2). Articles that addressed similar risks were reviewed collectively to answer the research questions. An overview of the selected articles is presented in the Results of Systematic Literature Review (Section 3). The main findings and discussions regarding safety risks, mitigation measures, current and future research from this review are presented in the Discussion of Risk Categories and Call for Future Research (Section 4), grouped by the safety risk categories identified in the content analysis.

2.1. Phase 1: Planning and Computer Search

During this study's planning and computer search phase, the databases, research questions, and inclusion and exclusion criteria were determined to select the most relevant literature. This review was conducted using the Scopus, Web of Science, Science Direct, and PubMed databases. These databases were selected because they contain the main peer-reviewed journals in the construction and safety management fields and have frequently been used for construction and safety management-related literature reviews (Varghese et al., 2018; Xia et al., 2018, 2020; Zhou et al., 2015). The primary inclusion and exclusion criteria for this study were to select peer-reviewed journal articles available in English, that explicitly detailed information regarding risks, mitigation measures, or research relevant to the safety of PV installers.

To ensure quality and content accuracy, journal articles were selected as the primary source of information. However, solar installation safety manuals, reports, and conference papers were utilized to provide additional support and context to the risks and mitigation measures identified in journal articles. Table 3 shows the guidelines utilized for this review, including the inclusion and exclusion criteria used for selecting articles to include in this study. Articles were identified and examined based on these criteria for eligibility to participate in this study.

2.2. Phase 2: Eligibility Evaluation

Articles were gathered through the Scopus, Web of Science, Science Direct, and PubMed databases iteratively and screened thoroughly to determine their consistency with this study's inclusion and exclusion criteria. Figure 1 depicts the article selection flowchart for this study based on the PRISMA guidelines. First, the study population was identified: relevant articles were selected based on their titles' consistency with the selection criteria (n = 365). Then, duplicate and non-journal articles were removed (n = 177), and the abstracts of the remaining articles (n = 185) were screened for eligibility. The full-text articles with eligible abstracts were then screened and accepted to be included in this study (n = 31) if they were consistent with the selection criteria.

During full-text article screening, articles were rejected for four reasons (Figure 1): (1) The article was not applicable to solar installation work but was focused on other aspects of the PV lifecycle (e.g., operations, or maintenance); (2) the article did not focus on occupational safety; (3) the article did not focus on human safety; and (4) the article was not a journal article. Twenty-six articles did not focus on or provide safety information regarding the occupational risks present during PV installation work (Reason 1). For example, Ju et al. (2019) and Kristensen et al. (2021) focused on risk mitigation of the fire hazards associated with PV systems during their operations or maintenance rather than during installation. An additional five articles did not provide any information regarding occupational safety risks (Reason 2). For example, Tsoutsos et al. (2005) and Turney & Fthenakis (2011) detailed information solely about PV systems' environmental impact rather than the occupational safety risks associated with PV installation work. One of the articles did not focus on human safety (Reason 3) and focused more on bird safety in relation to solar installations (Kosciuch et al., 2020). One article discussed how to mitigate fire risks for distributed PV stations, however, it was a conference article (Reason 4; Lu et al., 2018b); therefore, it was only used to provide additional support and context. Lastly, some articles (n = 3) were accepted based on their title and abstract; however, their full text could not be found despite an extensive web and library search supported by the University of Rhode Island library services. As a result, these articles were not included in this study. After this screening process, a content analysis was conducted on the selected articles.

2.3. Phase 3: Content Analysis

A qualitative content analysis process (Elo & Kyngäs, 2008) was utilized to organize and analyze the information found in each selected article (*n* = 31). This process was conducted from October 2021 to January 2022. First, each accepted article was reviewed in detail. Then, key information from each article was extracted and manually coded into ten categories in a Microsoft Excel spreadsheet codebook (Table 4). Then the coded articles' information was grouped according to the occupational safety risks they addressed (Figure 2). Figure 2 depicts keywords or phrases identified in each article to group the article into an occupational risk category. Articles that addressed similar risks were then reviewed collectively to answer the research questions (Table 3). The main findings and discussions regarding safety risks, effects, mitigation measures, current and potential research areas from this review are presented in the Results of Systematic Literature Review (Section 3) and Discussion of Risk Categories and Call for Future Research (Section 4) section.

Table 3 Systematic Literature Search Guidelines

Step	Description of Steps
Explicit Research Question(s)	What are the occupational safety risks associated with PV installations? What health and safety effects do these risks have on PV installers? What research is being conducted to mitigate these risks? What potential research areas need to be pursued?
Type of Literature	Journal articles
Database	Scopus, Web of Science, Science Direct, PubMed
Keywords	Four groups of keywords were used and combined in multiple combinations in the search: Group 1 - Solar Energy: Solar, photovoltaic, PV Group 2 - Safety: Injury, hazard, risk, health, accident, safe Group 3 - Mode: Installation, construction, installer, install Group 4 - Specific risk terms: Heat stress, stress, fall, height, shock, burn, electrocution, wound, cut, laceration, fire, ergonomic, manual, repetitive, handling, awkward, posture
Inclusion and exclusion criteria	The article deals with safety risks, mitigation measures, or research that was conducted to promote the safety of installers during PV installation work The study is available in English No limit was set for the time and location of the study

Table 4 Codebook for Content Analysis

Code	Description
Article title	Title of the article
Publication year	Year of publication
Journal Title	Title of the Journal
Research method(s)	Questionnaire, interview, case study, experiment, literature review, others
Geographical jurisdiction	Country or region from which the data were collected or research was conducted
Safety risk(s) identified	The occupational risk(s) that the study is about
Research objectives or questions	Research objectives and/or questions explicitly stated in the article
Major findings	Major findings explicitly stated in the article
Major contributions	Contributions explicitly stated in the article
Future work or direction	Future work explicitly stated in the article

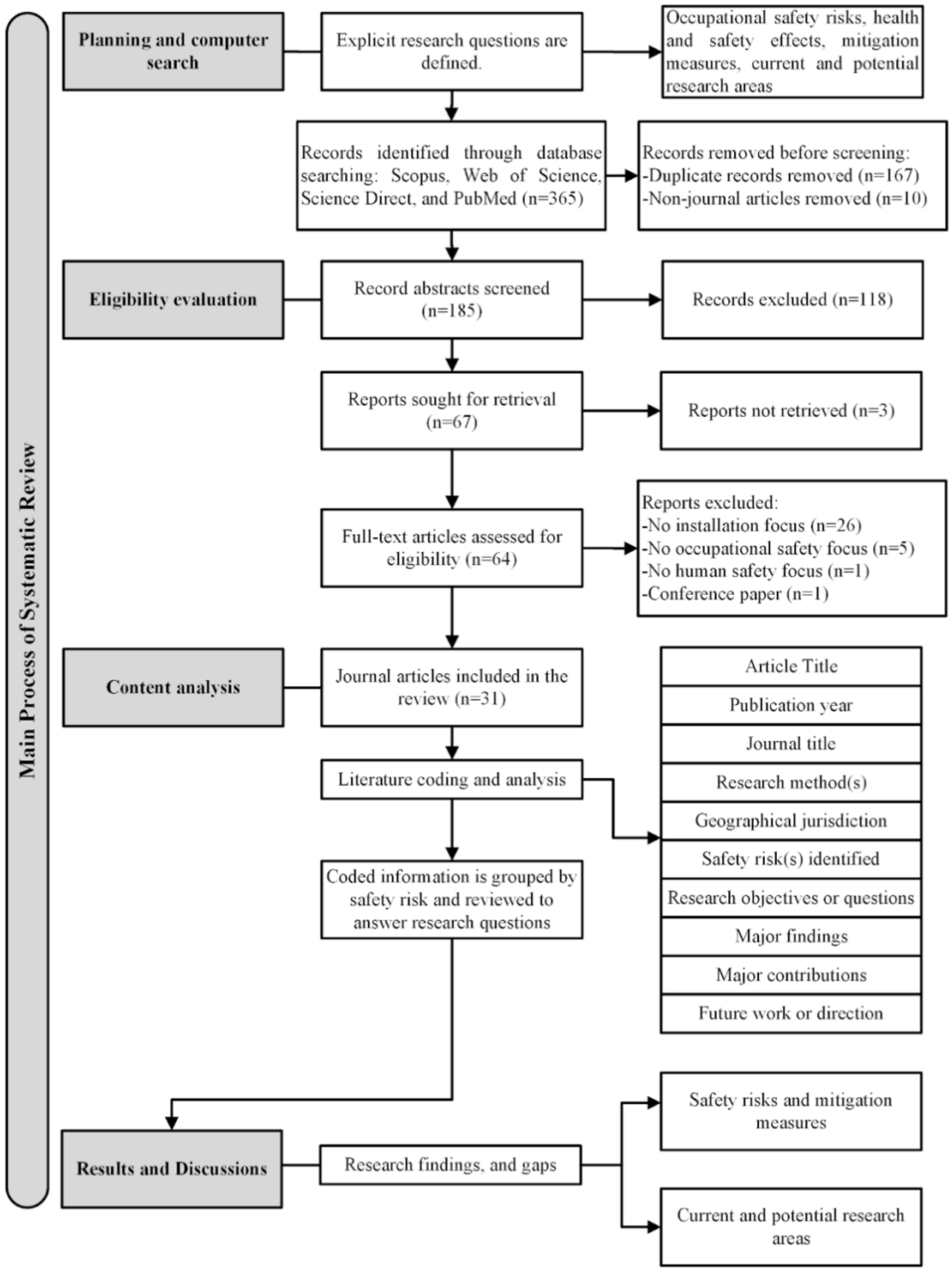

Figure 1 Main process of systematic review on solar occupational safety risks

Note: “Reports not retrieved” refers to articles whose full-text could not be found despite an extensive web and library search supported by the University of Rhode Island library services. As a result of this, these articles were not included in this study.

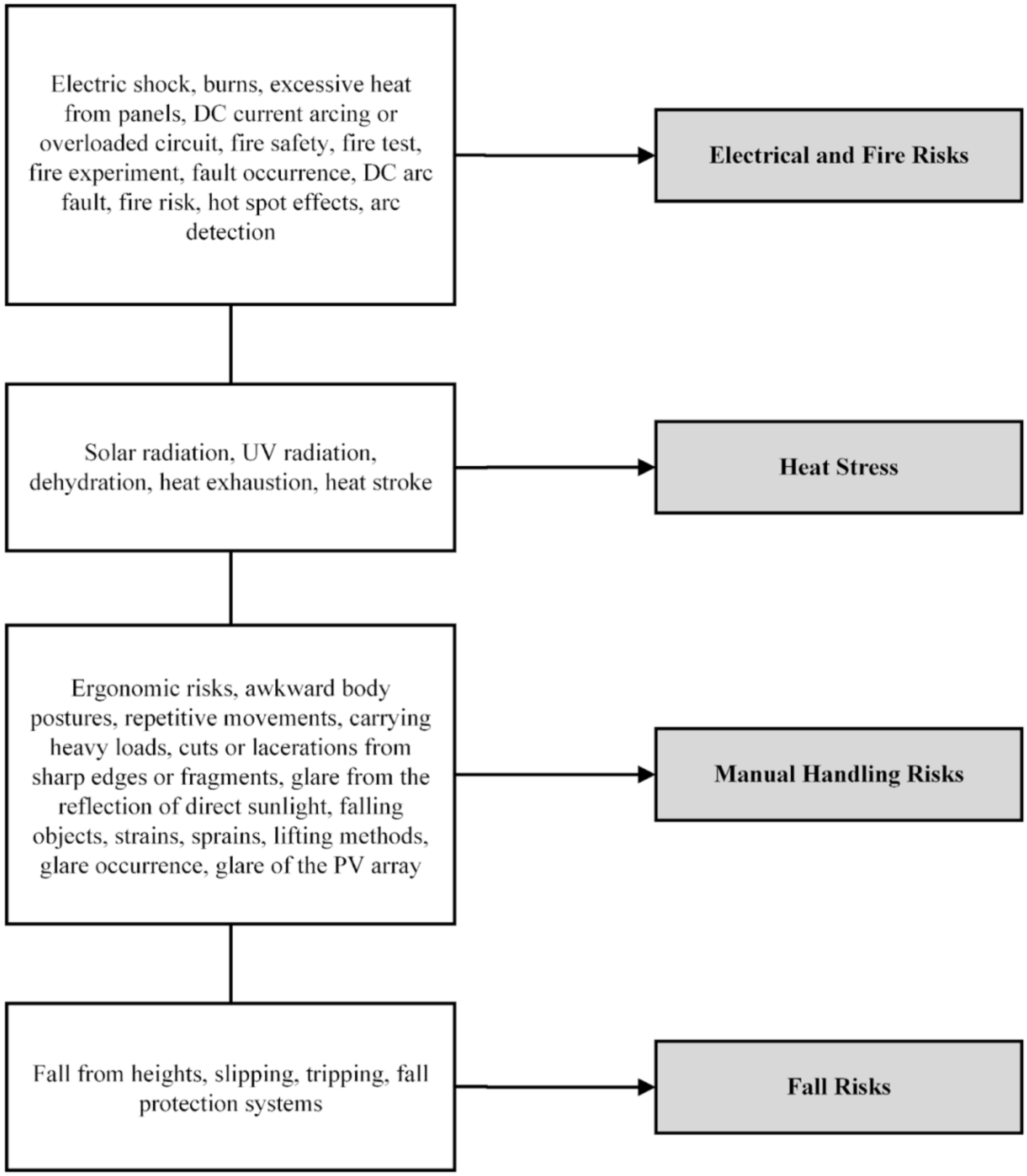

Figure 2 Keywords or phrases identified in selected articles and utilized to create occupational safety risk categories

Table 5 Journal articles included in review summary

Author (year)	Risks: Electrical & Fire	Heat Stress	Manual Handling	Falls	Research Method(s)	Geographical Jurisdiction	Journal Title
Aram et al. (2021)	Yes				Literature review	Unspecified	Journal of Cleaner Production
Bakhiyi et al. (2014)	Yes		Yes	Yes	Literature review	Canada	Environment International
Bücher et al. (1998)	Yes		Yes		Literature review	Multicontinental	Renewable Energy
Cancelliere (2016)	Yes				Risk assessment	Italy	Fire and Materials
Cancelliere & Liciotti (2016)	Yes				Experiment	Italy	Fire Technology
Chiabrando et al. (2009)			Yes		Case study, Risk assessment	Italy	Renewable and Sustainable Energy Reviews
Chow et al. (2017)	Yes				Experiment	China	Fire and Materials
Dewlaney et al. (2012)			Yes	Yes	Interview	USA	Journal of Construction Engineering Management
Erten & Utlu (2020)	Yes		Yes	Yes	Literature review	Turkey	Greenhouse Gases Science and Technology
Fortunato et al. (2012)				Yes	Interview, case study	USA	Journal of Construction Engineering Management
Guerin (2017a)	Yes				Case study	Australia	Solar Energy
Guerin (2017b)	Yes		Yes		Conceptual, risk assessment	Australia	Renewable and Sustainable Energy Reviews
Huang et al. (2017)	Yes				Experiment	Taiwan	Indoor and Built Environment
Ho et al. (2020)	Yes	Yes	Yes	Yes	Questionnaire, interview, case study	USA	Safety Science
Kristensen & Jomaas (2018)	Yes				Experiment	Denmark	Fire Technology
Levins (1987)	Yes				Literature review	USA	Solar Energy Materials & Solar Cells
Lu et al. (2018b)	Yes				Literature review	Unspecified	Renewable and Sustainable Energy Reviews
Moskowitz (1983)	Yes				Literature review	USA	Solar Energy Materials & Solar Cells
Rabbani et al. (2014)				Yes	Questionnaire, interview	Italy	European Journal of Government and Economics
Ramali et al. (2022)	Yes				Literature review	Malaysia	Fire Technology
Samaniego-Rascón et al. (2017)		Yes			Experiment	Mexico	Energy
Samaniego-Rascón et al. (2019)		Yes			Case study, literature review	Mexico	Safety Science
Sen et al. (2021)	Yes	Yes	Yes	Yes	Literature review	India	Risk Management and Healthcare Policy
Sovacool (2015)					Conceptual	Multicontinental	Energy
Sreenath et al. (2020c)			Yes		Simulation	Malaysia	Results in Engineering
Sreenath et al. (2020b)			Yes		Simulation	Malaysia	Energy Reports
Sreenath et al. (2020a)	Yes		Yes		Risk assessment	Unspecified	Environmental Impact Assessment Review
Sreenath et al. (2021)			Yes		Simulation	India	Cleaner Engineering and Technology
Tsoutsos et al. (2005)	Yes		Yes		Literature review	Unspecified	Energy Policy
Wu et al. (2020)	Yes				Literature review	Unspecified	Institute of Electrical and Electronics Engineers Access
Wybo (2013)	Yes				Interview	France	Renewable and Sustainable Energy Reviews

Note: Although Sovacool (2015) did not explicitly identify any of the risk categories as associated with solar installations, they provided important information about the current state of solar occupational safety and thus were included in this review. Multicontinental means the selected articles conducted research on multiple continents; this includes North America, Africa, the Middle East, Europe, Asia-Pacific, and South America

Table 6 Distribution of Selected Journal Articles

Journal Title	Number of Selected Articles
Safety Science	2
Renewable and Sustainable Energy Reviews	4
Environmental Impact Assessment Review	1
Environment International	1
Journal of Construction Engineering Management	2
Greenhouse Gases Science and Technology	1
Institute of Electrical and Electronics Engineers Access	1
Fire and Materials	2
Fire Technology	3
Risk Management and Healthcare Policy	1
Solar Energy Materials & Solar Cells	2
Energy Policy	1
Results in Engineering	1
Cleaner Engineering and Technology	1
Energy Reports	1
Energy	2
Renewable Energy	1
Indoor and Built Environment	1
Solar Energy	1
European Journal of Government and Economics	1
Journal of Cleaner Production	1

3. Results of Systematic Literature Review

Through a systematic literature search, 31 articles were selected as relevant for this study. A table summary of the selected articles', journal title, risk categories identified, geographical jurisdiction, and research method(s) used is depicted in Table 5. Four major risk categories were identified as being associated with PV installations (Figure 3): (1) electrical and fire risks, (2) heat stress, (3) manual handling risks, and (4) fall risks. Table 6 shows the distribution of the selected journal articles by journal title. Most of the articles conducted their research in North America, Europe, or Asia (Figure 4). They utilized the following research methods to conduct their studies (Figure 6): literature reviews, conceptual research, experiments, case studies, interviews, questionnaires, simulations, and risk assessment. Figure 5 shows the distribution of addressed safety risks in articles that conducted research in North America and Asia (the geographical locations with the most articles). Over 80% of the articles were published within the last decade (Figure 7), which indicates that PV installation occupational safety research and literature are still emerging.

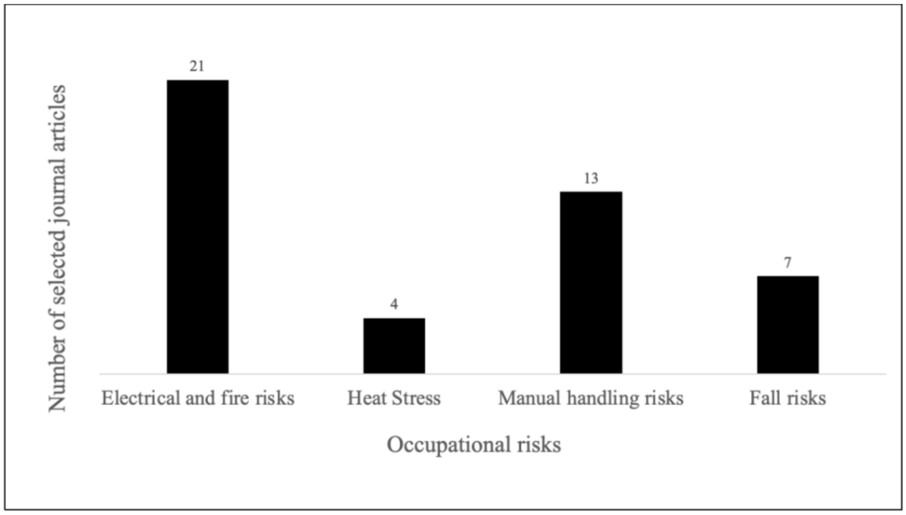

Figure 3 Occupational risk categories identified by the Selected Journal Articles

Note: Many selected articles identified multiple risks

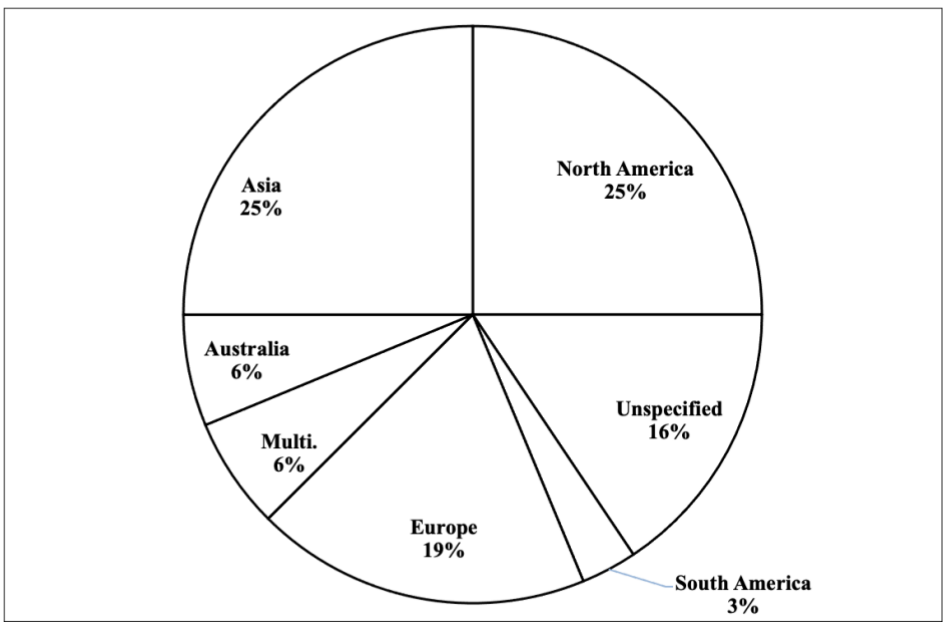

Figure 4 Continent where data was collected or research was conducted in selected journal articles

Note: This chart represents the percentage of selected articles that conducted research or collected data in each geographical location. Multicontinental (Multi.) means the selected articles conducted research on multiple continents; this category includes North America, Africa, the Middle East, Europe, Asia-Pacific, and South America.

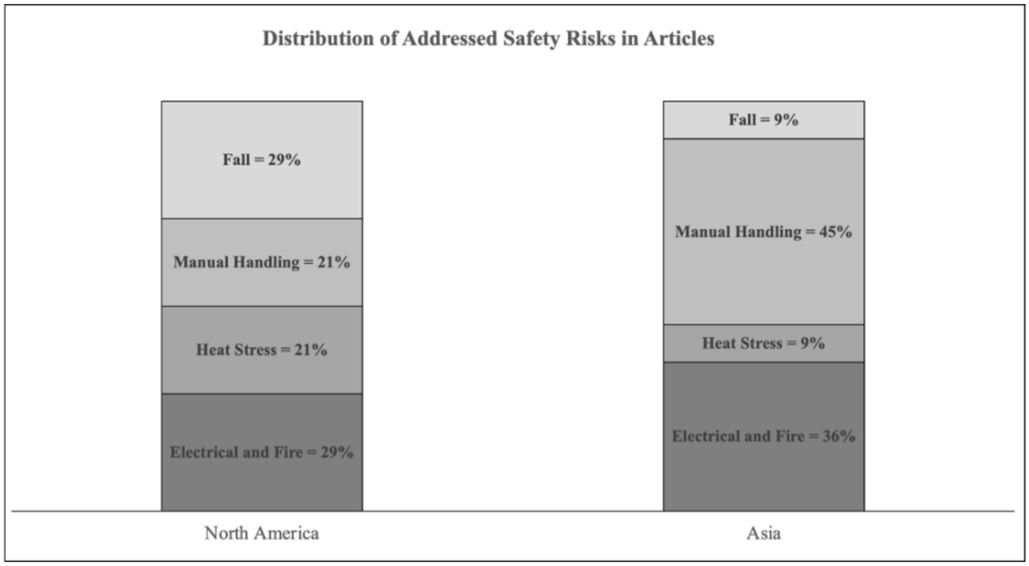

Figure 5 Distribution of Addressed Safety Risks in Articles that conducted research in North America and Asia (the geographical locations with the most articles)

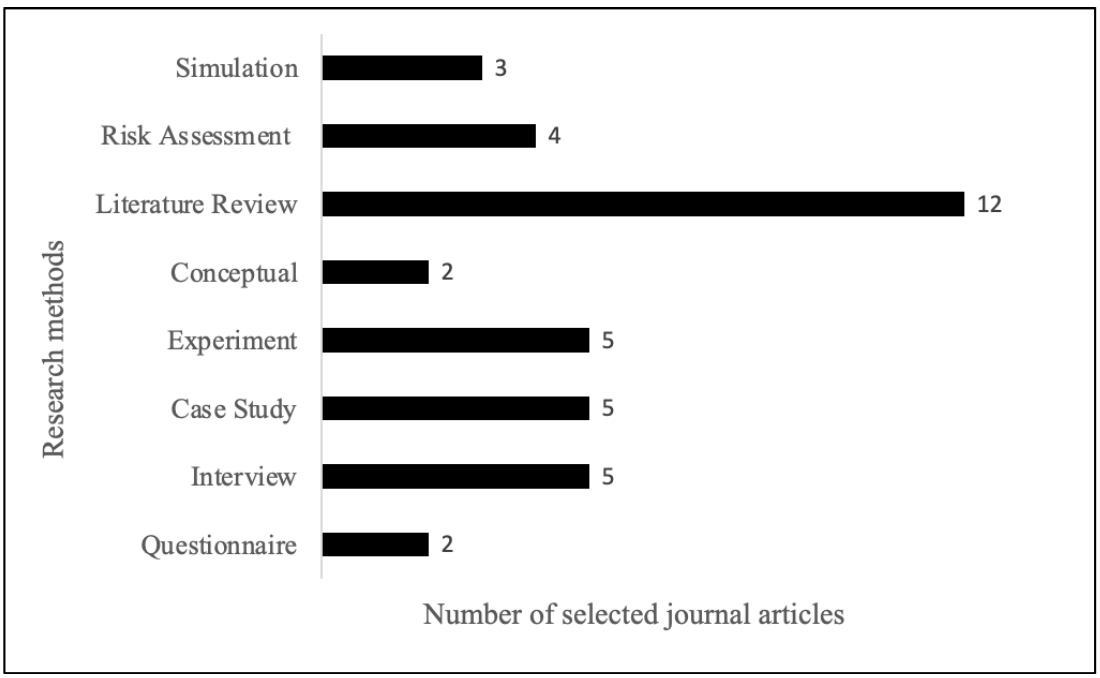

Figure 6 Research methods used in the selected journal articles

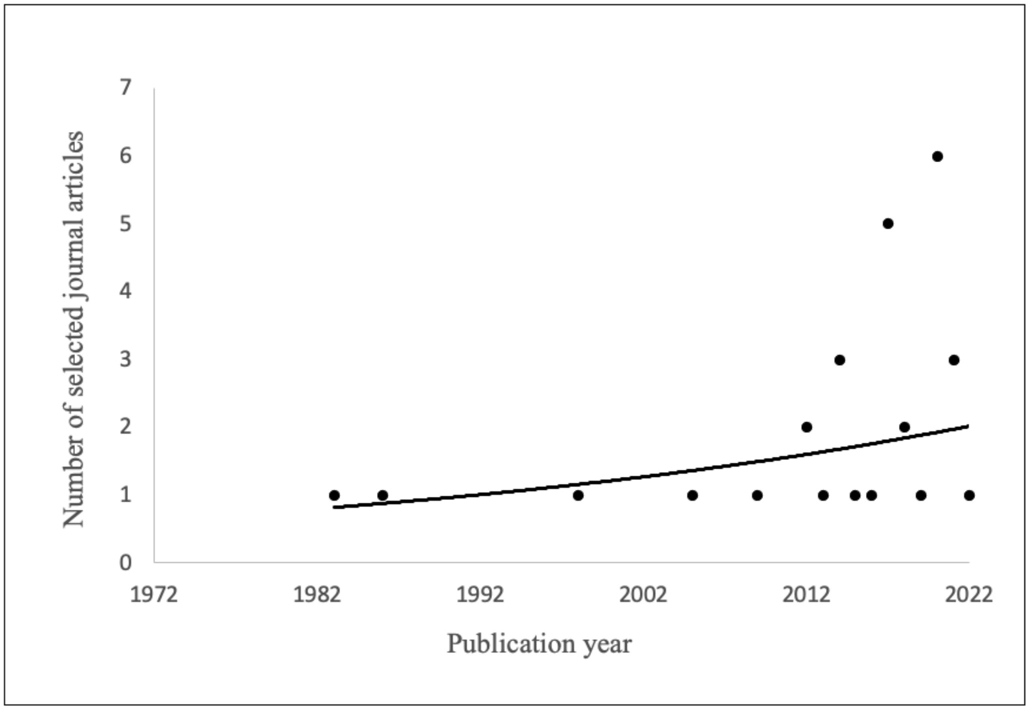

Figure 7 Publication year of selected journal articles on safety risks during PV installations

The articles selected were analyzed based on their classified risk categories. Table 7 provides a summary of the major findings in this study regarding the occupational risks, mitigation measures, current and potential research areas associated with PV installations. Electrical and fire risks were the most identified risk category in the literature (*n* = 21), and not surprisingly so considering the nature of the industry. However, the literature indicates that these risks are more common and hazardous during the solar operations and maintenance phase and not necessarily as prevalent during installations (Ho et al., 2020). Consequently, most of the research being conducted to mitigate electrical and fire risks involves testing the flame resistance of panel materials (Cancelliere & Liciotti, 2016; Chow et al., 2017) and their proper configuration on rooftops to reduce flame propagation (Ju et al., 2019; Kristensen et al., 2021; Kristensen & Jomaas, 2018). The research regarding electrical and fire risks that will be emphasized in this review is from articles that indicated that their research findings were applicable during PV installations. Although electrical and fire risks were identified most frequently in the literature, the risk of heat stress was also highlighted by a few research articles.

Building on the foundation of previous heat stress mitigation research in construction-related occupations (Rowlinson et al., 2014; Rowlinson & Jia, 2014; Yi & Chan, 2013), articles (*n* = 4) were found that identified heat stress as a PV installation risk. However, only two articles provided detailed guidelines to mitigate heat stress during PV installations. These two articles are considered in detail in the Discussion of Risk Categories and Call for Future Research (Section 4), and their potential effects on other risks, including manual handling and fall risks, are considered.

Although multiple articles identified manual handling (*n* = 13) and fall risks (*n* = 7) as associated with PV installations, only a few articles conducted manual handling or fall risk mitigation research for PV installations. Two articles were identified that conducted detailed case studies and interviews to explore PV installation manual handling risks, and only one article focused on fall risk mitigation research. Consequently, in the Discussion of Risk Categories and Call for Future Research (Section 4), information from articles that conducted manual handling and fall risk mitigation research in similar construction occupations to PV installers was utilized to highlight potential areas for future work.

Table 7 Occupational risks, mitigation measures, current and potential research areas

Identified hazard/risk	Sources	Recommended controls and mitigation measures	Current research areas	Potential research areas
Electrical shock, burns, electrocution, fire accidents	Chow et al. (2017); Flicker & Johnson (2016); Huang et al. (2017); Lu et al. (2018); Oregon Solar Energy Industries Association (2006); Romich & McGuire (2015); White & Doherty (2017); Wu et al. (2020)	Proper signage and barriers around electrical hazards Rubber insulated gloves and leather protectors Fire-rated clothing Arc flash protection Protective eyewear Safety footwear Electrical and fault detection devices (e.g., alarms, circuit interrupters)	Fault detection and diagnosis techniques PV panel design and configuration for flame resistance	PV panel design and configuration for flame resistance (database development) AI-based fault protection devices
Heat Stress, heat injuries, dehydration, heat exhaustion, heatstroke	California Department of Industrial Relations (2015); Hanson & Thatcher (2020); Haynes et al. (2018); Samaniego-Rascón et al. (2017); Samaniego-Rascón et al. (2019); Shakerian et al. (2021)	Acclimatization rules and procedures Work-rest schedule based on wet bulb globe temperature Monitor workers for heat stress symptoms	Work-rest schedule based on wet bulb globe temperature Solar radiation exposure guidelines	Development and application of work-rest schedules in different installation contexts and settings Understanding the awareness of solar workers of heat stress contributing factors Heat stress symptom detection devices Mitigation measures for cold stress
Repetitive tasks, heavy lifting, musculoskeletal disorders	Albers & Estill (2007); Choi (2008); Ho et al. (2020); López-Aragón et al. (2018); Ludewig and Borstad (2003); Sen et al. (2021)	Site-specific lifting programs Manual handling tools and equipment Breaks and stretching sessions Reduced vibration tools, and anti-vibration gloves	Prevention through design (lifting methods)	Mechanical lifting systems (lengthy setup time) Effects of glare from roof and panels Ergonomic assessments to understand MSD risks Installer risk perception studies
Falling from heights, slips, and trip accidents	California Fatality Assessment and Control Evaluation Program (2011); Dong et al. (2017); Ho et al. (2020); Oregon Solar Energy Industries Association (2006)	Hazards identification training Guardrails Safety nets Personal fall arrest systems and clothing Prevention through design on roofing attributes (e.g., composite shingle roofs are less slippery than metal roofs)	Prevention through design (roofing materials, slopes, accessories, fall protection systems, and electrical systems)	Fall protection systems (trip and heavyweight hazards) Risk perception studies

4. Discussions of Risk Categories and Call for Future Research

4.1. Electrical and Fire Risks

4.1.1. Safety Risks and Mitigation Measures

Multitudes of electrical components are involved in installing PV systems, including but not limited to combiners, inverters, transformers, and the PV modules themselves (Oregon Solar Energy Industries Association, 2006; White & Doherty, 2017). As a result, installers are exposed to safety risks, including electrical shocks, burns, electrocution, arc flash, and fault currents (California Fatality Assessment and Control Evaluation Program, 2009; Flicker & Johnson, 2016; Oregon Solar Energy Industries Association, 2006). An unavoidable aspect of the PV installation process is that some electrical components are live and energized (Wybo, 2013; Microgeneration Certification Scheme (MCS), 2012). This is especially applicable when handling PV modules since they have the unique ability to be energized when exposed to sunlight during electrical work, thus creating an environment where traditional regulations, such as Lockout/Tagout (LOTO), are no longer the primary safety solution. Additionally, if fault currents and other electrical hazards are undetected for a significant period of time, they can result in fire accidents (Bakhiyi et al., 2014; MCS, 2012). Fire accidents can then be aggravated by flammable materials on-site (Wybo, 2013). These electrical and fire risks can occur differently depending on the types and settings involved during PV installations.

The occurrence of electrical and fire risks can vary based on the type (e.g., rooftop, ground-mount), setting (e.g., residential, commercial, utility-scale), and weather conditions during PV installations. Greater electrocution risks exist when installing larger-scale PV systems due to the higher voltage and current ratings of the electrical components (White &

Doherty, 2017). Consequently, commercial and utility-scale installations present greater electrocution risks to installers than residential installations. During residential installations, areas surrounding high-voltage electrical lines are an additional risk factor. If installers mishandle ladders, metal brackets, and other lengthy conductive equipment, they can contact electrical lines, leading to electrocutions (California Fatality Assessment and Control Evaluation Program, 2009). During floating photovoltaic installations, the surrounding water body can also induce additional electrical safety risks (Sen et al., 2021). Extreme weather conditions can exacerbate electrical risks in all installation types and settings. For instance, when manually handling PV modules, rainy conditions can increase shock risks (Romich & McGuire, 2015), while hot and windy conditions can increase the risk of burns (White & Doherty, 2017). Considering the installation type, setting, and weather condition is crucial in mitigating electrical and fire risks.

Safety measures to mitigate electrical and fire risks include job hazard analysis, regular electrical and fire safety training, proper signage, and barriers around electrical hazards (Ramali et al., 2022; MCS, 2012; Oregon Solar Energy Industries Association, 2006). The implementation of good Lockout Tagout practices is also essential (U.S. Department of Labor, 2017c). Installers should be trained to identify shock hazards and use equipment and tools with proper insulation (Oregon Solar Energy Industries Association, 2006). Site-specific emergency response plans should also be developed and communicated with local fire and rescue responders to aid preparations in case of emergencies (Ramali et al., 2022; Romich & McGuire, 2015). In order to mitigate electrical risks from the PV panels being energized by sunlight, common safety recommendations include installing the systems at night (with adequate lighting) or covering panels with materials such as light-proof film coverings to reduce photon penetration; however, this practically makes the installation process more tedious (Wybo, 2013; MCS, 2012). More modern installations and panels attempt to mitigate these risks by designing easy quick-connect wire connections for safety and speed. Ultimately, when unsure about the “live” state of PV components and wiring, installers should assume they are electrically energized and proceed with caution (Romich & McGuire, 2015). When working with electrical components, the proper protective clothing includes rubber-insulated gloves and leather protectors (White & Doherty, 2017), fire-rated clothing, arc flash protection, protective eyewear, and safety footwear (Ramali et al., 2022; Romich & McGuire, 2015). Understanding how to safely proceed with PV installations or maintenance while working with energized components is an area in need of constant research.

4.1.2. Current and Potential Research Areas

Research conducted to mitigate the electrical risks associated with PV installations involves developing and reviewing fault detection and diagnosis techniques (Flicker & Johnson, 2016; Lu et al., 2018b; Wu et al., 2020). Detecting fault currents on time is crucial for reducing electric shock or fire risks. Ground fault protection devices are commonly used to detect and trip (shut off) the circuit in DC-grounded PV systems (Flicker & Johnson, 2016). Flicker & Johnson (2016) conducted simulations to understand the limitations of fuse-based ground fault protection devices and propose trip-setting recommendations for alternative ground fault protection devices in PV systems. Through reinforcing simulations with numerical and analytical modeling and experimental data, Flicker & Johnson (2016) provided industry recommendations regarding ground fault detection settings and tripping thresholds for PV systems. Other articles reviewed arc fault diagnosis methods or algorithms that can be utilized in safety devices, such as alarm systems and arc fault circuit interrupters, to detect and alert electrical workers of arc fault risks (Lu et al., 2018b; Wu et al., 2020). Examples of these methods include the Fast Fourier Transforms, Wavelet Transforms, and Artificial Intelligence (AI) based methods (e.g., artificial neural networks, fuzzy logic, support vector machines). These methods are important areas to explore in order to improve the efficiency of fault protection devices that mitigate electric shock and potential fire risks.

To reduce the fire risks associated with PV installations, experimental studies have been conducted to understand the fire behavior of various PV panel types and designs (Chow et al., 2017; Huang et al., 2017). Chow et al. (2017) performed a cone calorimeter experiment to study the fire behavior of commonly used polycrystalline silicon PV panel samples. Based on their experiments, they concluded that the PV panels examined release toxic gasses when exposed to high levels of heat flux. This can be an additional risk for installation workers if there is a fire outbreak on-site. Huang et al. (2017) also investigated the fire behaviors of PV modules, but they focused on the fire resistance of building-integrated PV modules with different junction box designs. They found that different junction box designs can improve the fire-resistant capabilities of building-integrated PVs. These studies provide a foundation for future research by facilitating a better understanding of the fire resistance capabilities of various PV panel types and designs.

A key focus for future research and exploration regarding electrical and fire safety involves developing databases to support AI-based fault protection devices, panel designs, and configurations. Although no fault diagnosis method guarantees accurate detection of all arc fault occurrences, AI-based methods can achieve the highest level of accuracy (Wu et al., 2020). Limitations in AI-based fault diagnosis methods research such as requiring large amounts of data for the training set and a huge computational load (Lu et al., 2018b; Wu et al., 2020), provide barriers to more widespread use of these methods in fault protection devices. However, the increase in fault cases provides data opportunities for more databases to aid in the research and implementation of AI-based fault protection devices (Wu et al., 2020). Databases are also needed to detail the flame resistance capabilities of different PV panel types and configurations (Chow et al., 2017), informing installers of the best ways to install panels to mitigate potential fire risks. Although research into electrical and fire safety during installations is crucial, it is also essential to consider the heat effect from sun exposure on installers.

4.2. Heat Stress

4.2.1. Safety Risks and Mitigation Measures

Heat stress is caused by working in extreme heat conditions and can result in heat-related illnesses such as heat cramps, exhaustion, and strokes (Acharya et al., 2018; Bonauto et al., 2007). In the U.S., over 600 people are killed from extreme heat annually (Centers for Disease Control and Prevention, 2019), with workers in the construction industry historically being thirteen times more likely to die from heat-related illnesses (HRIs) than in other industries (Gubernot et al., 2015). Photovoltaic installers are exposed to HRIs from working in hot temperatures for prolonged periods. Solar panels are typically installed in geographic locations with high sun and heat exposure (Hanson & Thatcher, 2020) due to energy density and higher financial rates of return on investment, thus increasing the risk of HRIs. The direct beam light reflection from the panel, strenuous activities (e.g., repetitive lifting of heavy loads), and PPE (e.g., safety helmets, reflective vests, and safety boots) involved in PV installations can also make working in hot temperatures mentally and physically challenging (Acharya et al., 2018; Oregon Solar Energy Industries Association, 2006; Rowlinson et al., 2014). Signs of HRI's include, but are not limited to, high body temperature, profuse sweating, confusion, slurred speech, and dizziness (Centers for Disease Control and Prevention, 2018). Monitoring workers for these signs can aid in the early detection and mitigation of heat-related illnesses.

In order to reduce the risk of HRI's, installers need fluids and frequent rest in a shaded and cool area (California Department of Industrial Relations, 2015; Hanson & Thatcher, 2020). Work-rest cycles are essential to reducing the effects of heat stress on workers. Work-rest schedules can be created for PV installation work using a heat stress index to measure heat effects. The most commonly used heat stress index is the Wet Bulb Globe Temperature, which incorporates the air temperature, humidity, radiant heat, and wind speed to quantify heat stress levels (Acharya et al., 2018; Rowlinson & Jia, 2014; Rowlinson et al., 2014). To reduce the effects of heat stress, on-site workload can start small and gradually increase to allow installers to acclimate to their environment (OSHA, n.d.; Samaniego-Rascón et al., 2019). It is also vital for employers to continuously monitor workers for signs of HRIs while working in hot temperature conditions (Hanson & Thatcher, 2020; California Department of Industrial Relations, 2015; OSHA, n.d). Workers can be monitored using physiological signs such as pulse rate, temperature, body weight, blood pressure, respiratory rate, and alert-ness; their workload should be adjusted based on these factors

(OSHA, n. d). Further research into work-rest schedules for installers is an important step in mitigating heat stress.

4.2.2. Current and Potential Research Areas

Only two studies conducted detailed heat stress mitigation research geared toward solar installers. These studies developed work-rest schedules and solar radiation exposure guidelines for solar workers in a solar facility in Mexico (Samaniego-Rascón et al., 2017; Samaniego- Rascónetal.,2019). Samaniego-Rascón et al. (2017) studied the effects of solar radiation leading to sunburns and other forms of skin damage in solar workers. They found that it took less than 35 min for unprotected solar workers with non-adapted skin to get sunburn when exposed to the highest levels of constant solar radiation. They also found that workers with adapted skin could be unprotected for a significantly longer period before getting a sunburn (anywhere from 1.4 to 5.7 times longer, depending on their skin type). Consequently, they provided recommendations and information regarding skin adaptation techniques, adequate work times, skin protection resources, and clothing (e.g., sunscreen application guidelines and hats for shade). Similarly, Samaniego-Rascón et al. (2019) conducted another case study in a solar facility in Mexico to develop work-rest schedules for solar workers. They collected data and proposed detailed work-rest schedule recommendations for solar workers based on the wet bulb globe temperature and the work capacity of the task performed. For example, Samaniego-Rascón et al. (2019) suggested that solar workers without acclimatization need to rest for 45 min per hour when they have a heavy workload (400 kcal/ h) and for 30 min per hour when the workload is moderate (300 kcal/h). These studies provide a foundation for future HRI assessment studies for solar workers. Future work can include developing and applying these studies to various installation contexts and settings.

Heat stress studies have been conducted in construction occupations with similar tasks as PV installers (e.g., manual handling, roofing; Haynes et al., 2018; Shakerian et al., 2021; Varghese et al., 2020). In research by Varghese et al. (2020), health and safety representatives (HSRs) in Australian workplaces were surveyed to understand the fac- tors that contribute to HRIs and effective preventative measures. Varghese et al. (2020) identified the absence of shaded working areas, wearing PPE (leading to higher body temperature), and rushed activity as the most common contributors to HRIs. They also reported manual handling (musculoskeletal), hand injuries, HRIs (e.g., fatigue, muscle or heat cramps, dehydration) as the most frequent injuries associated with working in hot conditions. Finally, Varghese et al. (2020) highlighted the most common organizational barriers to mitigating heat stress: inadequate resources and facilities and a lack of health and safety training.

Since there are only a few heat stress studies that have been specifically conducted on the solar worker population (Samaniego-Rascón et al., 2017; Samaniego-Rascón et al., 2019), an important next step for future research would be understanding the awareness of solar installation workers, supervisors, managers, and HSRs regarding heat stress contributing factors and mitigation measures (Haynes et al., 2018). Key questions to explore include: Are solar workers adequately provided heat stress health and safety training? What resources are in place on solar sites to mitigate heat stress? Worker interviews, questionnaires, and observational studies are methods that can provide a good starting point for gathering this information. Through studies of this kind, awareness regarding heat stress as an occupational hazard and the next steps for heat stress mitigation research in the solar safety realm can be clarified. Other potential research areas include the potential application of heat stress symptom detection devices on solar workers (Shakerian et al., 2021), exploring the effects and mitigation measures for cold stress (Ho et al., 2020), and understanding if there is a relationship between heat stress and musculoskeletal injuries during solar installation work (Varghese et al., 2020).

4.3. Manual Handling Risks

4.3.1. Safety Risks and Mitigation Measures

PV installation projects involve risk factors and working conditions that expose installers to manual handling risks. PV panels are typically 40″ × 66″ or 40″×78″ in size and weigh 30 to 40 pounds in residential settings (Ho et al., 2020), and are even larger and heavier in commercial and utility-scale settings. Additionally, panels tend to emit excessive heat (Bakhiyi et al., 2014). Repetitively lifting these panels and other equipment at awkward postures (e.g., bending, kneeling, overhead reach) as is required during installations (Oregon Solar Energy Industries Association, 2006) can lead to manual handling injuries such as musculoskeletal disorder risks, wounds, cuts, impact injuries, and thermal burns (Bakhiyi et al., 2014; Oregon Solar Energy Industries Association, 2006). The potential for PV installers contracting MSDs due to repetitive manual handling tasks is a primary concern that has seldom been addressed in the literature (Sen et al., 2021).

Musculoskeletal disorders are injuries that damage the musculoskeletal system (i.e., muscles, nerves, tendons, joints, and ligaments). They are caused by performing tasks that involve repetitive motion, force, vibration, and awkward postures (Albers & Estill, 2007). The 2018 survey of occupational injuries and illnesses reported that work-related musculoskeletal injuries account for 30.3% of days-away-from-work cases in the U.S. private industry (U.S. Bureau of Labor Statistics, 2019, p. 20). During PV installations, installers are likely exposed to MSD risks associated with performing repetitive manual handling tasks and the frequent use of vibrating hand and power tools. Hanson and Thatcher (2020) point out that solar panels can be challenging to handle due to their size and weight. Manual handling tasks typically involved in PV installations include, but are not limited to, lifting, lowering, pushing, pulling, and carrying panels and their constituent parts from one location to another within the installation area (Solar Energy Solutions Group, 2008). These are common manual handling tasks in the residential construction domain; thus, the risk of contracting sprains, strains, and soft tissue injuries is likely associated with these tasks (National Institute for Occupational Safety and Health [NIOSH], 2013). Common soft tissue injuries that are likely associated with these types of manual handling tasks include, but are not limited to, shoulder injuries (e.g., rotator cuff bursitis, tendinitis, and tears) and back injuries (e.g., hip-low back strain, bulging or herniated discs, pinched nerves, L5-S1 damage) (Albers & Estill, 2007; NIOSH, 2013). Moreover, PV installers are also potentially exposed to the risk of contracting Hand-Arm Vibration Syndrome (Vergara et al., 2008; Weir & Lander, 2005) from the frequent use of vibrating hand and power tools such as drills and saws (U.S. Bureau of Labor Statistics, 2020). These MSD risks can be exacerbated by working in extreme weather conditions, such as heat, wind, or rain, or on various angled working surfaces, such as sloped or inclined rooftops (Hanson & Thatcher, 2020, p. 180). In these conditions, risk mitigation is incredibly challenging.

The manual handling and MSD risks associated with PV installations can be mitigated by conducting site-specific ergonomics programs and utilizing lifting tools and equipment to eliminate unnecessary lifting. Choi et al. (2016) studied work-related MSD and effective safety practices for construction workers and emphasized the importance of employers creating and implementing a site-specific ergonomics program that identifies and educates workers about the lifting and manual handling hazards present in unique sites. Another strategy for reducing ergonomic stress during lifting is to store materials on the worksite. Ergonomics manuals typically recommend storing materials close to their use location, between knee and chest height, for ease of lifting (NIOSH, 2013). Employers can also place restrictions on the maximum load an individual can handle based on various ergonomic safety factors. These factors include the availability of lifting equipment and workers' strength, fitness, medical health, lift duration, and postures assumed during the lift (Choi et al., 2016; Health and Safety Executive, 2016). Workers should also be encouraged to take short breaks during manual handling to rest their muscles and joints (NIOSH, 2013) and regularly stretch and exercise (Ludewig & Borstad, 2003). Simple tools and equipment, such as dollies and carts, can safely transport materials short distances (NIOSH, 2013; Oregon Solar Energy Industries Association, 2006). Reduced vibration tools and anti-vibration gloves can mitigate the risk of contracting HAVS (Albers & Estill, 2007). Powered and mechanical lifting equipment, such as cranes and fork trucks, can transport heavy materials for longer distances (NIOSH, 2013). Hoists can be used to lift solar panels to elevated working surfaces. Manually lifting panels to these surfaces can increase the risk of MSDs and also result in increased risks of workers falling from elevated working surfaces (Oregon Solar Energy Industries Association, 2006). These mitigation methods can reduce manual handling risks, but more research is needed to understand the specific ergonomic obstacles installers face.

4.3.2. Current and Potential Research Areas

There is a lack of research to mitigate manual handling and MSD risks in the PV installation sector. Only two studies identified in this paper made detailed risk mitigation research proposals regarding PV installation manual handling risks (Ho et al., 2020; Sen et al., 2021). Ho et al. (2020) conducted a Prevention through Design (PtD) study to understand the safety risks associated with installing solar systems on residential buildings. Through interviews and case studies, Ho et al. (2020) found that solar professionals perceived mechanical lifting equipment (e.g., ladder hoists) as inconvenient because of their lengthy setup time. As a result, to save time, the workers performed manual lifting tasks in ergonomically unsafe ways (e.g., manual lifting of panels on ladders). Future research can explore how widespread this perception is amongst installers and ways to re-design tasks and equipment to mitigate this obstacle. Sen et al. (2021) also identified manual handling and ergonomic risks associated with installing PV systems (floating photovoltaics). They identified lower back pain, MSDs, cuts, and bruises as potential occupational risks that floating photovoltaic installers experience and proposed basic ergonomic design interventions such as lowering loads, task rotation, and layout redesigns to mitigate these risks.

Future research regarding the manual handling and MSD risks of solar workers should focus on gathering information on the tasks, demographics of solar workers, and parts of the body at the highest risk of musculoskeletal injuries (López-Aragón et al., 2018). Common ergonomic assessments such as the standardized nordic assessment (Kuorinka et al., 1987), the NIOSH equation (NIOSH, 2021), and the Rapid Upper Limb Assessment (McAtamney & Corlett, 1993) that have been used in other industries can be explored and applied to solar installation work. These assessments can potentially provide insights into the basic ergonomic challenges experienced by solar installers. Moreover, the continued development of passive exoskeletal systems that can support workers' back and core muscles as they perform construction manual handling tasks (Antwi-Afari et al., 2021) is an emerging area of research that could be applied to solar installation work. Finally, research can explore how other hazards (e.g., glare from panels, electrical tasks) might increase manual handling or MSD risks and the potential for other dangerous accidents (Chiabrando et al., 2009; Sreenath et al., 2020b; Sreenath et al., 2021), such as fall accidents.

4.4. Fall Risks

4.4.1. Safety Risks and Mitigation Measures

Falls from elevated surfaces are the most significant contributing occupational hazard to fatalities in the construction industry (Dong et al., 2019; U.S. Department of Labor, 1990). Photovoltaic installations performed on elevated working surfaces expose installers to the risk of falling from dangerous heights. Based on the most frequent fall accident locations and occurrences in the construction industry over time, falls from elevations are likely more prevalent among rooftop PV installers, with the majority of falls potentially occurring from ladders, roofs, scaffolds, and floors with openings, at elevations of 30 ft or less (Dong et al., 2019; Huang & Hinze, 2003). Fall risks increase in extreme weather conditions, such as rain, wind, ice, or heavy snow (Hanson & Thatcher, 2020). In addition, working with electrical components can cause electrical shocks or trip hazards, increasing fall risks (Romich & McGuire, 2015; Oregon Solar Energy Industries Association, 2006). Roofers, in particular, have similar tasks to PV installers and are known to have the highest rates of fatal fall occurrences in the construction industry (Dong et al., 2019; Huang & Hinze, 2003). This strongly indicates that rooftop PV installers are at a high risk of falling from heights. Fall risks are increased due to limited walking space, which can cause installers to walk closer to the edge of rooftop hatches and skylights (U.S. Department of Labor., 2017a).

Fall occurrences can be reduced by training workers to recognize and safely respond to fall hazards. It is also crucial to provide workers with adequate fall safety devices to protect them during fall incidents. The Occupational Safety and Health Administration requires workers exposed to fall hazards at elevations of 6ft or more to be protected by either a guardrail system, safety nets, or personal fall arrest systems (U. S. Department of Labor., 2017b). Regular safety inspections and audits should be performed by management personnel to ensure that the proper fall protection systems and practices are being utilized on-site (California Fatality Assessment and Control Evaluation Program, 2011). Additionally, workers should be trained to adequately secure and use ladders and keep the work site free from obstacles that may cause trip hazards (Oregon Solar Energy Industries Association, 2006). Although construction workers receive ladder and fall safety training, 75% of fatal falls occur from roofs, ladders, and scaffolding (Dong et al., 2019). More research and investigations are required to find the root cause of this phenomenon.

4.4.2. Current and Potential Research Areas

Previous studies in the U.S. construction industry have revealed the following regarding fall accident risk factors: (1) roofers as an occupation or rooftop construction activities have the highest ratios of fall accidents (Halabi et al., 2022); (2) the majority of falls from heights tend to occur at lower elevations (less than 30 ft; Huang & Hinze, 2003; Halabi et al., 2022); (3) many these fall accidents occur either because workers "misjudge hazardous situations" or lack or wear insufficient fall protection equipment (Huang & Hinze, 2003, p. 268); and (4) there has been no clear reduction over time in the number of fall accidents that are associated with the lack or incorrect use of fall protection equipment (Kang, 2018; Halabi et al., 2022). In order to make progress in the reduction of fall accidents in the U.S. construction industry and other occupations with similar tasks (e.g., solar installations), these risk factors need to be sufficiently addressed.

Although there is a lack of formalized reporting and verification of solar worker fall accident data, it is clear that most residential and commercial solar installers are exposed to the risk factors clarified in the previous paragraph. Ho et al.'s (2020) PtD study on solar safety for residential buildings identified, through worker interviews, that solar professionals found fall protection systems to be inconvenient (i.e., heavyweight and conducive to tripping hazards). An important area for future research is understanding solar workers' perception of fall protection systems and identifying any obstacles that hinder their use. This research area may lead to task or equipment redesign to improve the usability and safety of fall protection systems. Additional research questions to explore include: Do solar workers correctly use fall protection systems? What fall hazards and fall protection training programs are available to them? Are these training programs regular? What other safety risks frequently contribute to fall accidents among solar workers (e.g., electric shock, glare)? The most common fall accident risk factors make it clear that a priority moving forward should be greater education and effective enforcement of adequate fall protection systems, especially for residential and commercial rooftop solar installations.

5. Conclusion

This study conducts a systematic literature review to understand the current state of PV installation safety. After an extensive literature search, screening, and eligibility evaluation, 31 articles were selected from a study population of 365 articles through the Scopus, Web of Science, Science Direct, and PubMed databases. Through reviewing these articles, four major safety risk categories were identified as being associated with PV installations: (1) electrical and fire risks, (2) heat stress, (3) manual handling risks, and (4) fall risks. Major findings and discussions were presented regarding these occupational risk categories, their health and safety effects, mitigation measures, and current and potential research areas.

A major finding in this review was that most of the previous and current research literature on PV installation safety focuses on the electrical and fire safety realm. Relatively fewer papers conducted risk mitigation research on fall accidents, manual handling risks, and heat stress within the solar industry in detail. Recent heat stress studies (Samaniego-Rascoń et al., 2017; Samaniego-Rascoń et al., 2019) have provided a starting point for future research by exploring work-rest schedules and skin adaptation techniques for solar workers. Moreover, much can be learned about solar worker falls and manual handling risk mitigation from research in other similar construction occupations. With respect to fall risk mitigation, there is a clear need for more effective ways to enforce and educate workers regarding the importance of utilizing fall protection systems, especially during construction projects on lower elevations (less than 30ft). Although OSHA regulations (OSHA, 2015) provide clear fall protection guidelines, research indicates that implementing these guidelines needs improvement (Halabi et al., 2022). Within the sphere of manual handling, installers are exposed to MSD risks, which is a relatively unexplored solar safety research area. Potential areas for future research to address MSD risks include utilizing ergonomic assessments (e.g., the standardized nordic assessment) to gather information about the tasks, demographics of solar workers, and parts of the body at the highest risks of musculoskeletal injuries. These studies can provide insights into the fundamental ergonomic challenges experienced by solar installers and inform policies to improve the safety and efficiency of the PV installation process.

The limitations of this systematic literature review mainly center on aspects of the literature search and content analysis. The literature search is based on four databases (Scopus, Web of Science, Science Direct, and PubMed). Although these databases have been commonly used in safety literature reviews, other databases, such as EBSCO Host and Engineering Village, can also be utilized to explore the possibility of finding key additional solar safety research literature. Therefore, the results and discussions of this study are limited by the specific databases used to conduct the literature search. The literature search in this review was also limited to articles that were available in English; therefore, articles that were unavailable in English that were published in countries with a robust solar presence (e.g., China) were excluded from the study. Also, the content analysis procedures, although rigorous, were conducted manually (no content analysis software was used) by only the present first author; therefore, there is a risk of cognitive bias in the presentation of the results and discussions. This systematic review aimed to provide a broad overview of the current state of PV installation safety and research rather than meticulous details or solutions of every major finding. The results and discussions from this review were based solely on the main and supporting articles selected through the systematic review process. More specific research is required in each of the identified risk categories to understand and improve the current state of PV installation safety, with a potential outcome being a detailed bowtie diagram of empirically studied preventions, mitigations, and consequences.

This systematic review contributes to the solar safety community by detailing the various occupational risks installers face, clarifying how one safety risk can aggravate another, and highlighting the unique hazards present in various PV installation types and settings (e.g., from residential to commercial to utility-scale solar). Practically, this research can help safety professionals, researchers, installation companies, and policymakers gain a deeper understanding of solar occupational safety risks, which can inform the ongoing development of safety protocols, policies, and guidelines for PV installation work. Additionally, this research highlights the current solar safety research areas and proposes potential areas for future research, thus providing a foundation and starting point for future work.

Acknowledgements

Thank you to the University of Rhode Island's Sustainable Innovative Solutions (SIS) Lab for their unwavering support. A special thanks to the Penn State Solar Fab Collaborative and Dr. Frey R. S. Brownson for their guidance and encouragement.

References

Acharya, P., Boggess, B., Zhang, K., 2018. Assessing Heat Stress and Health among Construction Workers in a Changing Climate: A Review. International Journal of Environmental Research and Public Health 15 (2), 247. https://doi.org/10.3390/ijerph15020247.

Ahn, E., Kang, H., 2018. Introduction to systematic review and meta-analysis. Korean Journal of Anesthesiology 71 (2), 103–112. https://doi.org/10.4097/kjae.2018.71.2.103.

Albers, J.T. & Estill, C.F. (2007). *Simple solutions: Ergonomics for construction workers* (NIOSH Publication No. 2007-122).

Albert, A., Pandit, B., Patil, Y., 2020. Focus on the fatal-four: Implications for construction hazard recognition. Safety Science 128, 104774. https://doi.org/10.1016/j.ssci.2020.104774.

Antwi-Afari, M.F., Li, H., Anwer, S., Li, D., Yu, Y., Mi, H.-Y., Wuni, I.Y., 2021. Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers. Safety Science 142, 105382. https://doi.org/10.1016/j.ssci.2021.105382.

Aram, M., Zhang, X., Qi, D., Ko, Y., 2021. A State-of-the-Art Review of Fire Safety of Photovoltaic Systems in Buildings. Journal of Cleaner Production 308, 127239. https://doi.org/10.1016/j.jclepro.2021.127239.

Ayodele, O.A., Chang-Richards, A., Gonza´lez, V., 2020. Factors Affecting Workforce Turnover in the Construction Sector: A Systematic Review. Journal of Construction Engineering and Management 146 (2), 03119010. https://doi.org/10.1061/(asce) co.1943-7862.0001725.

Bakhiyi, B., Labr`eche, F., Zayed, J., 2014. The photovoltaic industry on the path to a sustainable future — Environmental and occupational health issues. Environment International 73, 224–234. https://doi.org/10.1016/j.envint.2014.07.023.

Bonauto, D., Anderson, R., Rauser, E., Burke, B., 2007. Occupational heat illness in Washington State, 1995–2005. American Journal of Industrial Medicine 50 (12), 940–950. https://doi.org/10.1002/ajim.20517.

Bücher, K., Kleiss, G., Da ̈tzner, D., 1998. Photovoltaic modules in buildings: Performance and safety. Renewable Energy 15 (1–4), 545–551. https://doi.org/10.1016/s0960- 1481(98)00222-5.

California Department of Industrial Relations, 2015. May 14) *Heat Illness Prevention Regulation Amendments*. Accessed: 18 January 2022.

https://www.dir.ca.gov/dosh/d ocuments/Heat-Illness-Prevention-Regulation-Amendments.pdf.

California Fatality Assessment and Control Evaluation Program (2009, January 27). *Laborer dies when he falls 35 Feet from a scaffold after being electrocuted.* California Department of Public Health. https://www.cdc.gov/niosh/face/pdfs/08CA006.pdf (Accessed: 15 July 2020).

California Fatality Assessment and Control Evaluation Program (2011, April 27). *Solar panel installer dies when he falls off a roof.* California Department of Public Health. https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/OHB/FACE/Pages/10CA003.aspx (Accessed: 15 July 2020).

California Fatality Assessment and Control Evaluation Program. (2020, January 22). Preventing worker deaths in the solar industry. California Department of Public Health. https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/OHB/FACE/Pages/Solar.aspx (Accessed: 22 September 2021).

Cancelliere, P., 2016. PV electrical plants fire risk assessment and mitigation according to the Italian national fire services guidelines. Fire and Materials 40 (3), 355–367. https://doi.org/10.1002/fam.2290.

Cancelliere, P., Liciotti, C., 2016. Fire Behaviour and Performance of Photovoltaic Module Backsheets. Fire Technology 52 (2), 333–348. https://doi.org/10.1007/s10694-014-0449-7.

Centers for Disease Control and Prevention (2018, June 6). *Heat Stress- Heat Related Illness*. https://www.cdc.gov/niosh/topics/heatstress/heatrelillness.html (Accessed: 18 January 2022).

Centers for Disease Control and Prevention (2019, July 8). *Extreme Heat*. https://www.cdc.gov/disasters/extremeheat/index.html (Accessed: 15 July 2020).

Chiabrando, R., Fabrizio, E., Garnero, G., 2009. The territorial and landscape impacts of photovoltaic systems: Definition of impacts and assessment of the glare risk. Renewable and Sustainable Energy Reviews 13 (9), 2441–2451. https://doi.org/10.1016/j.rser.2009.06.008.

Choi, S.D., Yuan, L., Borchardt, J.G., 2016. Musculoskeletal Disorders in Construction: Practical Solutions from the Literature. Professional safety. 61, 26–32.

Chow, C.L., Han, S.S., Ni, X.M., 2017. A study on fire behaviour of combustible components of two commonly used photovoltaic panels. Fire and Materials 41 (1), 65–83. https://doi.org/10.1002/fam.2366.

National Resource Defense Council. (2020, September 15). *Race to 100% Clean: State Renewable Portfolio Standards.* https://www.nrdc.org/resources/race-100-clean (Accessed: 22 September 2021).

Dewlaney, K.S., Hallowell, M.R., Fortunato, B.R., 2012. Safety Risk Quantification for High Performance Sustainable Building Construction. Journal of Construction Engineering and Management 138 (8), 964–971. https://doi.org/10.1061/(asce) co.1943-7862.0000504.

Dong, X.S., Largay, J.A., Choi, S.D., Wang, X., Cain, C.T., Romano, N., 2017. Fatal falls and PFAS use in the construction industry: Findings from the NIOSH FACE reports. Accident Analysis & Prevention 102, 136–143. https://doi.org/10.1016/j. aap.2017.02.028.

Dong, X.S., Jackson, R., Varda, D., Betit, E., Bunting, J., 2019. Trends of Fall Injuries and Prevention in the Construction Industry. CPWR.

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing*, *62*(1), 107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x

Erten, B., & Utlu, Z. (2020). Photovoltaic system configurations: an occupational health and safety assessment. *Greenhouse Gases: Science and Technology*, *10*(4), 809–828.

Flicker, J., & Johnson, J. (2016). Photovoltaic ground fault detection recommendations for array safety and operation. *Solar Energy*, *140*, 34–50. https://doi.org/10.1016/j.solener.2016.10.017

Fortunato, B.R., Hallowell, M.R., Behm, M., Dewlaney, K., 2012. Identification of Safety Risks for High-Performance Sustainable Construction Projects. Journal of Construction Engineering and Management 138 (4), 499–508. https://doi.org/ 10.1061/(asce)co.1943-7862.0000446.

Garrisson, H., Scholey, A., Ogden, E., Benson, S., 2021. The effects of alcohol intoxication on cognitive functions critical for driving: A systematic review. Accident Analysis & Prevention 154, 106052. https://doi.org/10.1016/j.aap.2021.106052.

Gubernot, D.M., Anderson, G.B., Hunting, K.L., 2015. Characterizing occupational heat-related mortality in the United States, 2000–2010: Analysis using the census of fatal occupational injuries database. American Journal of Industrial Medicine 58 (2), 203–211. https://doi.org/10.1002/ajim.22381.

Guerin, T., 2017a. A case study identifying and mitigating the environmental and community impacts from construction of a utility-scale solar photovoltaic power plant in eastern Australia. Solar Energy 146, 94–104. https://doi.org/10.1016/j.solener.2017.02.020.

Guerin, T.F., 2017b. Evaluating expected and comparing with observed risks on a large-scale solar photovoltaic construction project: A case for reducing the regulatory burden. Renewable and Sustainable Energy Reviews 74, 333–348. https://doi.org/10.1016/j.rser.2017.02.040.

Haidich, A.B., 2010. Meta-analysis in medical research. Hippokratia 14 (Suppl 1), 29–37. Halabi, Y., Xu, H., Long, D., Chen, Y., Yu, Z., Alhaek, F., Alhaddad, W., 2022. Causal factors and risk assessment of fall accidents in the U.S. construction industry: A comprehensive data analysis (2000–2020). Safety Science 146, 105537. https://doi. org/10.1016/j.ssci.2021.105537.

Hanson, M., Thatcher, A., 2020. Identifying Human Factors and Ergonomic Issues in Green Jobs: Facilitating Sustainable Green Jobs. In: Thatcher, A., Zink, K.J., Fischer, K. (Eds.), Human Factors for Sustainability: Theoretical Perspectives and Global Applications. CRC Press Taylor and Francis Group, pp. 171–192.

Haynes, E., Kramer, D.M., Strahlendorf, P., Holness, D.L., Kushner, R., Tenkate, T., 2018. A cross-Canada knowledge transfer and exchange workplace intervention targeting the adoption of sun safety programs and practices: Sun Safety at Work Canada. Safety Science 102, 238–250. https://doi.org/10.1016/j.ssci.2017.10.013.

Health and Safety Executive (2016). Musculoskeletal disorders: Manual handling. htt ps://www.hse.gov.uk/pubns/books/l23.htm.

Ho, C., Lee, H.W., Gambatese, J.A., 2020. Application of Prevention through Design (PtD) to improve the safety of solar installations on small buildings. Safety Science 125, 104633.

Huang, X., Hinze, J., 2003. Analysis of Construction Worker Fall Accidents. Journal of Construction Engineering and Management 129 (3), 262–271. https://doi.org/10.1061/(asce)0733-9364(2003)129:3(262).

Huang, Y.-C., Lee, S.-K., Chan, C.-C., Wang, S.-J., 2017. Full-scale evaluation of fire-resistant building integrated photovoltaic systems with different installation positions of junction boxes. Indoor and Built Environment 27 (9), 1259–1271. https://doi.org/10.1177/1420326x17713256.

Interstate Renewable Energy Council, 2021a. Net Solar Jobs Growth since 2010. Accessed: 22 September 2021. https://irecusa.org/programs/solar-jobs-census/.

Interstate Renewable Energy Council, 2021b. National Solar Jobs Census 2020. Accessed: 22 September 2021. https://irecusa.org/wp-content/uploads/2021/07/National- Solar-Jobs-Census-2020-FINAL.pdf.

Ju, X., Zhou, X., Gong, J., Zhao, K., Peng, Y., Zhang, C., Ren, X., Yang, L., 2019. Impact of flat roof–integrated solar photovoltaic installation mode on building fire safety. Fire and Materials 43 (8), 936–948. https://doi.org/10.1002/fam.2755.

Kang, Y., 2018. Use of Fall Protection in the US Construction Industry. Journal of Management in Engineering 34 (6), 04018045. https://doi.org/10.1061/(asce) me.1943-5479.0000655.

Kosciuch, K., Riser-Espinoza, D., Gerringer, M., Erickson, W., 2020. A summary of bird mortality at photovoltaic utility scale solar facilities in the Southwestern U.S. PLoS ONE 15 (4), e0232034. https://doi.org/10.1371/journal.pone.0232034.

Kristensen, J.S., Faudzi, F.B.M., Jomaas, G., 2021. Experimental study of flame spread underneath photovoltaic (PV) modules. Fire Safety Journal 120, 103027. https://doi.org/10.1016/j.firesaf.2020.103027.

Kristensen, J.S., Jomaas, G., 2018. Experimental Study of the Fire Behaviour on Flat Roof Constructions with Multiple Photovoltaic (PV) Panels. Fire Technology 54 (6), 1807–1828. https://doi.org/10.1007/s10694-018-0772-5.

Kuorinka, I., Jonsson, B., Kilbom, A., Vinterberg, H., Biering-Sørensen, F., Andersson, G., Jørgensen, K., 1987. Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. Applied Ergonomics 18 (3), 233–237. https://doi.org/10.1016/0003-6870(87)90010-x.

Levins, A., 1987. Photovoltaic energy systems and consumer product safety. Solar Cells 19 (3–4), 325–332. https://doi.org/10.1016/0379-6787(87)90087-1.

López-Aragón, L., López-Liria, R., Callejón-Ferre, Á.-J., & Pérez-Alonso, J. (2018). Musculoskeletal disorders of agricultural workers in the greenhouses of Almería (Southeast Spain). Safety Science, *109*, 219–235. https://doi.org/10.1016/j.ssci.2018.05.023

Lorenc, T., Felix, L., Petticrew, M., Melendez-Torres, G.J., Thomas, J., Thomas, S., O'Mara-Eves, A., Richardson, M., 2016. Meta-analysis, complexity, and heterogeneity: a qualitative interview study of researchers' methodological values and practices. Systematic Reviews 5 (1), 192. https://doi.org/10.1186/s13643-016-0366-6.

Lu, S., Phung, B.T., Zhang, D., 2018b. A comprehensive review on DC arc faults and their diagnosis methods in photovoltaic systems. Renewable and Sustainable Energy Reviews 89, 88–98. https://doi.org/10.1016/j.rser.2018.03.010.

Lu, J., Zan, W., Bao, W., 2018a. A Novel Fire Control System for Distributed Photovoltaic Station. Energy Procedia 150, 94–98. https://doi.org/10.1016/j.egypro.2018.09.002.

Ludewig, P.M., Borstad, J.D., 2003. Effects of a home exercise program on shoulder pain and functional status in construction workers. Occupational and Environmental Medicine 60 (11), 841–849.

McAtamney, L., Corlett, E.N., 1993. RULA: a survey method for the investigation of work-related upper limb disorders. Applied Ergonomics 24 (2), 91–99. https://doi.org/10.1016/0003-6870(93)90080-s.

Microgeneration Certification Scheme (MCS), 2012. Guide to the Installation of Photovoltaic Systems. Accessed: 12 January 2022. https://mcscertified.com/wp-content/uploads/2019/08/PV-Book-ELECTRONIC.pdf.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Group, T.P., 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Medicine 6 (7), e1000097. https://doi.org/10.1371/journal.pmed.1000097.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Group, T.P, 2010. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. International Journal of Surgery 8 (5), 336–341. https://doi.org/10.1016/j.ijsu.2010.02.007.

Moskowitz, P.D., Coveney, E.A., Rabinowitz, S., Barancik, J.I., 1983. Rooftop photovoltaic arrays: Electric shock and fire health hazards. Solar Cells 9 (4), 327–336. https://doi.org/10.1016/0379-6787(83)90026-1.

National Institute for Occupational Safety and Health. (2013). Simple solutions for home building workers. https://www.cdc.gov/niosh/docs/2013-111/default.html.

NIOSH (2021). Applications Manual for the Revised NIOSH Lifting Equation. (NIOSH Publication No. 94-110). 10.26616/NIOSHPUB94110revised092021.

Occupational Safety and Health Administration. (2011). *Construction Focus Four: Outreach Training Packet.* https://www.osha.gov/sites/default/files/constrfocusfour_ introduction.pdf (Accessed: 22 September 2021).

Occupational Safety and Health Administration. (2015). *Fall Protection in Construction.* https://www.osha.gov/sites/default/files/publications/OSHA3146.pdf (Accessed: 5 November 2022).

Occupational Safety and Health Administration. (2018). *Employee Falls From Roof and Fractures Foot.* https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=109537.015 (Accessed: 22 September 2021).

Occupational Safety and Health Administration. (n.d.) Heat Hazard Recognition. https://www.osha.gov/SLTC/heatillness/heat_index/pdfs/all_in_one.pdf (Accessed: 15 July 2020).

Occupational Safety and Health Administration. (2020). *Employee Contacts Overhead Power Line, Falls, Dies.* https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=124922.015 (Accessed: 22 September 2021).

Ong, N. A. F. M. N., Tohir, M. Z. M., Mutlak, M. M., Sadiq, M. A., Omar, R., & Said, M. S. M. (2022). BowTie analysis of rooftop grid-connected photovoltaic systems. Process Safety Progress, 41(S1), S106–S117. 10.1002/prs.12338.

Oregon Solar Energy Industries Association. (2006). *Solar Construction Safety*. https://www.coshnetwork.org/sites/default/files/OSEIA_Solar_Safety_12-06.pdf (Accessed: 22 September 2021).

Rabbani, E.R.K., de Lima, A.N.F., Santos, F.J.B., Costa, V.A. de S., Malafaya-Baptista, F., 2014. Sustainability Measures and Potential Impacts on Occupational Safety and Health: Brazilian Constructions. EJGE 19, 17675–17691.

Ramali, M.R., Ong, N.A.F.M.N., Said, M.S.M., Yusoff, H.M., Baharudin, M.R., Tharima, A. F., Akashah, F.W., Tohir, M.Z.M., 2022. A Review on Safety Practices for Firefighters During Photovoltaic (PV) Fire. Fire Technology 1–24. https://doi.org/10.1007/ s10694-022-01269-4.

Romich, E., & McGuire, K. (2015). On-Farm Solar Electric System Safety. https://ohioline.osu.edu/factsheet/CDFS-4105 (Accessed: 15 July 2020).

Rowlinson, S., Jia, Y.A., 2014. Application of the Predicted Heat Strain Model in Development of Localized, Threshold-based Heat Stress Management Guidelines for the Construction Industry. The Annals of Occupational Hygiene 58 (3), 326–339. https://doi.org/10.1093/annhyg/met070.

Rowlinson, S., YunyanJia, A., Li, B., ChuanjingJu, C., 2014. Management of climatic heat stress risk in construction: A review of practices, methodologies, and future research. Accident Analysis & Prevention 66, 187–198. https://doi.org/10.1016/j.aap.2013.08.011.

Samaniego-Rasco´n, D., da Silva, M.C.G., Ferreira, A.D., Cabanillas-Lopez, R.E., 2019. Solar energy industry workers under climate change: A risk assessment of the level of heat stress experienced by a worker based on measured data. Safety Science 118, 33–47. https://doi.org/10.1016/j.ssci.2019.04.042.

Samaniego-Rascó n, D., Ferreira, A. D., & Silva, M. G. da. (2017). Cumulative and momentary skin exposures to solar radiation in central receiver solar systems. Energy, 137, 336–349. 10.1016/j.energy.2017.02.170.

Sen, A., Mohankar, A.S., Khamaj, A., Karmakar, S., 2021. Emerging OSH Issues in Installation and Maintenance of Floating Solar Photovoltaic Projects and Their Link with Sustainable Development Goals. Risk Management and Healthcare Policy 14, 1939–1957. https://doi.org/10.2147/rmhp.s304732.

Shakerian, S., Habibnezhad, M., Ojha, A., Lee, G., Liu, Y., Jebelli, H., Lee, S., 2021. Assessing occupational risk of heat stress at construction: A worker-centric wearable sensor-based approach. Safety Science 142, 105395. https://doi.org/10.1016/j. ssci.2021.105395.

Solar Energy Industries Association. (2020). *Solar Industry Research Data*. https://www. seia.org/solar-industry-research-data (Accessed: 1 October 2021).

Solar Energy Solutions Group. (2008). Solar Power System Installation Manual. https:// www.solarelectricsupply.com/media/custom/upload/sharp-all-installation.pdf (Accessed: 15 July 2020).

Solar Power Europe. (2019). *Global Market Outlook For Solar Power 2019-2023*. SolarPower Europe. https://www.solarpowereurope.org/wp-content/uploads/ 2019/09/20190510_SolarPower-Europe_Global-Market-Outlook-for-Solar-Power- 2019-2023.pdf?cf_id=40062 (Accessed: 22 September 2021).

Solar Power Europe. (2021). *Global Market Outlook For Solar Power 2021-2025*. SolarPower Europe. https://www.solarpowereurope.org/wp-content/uploads/ 2021/07/SolarPower-Europe_Global-Market-Outlook-for-Solar-2021-2025_V3.pdf? cf_id=40063 (Accessed: 22 September 2021).

Sovacool, B.K., Kryman, M., Laine, E., 2015. Profiling technological failure and disaster in the energy sector: A comparative analysis of historical energy accidents. Energy 90, 2016–2027. https://doi.org/10.1016/j.energy.2015.07.043.

Sreenath, S., Sudhakar, K., Yusop, A.F., 2020a. Solar photovoltaics in airport: Risk assessment and mitigation strategies. Environmental Impact Assessment Review 84, 106418. https://doi.org/10.1016/j.eiar.2020.106418.

Sreenath, S., Sudhakar, K., Yusop, A.F., Solomin, E., Kirpichnikova, I.M., 2020b. Solar PV energy system in Malaysian airport: Glare analysis, general design and performance assessment. Energy Reports 6, 698–712. https://doi.org/10.1016/j. egyr.2020.03.015.

Sreenath, S., Sudhakar, K., Yusop, A.F., Cuce, E., Solomin, E., 2020c. Analysis of solar PV glare in airport environment: Potential solutions. Results in Engineering 5, 100079. https://doi.org/10.1016/j.rineng.2019.100079.

Sreenath, S., Sudhakar, K., Yusop, A.F., 2021. Effect of PV material, texturing, orientation and tracking on glare impact: A simulation study from an Indian airport. Cleaner Engineering and Technology 4, 100236. https://doi.org/10.1016/j.clet.2021.100236.

Tsoutsos, T., Frantzeskaki, N., Gekas, V., 2005. Environmental impacts from the solar energy technologies. Energy Policy 33 (3), 289–296. https://doi.org/10.1016/s0301-4215(03)00241-6.

Turney, D., Fthenakis, V., 2011. Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews 15 (6), 3261–3270. https://doi.org/10.1016/j.rser.2011.04.023.

U.S. Bureau of Labor Statistics (2019, November 7). 2018 Survey of Occupational Injuries and Illnesses. https://www.bls.gov/iif/soii-charts-2018.pdf (Accessed: 22 September 2021).

U.S. Bureau of Labor Statistics. (2016, November 10). Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2015. https://www.bls.gov/news.release/pdf/osh2.pdf (Accessed: 22 September 2021).

U.S. Bureau of Labor Statistics. (2018, August 28). Back Injuries Prominent in Work-related Musculoskeletal Disorder Cases in 2016. https://www.bls.gov/opub/ted/2018/back-injuries-prominent-in-work-related-musculoskeletal-disorder-cases-in-2016.htm?view_full (Accessed: 22 September 2021).

U.S. Bureau of Labor Statistics. (2020, April 10). *Solar Photovoltaic Installers - What Solar Photovoltaic Installers Do*. https://www.bls.gov/ooh/construction-and-extraction/ solar-photovoltaic-installers.htm#tab-2 (Accessed: 15 July 2020).

U.S. Bureau of Labor Statistics. (2021, September 8). Solar Photovoltaic Installers. https://www.bls.gov/ooh/construction-and-extraction/solar-photovoltaic-installers.htm (Accessed: 22 September 2021).

U.S. Department of Labor (1990, November) *Analysis of Construction Fatalities-The OSHA Database 1985-1989*. https://apps.dtic.mil/dtic/tr/fulltext/u2/a400187.pdf (Accessed: 15 July 2020).

U.S. Department of Labor. (2017a). *Green Job Hazards: Solar Energy*. Occupational Safety and Health Administration. https://www.osha.gov/green-jobs/solar (Accessed: 22 September 2021).

U.S. Department of Labor. (2017b). *Solar Energy: Falls*. Occupational Safety and Health Administration. https://www.osha.gov/green-jobs/solar/falls (Accessed: 27 January 2021).

U.S. Department of Labor. (2017c). *Solar Energy: Lockout/Tagout*. Occupational Safety and Health Administration. https://www.osha.gov/green-jobs/solar/falls (Accessed: 15 July 2020).

Varghese, B.M., Hansen, A., Bi, P., Pisaniello, D., 2018. Are workers at risk of occupational injuries due to heat exposure? A comprehensive literature review. Safety Science 110, 380–392. https://doi.org/10.1016/j.ssci.2018.04.027.

Varghese, B.M., Hansen, A.L., Williams, S., Bi, P., Hanson-Easey, S., Barnett, A.G., Heyworth, J.S., Sim, M.R., Rowett, S., Nitschke, M., Corleto, R.D., Pisaniello, D.L., 2020. Heat-related injuries in Australian workplaces: Perspectives from health and safety representatives. Safety Science 126, 104651. https://doi.org/10.1016/j. ssci.2020.104651.

Vergara, M., Sancho, J.-L., Rodríguez, P., & P´erez-Gonz´alez, A. (2008). Hand-transmitted vibration in power tools: Accomplishment of standards and users' perception. *International Journal of Industrial Ergonomics, 38*(9–10), 652–660. doi: 10.1016/j. ergon.2007.10.014.

Wang, D., Xie, X., Na, Z., Shen, W., Fan, X., 2021. Photovoltaic Power System Fault Warning based on State Assessment. IOP Conference Series: Earth and Environmental Science 632 (3), 032063. https://doi.org/10.1088/1755-1315/632/3/032063.

Weir, E., Lander, L., 2005. Hand-arm vibration syndrome. CMAJ. 172 (8), 1001–1002. https://doi.org/10.1503/cmaj.045314.

White, J.R., Doherty, M., 2017. Hazards in the Installation and Maintenance of Solar Panels. IEEE. https://doi.org/10.1109/ESW.2017.7914834.

Wu, Z., Hu, Y., Wen, J.X., Zhou, F., Ye, X., 2020. A Review for Solar Panel Fire Accident Prevention in Large-Scale PV Applications. IEEE Access 8, 132466–132480. https:// doi.org/10.1109/access.2020.3010212.

Wybo, J.-L., 2013. Large-scale photovoltaic systems in airports areas: safety concerns. Renewable and Sustainable Energy Reviews 21, 402–410. https://doi.org/10.1016/ j.rser.2013.01.009.

Xia, N., Zou, P.X.W., Griffin, M.A., Wang, X., Zhong, R., 2018. Towards integrating construction risk management and stakeholder management: A systematic literature review and future research agendas. International Journal of Project Management 36 (5), 701–715. https://doi.org/10.1016/j.ijproman.2018.03.006.

Xia, N., Xie, Q., Griffin, M.A., Ye, G., Yuan, J., 2020. Antecedents of safety behavior in construction: A literature review and an integrated conceptual framework.

Accident Analysis & Prevention 148, 105834. https://doi.org/10.1016/j.aap.2020.105834.

Yi, W., Chan, A.P.C., 2013. Optimizing work–rest schedule for construction rebar workers in hot and humid environment. Building and Environment 61, 104–113. https://doi.org/10.1016/j.buildenv.2012.12.012.

Zhou, Z., Goh, Y.M., Li, Q., 2015. Overview and analysis of safety management studies in the construction industry. Safety Science 72, 337–350. https://doi.org/10.1016/j. ssci.2014.10.006.

CHAPTER 3

MANUSCRIPT 3: Solar Installation Safety Risk Perceptions: A Survey Study

Prepared for submission to Applied Ergonomics

Jesse C. Duroha[1], Simona Trandafir, Ph. D.[2] , Corey Lang, Ph. D.[2] and Gretchen A. Macht, Ph. D.[1]

[1]*Department of Mechanical, Industrial & Systems Engineering, University of Rhode Island, Kingston, RI, USA*

[2]*Department of Environmental & Natural Resource Economics, University of Rhode Island, Kingston, RI, USA*

ABSTRACT

Photovoltaic (PV) installers experience significant safety risks, however, reporting and research on PV installation risks and injuries is limited. Understanding the risk perception of solar workers can supplement, support, and inform safety risk mitigation. This research involved a survey study on PV installers in the United States to understand their perception of the likelihood and severity of installation risks. A Latent Class Analysis (LCA) was utilized to determine whether the perception categories were associated with the respondents. Installation size, company longevity, and work experience were explored as grouping variables. An LCA revealed three types of installers based on risk perception (High, Moderate, and Low), with most installers having a Moderate perception of the Likelihood ($\gamma = 77.38\%$) and Severity ($\gamma = 76.22\%$) of safety risks. This study clarifies the installers' risk perceptions and informs solar companies, safety professionals, policy makers, and researchers as they develop and implement safety measures.

1. Introduction

Solar energy generation has continued to rise globally in response to the increasing demand and interest in clean energy resources (United Nations, 2021; Solar Power Europe, 2019, 2021, 2022). In recent years, multiple countries in various geographic regions (e.g., Germany, Japan, Spain, Brazil, Chile, and Poland) have maintained a strong and promising solar presence (Solar Power Europe, 2022). Meanwhile, in 2021, China and the United States (U.S.) led the way with a 14% and 42% increase in installations, respectively (Solar Power Europe, 2022). Specifically, the U.S. solar workforce has experienced significant growth in the past decade to support this increasing need and is on the trajectory to continue expanding (Interstate Renewable Energy Council, 2021). Various states (e.g., Rhode Island, Hawaii, Virginia, California, and New Mexico) across the U.S. are dedicating themselves to renewable energy electricity generation goals (National Resources Defense Council, 2020). Consequently, the National Solar Job Census projected that solar employment in the U.S. will reach 400,000 workers by 2030 and will need to reach 900,000 workers by 2035 to achieve the 100% carbon pollution-free power sector goal (Interstate Renewable Energy Council, 2021; White House, 2021). A crucial component in supporting national and statewide clean electricity goals is ensuring the safety and well-being of installation workers in this rapidly expanding solar energy industry.

Solar installation workers are exposed to severe occupational safety risks, including but not limited to falling from heights, musculoskeletal disorder (MSD) risks, electrical risks and hazards, and heat stress (Duroha & Macht, 2023; Hanson & Thatcher, 2020; U.S. Department of Labor, 2017). Even though these risks are known to have significant injury impacts in other traditional construction occupations (Albert et al., 2020; Centers for

Disease Control and Prevention, 2019; Gubernot et al., 2015; Occupational Safety and Health Administration [OSHA], 2011; U.S. Bureau of Labor Statistics, 2019), there is a lack of formalized reporting, verification, and research on how they specifically affect solar installation workers in terms of injuries, fatalities, and aggravating factors (Duroha & Macht, 2021; Sovacool et al., 2015). The few publicly available solar worker accident reports indicate insufficient use of administrative and engineering controls and personal protective equipment as significant contributors to installer injuries and fatalities (California Fatality Assessment and Control Evaluation Program, 2020; OSHA 2018, 2020). Consequently, there is a disconnect between injuries and their reporting, as well as a research gap that requires a deeper understanding and awareness of the safety risks, aggravating factors, and mitigation measures associated with solar installation work.

Historically, the solar safety research literature has focused almost exclusively on risk mitigation for electrical and fire safety (Cancelliere & Liciotti, 2016; Levins, 1986; Wu et al., 2020). Research studies focusing on other solar installation safety risks (e.g., falling from heights, MSD risks, heat stress) are relatively new and still emerging (Duroha & Macht, 2021). These studies primarily include literature reviews identifying safety risks (Bakhiyi et al., 2014; Duroha et al., 2020; Duroha & Macht, 2021; Erten & Utlu, 2020; Hanson & Thatcher, 2020; Sen et al., 2021), heat stress studies to explore work-rest schedule recommendations (Samaniego-Rascón et al., 2017; Samaniego-Rascón et al., 2019), and improvement to residential solar safety (Ho et al., 2020). These recent studies imply a movement in the literature to comprehensively understand and mitigate solar occupational safety risks.

Safety risk perception (SRP) represents a research area that is currently underrepresented in the existing literature on solar safety. Exploring this aspect can enhance the knowledge established by recent work on solar safety. Risk perception research deals with understanding an individual's subjective judgment of the value or impact of risk (Aven & Ren, 2009, p.1) and typically involves data collected directly from a study population in the form of questionnaires or interviews. Analysis of the study population's risk perceptions can aid companies, stakeholders, and researchers in understanding how to meet the needs of the study population. Within the solar safety realm, measuring the SRP of installation workers can be a valuable tool for identifying and understanding areas of high perceived risk. SRP studies have been conducted worldwide in the construction industry on various populations and occupations (e.g., laborer, masonry, excavator) (Lette et al., 2018; Rodríguez-Garzon et al., 2016; Xia et al., 2017; Zou & Zhang, 2009). These studies have focused on various topics, such as safety compliance and participation (Xia et al., 2017), the prevalence of safety injuries and their associated factors (Lette et al., 2018; Zou & Zhang, 2009), and the influence of socio-demographic variables (e.g., age, safety training, occupation, company size) on SRP (Rodríguez-Garzon et al., 2016). These studies' findings have served as risk management guidelines (Rodríguez-Garzon et al., 2016) and identify prevalent injuries and common risk factors (Lette et al., 2018). These limited but significant risk perception studies have provided a foundation, but it is critical to build on this foundation with further studies focused on the solar industry.

Some previous solar safety research studies have involved identifying, reviewing, and performing experiments to mitigate the occupational risks PV installers experience (Bakhiyi et al., 2014; Guerin, 2017; Ho et al., 2020; Samaniego-Rascón et al., 2019;

Sreenath et al., 2020; Wu et al., 2020). However, these studies rarely account for the installer's perception of safety risks. Ho et al. (2020) is the only solar safety study, that the authors are aware of to date, that incorporates the SRP of solar workers. Ho et al. (2020) prevention-through-design study involved interviews of solar professionals (n = 16) to understand their residential installation risk factors and proposed design recommendations to minimize these hazards. Their findings provided a valuable starting point regarding insights into tasks and safety systems installers find inconvenient. Furthermore, these results underscore the value of accounting for workers' perspectives when proposing safety measures. Objective experiments or quantitative case studies are crucial; however, the installers' perspective regarding their safety challenges can provide additional insights regarding the mitigation measures they need to effectively uphold safety standards. Hence, understanding the perception of solar workers regarding safety risks and obstacles can supplement, support, and inform objective studies and safety measures to provide a more comprehensive approach to solar risk mitigation.

Although solar safety literature has made recent progress in identifying and exploring common solar safety risk factors and mitigation measures (Bakhiyi et al., 2014; Duroha et al., 2020; Duroha & Macht, 2021; Erten & Utlu, 2020; Hanson & Thatcher, 2020; Sen et al., 2021), it is still unclear how these risks affect installers in various working circumstances and conditions. Accordingly, this research aims to: (i) understand the perceptions of solar workers regarding various installation safety risks and (ii) explore how these perceptions vary with different factors (installation size, company longevity, and work experience). A solar SRP questionnaire was developed through an extensive literature review and solar worker interviews. The questionnaire was then administered with U.S. solar workers as the target population. Since the risk associated with an event is known to be a function of its likelihood and severity (Aven & Renn, 2009; Xia et al., 2017), the questionnaire included questions regarding both on various occupational risks. A Latent Class Analysis (LCA) was then performed to analyze the survey data and answer the research objectives. This study directly contributes to the solar safety community by providing insights into the workers' perception of the safety risks they experience. These insights can inform solar installation companies, safety professionals, and researchers as they seek to implement site and situation-specific measures that promote installation safety.

2. Methods

This research aimed to measure the perception of solar workers regarding various installation safety risks and explore how these perceptions vary with installation size, company longevity, and work experience. To do so, an SRP questionnaire was developed based on literature review and industry expert interviews, and administered to U.S. solar workers. The survey data was analyzed using an LCA to group solar workers based on their perception of the likelihood and severity of safety risks. This LCA analysis resulted in a *Likelihood* LCA model and *Severity* LCA model that depict the installers' perceptions. Then, installation size, company longevity, and work experience were applied to the LCA models as grouping variables to assess how the installer's perception varies with these factors. The survey process, such as the questionnaire development and interviews, complied with the University of Rhode Island's Institutional Review Board (HU2122-203).

2.1. Data Collection

A 66-item questionnaire was developed based on an extensive literature review (Duroha & Macht, 2023) and assessed for suitability and clarity through solar industry expert interviews. The questionnaire consisted of the following sections: 1: Introduction; 2: Type of Work; 3: SRP; 4: Training and Certifications; 5: Risk Tolerance and New Environmental Paradigm; 6: Demographics; and 7: Optional Online Raffle (opt-in). This study focused on two sections: 2: Type of Work (3 items) and 3: SRP (15 items).

The survey's design and questions underwent multiple iterations based on feedback from two solar industry experts' interview sessions in August and October of 2021. The questionnaire was then advertised at the American Solar Energy Society (ASES) Conference in 2022, and on their members' only ASES Everything Solar Forum. In order to collect data from a broad and relevant population, the researchers joined a private solar installers' Facebook group, named "Solar Installers" with over 15,000 members. The group's goal was to create a community on social media where solar installers could showcase and share knowledge regarding every aspect of the PV installation process. Posts from members on the group page include solar product pictures and information, installer job opportunities, and recommendations regarding installation practices. The survey link and advertisement flier were reviewed by the administrators of this group, and permitted to be posted. Participation was voluntary, and participants could opt into an online raffle to win gift cards.

2.2. Sample

The data collection for this study was conducted using QUALTRICS® and received 589 participants between June and July 2022. The inclusion and exclusion criteria for survey participants were solar workers in the U.S. who had professional experience installing, modifying, maintaining, or repairing solar photovoltaic systems. Consequently, when this research uses the terms 'solar installation worker' or 'solar installer,' it refers to solar workers who meet these criteria.

During the data cleaning process, we excluded participants who did not work in the U.S. (n = 32), or who indicated they did not have professional experience installing solar systems (n = 2). Participants without demographics were also excluded (n = 206). Duplicate participants (n = 28) and participants with unrealistically low (less than 7 minutes) and high (greater than 50 minutes) questionnaire completion duration (n = 31) were excluded.

Table 8 details the demographic characteristics of the sample, including race, education, and employment status. The sample in this study had a good representation of installers from various racial backgrounds and education levels in line with the national solar worker census proportions (Interstate Renewable Energy Council, 2022). Installers in this study identified as White (61%), African American (15.2%), and Hispanic or Latino (11.0%). Most participants considered themselves full-time employees (64.1%), and a majority declared an associate degree (71.1%) or some college background.

Additionally, QUALTRICS® records the latitude and longitude location where participants took the survey. The distribution of the respondents' geographic locations is provided in Appendix B (Table B.1). Although conclusions are limited due to VPN issues, Table B.1 indicates that participants took the survey from a wide variety of locations (40 states), with the top three states: California (*n* = 57), New York (*n* = 21), and Washington (*n* = 20). This resulted in an analytic dataset of 290 survey respondents.

Table 8 Demographic profile of survey participants

		Sample size (n)	Percentage (%)
Race	White	177	61.0
	Hispanic, Latino, or Spanish origin	32	11.0
	Black or African American	44	15.2
	American Indian or Alaska Native	12	4.1
	Asian	21	7.2
	Native Hawaiian or Pacific Islander	2	0.7
	Other (please specify)	2	0.7
Education	High school degree	84	29.0
	Associates degree or some college but no college degree	149	51.4
	Bachelor's degree or more	57	19.7
Employment status	Full-time (30 hours or more)	186	64.1
	Part-time, self-employed, unemployed, other	104	35.9
Individual income (before taxes for 2021)	Less than $69,999	197	67.9
	$70,000 or greater	93	32.1
Political views	Independent	32	11.0
	Democrat	136	46.9
	Republican	108	37.2
	Prefer not to say	14	4.8

Note: Analytic dataset (*n* = 290).

2.3. Variables

The SRP section (15-items) was a crucial part of this study and detailed various occupational risk situations (e.g., falling from heights, electrocution, heat stroke, struck-by falling objects) that were adapted from previous safety studies within the construction industry (Bakhiyi et al., 2014; Elmoujaddidi & Bachir, 2020; Hanson & Thatcher, 2020; Samaniego-Rascón et al., 2019; Xia et al., 2017). The risk perception construct was found to have good reliability with the Cronbach's alpha on the overall construct (α = 0.88) exceeding 0.7, and with acceptable construct validity on the likelihood responses (α = 0.79), and the severity responses (α = 0.81) (Tavakol & Dennick, 2011). The list of items included in this study's analysis is provided in Appendix A.

We examined the 15-items assessing SRP, where respondents were asked about their perception of the likelihood and severity of various occupational risk situations. Respondents were asked to rate the likelihood and severity of each SRP item on a frequentist Likert scale: "Extremely Low," "Low," "Neutral," "High," and "Extremely High," with a "Not Applicable" option provided. The frequentist Likert scale was dichotomized into two levels (1 = Extremely Low, Low, Neutral; 2 = High, Extremely High) and utilized to generate latent class models for risk *Likelihood* and *Severity*.

Three factors, installation size, company longevity, and work experience, were utilized as grouping variables within the latent class models. The installation size was grouped into *residential* (regularly installed less than 10 kW PV systems) and *meso or commercial* (regularly installed 10 kW - 5 MW PV systems; Ramasay et al., 2021). The bigger installation size was coded with a higher score (e.g., 0 = *residential*, 1 = *meso or commercial*). Company longevity was bifurcated at the median years of operation or establishment. The *new company* group included participants who worked for a company that had been installing PV systems for 5-years or less. The *established company* group included participants who worked for a company that had been installing PV systems for 6-years or more. The more established company group was coded with a higher score (e.g., 0 = *new company,* 1 = *established company*). Work experience was also bifurcated at the median (*entry-level* ≤ 4 years; *experienced* > 4 years). The more experienced group was coded with a higher score (e.g., 0 = *entry-level*, 1 = *experienced*).

2.4. Statistical Analysis

In this study, an LCA was utilized as the statistical analysis method. An LCA is a statistical procedure utilized to identify mutually exclusive groups of individuals based on their responses to observed categorical variables (Lanza et al., 2007; Weller et al., 2020). An LCA outputs models with varying numbers of classes. Classes within each model have an associated membership parameter (ɣ-estimates) and item-response probability values (ρ-estimates). The best-fitting and most appropriate latent class model was selected through consideration of various model selection tools: likelihood-ratio G2 statistic (which compares expected to observed response proportions), Akaike’s Information Criteria (AIC), Bayesian Information Criteria (BIC) (Akaike, 1974; Lanza et al., 2007), Entropy (Weller et al., 2020), Bootstrap Likelihood Ratio Test (BLRT) (Collins et al., 1993), and model interpretability (Lanza et al., 2007). Model fit was determined as a balance of these metrics, with weight given to the BLRT’s ability to estimate a significant difference between model sizes (i.e., one through five). Once the best model was identified, grouping variables (installation size, company longevity, and work experience) were explored to understand how various groups influence latent class membership. The analysis was conducted using the *PROC LCA* command in *SAS 9.4* (Lanza et al., 2007).

3. Results

3.1. LCA Model Selection

An LCA was performed, and model selection tools were utilized to select the best-fitting and most appropriate models. The 3-class model was selected for *Likelihood* and *Severity* (Tables 9 and 10). Tabular depictions of each model are presented in Appendix B. The model selection process for the *Likelihood* and *Severity* models was similar. For both models, the lowest AIC and BIC values occur in the 3-class model and the 4-class model. The 4-class model was not selected because the BLRT was insignificant (*Likelihood*, p = 0.53; *Severity*, p = 0.64), indicating the 4-class model did not fit statistically better than the 3-class model. These BLRT values confirmed that the 3-class model was the best-fitting *Likelihood* and *Severity* model. Additionally, the entropies for the 3-class models were above 0.8 and, therefore, acceptable (Weller et al., 2020); thus, indicating that the models accurately defined and classified the latent classes. The ɣ-parameters and ρ-parameters for the 3-class *Likelihood* and *Severity* models were distinguishable and meaningful when interpreted (Tables 11 and 12).

3.2. LCA Model Description

Interpreting the *Likelihood* LCA Model, Table 11 indicates that 9.97% of respondents are expected to belong to Latent Class 1 and perceive all the safety risk characteristics to have high probabilities ($\rho > 0.85$) of occurring during installations. Consequently, Latent Class 1 was named the "High Likelihood" Class. Conversely, 77.38% of participants are expected to belong to Latent Class 2 and perceive all the safety risk characteristics to have moderate probabilities ($0.30 < \rho < 0.50$) of occurring during installations. Latent Class 2 was named the "Moderate Likelihood" Class. Lastly, 12.66% of participants are expected to belong to Latent Class 3 and perceive all the safety risk characteristics to have low probabilities ($\rho < 0.15$) of occurring during installations. Latent Class 3 was named the "Low Likelihood" Class.

Interpreting the *Severity* LCA Model, Table 12 indicates 11.96% of respondents are expected to belong to Latent Class 1 and perceive all the safety risk characteristics to have a high severity or level of danger ($\rho > 0.85$) associated with them. Conversely, 76.22% of participants are expected to belong to Latent Class 2 and perceive all the safety risk characteristics to have a moderate level of danger ($0.30 < \rho < 0.55$) associated with them. Lastly, 11.82% of participants are expected to belong to Latent Class 3 and perceive all the safety risk characteristics to have a low level of danger ($\rho < 0.15$) associated with them. The same reasons and naming convention were utilized to name the *Severity LCA Model* classes (Table 12); therefore, they were named "High Severity," "Moderate Severity," and "Low Severity." Tables 13 and 14 provide a visual representation of the *Likelihood* and *Severity* LCA Models, respectively.

Table 9 Model selection tools for baseline LCA Likelihood model

No. of classes	Likelihood ratio G2	Degrees of freedom (df)	AIC	BIC	Entropy	*p* from BLRT
1	2846.19	32752	2876.19	2931.24	1.00	
2	2277.52	32736	2339.52	2453.29	0.99	0.01**
3	**2082.64**	**32720**	**2176.64**	**2349.13**	**0.98**	**0.01****
4	2050.27	32704	2176.27	2407.47	0.85	0.53
5	2014.52	32688	2172.52	2462.44	0.77	0.35

Note: AIC = Akaike's Information Criteria, BIC = Bayesian Information Criteria, BLRT = Bootstrap Likelihood Ratio Test.
*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

Table 10 Model selection tools for baseline LCA Severity model

No. of classes	Likelihood ratio G2	Degrees of freedom (df)	AIC	BIC	Entropy	*p* from BLRT
1	2991.19	32752	3021.19	3076.24	1.00	
2	2619.88	32736	2681.88	2795.64	0.94	0.01**
3	**2214.32**	**32720**	**2308.32**	**2480.80**	**0.98**	**0.01****
4	2182.50	32704	2308.50	2539.71	0.89	0.64
5	2154.94	32688	2312.94	2602.86	0.80	0.98

Note: AIC = Akaike's Information Criteria, BIC = Bayesian Information Criteria, BLRT = Bootstrap Likelihood Ratio Test.
*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

Table 11 Class membership probabilities (ɣ-estimates) and item-response probability (ρ-estimates) for the 3-class Likelihood model

Safety Risk Characteristic	Latent Class 1: High Likelihood (*Standard Error*)	Latent Class 2: Moderate Likelihood (*Standard Error*)	Latent Class 3: Low Likelihood (*Standard Error*)
Class membership probability (ɣ)	*9.97 %* (*0.0176*)	*77.38 %* (*0.0253*)	*12.66 %* (*0.0204*)
Surfaces collapsing under workers weight (e.g., roofs, structural components, PV panels)	0.9918 (*0.0178*)	0.3392 (*0.0317)*	0.0033 (*0.0096*)
Falling from heights (e.g., roofs, ladders, working platforms)	0.9930 (*0.0157*)	0.4104 (*0.0330*)	0.0044 (*0.0117*)
Struck-by falling objects (e.g., tools, and equipment)	0.9609 (*0.0368*)	0.3577 (*0.0321*)	0.0788 (*0.0471*)
Falling, slipping, or tripping on-site (e.g., lack of space, tripping on electrical wiring or fall protection)	0.9925 (*0.0170*)	0.4058 (*0.0329*)	0.0595 (*0.0435*)
Electric shock or burn (e.g., from electrical wiring, live components)	0.9931 (*0.0153*)	0.3835 (*0.0326*)	0.0050 (*0.0138*)
Electric shock or burn leading to falling from heights (e.g., roof, ladder, working platform)	0.9930 (*0.0154*)	0.3744 (*0.0324*)	0.0059 (*0.0163*)
Thermal burns from handling solar panels (e.g., heat from panels)	0.9593 (*0.0383*)	0.4010 (*0.0328*)	0.0053 (*0.0144*)
Dehydration (e.g., body cramps, feeling thirsty, dizzy, or tired)	0.8926 (*0.0578*)	0.3868 (*0.0327*)	0.0913 (*0.0531*)
Heat stroke (e.g., loss of consciousness, seizures, or high body temperatures)	0.9238 (*0.0508*)	0.4056 (*0.0329*)	0.1132 (*0.0575*)
Wounds or cuts from handling materials or tools (e.g., sharp edges, fragments, power or hand tools)	0.9928 (*0.0159*)	0.3879 (*0.0327*)	0.0052 (*0.0142*)
Working in confined spaces (e.g., unable to breathe properly, awkward posture)	0.8523 (*0.0675*)	0.3762 (*0.0325*)	0.0038 (*0.0107*)
Glare from panels or roofing materials (e.g., loss of visibility, dizziness, heat stress)	0.9930 (*0.0158*)	0.4014 (*0.0329*)	0.0042 (*0.0114*)
Injuries from repetitive lifting of solar panels and other materials (e.g., muscle pulls, back pain, sprains, and strains)	0.9929 (*0.0156*)	0.3476 (*0.0320)*	0.0875 (*0.0537*)
Injuries from repetitive use of hand and power tools (e.g., pains in hands or wrist area)	0.9268 (*0.0489*)	0.3734 (*0.0325)*	0.0099 (*0.0263*)
Electrical components or site materials catching fire (e.g., solar panels, electrical wiring, live components, nearby flammable materials)	0.9931 (*0.0154*)	0.3836 (*0.0326*)	0.0042 (*0.0116*)

Table 12 Class membership probabilities (ɣ-estimates) and item-response probability (ρ-estimates) for 3-class Severity

Safety risk characteristic	Latent class 1: High Severity (*Standard Error*)	Latent class 2: Moderate Severity (*Standard Error*)	Latent class 3: Low Severity (*Standard Error*)
Class membership probability (*ɣ*)	*11.96 %* (*0.0194*)	*76.22 %* (*0.0256*)	*11.82 %* (*0.0194*)
Surfaces collapsing under workers weight (e.g., roofs, structural components, PV panels)	0.9733 (*0.0367*)	0.4844 (*0.0338*)	0.0053 (*0.0131*)
Falling from heights (e.g., roofs, ladders, working platforms)	0.9679 (*0.0319*)	0.4376 (*0.0336*)	0.0325 (*0.0306*)
Struck-by falling objects (e.g., tools, and equipment)	0.9668 (*0.0303*)	0.5134 (*0.0338*)	0.0294 (*0.0314*)
Falling, slipping, or tripping on-site (e.g., lack of space, tripping on electrical wiring or fall protection)	0.9915 (*0.0198*)	0.4046 (*0.0331*)	0.0041 (*0.0109*)
Electric shock or burn (e.g., from electrical wiring, live components)	0.9666 (*0.0309*)	0.3915 (*0.0330*)	0.0265 (*0.0305*)
Electric shock or burn leading to falling from heights (e.g., roof, ladder, working platform)	0.9947 (*0.0125*)	0.4192 (*0.0334*)	0.1394 (*0.0617*)
Thermal burns from handling solar panels (e.g., heat from panels)	0.9644 (*0.0325*)	0.5029 (*0.0338*)	0.0294 (*0.0313*)
Dehydration (e.g., body cramps, feeling thirsty, dizzy, or tired)	0.8893 (*0.0565*)	0.4927 (*0.0338*)	0.0080 (*0.0204*)
Heat stroke (e.g., loss of consciousness, seizures, or high body temperatures)	0.9671 (*0.0304*)	0.4942 (*0.0338*)	0.0066 (*0.0167*)
Wounds or cuts from handling materials or tools (e.g., sharp edges, fragments, power or hand tools)	0.9940 (*0.0142*)	0.4365 (*0.0335*)	0.0589 (*0.0417*)
Working in confined spaces (e.g., unable to breathe properly, awkward posture)	0.9349 (*0.0434*)	0.4455 (*0.0336*)	0.0898 (*0.0493*)
Glare from panels or roofing materials (e.g., loss of visibility, dizziness, heat stress)	0.9675 (*0.0323*)	0.4401 (*0.0335*)	0.0044 (*0.0114*)
Injuries from repetitive lifting of solar panels and other materials (e.g., muscle pulls, back pain, sprains, and strains)	0.9941 (*0.0135*)	0.4103 (*0.0333*)	0.0349 (*0.0331*)
Injuries from repetitive use of hand and power tools (e.g., pains in hands or wrist area)	0.8804 (*0.0489*)	0.4440 (*0.0337)*	0.0807 (*0.0494*)
Electrical components or site materials catching fire (e.g., solar panels, electrical wiring, live components, nearby flammable materials)	0.9479 (*0.0417*)	0.4567 (*0.0336*)	0.0052 (*0.0132*)

Table 13 Visual Representation of the LCA Likelihood model

Saftey Risk Characteristic	High Likelihood	Moderate Likelihood	Low Likelihood
Class membership probability	*9.97%*	*77.38%*	*12.66%*
Surface collapses	●	○	
Falling from heights	●	○	
Struck-by falling objects	●	○	
Falling, slipping, or tripping	●	○	
Electric shock or burn	●	○	
Electric shock/burn leads to falling	●	○	
Thermal burns	●	○	
Dehydration	●	○	
Heat stroke	●	○	
Wounds or Cuts	●	○	
Confined Spaces	●	○	
Glare	●	○	
Injuries from repetitive actions	●	○	
Injuries from repetitive tools	●	○	
Electrical fires	●	○	
Key: (blank) < 30%	30% ≤ ○ > 50%	50% ≤ • < 75%	● ≥ 75%

Table 14 Visual Representation of the LCA Severity model

Saftey Risk Characteristic	High Severity	Moderate Severity	Low Severity
Class membership probability	*11.96%*	*76.37%*	*11.82%*
Surface collapses	●	○	
Falling from heights	●	○	
Struck-by falling objects	●	•	
Falling, slipping, or tripping	●	○	
Electric shock or burn	●	○	
Electric shock/burn leads to falling	●	○	
Thermal burns	●	•	
Dehydration	●	○	
Heat stroke	●	○	
Wounds or Cuts	●	○	
Confined Spaces	●	○	
Glare	●	○	
Injuries from repetitive actions	●	○	
Injuries from repetitive tools	●	○	
Electrical fires	●	○	
Key: (blank) < 30%	30% ≤ ○ > 50%	50% ≤ • < 75%	● ≥ 75%

3.3. LCA Grouping Variables

The results of the grouping variable LCA are shown for *Likelihood* (Table 15) and *Severity* (Table 16). To test for measurement invariance between groups, the model was first fit with free ρ-parameter estimation and then with restrictions that equate the ρ-parameters across groups. The model fits were compared and not found to be significantly different for any of the grouping variables: Installation Size (*Likelihood*, p = 0.89; *Severity*, p = 0.99); Company Longevity (*Likelihood*, p = 0.94; *Severity*, p = 0.91); Work Experience (*Likelihood*, p = 0.46; *Severity*, p = 0.99). This provides evidence that measurement invariance holds and indicates that classes have the same meaning for each group.

Tables 15 and 16 show the Latent Class membership probabilities for each of the grouping variables for the *Likelihood* and *Severity* model, respectively. For instance, interpreting the grouping variable results for *Likelihood* (Table 15) with Installation size as a grouping variable indicates that 53.8% of participants who perform *residential* installations are expected to belong to the *Moderate Likelihood Class* (i.e., these participants have a moderate perception of the likelihood of the safety risk characteristics). Conversely, 25.2% and 20.8% of participants who perform *residential* installations are expected to belong to the *Low Likelihood Class* and *High Likelihood Class*, respectively.

Table 15 Likelihood latent class membership probabilities in 3-class model with grouping variables

Grouping Variable	Groups	Sample Size (n)	High Likelihood (ɣ)	Moderate Likelihood (ɣ)	Low Likelihood (ɣ)
Installation Size	Residential (0-10 kW)	99	25.2 %	53.8 %	20.8 %
	Meso or Commercial (10kW-5MW)	191	2.0 %	88.9 %	8.9 %
Company Longevity	New Company (0-5 years)	116	0.01 %	85.5 %	13.5 %
	Established Company (6+ years)	174	16.0 %	71.8 %	12.0 %
Work Experience	Entry-level (0-4 years)	147	0.01 %	86.6 %	12.5 %
	Experienced (5+ years)	143	18.8 %	68.3 %	12.8 %

Table 16 Severity latent class membership probabilities in 3-class model with grouping variables

Grouping Variable	Groups	Sample Size (n)	High Severity (ɣ)	Moderate Severity (ɣ)	Low Severity (ɣ)
Installation Size	Residential (0-10 kW)	99	26.3 %	54.2 %	19.4 %
	Meso or Commercial (10kW-5MW)	191	3.8 %	88.3 %	7.8 %
Company Longevity	New Company (0-5 years)	116	1.7 %	86.1 %	12.0 %
	Established Company (6+ years)	174	19.1 %	69.1 %	11.6 %
Work Experience	Entry-level (0-4 years)	147	4.7 %	82.6 %	12.6 %
	Experienced (5+ years)	143	19.4 %	69.5 %	10.9 %

4. Discussion

This research aimed to measure the perception of solar workers regarding various installation safety risks and explore how these perceptions vary with installation size, company longevity, and work experience. Accordingly, this research achieved Aim 1 by directly collecting and assessing the perceptions of solar workers regarding various installation safety risks. Moreover, Aim 2 was also achieved by associating these perceptions with latent class groups through LCA and then seeing where the participants' probability of membership was located based on these three factors: installation size, company longevity, and work experience.

Solar installation workers are known to experience some of the most severe and significant construction safety risks. These risks include (i) falls from elevated working surfaces, (ii) electrical risks and hazards (e.g., electric shock, burns, electrocution, and arc flash hazards), (iii) heat stress from working for prolonged periods in hot temperatures, and (iv) musculoskeletal disorder (MSD) risks from repetitive manual handling at awkward postures (California Fatality Assessment and Control Evaluation Program, 2020; Hanson & Thatcher, 2020; OSHA 2018, 2020; U.S. Department of Labor, 2017). Fall accidents and electrocutions have historically been part of the construction industry's four most frequent causes of fatalities, also called the 'Fatal Four' (Albert et al., 2020; OSHA, 2011). Construction industry workers historically have the highest proportion (36.8%) of heat-related illness deaths (Gubernot et al., 2015). Work-related musculoskeletal injuries account for approximately 30% of days-away-from-work cases in the U.S. private industry (U.S. Bureau of Labor Statistics, 2016, 2018, 2019). However, results from this survey study indicate that most solar installation workers feel moderately safe during installations (i.e., have a moderate perception of the likelihood and severity of these safety risks). An optimistic interpretation of these results suggests that the installation workers in this study work for companies with a generally good safety culture. Conversely, a pessimistic interpretation suggests that solar installers lack awareness regarding the likelihood and severity of these risks. More formalized reporting and verification of solar worker accident data, frequency, and causes is needed to fully explore or come to any generalizable conclusions regarding these interpretations.

The results from this study reveal that there is more uniformity in the perception of *meso or commercial* installation workers, compared to *residential* workers, regarding installation risks. The vast majority of *meso or commercial* workers in this study belong to the *Moderate Likelihood Class* (88.9%) and the *Moderate Severity Class* (88.3%). However, as the installation size decreases to *residential* (Tables 15 and 16), the proportion of installation workers in the *High Likelihood Clas*s and *High Severity Class* increases substantially from less than 5% (Meso or Commercial) to greater than 25% (*residential*). This is consistent with general construction safety studies that report a higher rate of injury for some risks, especially fall-related risks, from smaller building projects due to a lack of resources, education, and insufficient safety equipment (Huang & Hinze, 2003; Halabi et al., 2022; Dong et al. 2019).

The increase in the proportion of *residential* installation workers in the *High Likelihood Clas*s and *High Severity Class* could be tied to smaller construction building projects having higher rates of injury. This phenomenon is well documented regarding *falling from heights* within the construction industry. Historically, the majority of fatalities associated with falling from heights in the construction industry tend to occur at lower elevations (less than 30 ft) (Huang & Hinze, 2003; Halabi et al., 2022; Dong et al. 2019). As an explanation for this phenomenon, Huang & Hinze (2003) proposed that workers tend to misjudge hazardous situations and use insufficient personal protective equipment or inoperative safety devices at lower elevations. *Residential* workers may more frequently misjudge, overlook, or neglect inconvenient but necessary safety practices at lower elevations and consequently experience higher rates of injury. Moreover, recent studies highlight that *residential* solar workers have an aversion to some safety measures, such as mechanical lifting equipment and fall protection systems, due to lengthy setup time, and heavyweight fall protection clothing and trip hazard concerns (Ho et al., 2020). Research that explores these concerns in more detail would be valuable in understanding how to enhance safety systems to meet the needs of *residential* installers.

Lastly, Tables 15 and 16 indicate that the vast majority of solar installation workers with Entry-level work experience or who are in a New Company belong to the *Moderate Likelihood Clas*s and *Moderate Severity Class* (over 80%). Experienced solar installation workers or workers in an Established Company have a substantially higher proportion of workers in the *High Likelihood Clas*s and *High Severity Class* (over 16%) than New Company or Entry-level installers (less than 5%). A potential explanation for these results is that installation workers with more experience or in more established companies have likely received more safety education and resources and, as a result, have a greater understanding and awareness of the likelihood and severity of safety risks. Moreover, installation companies may assign less risky tasks to entry-level installation workers relative to the more experienced installers.

Considering the results in this study and others cited in this research, it is recommended for companies to make a deliberate and concerted effort to ensure their workers understand the levels of risks that occur during solar installations at all levels. More specifically, for solar installation companies and safety professionals to work with their solar installers to see if they share some of the obstacles discussed. For instance, we recommend companies have discussions with their workers on their willingness to overlook or neglect inconvenient, but necessary safety practices at lower working elevations. Other questions to discuss with their workers include whether they find the fall protection equipment heavy or conducive to trip hazards, and whether they avoid mechanical lifting systems. As this information is ascertained, site-safety plans should be geared towards re-designing tasks and safety systems to remove obstacles, in order to encourage and enforce safety standards. Specifically, companies that do work in the *meso or commercial* installation size could continue to encourage a culture of safety through worker incentives or additional training. Lastly, newer solar companies are at risk as growth continues to significantly increase overtime and should be supported through various stakeholder and regulatory groups to report and maintain safety training levels. Ultimately, safety plans will vary based on site-specific needs, but special attention should be placed on proactive mitigation procedures (e.g., setting up mechanical lifting systems ahead of time to assist with lifting tasks and investing in fall protection equipment that is lightweight but still effective).

Also, there is a substantial lack of latent class membership in the *High Likelihood Class* and *High Severity Class* for the Entry-level installer and the New Company groups relative to Experienced installer and Established Company groups, respectively (Tables 15 and 16).

Consequently, this study recommends a strong emphasis on safety hazard identification and mitigation during mentorship and apprenticeship programs (Interstate Renewable Energy Council, 2023). More experienced installers can help to increase the safety knowledge and awareness of entry-level installers regarding risk factors and mitigation measures through organizational structured sharing, such as mentorship or brown bag lunch meetings. This study's results highlight the importance of, and the need for, more exchange of safety knowledge and information between solar companies to facilitate learning between newer and more established companies. Key opportunities for these interactions include solar and training conferences, such as the ASES Conferences (ASES, 2023) and the North American Board of Certified Energy Practitioners Conferences (NABCEP, 2023).

As the solar industry continues to grow, the level of skilled labor required to perform solar work has also increased. In the U.S., the most recent National Solar Jobs Census revealed that solar employers have found it increasingly difficult to find qualified applicants over the years, especially in the installation and project development sector (Interstate Renewable Energy Council, 2023). The Census reports that the top reasons for this hiring difficulty are competition (with other construction occupations) or a small pool of applicants, and a lack of experience, training, or technical skills (Interstate Renewable Energy Council, 2023). At the entry-level, most solar companies primarily hire workers from community colleges or other training programs. However, due to the solar installation demand and hiring challenges, solar companies are willing to hire workers with little experience (Interstate Renewable Energy Council, 2023). Nevertheless, solar companies typically provide on-the-job training programs to assist with safety and/or skills. These on-the-job training programs are occasionally provided in partnership with community colleges and local nonprofit organizations (Interstate Renewable Energy Council, 2023). Yet, based on the National Solar Jobs Census results, a lack of training (which includes safety training) remains a barrier to the growth and development of the solar workforce. Therefore, it is imperative to the solar industry's growth to explore the safety training available to their installers. No study to date has investigated the level or efficacy of safety training installers receive in the U.S. More research is needed to explore the level of safety training solar installers receive to identify better means to educate workers to maintain on-site safety practices.

Finally, this study's questionnaire is the first to propose a solar installation safety risk construct with an extensive list of solar installation risk items. This construct can be used as a starting point by solar installation companies to understand the risk perception of their workers and adjust training accordingly to meet their needs. Innovative training approaches that can aid safety education should be considered and evaluated wherever possible, for instance, the use of virtual or augmented reality to supplement safety training regarding working from heights (Erten et al., 2022; Rey-Becerra et al., 2023; Wolf et al., 2022). Training programs should be adaptable to trainees' different learning characteristics (Xu et al., 2023). Cultural or language barriers should also be considered in the design of training programs (Shepherd et al., 2021; Vignoli et al., 2021), especially since the solar workforce is gradually growing more diverse (Interstate Renewable Energy Council, 2023). Installation companies should also strongly encourage and provide necessary resources for workers to obtain relevant safety certifications. Examples of these include the

OSHA 10-Hour, OSHA 30-Hour (OSHA, 2023; OSHA Training, 2023), North American Board of Certified Energy Practitioners Certifications (NABCEP, 2023), and the Residential & Commercial Photovoltaic Systems Certificate (Solar Energy International, 2022). These certifications should be strongly encouraged, especially for *residential* installation workers, since federal and state regulations tend not to mandate safety certifications for smaller, lower-cost construction projects (OSHA Training, 2023).

4.1. Limitations & Future Work

The limitations of this work mainly center around the questionnaire design and the survey sample. For the sake of usability and conciseness within the questionnaire, *residential* and *meso or commercial* installations were denoted by PV system capacity (e.g., 0 - 10 kW as *residential*), and additional contextual information that could be used to describe these types of installations was not included. Although the authors are confident that the average solar worker would understand this method of representing installation size, the lack of contextual information can make it open for interpretation by survey participants. Additionally, the data collection methodology for the study was based on convenience sampling. While this study provides valuable information regarding solar worker risk perception, its results are not necessarily generalizable to the U.S. solar installation population. Consequently, a future study that expands the current study's data collection (i.e., stratified random sampling) and recruitment procedures would be encouraged. While not ideal, this is a complex population to reach, particularly if one desires geographic representation and a large sample size.

The purpose of this work was to understand the solar workers' perceptions regarding installation risks. The authors of this work acknowledge that perception and reality are not always the same. This work cannot replace the need for solar worker injury, accident, fatality reporting, and verification data (Sovacool et al., 2015). Future work that can enhance the findings of this research includes exploring the current state of workplace health and safety training and certifications associated with solar installation work. Additionally, conducting ergonomic observational studies to understand the solar installation ergonomic risk factors. Tools such as the NIOSH equation (NIOSH, 2021), the Standardized Nordic Assessment (Kuorinka et al., 1987), and the Rapid Upper Limb Assessment (McAtamney & Corlett, 1993) could be particularly useful in this regard.

5. Conclusion

The study aimed to explore the SRP of solar installation workers and how it varies based on different factors (installation size, company longevity, and work experience). An LCA revealed that solar workers typically fall into three groups based on their responses to the risk perception questions: (1) *High Likelihood/Severity*, (2) *Moderate Likelihood/Severity*, and (3) *Low Likelihood/Severity*. Most workers have a moderate perception of the likelihood or severity of safety risks. The proportion of membership in the High Likelihood/Severity class increased substantially as installation size decreased to residential and as company longevity and work experience increased. This paper provides a valuable account of the solar workers' safety risk perception and discusses areas where more research is needed to enhance installation safety. This perspective can provide valuable guidance to solar installation companies and safety professionals as they strive to implement measures that mitigate safety risks on-site.

Acknowledgments

Special thanks to Dr. Valerie Maier-Speredelozzi at The University of Rhode Island for providing support, guidance, and direction. Further, special thanks to Sara Lang, Jonah Crema, and Michael Cascione for assisting with the questionnaire development and research. Special thanks to Sara Nunes, Malinda Fry, Chidera Duroha, and Brian Duroha for assisting with data table visualization. Robert Hatch Multistate RH01234 provided partial funding support for this project. Finally, thanks to all the Sustainable Innovative Solutions (SIS) Lab members for their support.

References

Acharya, P., Boggess, B., Zhang, K., 2018. Assessing Heat Stress and Health among Construction Workers in a Changing Climate: A Review. International Journal of Environmental Research and Public Health 15 (2), 247. https://doi.org/10.3390/ijerph15020247.

Akaike, H. (1974), “A new look at the statistical model identification”, *IEEE Transactions on Automatic Control*, Vol. 19 No. 6, pp. 716–723, doi: 10.1109/tac.1974.1100705.

Albert, A., Pandit, B., & Patil, Y. (2020). Focus on the fatal-four: Implications for construction hazard recognition. Safety Science, 128, 104774.https://doi.org/10.1016/j.ssci.2020.104774

Aven, T., & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*, *12*(1), 1–11. https://doi.org/10.1080/13669870802488883

Bakhiyi, B., Labrèche, F., & Zayed, J. (2014). The photovoltaic industry on the path to a sustainable future — Environmental and occupational health issues. *Environment International*, *73*, 224–234. https://doi.org/10.1016/j.envint.2014.07.023

California Fatality Assessment and Control Evaluation Program. (2020, January 22). Preventing worker deaths in the solar industry. California Department of Public Health. https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/OHB/FACE/Pages/Solar.aspx (Accessed: 1 August 2022)

Center for Decision Sciences. (2022). *Original 40-item Domain-Specific Risk-Taking (DOSPERT) Scale (2002)*. Columbia Business School. https://www8.gsb.columbia.edu/decisionsciences/research/tools/dospert (Accessed: 26 February 2022)

Centers for Disease Control and Prevention (2019, July 8). *Extreme Heat*. https://www.cdc.gov/disasters/extremeheat/index.html (Accessed: 26 July 2022)

Chi, H., Vu, T., Vo-Thanh, T., Nguyen, N. P., & Van-Nguyen, D. (2020). Workplace health and safety training, employees’ risk perceptions, behavioral safety compliance, and perceived job insecurity during COVID-19: Data of Vietnam. *Data in Brief*, *33*, 106346. https://doi.org/10.1016/j.dib.2020.106346

Collins, L. M., Fidler, P. L., Wugalter, S. E., & Long, J. D. (1993). Goodness-of-Fit Testing for Latent Class Models. *Multivariate Behavioral Research*, *28*(3), 375–389. https://doi.org/10.1207/s15327906mbr2803_4

Dong, X. S., Jackson, R., Varda, D., Betit, E., & Bunting, J. (2019). Trends of Fall Injuries and Prevention in the Construction Industry. *CPWR.*

Dunlap, R. E., & Liere, K. D. V. (2008). The "New Environmental Paradigm." *The Journal of Environmental Education*, *40*(1), 19–28. https://doi.org/10.3200/joee.40.1.19-28

Duroha, J. C., Brownson, J. R. S., & Macht, G. A. (2020). Occupational Risks Associated with Solar Installations: A Review. *Proceedings of American Solar Energy Society 2020 Annual Conference*. https://doi.org/10.18086/solar.2020.01.08

Duroha, J. C., & Macht, G. A. (2021). Solar Installations & Their Occupational Risks. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *65*(1), 1243–1247. https://doi.org/10.1177/1071181321651275

Duroha, J. C., & Macht, G. A. (2023). Solar installation occupational risks: A systematic review. *Safety Science, 160*, 106048. https://doi.org/10.1016/j.ssci.2022.106048

Elmoujaddidi, F., & Bachir, A. (2018). Perceived risk, safety climate and safety behavior on Moroccan construction sites. *International Journal of Occupational Safety and Ergonomics*, *26*(1), 1–22. https://doi.org/10.1080/10803548.2018.1546461

Erten, B., & Utlu, Z. (2020). Photovoltaic system configurations: an occupational health and safety assessment. *Greenhouse Gases: Science and Technology*, *10*(4), 809–828.

Guerin, T. F. (2017). Evaluating expected and comparing with observed risks on a large-scale solar photovoltaic construction project: A case for reducing the regulatory burden. *Renewable and Sustainable Energy Reviews*, *74*, 333–348. https://doi.org/10.1016/j.rser.2017.02.040

Gubernot, D. M., Anderson, G. B., & Hunting, K. L. (2015). Characterizing occupational heat-related mortality in the United States, 2000–2010: Analysis using the census of fatal occupational injuries database. *American Journal of Industrial Medicine*, *58*(2), 203–211. https://doi.org/10.1002/ajim.22381

Halabi, Y., Xu, H., Long, D., Chen, Y., Yu, Z., Alhaek, F., & Alhaddad, W. (2022). Causal factors and risk assessment of fall accidents in the U.S. construction industry: A comprehensive data analysis (2000–2020). Safety Science, *146*, 105537. https://doi.org/10.1016/j.ssci.2021.105537

Han, Y., Jin, R., Wood, H., & Yang, T. (2019). Investigation of Demographic Factors in Construction Employees' Safety Perceptions. *KSCE Journal of Civil Engineering*, *23*(7), 2815–2828. https://doi.org/10.1007/s12205-019-2044-4

Hanson, M., & Thatcher, A. (2020). Identifying Human Factors and Ergonomic Issues in Green Jobs: Facilitating Sustainable Green Jobs. In A. Thatcher, K. J. Zink & K.

Fischer (Eds.), *Human Factors for Sustainability: Theoretical Perspectives and Global Applications* (pp. 171-192). CRC Press Taylor and Francis Group.

Ho, C., Lee, H. W., & Gambatese, J. A. (2020). Application of Prevention through Design (PtD) to improve the safety of solar installations on small buildings. *Safety Science*, *125*, 104633. https://doi.org/10.1016/j.ssci.2020.104633

Ibarra-Mejía, G., Gómez-Bull, K. G., & Vargas-Salgado, M. M. (2021). Differences in Workplace Risk Perception between Foreign-Born and First-Generation Mexican American Construction Workers. *International Journal of Environmental Research and Public Health*, *18*(11), 5652. https://doi.org/10.3390/ijerph18115652

Interstate Renewable Energy Council. (2021). *National Solar Jobs Census 2020*. https://irecusa.org/wp-content/uploads/2021/07/National-Solar-Jobs-Census-2020-FINAL.pdf (Accessed: 16 July 2023)

Interstate Renewable Energy Council. (2022). *National Solar Jobs Census 2021*. https://irecusa.org/wp-content/uploads/2022/10/National-Solar-Jobs-Census-2021.pdf (Accessed: 22 July 2022)

Kang, Y. (2018). Use of Fall Protection in the US Construction Industry. *Journal of Management in Engineering*, *34*(6), 04018045. https://doi.org/10.1061/(asce)me.1943-5479.0000655

Kuorinka, I., Jonsson, B., Kilbom, A., Vinterberg, H., Biering-Sørensen, F., Andersson, G., & Jørgensen, K. (1987). Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. *Applied Ergonomics*, *18*(3), 233–237. https://doi.org/10.1016/0003-6870(87)90010-x

Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, *47*(260), 583-621.

Lanza, S.T., Collins, L.M., Lemmon, D.R. and Schafer, J.L. (2007), "PROC LCA: A SAS Procedure for Latent Class Analysis", *Structural Equation Modeling: A Multidisciplinary Journal*, Vol. 14 No. 4, pp. 671–694, doi: 10.1080/10705510701575602.

Lanza, S.T., Tan, X. and Bray, B.C. (2013), "Latent Class Analysis With Distal Outcomes: A Flexible Model-Based Approach", Structural Equation Modeling: A Multidisciplinary Journal, Vol. 20 No. 1, pp. 1–26, doi: 10.1080/10705511.2013.742377.

Lette, A., Ambelu, A., Getahun, T., & Mekonen, S. (2018). A survey of work-related injuries among building construction workers in southwestern Ethiopia. *International Journal of Industrial Ergonomics*, *68*, 57–64. https://doi.org/10.1016/j.ergon.2018.06.010

Mann, H. B., & Whitney, D. R. (1947). On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. *The Annals of Mathematical Statistics*, *18*(1), 50–60. http://www.jstor.org/stable/2236101

McAtamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. Applied Ergonomics, *24*(2), 91–99. https://doi.org/10.1016/0003-6870(93)90080-s

National Resource Defense Council. (2022, April 14). *Race to 100% Clean: State Renewable Portfolio Standards.* https://www.nrdc.org/resources/race-100-clean (Accessed: 22 July 2022)

NIOSH (2021). Applications Manual for the Revised NIOSH Lifting Equation. (NIOSH Publication No. 94-110). https://doi.org/10.26616/NIOSHPUB94110revised092021

Occupational Safety and Health Administration. (2011). *Outreach Training Program.* https://www.osha.gov/training/outreach/construction (Accessed: 27 July 2022)

Occupational Safety and Health Administration. (2018). *Employee Falls From Roof and Fractures Foot.* https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=109537.015 (Accessed: 1 August 2022)

Occupational Safety and Health Administration. (2020). *Employee Contacts Overhead Power Line, Falls, Dies.* https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=124922.015 (Accessed: 1 August 2022)

Oregon Solar Energy Industries Association. (2006). *Solar Construction Safety*. https://www.coshnetwork.org/sites/default/files/OSEIA_Solar_Safety_12-06.pdf (Accessed: 22 September 2021)

Ramasay, V., Feldman, D., Desai, J., & Margolis, R. (2021). U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/80694.pdf

Rodríguez-Garzon, I., Martínez-Fiestas, M., Delgado-Padial, A., & Lucas-Ruiz, V. (2016). An Exploratory Analysis of Perceived Risk among Construction Workers in Three Spanish-Speaking Countries. *Journal of Construction Engineering and Management*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001187

Rowlinson, S., YunyanJia, A., Li, B., & ChuanjingJu, C. (2014). Management of climatic heat stress risk in construction: A review of practices, methodologies, and future research. *Accident Analysis & Prevention*, *66*, 187–198. https://doi.org/10.1016/j.aap.2013.08.011

Samaniego-Rascoń, D., Ferreira, A. D., & Silva, M. G. da. (2017). Cumulative and momentary skin exposures to solar radiation in central receiver solar systems. *Energy, 137*, 336–349. https://doi.org/10.1016/j.energy.2017.02.170

Samaniego-Rascón, D., Silva, M. C. G. da, Ferreira, A. D., & Cabanillas-Lopez, R. E. (2019). Solar energy industry workers under climate change: A risk assessment of the level of heat stress experienced by a worker based on measured data. *Safety Science*, *118*, 33–47. https://doi.org/10.1016/j.ssci.2019.04.042

Schwarz, G. (1978), "Estimating the Dimension of a Model", *The Annals of Statistics*, Vol. 6 No. 2, doi: 10.1214/aos/1176344136.

Sen, A., Mohankar, A. S., Khamaj, A., & Karmakar, S. (2021). Emerging OSH Issues in Installation and Maintenance of Floating Solar Photovoltaic Projects and Their Link with Sustainable Development Goals. *Risk Management and Healthcare Policy*, *14*, 1939–1957. https://doi.org/10.2147/rmhp.s304732

Solar Energy Industries Association. (2022). *Solar Industry Research Data*. https://www.seia.org/solar-industry-research-data (Accessed: 30 November 2022)

Sovacool, B. K., Kryman, M., & Laine, E. (2015). Profiling technological failure and disaster in the energy sector: A comparative analysis of historical energy accidents. *Energy*, *90*, 2016–2027. https://doi.org/10.1016/j.energy.2015.07.043

Sreenath, S., Sudhakar, K., & Yusop, A. F. (2020). Solar photovoltaics in airport: Risk assessment and mitigation strategies. *Environmental Impact Assessment Review*, *84*, 106418. https://doi.org/10.1016/j.eiar.2020.106418

White House. (2021, April 22). *Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies.* https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ (Accessed: 22 July 2022)

U.S. Department of Labor (1990, November) *Analysis of Construction Fatalities-The OSHA Database 1985-1989.* https://apps.dtic.mil/dtic/tr/fulltext/u2/a400187.pdf (Accessed: 15 July 2020)

U.S. Department of Labor. (2017). *Green Job Hazards: Solar Energy*. Occupational Safety and Health Administration. https://www.osha.gov/green-jobs/solar (Accessed: 22 July 2022)

Weller, B. E., Bowen, N. K., & Faubert, S. J. (2020). Latent Class Analysis: A Guide to Best Practice. *Journal of Black Psychology*, *46*(4), 287–311. https://doi.org/10.1177/0095798420930932

White, J. R., & Mike Doherty (2017). Hazards in the Installation and Maintenance of Solar Panels. *IEEE*. 10.1109/ESW.2017.7914834

Wu, Z., Hu, Y., Wen, J. X., Zhou, F., & Ye, X. (2020). A Review for Solar Panel Fire Accident Prevention in Large-Scale PV Applications. *IEEE Access*, *8*, 132466–132480. https://doi.org/10.1109/access.2020.3010212

Xia, N., Wang, X., Griffin, M. A., Wu, C., & Liu, B. (2017). Do we see how they perceive risk? An integrated analysis of risk perception and its effect on workplace safety behavior. *Accident Analysis & Prevention*, *106*, 234–242. https://doi.org/10.1016/j.aap.2017.06.010

Zou, P. X. W., & Zhang, G. (2009). Comparative Study on the Perception of Construction Safety Risks in China and Australia. Journal of Construction Engineering and Management.

CHAPTER 4

MANUSCRIPT 4: Ranking Solar Installation Safety Risk Perceptions: A Case of Installation Size

Prepared for submission to the Proceedings of the Human Factors and Ergonomics Society International Annual Meeting

Jesse C. Duroha[1], Simona Trandafir, Ph. D.[2] , Corey Lang, Ph. D.[2] and Gretchen A. Macht, Ph. D.[1]

[1]*Department of Mechanical, Industrial & Systems Engineering, University of Rhode Island, Kingston, RI, USA*

[2]*Department of Environmental & Natural Resource Economics, University of Rhode Island, Kingston, RI, USA*

Abstract

The U.S. solar installation workforce is growing rapidly to meet the nation's clean energy goals. Solar installers are known to experience significant occupational safety risks. However, research regarding the safety risks associated with solar installations is limited. This research presents a survey study (n = 290) to measure installers' risk perception. A risk significance score is calculated and ranked for both Residential and Meso or Commercial installers. Heat-related risks, falling from heights, and glare were the top concerns associated with Residential work. Whereas, heat-related risks, along with struck-by-falling objects, and falling, slipping, or tripping, were the top concerns for Meso or Commercial work. The results of this study also indicate that Residential installers have uniformly higher risk perceptions across all categories than Meso or Commercial installers. Overall, this work informs solar companies and safety professionals regarding the safety risks that installation workers are most concerned about as they develop and implement mitigation measures.

1. Introduction

The demand for solar energy in the U.S. continues to rise, and consequently, the solar workforce is growing to meet this need (Interstate Renewable Energy Council, 2021; Interstate Renewable Energy Council, 2023; White House, 2021). Solar employment has "more than doubled in the past decade from about 105,000 to 255,000 jobs," with the installation and project development sector experiencing the most growth (Interstate Renewable Energy Council, 2022, p. 12). The solar workforce is projected to reach 400,000 workers by 2030 and will need to reach 900,000 workers by 2035 to meet the U.S. clean energy goals (Interstate Renewable Energy Council, 2021; White House, 2021). To support this growth, a key area of research is safety for solar installation workers.

Solar installation workers are known to experience severe occupational risks (U.S. Department of Labor, 2017; Hanson & Thatcher, 2020; Occupational Safety and Health Administration [OSHA], 2011). These risks include: falling from heights, electrical shock, manual handling risks, and heat-related illnesses (Duroha & Macht, 2023). However, solar risk mitigation research and accident investigation reporting are limited and primarily focuses on more conspicuous installation safety risks, such as electrical and fire risks (Duroha & Macht, 2023; Ong et al., 2022; Sovacool et al., 2015; Wang et al., 2021). More research is needed to comprehensively explore the safety risks associated with solar installations.

Previous research in the construction realm identifies that some safety risks are more prevalent in smaller construction projects. This is especially the case regarding fall-related risks (Huang & Hinze, 2003; Halabi et al., 2022). Halabi et al. (2022) did a study to investigate the leading contributing factors of fall accidents in the U.S. They found that the majority of fall accidents in the U.S. occur on low-cost residential and commercial building projects at lower elevations (at 30 feet or less). This result is consistent with historical fall injury rates being more prevalent in smaller residential or commercial building projects (Huang & Hinze, 2003; Halabi et al., 2022; Dong et al., 2019). As an explanation for this phenomenon, Huang & Hinze (2003) proposed that workers tend to misjudge hazardous situations and use insufficient personal protective equipment or inoperative safety devices at lower elevations. It would be interesting to understand if this phenomenon, of smaller projects having greater safety risk, applies to solar installations.

Risk perception studies in specific construction occupations (e.g., laborer, masonry, excavator) have explored a wide variety of safety issues (Lette et al., 2018; Xia et al., 2017; Zou & Zhang, 2009). Areas these studies have explored include prevalent injury and risk factors (Lette et al., 2018), obstacles to safety compliance and participation (Zou & Zhang, 2009), and the influence risk perception has on risk behavior (Xia et al., 2017). Understanding the perceptions of solar workers regarding the safety risks and challenges they experience during installations can provide valuable information that informs on-site risk mitigation and training programs. Recent solar safety studies have explored the installers' perspective regarding the safety risks they face on-site (Erten et al., 2022; Ho et al., 2020; Sen et al., 2021). Ho et al. (2020) interviewed sixteen solar professionals and identified obstacles to their use of proper lifting methods and fall protection systems. The solar workers in their study expressed an aversion to mechanical lifting equipment due to lengthy setup times and consequently would lift solar panels using convenient but unsafe lifting methods. The solar workers in Ho et al. (2020) also identified that fall protection equipment was heavy and conducive to tripping hazards. Erten et al. (2022) conducted a multipronged survey of literature, field studies, and interviews to understand the level of occupational health and safety (OHS) practice and training among solar workers in Turkey. They then utilized this information to develop sample gamification scenarios aimed at providing virtual reality training for solar workers while working from heights. These emerging studies have provided a foundation for future work that aims to utilize solar worker safety risk perceptions to inform risk mitigation.

A tool that has been useful for understanding the relative significance of risk situations to groups in various fields is the Risk Significance Score (RSS) (Chen, 2018; Shen et al., 2001; Gunduz & Ahsan, 2018; Zou & Zhang, 2009). The RSS was utilized by Shen et al. (2001) to assess the relative importance of financial, management, and technical risks associated with construction joint ventures. After conducting a survey study, Shen et al. (2001) used the RSS to combine responses about the likelihood and severity of each risk, rank their importance to stakeholders, and propose practical risk management strategies. The RSS has also been used in the medical field to assess and manage the risks associated with medical-device related pressure ulcers (Chen, 2018). Within the realm of construction safety, the RSS or a similar methodology has been utilized to rank the workers' perception of safety risk factors (e.g., inappropriate signage, unavailability of materials, damaged equipment) (Zou & Zhang, 2009; Gunduz & Ahsan, 2018). The RSS provides a helpful index for ranking workers' perception of risk situations within survey studies and providing risk management recommendations.

Generally, access to research in this area and based on the level of solar growth, previous solar safety research lacks a comprehensive approach to exploring risks. To the authors' knowledge, no study to date has investigated how solar workers' perception of risks varies based on installation size. This study aims to contribute to this research gap by exploring the perception of solar installers regarding a comprehensive array of installation safety risks. Duroha et al. (forthcoming) conducted a safety risk perception (SRP) survey on solar workers in the U.S. (n = 290) to understand their perception of the likelihood and severity of fifteen installation safety risks. This study expands the Duroha et al. (forthcoming) work by generating a RSS based on survey responses and utilizing it to understand the risk situations that are most important to solar workers. This study also examines the RSS to understand how solar workers' perception of risk varies based on installation size (i.e., *Residential* vs. *Meso or Commercial* installations). This research can inform solar companies and safety professionals, regarding the installers perspective of the safety risks and challenges they face in different installation contexts. This work can support solar companies and safety professionals as they seek to develop effective training programs and site-specific mitigation measures.

2. Methodology

2.1. Survey Development

A 66-item questionnaire was developed based on an extensive literature review and solar industry expert interviews. The questionnaire consisted of the following sections: 1: Introduction; 2: Type of Work; 3: SRP; 4: Training and Certifications; 5: Risk Tolerance and New Environmental Paradigm; 6: Demographics; and 7: Optional Online Raffle (opt-in).

The survey's design and questions underwent multiple iterations based on feedback from two solar industry experts' in August and October of 2021. The questionnaire was advertised at the American Solar Energy Society (ASES) Conference in 2022, and on their members' only ASES Everything Solar Forum. In order to collect data from a broad and relevant population, the researchers joined a private solar installers' Facebook group, named "Solar Installers" with over 15,000 members. The group's goal was to create a community on social media where solar installers could showcase and share knowledge regarding every aspect of the PV installation process. Survey participation was voluntary, and participants could opt into an online raffle to win gift cards. The survey process complied with the University of Rhode Island's Institutional Review Board (HU2122-203). The data collection for this study was conducted using QUALTRICS®.

2.2. Sample

The inclusion and exclusion criteria for the survey participants were the solar workers in the U.S. who had professional experience installing, modifying, maintaining, or repairing solar photovoltaic systems. The survey initially had 589 participants. During the data cleaning process, we excluded participants who did not work in the U.S. (*n* = 32), or who indicated they did not have professional experience installing solar systems (*n* = 2). Participants who did not answer any of the demographic questions and thus could not be identified were also excluded (*n* = 206). Duplicate participants (*n* = 28) and participants with unrealistically low (less than 7 minutes) and high (greater than 50 minutes) questionnaire completion duration (*n* = 31) were excluded.

This resulted in an analytic dataset (*n* = 290) that met the inclusion and exclusion criteria for the study. Figures 8 and 9 show the demographic profile of the analytic dataset. Installers in this study were from various racial and ethnic backgrounds including: White (61%), African American (15.2%), and Hispanic or Latino (11.0%). The majority of participants declared an associate degree or some college background (71%). Additionally, 64% of participants considered themselves full-time employees, while the remaining 36% identified as either part-time, self-employed, unemployed, or other.

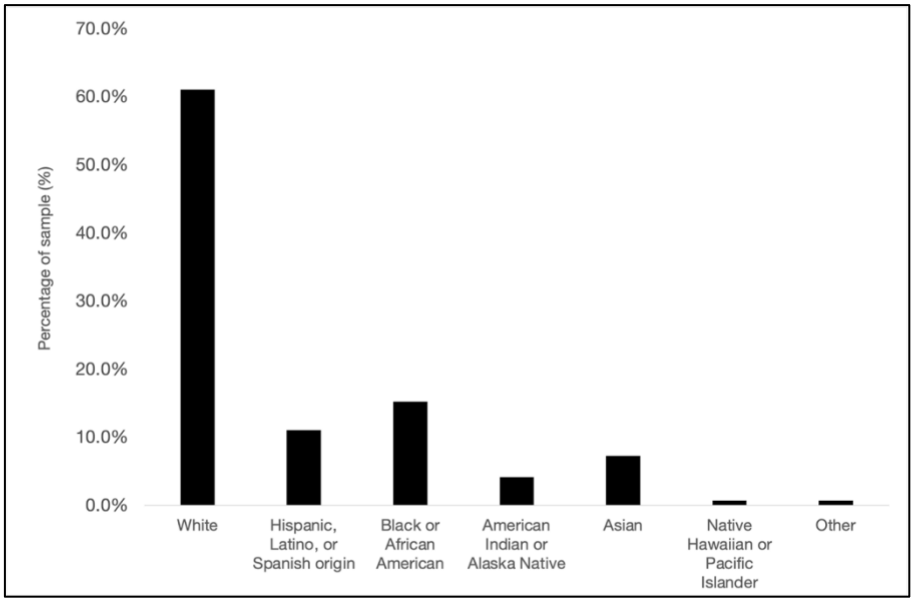

Figure 8 Demographic profile of survey participants' race and ethnicities

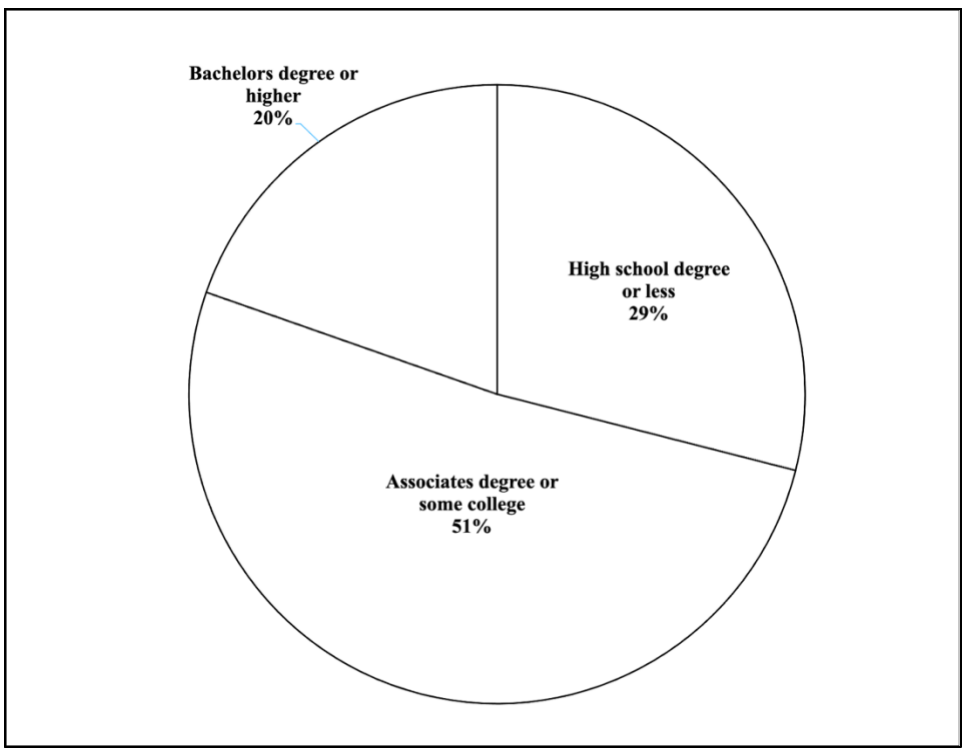

Figure 9 Pie chart of survey participants' education level

2.3. Variables

This study focused on two sections within the questionnaire: Type of Work (1 item) and SRP (15 items). The SRP section of the questionnaire consisted of 15-items that focused on installation safety risk situations (e.g., falling from heights, electric shock, repetitive lifting, heat stress). Survey participants were asked to rate the *likelihood* and *severity* of each SRP item on a frequentist Likert scale: "Extremely Low," "Low," "Neutral," "High," and "Extremely High," with a "Not Applicable" option provided.

Additionally, within the Type of Work section of the questionnaire, participants were asked: 'What is the approximate size of the solar photovoltaic systems you regularly install? [Select all that apply: 0-5 kW, 5-10 kW, 10-25 kW, 25-50 kW, 50-100 kW, 100 kW-1 MW, 1-5 MW, 5+ MW]'. Installers were labeled as *Residential* if they indicated regularly installing systems that are 0-10 kW in size (n = 99) and labeled as *Meso or commercial* if they regularly installed systems between 10 kW - 5 MW (n = 191). This method of grouping based on installation size is consistent with the U.S. Department of Energy's National Renewable Energy Laboratory's (NREL) grouping of the PV sector (Ramasay et al., 2021).

2.4. Risk Significance Score

The survey responses (*n* = 290) were utilized to calculate a Risk Significance Score (RSS) for each of the 15 risk situations in the questionnaire. The RSS for each risk assessed by each participant was calculated using Equation (1), similar to Shen et al. (2001) and Zou & Zhang (2009):

$$RSS = \frac{1}{n}\sum_{i=1}^{n} L_i S_i \quad (1)$$

Where:

$L_i = $ *likelihood* score assessed by respondent i,

$S_i = $ *severity* score assessed by respondent i,

$n = $ total number of observations

Participants' *likelihood* and *severity* responses were coded as (0.1 = Extremely Low; 0.3 = Low, 0.5 = Neutral; 0.7 = High, 0.9 = Extremely High). This range matched prior research (Zou & Zhang, 2009). The "Not Applicable" response option was coded as a blank cell. The RSS was calculated for two groups of solar installers: *Residential* installers (less than 10 kW PV systems) and *Meso or Commercial* installers (10 kW - 5 MW PV systems). The RSS results of each risk for *likelihood* and *severity* were then ranked to understand their relative importance.

2.5. Analysis

The primary purpose of this research was to understand and create an ordered list, through the RSS, describing the solar installers' risk perceptions. A Pearson correlation test (Boslaugh & Wattters, 2008) was then conducted to assess whether RSS values for *Residential* and *Meso or Commercial* installers are correlated or following similar response patterns. The analysis was conducted with *Excel* and *R Studio*.

3. Results

The RSS for 15 installation risk situations was calculated and ranked for *Residential* and *Meso or Commercial* installers separately. The results of this analysis are presented in Table 17. *Residential* solar installation participants were primarily concerned about (1) *dehydration*, (2) *falling from heights*, (3) *thermal burns* (i.e., from handling solar panels*)*, (4) *heat stroke*, and (5) *glare from panels or roofing materials*. While, *Meso or Commercial* solar installation participants were primarily concerned about (1) *heat stroke*, (2) *thermal burns from handling solar panels*, (3) *struck-by falling object*s, (4) *electric shock or burn leading to falling from heights*, and (5) *falling, slipping, or tripping on-site*.

Residential respondents had a higher perception of risk than *Meso or Commercial* respondents. Figure 10 presents a graph of the *Residential* and *Meso or Commercial* RSS scores. This graph shows that for all 15 risk situations, the *Residential* RSS is higher than the *Meso or Commercial* RSS. The RSS for *Residential* installers ranges from 0.311 to 0.390. While the RSS for *Meso or Commercial* ranges from 0.269 to 0.278 (Table 17). The

RSS values are generally close to 0.3 (Low risk), indicating that solar installation workers do not perceive these risks as unmanageable.

Additionally, there was a lack of correlation between the *Residential* and *Meso or Commercial* average responses. Pearson correlation tests yielded non-significant results (= 0.05) when applied to the RSS Values (p = 0.56, r = 0.163) and Ranks (p = 0.90, r = -0.032). This indicates that the perception of risks between these groups are not significantly related.

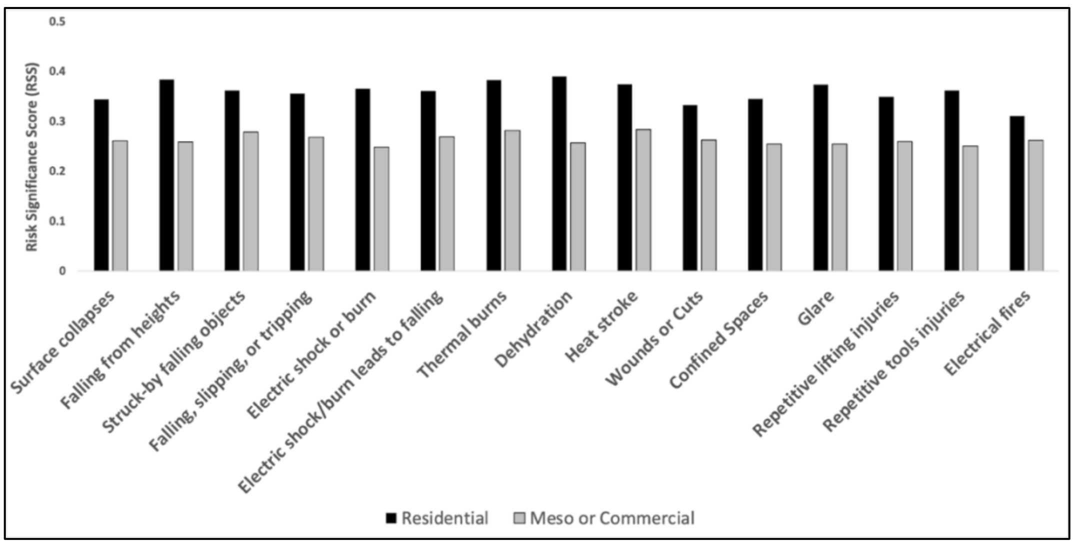

Figure 10 Risk Significance Score for Residential and Meso or Commercial Installers

Table 17 Risk Significance Score for Residential and Meso or Commercial Installers

Risks	Residential			Meso or Commercial		
	RSS	SD	**Rank**	RSS	SD	**Rank**
Surface collapses	0.345	0.272	**13**	0.261	0.272	**8**
Falling from heights	0.384	0.271	**2**	0.259	0.271	**10**
Struck-by falling objects	0.362	0.270	**7**	0.279	0.270	**3**
Falling, slipping, or tripping	0.356	0.286	**10**	0.269	0.286	**5**
Electric shock or burn	0.366	0.269	**6**	0.248	0.269	**15**
Electric shock/burn leads to falling	0.360	0.284	**9**	0.269	0.284	**4**
Thermal burns	0.383	0.271	**3**	0.282	0.271	**2**
Dehydration	0.390	0.287	**1**	0.257	0.287	**11**
Heat stroke	0.375	0.278	**4**	0.284	0.278	**1**
Wounds or Cuts	0.333	0.275	**14**	0.263	0.275	**6**
Confined Spaces	0.345	0.278	**12**	0.255	0.278	**12**
Glare	0.374	0.265	**5**	0.254	0.265	**13**
Repetitive lifting injuries	0.350	0.260	**11**	0.259	0.260	**9**
Repetitive tools injuries	0.361	0.281	**8**	0.250	0.281	**14**
Electrical fires	0.311	0.292	**15**	0.262	0.292	**7**

Note: Analytic dataset (n = 290)

4. Discussions

The RSS results in this study revealed that *Residential* installers are generally more concerned about installation safety risks than *Meso or Commercial* installers. This result is consistent with previous construction safety literature that identifies rates of injuries for certain risks (especially fall-related risks) being higher in smaller building projects (Huang & Hinze, 2003; Halabi et al., 2022; Dong et al., 2019). Reasons for this include smaller building (*Residential*) projects generally tend to have fewer resources (i.e., safety, training, financial) and policy incentives to ensure safety on-site. Moreover, *Residential* installers may have a tendency to misjudge, overlook, or neglect hazardous situations and use insufficient personal protective equipment because they associate less risk with smaller building projects.

The RSS resulting values (Table 17) are generally close to 0.30, which is considered low risk in the scale according to the literature (Shen et al., 2001; Zou & Zhang, 2009). This suggests that the solar installation workers in this study do perceive the safety risks as manageable. The magnitude of the RSS values are similar to those obtained in Zou & Zhang (2009). In Zou & Zhang (2009)'s survey study, construction worker RSS values for "poor precautions on working from heights" and "poor electrical safety" that ranged from 0.26-0.47. Our RSS values overlap with the literature indicates that solar workers' risk perception is not substantially different from other construction occupations.

The most important risks to *Residential* installation workers were the heat-related risks (i.e., *dehydration*, *heat stroke*, and *thermal burns*), *falling from heights,* and *glare.*

Whereas, *Meso or Commercial* installers found the heat-related risks along with *struck-by falling objects*, and *falling, slipping, or tripping* most important. Previous research has provided a detailed review of the effects, mitigation measures, and future research needed to address these risks (Duroha & Macht 2023). Workplace health and safety programs can utilize these results to inform and prioritize their mitigation measures and safety training efforts. Based on the results of this study, key safety measures and training that should be prioritized for both *Residential* and *Meso or Commercial* installations include work-rest schedules (Samaniego-Rascoń et al., 2019), early detection of heat-related illness, fall hazard identification (Erten et al., 2022), fall protection systems, electric shock and burn mitigation and clothing (White & Doherty, 2017), and an organized site layout.

4.1. Future Work & Limitations

A key limitation of this work is that the RSS equation only accounts for the *likelihood* and *severity* of risks. According to Zou & Zhang (2009), they feel that the equation may overlook outlier events (e.g., risks with a very low likelihood but a very high severity) without considering other metrics. Consequently, a future study that provides additional context to the risk questions would be encouraged. For instance, the failure modes and effect analysis (FMEA) would be a useful tool because it incorporates the *likelihood*, and *severity* of a risk situation, as well as the probability of safety measures adequately detecting or mitigating the risk (Ford et al., 2009; Younge et al., 2015). The FMEA can be used in conjunction with worker interviews to expand this study and further define areas of high risk within solar installation work. Additionally, future work could capture these

RSS values along with statistics on solar installer worker injuries to corroborate the rankings presented in this paper.

Another area of future work revolves around the standard deviation (SD) of workers' risk perceptions in this study. The standard deviation of the RSS in Table 17 are large in magnitude (0.260 to 0.287), which indicates substantial heterogeneity in workers' risk perception. This is especially clear in the case of *dehydration,* which has the largest RSS and SD for *Residential*. This means that some workers are reporting a very high risk of *dehydration*, while others are reporting a very low risk. Future work should center around understanding what types of workers are experiencing high and low risk in different situations. The introduction of additional factors to the analysis, such as age, work experience, and level of training to understand how various factors influence worker risk perceptions, would be valuable.

5. Conclusion

The study's aim was to measure the risk perception of solar installation workers. An RSS was utilized to quantify and rank the perception of solar workers regarding 15 installation safety risks based on the size of the installation. This study found that heat-related risks, *falling from heights*, and *glare* were the top concerns associated with *Residential* work. Whereas, heat-related risks, along with *struck-by-falling objects*, and *falling, slipping, or tripping,* were the top concerns for *Meso or Commercial* work. The results of this study can be used to inform workplace health and safety programs and site-specific safety plans regarding the relative importance of safety risks to installation workers.

Acknowledgments

Special thanks to Dr. Valerie Maier-Speredelozzi at The University of Rhode Island for providing support, guidance, and direction. Further, special thanks to Sara Lang, Jonah Crema, Michael Cascione for assisting with the questionnaire development and research. Special thanks to Sara Nunes, and Malinda Fry for assisting with data table visualization. Robert Hatch Multistate RH01234 provided partial funding support for this project. Finally, thanks to all the Sustainable Innovative Solutions (SIS) Lab members for their support.

References

Boslaugh, S., Watters, P. A. (2008). *Statistics in a nutshell - a desktop quick reference.* O'Reilly.

Chen, L. (2018). The risk management of medical device-related pressure ulcers based on the Australian/New Zealand Standard. *Journal of International Medical Research*, *46*(10), 4129–4139.

Dong, X. S., Jackson, R., Varda, D., Betit, E., & Bunting, J. (2019). Trends of Fall Injuries and Prevention in the Construction Industry. *CPWR.*

Duroha, J. C., & Macht, G. A. (2023). Solar installation occupational risks: A systematic review. *Safety Science*, *160*, 106048.

Duroha, J. C., Trandafir, S., Lang, C., Macht, G. A. (forthcoming). Solar Installers Safety Risk Perceptions: A Survey Study.

Erten, B., Oral, B., & Yakut, M. Z. (2022). The role of virtual and augmented reality in occupational health and safety training of employees in PV power systems and evaluation with a sustainability perspective. *Journal of Cleaner Production*, *379*, 134499.

Ford, E. C., Gaudette, R., Myers, L., Vanderver, B., Engineer, L., Zellars, R., Song, D. Y., Wong, J., & DeWeese, T. L. (2009). Evaluation of Safety in a Radiation Oncology Setting Using Failure Mode and Effects Analysis. *International Journal of Radiation Oncology, Biology, Physics*, *74*(3), 852–858.

Gunduz, M., & Ahsan, B. (2018). Construction safety factors assessment through Frequency Adjusted Importance Index. *International Journal of Industrial Ergonomics*, *64*, 155–162.

Halabi, Y., Xu, H., Long, D., Chen, Y., Yu, Z., Alhaek, F., & Alhaddad, W. (2022). Causal factors and risk assessment of fall accidents in the U.S. construction industry: A comprehensive data analysis (2000–2020). Safety Science, *146*, 105537.

Hanson, M., & Thatcher, A. (2020). Identifying Human Factors and Ergonomic Issues in Green Jobs: Facilitating Sustainable Green Jobs. In A. Thatcher, K. J. Zink & K. Fischer (Eds.), *Human Factors for Sustainability: Theoretical Perspectives and Global Applications* (pp. 171-192). CRC Press Taylor and Francis Group.

Ho, C., Lee, H. W., & Gambatese, J. A. (2020). Application of Prevention through Design (PtD) to improve the safety of solar installations on small buildings. Safety Science, 125, 104633.

Huang, X., & Hinze, J. (2003). Analysis of Construction Worker Fall Accidents. *Journal of Construction Engineering and Management*, *129*(3), 262–271.

Interstate Renewable Energy Council. (2021). *National Solar Jobs Census 2020*.https://irecusa.org/wp-content/uploads/2021/07/National-Solar-Jobs-Census-2020-FINAL.pdf (Accessed: 20 July 2023)

Interstate Renewable Energy Council. (2022). *National Solar Jobs Census 2021*.https://irecusa.org/wp-content/uploads/2022/10/National-Solar-Jobs-Census-2021.pdf (Accessed: 20 July 2023)

Interstate Renewable Energy Council. (2023). *National Solar Jobs Census 2022*. https://irecusa.org/programs/solar-jobs-census/ (Accessed: 20 July 2023)

Lette, A., Ambelu, A., Getahun, T., & Mekonen, S. (2018). A survey of work-related injuries among building construction workers in southwestern Ethiopia. *International Journal of Industrial Ergonomics*, *68*, 57–64.

Occupational Safety and Health Administration. (2018). *Employee Falls From Roof and Fractures Foot.* https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=109537.015 (Accessed: 1 August 2022)

Ong, N. A. F. M. N., Tohir, M. Z. M., Mutlak, M. M., Sadiq, M. A., Omar, R., & Said, M. S. M. (2022). BowTie analysis of rooftop grid-connected photovoltaic systems. *Process Safety Progress*, *41*(S1), S106–S117.

Ramasay, V., Feldman, D., Desai, J., & Margolis, R. (2021). U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021. National Renewable Energy Laboratory.

Samaniego-Rascón, D., Silva, M. C. G. da, Ferreira, A. D., & Cabanillas-Lopez, R. E. (2019). Solar energy industry workers under climate change: A risk assessment of the level of heat stress experienced by a worker based on measured data. *Safety Science*, *118*, 33–47. https://doi.org/10.1016/j.ssci.2019.04.042

Sen, A., Mohankar, A. S., Khamaj, A., & Karmakar, S. (2021). Emerging OSH Issues in Installation and Maintenance of Floating Solar Photovoltaic Projects and Their Link with Sustainable Development Goals. *Risk Management and Healthcare Policy*, *14*, 1939–1957.

Shen, L. Y., Wu, G. W. C., & Ng, C. S. K. (2001). Risk Assessment for Construction Joint Ventures in China. *Journal of Construction Engineering and Management*, *127*(1), 76–81.

Sovacool, B. K., Kryman, M., & Laine, E. (2015). Profiling technological failure and disaster in the energy sector: A comparative analysis of historical energy accidents. *Energy*, *90*, 2016–2027.

U.S. Department of Labor. (2017). *Green Job Hazards: Solar Energy*. Occupational Safety and Health Administration. https://www.osha.gov/green-jobs/solar (Accessed: 22 July 2022)

Xia, N., Wang, X., Griffin, M. A., Wu, C., & Liu, B. (2017). Do we see how they perceive risk? An integrated analysis of risk perception and its effect on workplace safety behavior. *Accident Analysis & Prevention*, *106*, 234–242.

Wang, D., Xie, X., Na, Z., Shen, W., & Fan, X. (2021). Photovoltaic Power System Fault Warning based on State Assessment. *IOP Conference Series: Earth and Environmental Science*, *632*(3), 032063.

White, J. R., & Mike Doherty (2017). Hazards in the Installation and Maintenance of Solar Panels. *IEEE*. 10.1109/ESW.2017.7914834

White House. (2021, April 22). *Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies.* https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ (Accessed: 22 July 2022)

Younge, K. C., Wang, Y., Thompson, J., Giovinazzo, J., Finlay, M., & Sankreacha, R. (2015). Practical Implementation of Failure Mode and Effects Analysis for Safety and Efficiency in Stereotactic Radiosurgery. International Journal of Radiation Oncology*Biology*Physics, *91*(5), 1003–1008.

Zou, P. X., & Zhang, G. (2009). Comparative Study on the Perception of Construction Safety Risks in China and Australia. Journal of Construction Engineering and Management,*135*(7), 620–627.

CHAPTER 5

Conclusion & Contribution

This dissertation utilized industrial and systems engineering skills to understand the current state of safety associated with solar installation work. The main motivations for this work were the increasing demand for solar infrastructure, the rapidly growing solar industry, and the lack of accident investigation research, reporting, and verification available for solar workers. This dissertation contributes to this research gap are as follows:

Manuscript 1, *Solar Installations & Their Occupational Risks,* conducted a preliminary systematic literature review of the occupational safety risks associated with solar installations utilizing the Scopus database as its main source. Manuscript 2, *Solar Installation Occupational Risks: A Systematic Review,* conducts a more detailed systematic literature review utilizing the Scopus, Web of Science, Science Direct, and PubMed databases as sources. These works collectively found that the four major occupational safety risk categories associated with PV installations are: (1) electrical and fire risks, (2) heat stress, (3) manual handling risks, and (4) fall risks. This work also provided strong direction for future research into these risk categories.

In Manuscript 3, *Solar Installation Safety Risk Perceptions: A Survey Study*, a survey is developed and administered to solar installations to understand their safety risk perceptions. This work also aimed to understand how the level of work experience, installation type, and company size influence these risk perceptions. This research found three types of solar installation workers based on risk perception (High, Moderate, and Low), with most installers having a Moderate risk perception. This research also found that, the proportion of installers in the High Likelihood/Severity class increased substantially as installation size decreased to residential and as company longevity and work experience increased. Heat-related risks, falling from heights, and glare were the top concerns associated with residential work. Whereas, heat-related risks, along with struck-by-falling objects, and falling, slipping, or tripping, were the top concerns for meso or commercial work.

Manuscript 4, *Ranking Solar Installation Safety Risk Perceptions: A Case of Installation Size*, builds on the survey study conducted in Manuscript 3 and ranks the relative importance of various safety risks to installers during residential and meso or commercial installations. This study found that, solar installation workers perceived the safety risks in this study as manageable. Consequently, safety measures and training that should be prioritized for both residential and meso or commercial installations include work-rest schedules, early detection of heat-related illness, fall hazard identification, fall protection systems, electric shock and burn mitigation and clothing, and an organized site layout.

Future Work

Future work includes diving deeper into understanding the safety obstacles and challenges experienced by the solar installation workforce. Manuscript 1 and 2 found that musculoskeletal disorder injuries or cumulative trauma disorders are a relatively unexplored area within the solar safety research. This dissertation encourages future work to explore the prevalence of musculoskeletal disorder injuries associated with solar installation work. Tools such as the NIOSH equation, the Standardized Nordic Assessment, and the Rapid Upper Limb Assessment could be particularly useful in this regard.

Future work should also explore the current state of workplace health and safety training and certifications associated with solar installation work (Manuscript 3). Survey studies, worker interviews, and observational studies can be utilized to identify and propose workplace health and safety training recommendations for solar companies. Moreover, this dissertation also highlights the need for more formalized reporting and verification of solar worker accident and injuries data (i.e., frequency, causes, and fatalities). More formalized statistics on solar worker injuries can be utilized by future work to corroborate the RSS rankings presented in Manuscript 4 of this dissertation. Lastly, future work can utilize the failure modes and effect analysis, in conjunction with worker interviews, to expand the RSS methodology and further define areas of high risk within solar installation work.

Lessons Learned

Overall, this dissertation provides a strong foundation for future solar safety research. One of the aims of this work was to reveal the need for more risk mitigation research for renewable energy workers. Workforce safety and development are key in transitioning from fossil fuel-based energy to renewable energy sources. Many research ideas surfaced on the path toward this dissertation but could not be explored due to extenuating circumstances. An example of this was exploring Utility Scale PV system reliability through operations research. However, I am satisfied with this work's path and excited about its findings' value within the solar safety community.

The biggest lesson I learned was the importance of consistency and perseverance. The literature review, data collection and analysis involved in this dissertation were challenging. It was very interesting to learn new statistical techniques such as Latent Class Analysis. I also enjoyed learning about the entire solar safety landscape (risks, mitigation measures, training etc.). However, this involved many long days and late nights. Above all this research taught me that I can achieve incredible goals if I stay positive, never give up, and make an honest effort one day at a time.

Appendix A: Questionnaire Items

How many years of work experience, approximately, do you have within the solar industry?
(Multiple Choice: 0-6 months, 6 months-1 year, 1 year, 2 years, 3 years, 4 years, 5 years, 6 years, 7 years, 8 years, 9 years, 10 years, 11 years, 12 years, 13 years, 14 years, 15 years, 16 years, 17 years, 18 years, 19 years, 20+ years)

What is the approximate size of the solar photovoltaic systems you regularly install?
(Select all that apply: 0-5 kW, 5-10 kW, 10-25 kW, 25-50 kW, 50-100 kW, 100-1 MW, 1-5MW, 5+ MW)

How many years, approximately, has your company been installing solar photovoltaic systems?
(Multiple Choice: 0-9 months, 1-5 years, 6-10 years, 11-15 years, 16-20 years, 20+ years)

How would you rate the *likelihood* of the following occupational risks occurring during a solar installation?
(Frequentist Likert scale: Extremely Low, Low, Neutral, High, Extremely High; Not Applicable)

1. Surfaces collapsing under workers weight (e.g., roofs, structural components, PV panels)
2. Falling from heights (e.g., roofs, ladders, working platforms)
3. Struck-by falling objects (e.g., tools, and equipment)
4. Falling, slipping, or tripping on-site (e.g., lack of space, tripping on electrical wiring or fall protection)
5. Electric shock or burn (e.g., from electrical wiring, live components)
6. Electric shock or burn leading to falling from heights (e.g., roof, ladder, working platform)
7. Thermal burns from handling solar panels (e.g., heat from panels)
8. Dehydration (e.g., body cramps, feeling thirsty, dizzy, or tired)
9. Heat stroke (e.g., loss of consciousness, seizures, or high body temperatures)
10. Wounds or cuts from handling materials or tools (e.g., sharp edges, fragments, power or hand tools)
11. Working in confined spaces (e.g., unable to breathe properly, awkward posture)
12. Glare from panels or roofing materials (e.g., loss of visibility, dizziness, heat stress)
13. Injuries from repetitive lifting of solar panels and other materials (e.g., muscle pulls, back pain, sprains, and strains)
14. Injuries from repetitive use of hand and power tools (e.g., pains in hands or wrist area)
15. Electrical components or site materials catching fire (e.g., solar panels, electrical wiring, live components, nearby flammable materials)

How would you rate the *severity* of the following occupational risks occurring during a solar installation?
(Frequentist Likert scale: Extremely Low, Low, Neutral, High, Extremely High; Not Applicable)

1. Surfaces collapsing under workers weight (e.g., roofs, structural components, PV panels)
2. Falling from heights (e.g., roofs, ladders, working platforms)
3. Struck-by falling objects (e.g., tools, and equipment)
4. Falling, slipping, or tripping on-site (e.g., lack of space, tripping on electrical wiring or fall protection)
5. Electric shock or burn (e.g., from electrical wiring, live components)
6. Electric shock or burn leading to falling from heights (e.g., roof, ladder, working platform)
7. Thermal burns from handling solar panels (e.g., heat from panels)
8. Dehydration (e.g., body cramps, feeling thirsty, dizzy, or tired)
9. Heat stroke (e.g., loss of consciousness, seizures, or high body temperatures)
10. Wounds or cuts from handling materials or tools (e.g., sharp edges, fragments, power or hand tools)
11. Working in confined spaces (e.g., unable to breathe properly, awkward posture)
12. Glare from panels or roofing materials (e.g., loss of visibility, dizziness, heat stress)
13. Injuries from repetitive lifting of solar panels and other materials (e.g., muscle pulls, back pain, sprains, and strains)
14. Injuries from repetitive use of hand and power tools (e.g., pains in hands or wrist area)
15. Electrical components or site materials catching fire (e.g., solar panels, electrical wiring, live components, nearby flammable materials)

Appendix B – Latent Class Analysis Preliminary Tests & Models

Table B.1. Geographic Locations Distribution of Survey Participants

State Location	Number of Participants	Percentage of Participants
Alabama	3	1.00%
Alaska	10	3.40%
Arizona	7	2.40%
California	57	19.70%
Colorado	16	5.50%
Delaware	2	0.70%
Florida	16	5.50%
Georgia	5	1.70%
Hawaii	1	0.30%
Idaho	3	1.00%
Illinois	7	2.40%
Iowa	7	2.40%
Kansas	6	2.10%
Kentucky	1	0.30%
Maryland	1	0.30%
Massachusetts	8	2.80%
Michigan	3	1.00%
Minnesota	6	2.10%
Missouri	2	0.70%
Montana	1	0.30%
Nebraska	1	0.30%
Nevada	1	0.30%
New Jersey	6	2.10%
New Mexico	5	1.70%
New York	21	7.20%
North Carolina	1	0.30%
Ohio	10	3.40%
Oklahoma	2	0.70%
Oregon	9	3.10%
Pennsylvania	5	1.70%
Rhode Island	6	2.10%
South Carolina	3	1.00%
Tennessee	5	1.70%
Texas	20	6.90%
Utah	6	2.10%
Virginia	4	1.40%
Washington	20	6.90%
West Virginia	1	0.30%
Wisconsin	2	0.70%

Appendix C – Likelihood Latent Class Models

Table C.1. 1-Class Likelihood Model

Saftey Risk Characteristic	Latent Class 1:
Class membership probability	*100%*
Surface collapses	○
Falling from heights	○
Struck-by falling objects	○
Falling, slipping, or tripping	○
Electric shock or burn	○
Electric shock/burn leads to falling	○
Thermal burns	○
Dehydration	○
Heat stroke	○
Wounds or Cuts	○
Confined Spaces	○
Glare	○
Injuries from repetitive actions	○
Injuries from repetitive actions	○
Electrical fires	○

Key: (blank) < 30% 30% ≤ ○ < 50% 50% ≤ ● < 75% ⬤ ≥ 75%

Table C.2. 2-Class Likelihood Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:
Class membership probability	*10.01%*	*89.99%*
Surface collapses	⬤	
Falling from heights	⬤	○
Struck-by falling objects	⬤	○
Falling, slipping, or tripping	⬤	○
Electric shock or burn	⬤	○
Electric shock/burn leads to falling	⬤	○
Thermal burns	⬤	○
Dehydration	⬤	○
Heat stroke	⬤	○
Wounds or Cuts	⬤	○
Confined Spaces	⬤	○
Glare	⬤	○
Injuries from repetitive actions	⬤	○
Injuries from repetitive tools	⬤	○
Electrical fires	⬤	○
Key: (blank) < 30% 30% ≤ ○ > 50%	50% ≤ • < 75%	⬤ ≥ 75%

Table C.3. 3-Class Likelihood Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:	Latent Class 3:
Class membership probability	*9.97%*	*12.66%*	*77.38%*
Surface collapses	●		○
Falling from heights	●		○
Struck-by falling objects	●		○
Falling, slipping, or tripping	●		○
Electric shock or burn	●		○
Electric shock/burn leads to falling	●		○
Thermal burns	●		○
Dehydration	●		○
Heat stroke	●		○
Wounds or Cuts	●		○
Confined Spaces	●		○
Glare	●		○
Injuries from repetitive actions	●		○
Injuries from repetitive tools	●		○
Electrical fires	●		○
Key: (blank) < 30%	30% ≤ ○ > 50%	50% ≤ • < 75%	● ≥ 75%

Table C.4. 4-Class Likelihood Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:	Latent Class 3:	Latent Class 4:
Class membership probability	*9.95%*	*12.52%*	*58.91%*	*18.62%*
Surface collapses	●			•
Falling from heights	●		○	•
Struck-by falling objects	●		○	○
Falling, slipping, or tripping	●			●
Electric shock or burn	●		○	○
Electric shock/burn leads to falling	●		○	•
Thermal burns	●		○	○
Dehydration	●		○	
Heat stroke	●		○	○
Wounds or Cuts	●		○	
Confined Spaces	●		○	
Glare	●		○	•
Injuries from repetitive actions	●		○	○
Injuries from repetitive tools	●		○	○
Electrical fires	●		○	○
Key: (blank) < 30%	30% ≤ ○ > 50%	50% ≤ • < 75%	● ≥ 75%	

Table C.5. 5-Class Likelihood Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:	Latent Class 3:	Latent Class 4:	Latent Class 5:
Class membership probability	*9.87%*	*43.22%*	*11.36%*	*23.14%*	*12.41%*
Surface collapses	●		•	•	
Falling from heights	●	○	•	○	
Struck-by falling objects	●		○	•	
Falling, slipping, or tripping	●		•	•	
Electric shock or burn	●	○	•	○	
Electric shock/burn leads to falling	●	○	•	○	
Thermal burns	●	○	○	○	
Dehydration	●	○	○	○	
Heat stroke	●	○	○	○	
Wounds or Cuts	●	○		○	
Confined Spaces	●	○		○	
Glare	●		•	•	
Injuries from repetitive actions	●	○	•		
Injuries from repetitive tools	●	○	●		
Electrical fires	●	○	○	○	

Key: (blank) < 30% 30% ≤ ○ > 50% 50% ≤ • < 75% ● ≥ 75%

Appendix D – Severity Latent Class Models

Table D.1. 1-Class Severity Model

Safety Risk Characteristic	Latent Class 1:
Class membership probability	*100%*
Surface collapses	○
Falling from heights	○
Struck-by falling objects	•
Falling, slipping, or tripping	○
Electric shock or burn	○
Electric shock/burn leads to falling	○
Thermal burns	•
Dehydration	○
Heat stroke	○
Wounds or Cuts	○
Confined Spaces	○
Glare	○
Injuries from repetitive actions	○
Injuries from repetitive tools	○
Electrical fires	○

Key: (blank) < 30% 30% ≤ ○ > 50% 50% ≤ • < 75% ⬤ ≥ 75%

Table D.2. 2-Class Severity Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:
Class membership probability	*13.31%*	*86.69%*
Surface collapses		●
Falling from heights		●
Struck-by falling objects		●
Falling, slipping, or tripping		●
Electric shock or burn		○
Electric shock/burn leads to falling		●
Thermal burns		●
Dehydration		●
Heat stroke		●
Wounds or Cuts		●
Confined Spaces		●
Glare		●
Injuries from repetitive actions		●
Injuries from repetitive tools		●
Electrical fires		●
Key: (blank) < 30% 30% ≤ ○ > 50%	50% ≤ ● < 75%	⬤ ≥ 75%

Table D.3. 3-Class Severity Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:	Latent Class 3:
Class membership probability	*11.96%*	*76.37%*	*11.82%*
Surface collapses	●	○	
Falling from heights	●	○	
Struck-by falling objects	●	•	
Falling, slipping, or tripping	●	○	
Electric shock or burn	●	○	
Electric shock/burn leads to falling	●	○	
Thermal burns	●	•	
Dehydration	●	○	
Heat stroke	●	○	
Wounds or Cuts	●	○	
Confined Spaces	●	○	
Glare	●	○	
Injuries from repetitive actions	●	○	
Injuries from repetitive tools	●	○	
Electrical fires	●	○	
Key: (blank) < 30%	30% ≤ ○ > 50%	50% ≤ • < 75%	● ≥ 75%

Table D.4. 4-Class Severity Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:	Latent Class 3:	Latent Class 4:
Class membership probability	*11.83%*	*45.95%*	*30.30%*	*11.91%*
Surface collapses		○	●	●
Falling from heights		○	●	●
Struck-by falling objects		○	•	●
Falling, slipping, or tripping		○	○	●
Electric shock or burn		○	•	●
Electric shock/burn leads to falling		○	●	●
Thermal burns		•	○	●
Dehydration		•	○	●
Heat stroke		○	•	●
Wounds or Cuts		○	○	●
Confined Spaces		○		●
Glare		○	○	●
Injuries from repetitive actions		○		●
Injuries from repetitive tools		○		●
Electrical fires		○	•	●
Key: (blank) < 30%	30% ≤ ○ > 50%	50% ≤ • < 75%	● ≥ 75%	

Table D.5. 5-Class Severity Model

Saftey Risk Characteristic	Latent Class 1:	Latent Class 2:	Latent Class 3:	Latent Class 4:	Latent Class 5:
Class membership probability	*4.16%*	*11.84%*	*37.71%*	*34.46%*	*11.83%*
Surface collapses	•	●	•	○	
Falling from heights		●	○	•	
Struck-by falling objects		●	•	•	
Falling, slipping, or tripping	○	●	○	○	
Electric shock or burn		●	○	○	
Electric shock/burn leads to falling	○	●	○	○	
Thermal burns	●	●	•	○	
Dehydration	•	●	•	○	
Heat stroke		●	•	○	
Wounds or Cuts	•	●		•	
Confined Spaces	•	●	•	○	
Glare	•	●		•	
Injuries from repetitive actions	○	●		○	
Injuries from repetitive tools	•	●	○	○	
Electrical fires	•	●	•	○	
Key: (blank) < 30%	30% ≤ ○ > 50%	50% ≤ • < 75%	● ≥ 75%		

Appendix E- Interview Consent Form

IRB
Consent Form for Research

IRB Consent Form for Research

URI USE ONLY - IRB#:

The University of Rhode Island
Office for Research Integrity
Institutional Review Board

Informed Consent Form for Social Science Research
The University of Rhode Island

Dear Interview Participant:

You are invited to participate in The University of Rhode Island's (URI) interview about solar installation safety. This interview is part of a questionnaire development process to understand solar installers' perception of the safety risks associated with solar installations. The study's title is the *Risk Perceptions Associated with Solar Energy Installations Survey*. The goal of this interview is to receive feedback or suggestions from solar workers about the content and clarity of the *Risk Perceptions Associated with Solar Energy Installations Survey* questionnaire. This interview can be in-person or virtual depending on your availability or preference.

You are being invited to participate in this study because you are a solar professional.

Our research purpose is <u>not</u> to regulate or provide citations, but to understand your working conditions, and perspectives. We are not funded by or associated with any government or state agencies. This work will directly contribute to research at URI.

There are minimal known risks or benefits associated with this study. There is no cost to you to being a part of this interview. The interview questions in this study have been reviewed according to the URI Institutional Review Board procedures. The interview will take a discussion or dialogue format and will take less than one hour, and the information you provide is completely confidential and will not be disclosed to anyone without your permission.

Although there are no direct benefits of the study, your answers will help shape and develop this questionnaire to incorporate the proper terminology and right questions. Any feedback you provide will be strongly considered and potentially incorporated into the questionnaire.

Notes from the interview will be stored electronically through a secure server and will only be seen by the research investigators during the study. The only persons who will have access to these notes are the research investigators, and the Institutional Review Board (IRB). The information from this study may be published in scientific journals or presented at scientific meetings but the information will be reported as group or summarized data and your identity will be kept strictly confidential.

Your participation is very important to us if we are to gain a fair and accurate understanding of your perception regarding solar installation safety. However, the decision to participate in this

interview is entirely up to you. You may refuse to take part in the interview at any time without affecting your relationship with the investigators of this study or URI. Your decision will not result in any loss of benefits to which you are otherwise entitled. You have the right to withdraw completely from this interview at any point during the process; additionally, you have the right to request that the researchers not use any of your responses.

You must be at least 18 years of age or older to consent to take part in this research study.

If you have any questions about this study, please feel free to reach out to any of the research investigators through the following contacts:

Dr. Gretchen Macht (Assistant Professor, Industrial and Systems Engineering, University of Rhode Island) at macht@uri.edu.

Dr. Simona Trandafir (Associate Professor, Environmental and Natural Resource Economics, University of Rhode Island) at simona@uri.edu.

Jesse Duroha (Graduate Researcher, Industrial & Systems Engineering, University of Rhode Island) at jesse_duroha@uri.edu.

Additionally, you may contact the URI Institutional Review Board (IRB) if you have questions regarding your rights as a research participant or concerns which you do not feel you can discuss with the investigators listed above. The URI IRB may be reached by phone at (401) 874-4328 or by email at researchintegrity@etal.uri.edu. You may also contact the URI Vice President for Research and Economic Development by phone at (401) 874-4576.

Thank you for considering your participation in this research.

I have read and understand the above consent form, I certify that I am at least 18 years of age and by signing this form I indicate my willingness to voluntarily take part in the study.

______________________________________ _______________

Participant Name (please print) Date

______________________________________ _______________

Participant Signature Date

THE UNIVERSITY OF RHODE ISLAND

IRB
Consent Form for Research

____ ________________

Person Obtaining Consent Date