Institution: University of Warwick		
Unit of Assessment: B12 – Engineering		
Title of case study: Impact of fire and explosion research on industrial practices and government policy		
Period when the underpinning research was undertaken: 2014 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Jennifer X Wen	**Role(s) (e.g. job title):** Professor of Engineering	**Period(s) employed by submitting HEI:** May 2013 – Present
Period when the claimed impact occurred: 2016 - 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Professor Jennifer Wen's research has been applied to a range of safety-critical scenarios across the energy, built environment and transport sectors. Computational fluid dynamics (CFD) based models for cryogenic liquid hydrogen spill and hydrogen gas explosions, developed and validated in her team, have been used to conduct numerical simulations for global companies including Air Liquide and Shell India. This allowed them to quantify hazards of 'worst-case' scenarios and inform the development of mitigation measures to improve safety in hydrogen storage and utilization. The research has contributed to cost savings in the development of fire protection measures (FM Global) and enhanced consultancy activities (Det Norske Veritas, or DNV). Warwick's engineering model for vented hydrogen explosions led to the improved European Standard EN14994, which is applied across 34 countries. It has already been used by Arup and Bureau Veritas; and has benefited UK and Chinese government projects around the safe use of hydrogen for domestic heating and transport in support of their decarbonisation targets.

2. Underpinning research (indicative maximum 500 words)

In 2013 Professor Jennifer Wen established and currently leads Warwick FIRE, a multi-disciplinary research laboratory for fundamental and applied research in fire, explosions and other safety-related reactive and non-reactive flows. She is an authority in fire and explosion modelling through CFD. Her models address physical effects and consequence analysis for a range of accidental release scenarios, which are critical to the safe design and operation of facilities involving flammable gases/liquids. They have also undergone extensive validations with measurements from published laboratory and full-scale tests as well as with proprietary data from her wide network of industrial and academic collaborators. Professor Wen's research centres on the development and validation of physics based sub-models within the frame of open-source CFD code OpenFOAM® for the underlying physical and chemical processes associated with fire and explosion safety in conventional **[3.1]** and emerging energy technology applications **[3.2-3.5],** and the built environment **[3.6]**, each of which has been integral to the subsequent impacts on industry operations and safety standards. Key insights are as follows:

- Efficient CFD modelling approach for gas dispersion in complex geometries has been developed to save computational costs. The approach was based on the use of body-fitted grids for medium to large-scale objects while combining multiple small-scale obstacles in proximity and using porous media models to represent their blockage effects. Validation has been conducted with large-scale gas dispersion experiments carried out by KTP partner DNV **[3.1]**, funded in part through a TSB (Innovate UK) grant **[G1]**.
- A new engineering model (EM), an output of the HySEA grant **[G2],** for calculating peak overpressures in vented explosions has been developed based on external cloud formation and its combustion. The model addresses realistic accidental scenarios involving mixture

stratification, obstacles, initial turbulence and enclosures with different aspect ratios. It has been simplified into a single four parameter equation, with two parameters based on physical properties of different fuel mixtures and two based on the actual enclosure and obstacles geometry **[3.2]**. This greatly reduces the implementation and calculation effort. Validation has been conducted with measurements for hydrogen, natural gas and propane in different geometric configurations.

- HyFOAM, dedicated to hydrogen safety research, has been developed within the frame of OpenFOAM®. It has been further improved in HySEA project **[G2]** for modelling large scale explosions. The code uses the flame wrinkling combustion model with established formulations added to consider laminar flame speed variations with hydrogen concentration and non-unity Lewis number effects **[3.3-3.4]**. The improved model has been used to numerically study the worst-case scenario involving pressurized hydrogen storage cylinders enveloped by an explosion using measurements from large-scale tests commissioned by Shell Global Solutions for validation.
- Professor Wen's team has developed CFD based predictive tool for the pool spread, evaporation and cloud dispersion from cryogenic liquified natural gas and hydrogen spill **[3.5]** during the EU-funded Initial Training Network SafeLNG PITN-GA-2013-606754-SafeLNG (2014-2018) for which Wen was the Co-ordinator and Scientist in Charge **[G4]**. The model has been further improved by her researchers to predict cloud formation from potential accidental releases of cryogenic liquid hydrogen tanks in PRESLHY **[G3]**, focusing on the size of the maximum cloud within the flammability range.
- With funding from FM Global **[G5]**, Professor Wen's team has improved the treatment for thermal radiation in FireFOAM (2015 to 2019), the fire simulation solver within OpenFOAM with robust but computationally efficient grey gas models, as well as more detailed models which consider band dependence of gas radiation properties. They also developed a new 'box' model to capture the spectral properties of gas radiation **[3.6]**: this offers an effective and yet efficient solution to cater for the spectral radiative properties of gaseous combustion products and water droplets in simulating fire suppression by sprinklers.

3. References to the research (indicative maximum of six references) **Warwick = Bold**

<u>All research papers and conference proceedings underwent a peer-review process</u>
[3.1] Ahmed, I., Bengherbia, T., Zhvansky, R., Ferrara, G., **Wen, J. X.** and **Stocks, N. G.** (2016) *Validation of geometry modelling approaches for offshore gas dispersion simulations*. Journal of Loss Prevention in the Process Industries, 44. pp. 594-600. doi:10.1016/j.jlp.2016.07.009
[3.2] Sinha, A.and **Wen, J. X. (**2019) *A simple model for calculating peak pressure in vented explosions of hydrogen and hydrocarbons.* International Journal of Hydrogen Energy, 44 (40), pp. 22719-22732, doi:10.1016/j.ijhydene.2019.02.213 [**gold open access**]
[3.3] Madhav Rao, V. C., Sathiah, P. and **Wen, J. X**. (2018) *Effects of congestion and confining walls on turbulent deflagrations in a hydrogen storage facility-part 2 : numerical study.* International Journal of Hydrogen Energy, 43 (32). pp. 15593-15621. doi:10.1016/j.ijhydene.2018.06.100
[3.4] Madhav Rao, V. C. and **Wen, J. X.** (2019) *Numerical modelling of vented lean hydrogen deflagrations in an ISO container.* International Journal of Hydrogen Energy, 44 (17), pp. 8767-8779. doi:10.1016/j.ijhydene.2018.11.093
[3.5] Nazarpour, F., Dembele, S. and **Wen, J. X.** (2017) Modelling Hydrogen Spill, Spread, Evaporation and Dispersion. In: International Conference on Hydrogen Safety, Hamburg, Germany, 11-13 Sep. 2017. https://hysafe.info/uploads/2017_papers/152.pdf
[3.6] Sikic, I.**,** Dembele, S. and **Wen, J. X.** (2019) *Non-grey radiative heat transfer modelling in LES-CFD simulated methanol pool fires.* Journal of Quantitative Spectroscopy and Radiative Transfer. doi:10.1016/j.jqsrt.2019.06.004

<u>Grants</u>
[G1] Wen, J. X. (PI) and **Stocks, N.G.,** *University of Warwick and Det Norske Veritas Limited KTP* **Sponsor:** Innovate UK [508929] **Duration:** Jan 2014 – Dec 2015 **Award:** GBP80,299
[G2] Wen, J. X. (PI), *Improving Hydrogen Safety for Energy Applications (HySEA) through pre-normative research on vented deflagrations*. **Sponsor:** European Commission [671461] **Duration:** Sep 2015 - Nov 2018 **Award:** EUR450,390

[G3] Wen, J. X. (PI), *Pre-normative REsearch for Safe use of Liquide HYdrogen (PRESLHY)*. **Sponsor:** European Commission [779613] **Duration:** Jan 2018 - Dec 2020 **Award:** EUR94,047
[G4] Wen, J.X. (**Co-ordinator and Scientist in Charge**), *Numerical characterization and simulation of the complex physics underpinning the Safe handling of Liquefied Natural Gas (SafeLNG)*. **Sponsor:** European Commission [606754] **Duration:** Feb 2014 – Jan 2018 **Award:** EUR1,761,549.
[G5] Wen, J. X. (PI), *Development of sub-models for more accurate treatment of radiative heat transfer in FireFOAM for the simulations of fires and fire suppression by watermist*. **Sponsor:** FM Global **Duration:** Jan 2014 – Jun 2017 **Award:** GBP87,385

4. Details of the impact (indicative maximum 750 words)

Impact on industry (1): assisting hazard analysis and the development of mitigating measures to improve safety in hydrogen energy applications

As a zero-emissions fuel that is seen as a viable alternative to fossil fuels, hydrogen has been identified in the European Strategic Energy Technology Plan as having an important role to play in achieving a 60~80% reduction in greenhouse gases by 2050. Yet while it is inherently safer as well as more environmentally sound than other fuels, it has a wider flammability range. Hydrogen gas is odourless and pure hydrogen flames are invisible. Explosions - thankfully rare - can cause damage to facilities and/or surrounding properties, as well as injury or loss of life. A recent example includes damage of 60 homes in an explosion at a hydrogen fuel cell plant in California **[5.1a]**, with a vast emergency services response often required in these circumstances. The average cost of a hydrogen facility incident in monetary terms has been estimated at around USD33,000,000 **[5.1b]**.

Between 2016 and 2020 Professor Wen and her team worked with a range of global companies who are leaders in gas technology, applying Warwick FIRE's research to safety-critical scenarios across several industrial sectors, including energy, built environment and transport. These forward-planning strategies have at their heart the health and safety of employees and any others who might find themselves in the vicinity of a leak or explosion, but they also serve to foster confidence between companies, authorities and the public. Commercial benefits such as improved sales and cost savings have also been achieved in some cases.

Air Liquide S.A. is a French multinational company which supplies industrial gases and services to industries including medical, chemical and electronic manufacturers. It employs 50,000 staff across 80 countries and serves more than 2,000,000 customers and patients. The company is increasingly focusing on cryogenic liquid hydrogen (CryoLH2) as a storage medium in fuelling stations as its high density renders storage of large quantities possible in compact facilities. However, there are safety concerns related to accidental release of CryoLH2, which is typically −252.87°C and below the freezing temperature of oxygen (O_2) (-218.8°C). In addition, it evaporates with a volume expansion of 1:848, posing significant risk as a highly flammable gas **[5.2]** with a concomitant risk of suffocation in enclosed spaces. Between November 2019 and March 2020 Wen's team conducted CFD predictions of potential accidental releases from cryogenic tanks to assess the mitigation effects of retention pools in limiting the size of the dispersed hydrogen cloud. The predictions have enabled Air Liquide to establish internal rules about the compulsory requirements for retention pools and their recommended sizes according to the dimensions of the CryoLH2 storage tanks in different facilities. "*This has considerable impact on the safe operation of our worldwide hydrogen business*," says the Lead Engineer of Process Safety at Air Liquide. **[5.2].**

Bureau Veritas specialises in testing, inspection and certification across in a variety of sectors, from building and infrastructure through agri-food and commodities to marine and offshore, in over 140 countries. Between 2019 and early 2020, Service Risques Industriels of Bureau Veritas Exploitation used Warwick FIRE's engineering model (EM) for a hydrogen station case study to evaluate the maximum overpressure level in a container filled with hydrogen at high pressure. "*This constituted a vulnerability study to ensure customer safety… the EM correlation will be* *incorporated into our programme of risk studies for hydrogen and biogas going forward*," stated the Process Safety Engineer of Service Risques Industriels. **[5.3]**.

Shell India Markets Private Ltd "*plans to apply HyFOAM code in design analysis and facility siting to model large-scale hydrogen explosions in storage centres, hydrogen or/and multi-fuel refuelling stations*," says Shell India Markets' Technical Safety Engineer. Following the collaboration on the development of HyFOAM between 2016 and 2019, Shell have supplied Warwick FIRE with the in-house developed PDRFOAM, which will enable Professor Wen's group to extend its modelling to deal with more complex geometries. **[5.4]**.

Impact on industry (2): Reducing the cost in developing fire protection measures and conducting quantified risk analysis for the petrochemical industry

FM Global is a US-based international insurance company that specializes in loss prevention services in the Highly Protected Risk property insurance market sector. It has used the improved FireFOAM models within the company to evaluate fire risk and suppression methods to enhance practical fire protection measures. The Group Manager Fire Dynamics, says: "*The model and numerical tool that Warwick's research team contributed to develop has enabled our researchers and engineers to better understand heat transfer and fire dynamics, and to conduct technically robust engineering evaluation and design in a cost-effective manner*." **[5.5]** The application of the new tool has significantly reduced the number of costly large-scale fire tests (around USD100,000 (02-2020) each) and minimized the turnover time for engineering problem-solving. The code has been released by FM Global for free downloading by worldwide industry and academia for fire protection analysis **[5.6].** The company has been using the improved model since 2018; and coupled it with a physics-based model for radiation attenuation by watermist which they developed internally.

Det Norske Veritas (DNV GL) is an international accredited registrar and classification society, headquartered in Norway, which between 2014 and 2016 collaborated in a Knowledge Transfer Partnership (KTP) with Professor Wen. The KTP "*provided an important contribution to strengthen some of [DNV's] services… [which] relate to the risk assessment and advanced modelling of major hazardous scenarios in oil and gas installations*," according to the partner's final report. **[5.7]** The KTP led to an enhancement of the predictive accuracy of some specific modelling tools. DNV used the simplified geometric treatment in simulating gas dispersions on offshore oil platforms, floating production systems and process plants in their consultancy services for the oil and gas industry. This resulted in an increase of GBP400,000 in annual sales turnover (predicted to grow to GBP2,000,000 after three years) **[5.7]**, with a pre-tax profit of GBP100,000 in 2016.

Impact on policy makers: setting international standards, informing government policies

Hydrogen is expected to play an important role in helping to decrease carbon emissions as governments around the world set ambitious targets to avoid the most severe consequences of climate change. The EU has proposed to cut greenhouse gas emissions by at least 55% by 2030 in an effort to be climate neutral by 2050. China has come under international and domestic pressure to reduce its carbon footprint – the world's largest since 2004 – and in September 2020 President Xi Jinping pledged to stop releasing carbon emissions by 2060. The UK Government's 10-point green plan **[5.8]**, includes "*[boosting] hydrogen production, with the promise of a town heated entirely by hydrogen by the end of the decade*." Professor Wen's simplified engineering models (EM) and CFD techniques have been used in governments' planning from a safety perspective and for instigating risk mitigation measures as they scale-up hydrogen energy applications.

The European Committee for Standardisation (CEN) brings together national standardisation bodies of 34 countries to develop European and other technical standards. CEN/TC305 is the technical committee (TC) responsible for *Potentially Explosive Atmospheres - Explosion Prevention and Protection*, and CEN/TC305/WG3 is the working group (WG) for *Devices and Systems for Explosion Prevention and Protection*.

The CEN/TC305/WG3/ahGE meeting in Vienna on 14-15 June 2019 decided to include the EM, based on semi-empirical correlations developed by Warwick FIRE for vent panel design for explosion mitigation, in the next version of European Standards EN 14994 **[5.9]**. The standard, which will apply across 34 countries, comes into effect in mid-2021. From then, all European companies designing venting panels for hydrogen installations have to follow the new version of the standard. This will lead to wider applications of the EM, which has already received several applications **[5.3, 5.10a, 5.11a]** after it was published in gold open access **[3.2]**.

The Chinese Government's Energy Strategy Programme in February 2020 adopted the EM in the safe design of a hydrogen station in Guangdong province. The Vice Chair of the Standards Committee for Hydrogen Energy said he was confident that "*the Warwick FIRE EM will be widely used in China to help ensure the inherently safer design of these refuelling stations and other hydrogen energy applications*" **[5.10a]**. At the time of writing the supporting statement, another 50 hydrogen refuelling stations were planned for the remainder of 2020 **[5.10a]**; by June 2020, 11 had been built, with a further 200 now planned for construction in the next few years **[5.10b]**.

The UK's Department for Business, Energy and Industrial Strategy (BEIS), as part of the Government's Clean Growth Strategy, established Hy4Heat in 2018. This programme aims to establish whether it is technically possible, safe and convenient to use zero-carbon hydrogen gas in residential and commercial buildings and gas appliances; such projects, if successful, could represent a seismic shift in decarbonisation for the whole of the UK – around 35% of UK's CO_2 emissions come from the burning of natural gas, and the majority of this is from the heating of homes and cooking **[5.11a]**.

Hy4Heat is project-managed by Arup, who, in conducting a thorough assessment of the safety measures required, used the EM developed by Warwick FIRE to predict the consequences of an internal vented explosion following the ignition of a confined hydrogen cloud within a domestic setting **[5.11b]**. The Senior Consultant of Resilience and Risk, Arup, confirmed that "*the Warwick FIRE group has been critical to the analysis work in the Hy4Heat Safety Assessment since 2019.*"

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1a] Vice article (April 2020, https://tinyurl.com/131t9dgg)
[b] *Energy* paper (2015, doi:10.1016/j.energy.2015.07.043)
[5.2] Statement from the Lead Engineer for Process Safety, Air Liquide
[5.3] Statement from the Ingénieur Risques Industriels, Service Risques Industriels, Bureau Veritas Exploitation, France
[5.4] Statement from the Technical Safety Engineer, Shell Technology Centre Bangalore**,** Shell India Markets Private Limited
[5.5] Statement from the Staff Vice President, Manager of the Fire Dynamics group in the Research Division of FM Global
[5.6] https://github.com/fireFoam-dev/fireFoam-2.2.x
[5.7] Det Norske Veritas (DNV) Knowledge Transfer Partnership report (2016)
[5.8] The Guardian article (Nov 2020, https://tinyurl.com/4zcsensq)
[5.9] Statement from the Technical Director of GexCon AS, Norway. Convenor of CEN/TC305
[5.10a] Statement from the President of IAHE Standards Division; Vice Chair，ISO/TC197 Hydrogen Technology; Vice Chair, SAC/TC309 Hydrogen Energy Chair, SAC/TC31/SC8 Gas Cylinders/High Pressure Vehicle Fuel Tanks, Vice Director, National Safety Committee of Pressure Vessels and Vice President, China Society of Pressure Vessels, CSME **[b]** NOW Gmbh Hydrogen in China factsheet (https://tinyurl.com/1wagno0d)
[5.11a] Hy4Heat programme FAQ (https://tinyurl.com/5cv2vnue) **[b]** Statement from the Senior Consultant of Resilience and Risk, Arup on Hy4Heat project