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Fire Hazards at the Wildland Urban Interface: a Perspective From the WUIVIEW Project

Giordano E. Scarponi[a]*, Pascale Vacca[b], Elsa Pastor[b], Eulàlia Planas[b], Valerio Cozzani[a]

[a] LISES - Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum - Università di Bologna, via Terracini n.28, 40131 Bologna, Italy.
[b] Centre for Technological Risk Studies (CERTEC), Department of Chemical Engineering, Universitat Politècnica de Catalunya, BarcelonaTech, Catalonia.
giordano.scarponi@unibo.it

Wildland Urban Interface (WUI) fires are posing tremendous management challenges in terms of civil protection and fire mitigation. Many critical factors are contributing and increasing the risk at the WUI, such as the presence of all sorts of fuels whose hazard is poorly characterized and disregarded by residents, the existence of vulnerable elements in houses and industrial installations and the absence of standards that deal with the WUI problem at the homeowner/ property scale. The WUIVIEW project aims at developing an innovative risk management tool that will help WUI communities to adapt in order to face the new generation of forest fires. This is being done by designing, setting up and testing a virtual workbench service for the performance-based analysis of fire environments in the surroundings of buildings at the WUI. In this framework, a methodological approach for the assessment of LPG domestic tanks vulnerability under fire exposure at the WUI has been developed. The present work provides a demonstration of such methodology through a realistic case study, together with an overview of the WUIVIEW project activities.

1. Introduction

Forest fires affecting communities represent a rising problem in Europe. As the climate warms, hot and dry seasons in southern countries are lengthening and wildfires are behaving more often as real firestorms with huge intensities and large destructive potential (Dimitrakopoulos et al., 2011). In addition, human pressure on Mediterranean forests is continuously growing with an increase of ignitions and housing developments at the wildland-urban interface (WUI). Therefore, WUI fires are posing tremendous management challenges in terms of civil protection and fire mitigation (Manzello et al., 2018). Many critical factors are contributing and increasing the risk at the WUI: i) the presence of all sorts of fuels, jeopardizing structures, whose hazard is poorly characterized and disregarded by residents; ii) the existence of vulnerable elements in houses and industrial installations or warehouses whose response to and interaction with fire is unknown; iii) the absence of standards to deal with the WUI problem at the homeowner / property scale (Pastor et al., 2019).
The WUIVIEW project aims at developing an innovative risk management tool that will help WUI communities to adapt in order to face the new generation of forest fires that have already arisen due to climate change (Flannigan et al., 2016). This is being done by designing, setting up and testing a virtual workbench service for the performance-based analysis of fire environments in the surroundings of buildings at the WUI.
In this framework, particular attention is being devoted to the hazard associated with liquefied petroleum gas (LPG) storage tanks, used as energy source in WUI settlements. In fact, accidental fire exposure of this kind of infrastructures may cause their catastrophic failure, which in turn can generate extremely dangerous consequences, worsening the damage associated with the wildfires (Scarponi et al., 2018). Recent WUI fire events (e.g. Benitatxell, Spain, 2016; Madeira, Portugal, 2016; Calabassas, California, 2016; Mati, Greece, 2018) showed that this circumstance is all but unrealistic. Furthermore, a survey of regulations evidenced a lack of harmonization on LPG domestic tanks installation throughout European countries, with an important

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disagreement in the definition of safety distances. With the aim of providing a tool for the assessment of LPG tank vulnerability at the WUI, a methodology based on Computational Fluid Dynamics (CFD) modelling was developed (Scarponi et al., 2020). In the following, an overview on the WUIVIEW project structure is presented, together with a brief description of related research activities. Then, the methodological approach for the assessment of LPG domestic tanks vulnerability under fire exposure at the WUI, developed in the first phase of the project, is described. Examples of application are also provided, showing how the outcomes can deliver scientific evidence of the risk associated with LPG domestic tanks and help in policy-making process with the definition of improved provisions in terms of safety distances and maintenance actions. Results can have also relevance, in perspective, for the protection of larger scale tanks used in industrial installations.

2. Overview of the WUIVIEW project

The actions being undertaken under the scope of the WUIVIEW are organized in 3 phases (see Figure 1) involving several work packages (WP). The first one, already concluded, is the setup of the simulation framework. It consisted in the characterization of fire hazard of ornamental vegetation (WP2) and non-vegetal WUI fuels and LPG infrastructures (WP3). A detailed survey on fire protection systems and thermal properties of building materials, together with a review on building codes and regulations, was also carried out (WP4).

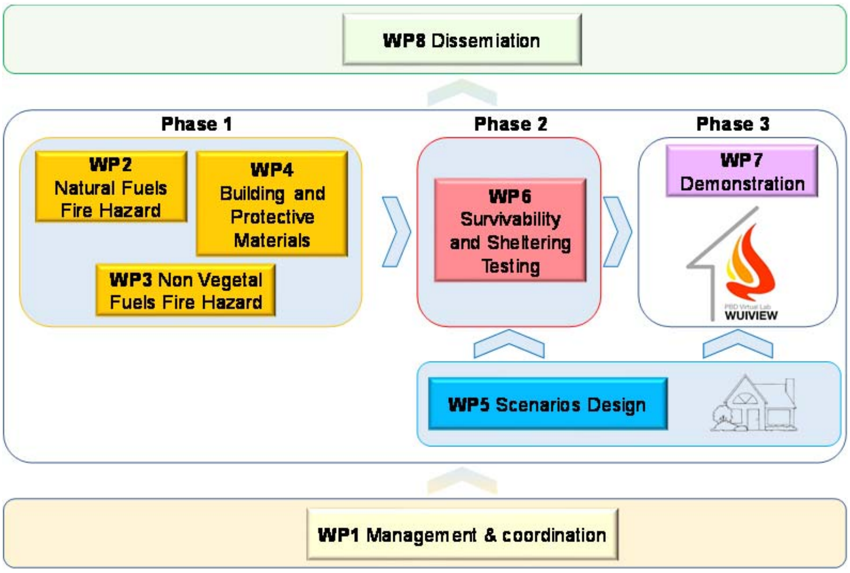

Figure 1: Project structure.

In the analysis phase (Phase 2), currently ongoing, the focus is placed on getting insights on the response to fire of typical building systems and materials relying on a performance-based design methodology. Based on an inventory of pattern scenarios (i.e. common situations repeatedly observed in WUI fires, involving systems and assets exposed to WUI fire sources) carried out in WP5 and using fire hazards and building characteristics gathered during Phase 1, simulations are being run to analyze homes' survivability and sheltering capacity (WP6) under different conditions.

WUIVIEW has originally been conceived to become a consultancy service to assess WUI vulnerability in real scenarios after the Action's lifetime. The technical feasibility of the service will be demonstrated in the final phase of the project (Phase 3). WP7 will make use of the WUIVIEW workbench to assess WUI fire hazards and house fire performance of preselected real WUI developments. The project is continuously coordinated and managed through WP1. Similarly, the outputs are being and will be disseminated during the entire duration of the project (WP8).

3. CFD methodology for LPG tank vulnerability assessment in the WUI

One of the key outcomes the first phase of the WUIVIEW project (in particular WP3) was the development of a methodology to assess LPG domestic tank vulnerability to WUI fire scenarios. Such methodology can be used as a tool to assist on safety distances definition to be prescribed by standards, driving regulators towards better-informed decision-making. The task of assessing whether the response of an LPG tank exposed to a

WUI fire scenario falls within acceptable safety limits is challenging, due to the complex physics and the diversity of the phenomena involved. Figure 2 shows a sketch of the problem addressed, together with the schematization of the proposed assessment methodology.

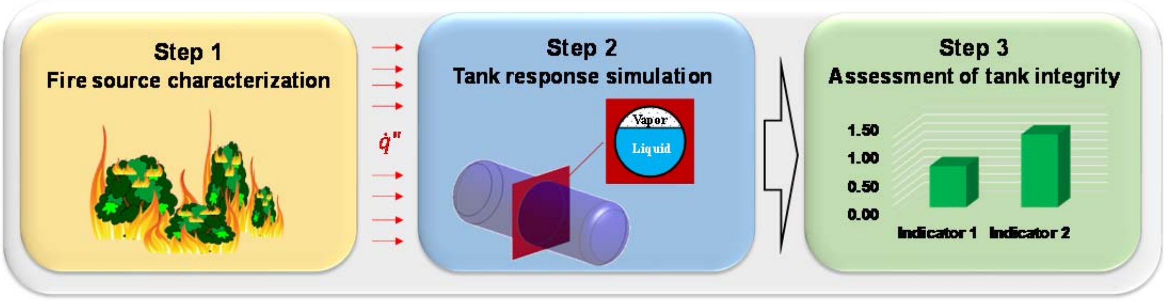

Figure 2: Schematization of the methodological approach.

The methodological approach is divided in three blocks: the characterization of the fire source, the simulation of the tank response and the consequence assessment. The aim of the first step is to quantify the heat load induced on the tank by the fire. This can be performed by different approaches, depending on available data, required accuracy and organizational factors such as time, costs and computational resources. Table 1 presents an overview of the possible options to define the fire scenario. The table also specifies the main inputs and the tools required to apply each approach.
Option 1 represents the case in which the analyst already knows the heat load to be applied to the storage tank (e.g. when this comes from regulations, standards, prescriptions or experience). Option 2 is based on the solid flame model concept (Eisenberg et al., 1975), where the flame is considered as a solid body having defined shape and dimensions, with a given emissive power. Thus, the incident radiation to remote points (e.g. the tank surface) is obtained using the view factor between the remote point and the solid body representing the flame. It must be pointed out that the solid flame model is only valid for a distant fire source. This limits the applicability of Option 2 to fire scenarios in which the flame is not in contact with the wall of the tank.

Table 1: Different strategies to characterize the considered fire sources.

Option	Main Inputs	Required tools
1) Direct definition	Expert judgment or prescriptions	None
2) Solid flame model	- Scenario geometry - Fire emissive power (as a function of time) or fire Heat Release Rate curve (and radiative fraction) - Fire shape	Tool for the calculation of view factors
3) Fire simulation	3.1: Fire prescription - Scenario geometry - Fire HRR curve - Ambient conditions (temperature, humidity and wind)	Fire simulation software (e.g. FDS)
	3.1: Fire prediction - Scenario geometry - Solid fuel composition, density, heat capacity and thermal conductivity - Solid fuel particle size distribution and moisture content (for vegetation) - Solid fuel pyrolysis curve - Ambient conditions (temperature, humidity and wind)	

Option 3 involves the use of a fire simulation software, in which the scenario under analysis is reproduced in detail. In the present methodology, the Fire Dynamic Simulator (FDS) by the National Institute of Standards and Technology (NIST) of the US Department of Commerce is considered as the reference tool to carry out the simulations. A distinction must be made according to the strategy adopted to simulate the fire: this can be either prescribed (Option *3.1 – Fire Prescription*), or predicted (Option *3.2 - Fire Prediction*). In the first case (Option 3.1) the burning element is modelled as a solid shape with an assigned Heat Release Rate (HRR) curve on its surface. In the second one (Option 3.2), all the steps characterizing the combustion process of a solid fuel are considered: the heat-up phase, the pyrolysis process leading to the production of gaseous fuels

and the final burning process (a comprehensive description of such processes can be found in Hurley et al. (1995). This last option represents the most advanced approach to the simulation of a fire scenario.
Step 1 of the methodology allows to define the boundary condition needed for the CFD simulation of the tank response when affected by a fire (Step 2). In the framework of the WUIVIEW project, the ANSYS® Fluent® 18.2.0 code was used to carry out this second step, applying the CFD modelling setup proposed by Scarponi et al. (2019). CFD simulations provide (among other data) pressurization curves, wall temperature profiles, temperature distribution in the liquid and vapor phases and evolution of the velocity field.
The last step of the methodology consists in the elaboration of the CFD simulations in order to assess whether the fire scenarios under analysis may compromise tank integrity. This is done by introducing two indicators (calculated on the basis of the results obtained in Step 2, see Table 2), that can be easily compared with threshold values, defining the limits within which a given scenario may be deemed safe. The first one, the "Weakened Surface Index" (WSI), provides a measure of the extension of mechanical weakening of the tank's steel structure due to high temperature (Manu et al., 2009). The second indicator, the "Pressure Relief Valve Index" (PRVI), quantifies how close the pressure reached in the tank is to the PRV set point. In fact, although the PRV opening represents a safety measure to prevent the tank rupture, the jet fire resulting from the ignition of the fluid released by the valve increases the heat load to the tank and the surroundings and may contribute to worsen the consequences of the fire. The threshold values for both indicators was set to 0.9 (i.e. if both indicators are below this value, the given scenario can be deemed safe).

Table 2: Indicators for the assessment acceptability of the LPG tank response to fire.

Option	Main Inputs	Required tools
WSI: Weakened Surface Index	$WSI = \frac{S_{a,max}}{S_c}$	$S_{a,max}$: maximum (over simulation time) surface area where the temperature is higher than 400°C S_c: critical surface area (0.48 m^2) (Scarponi et al., 2020)
PRVI: Pressure Relief Valve Index	$PRVI = \frac{p_{max}}{p_{PRV}}$	p_{max}: maximum pressure reached in the tank p_{PRV}: PRV set point

4. Case study

In order to provide a demonstration of how the methodology can be used to assess the vulnerability of an LPG domestic tank exposed to a realistic WUI fire scenario, a case study was set up.
The fire scenario is one of those identified during the research work carried out in WP5 of the project and it consists of a 10-m long burning hedgerow consisting of six ornamental trees (for this case study we used experimental data from Mell et al. (2009) of Douglas fir specie, with trees 2.05m high, 0.15m of clear trunk base and 1.90m of crown, with a conical canopy having a 1.6 m diameter base). A 1 m^3 LPG tank (diameter = 1000 mm, length = 1470 mm, wall thickness = 6 mm, with semi-elliptical ends), placed at 3 m form the hedgerow, was considered as the target. The filling degree was set to 80%. A schematic representation of the case study scenario is depicted in Figure 3a. Two different weather conditions were explored: calm and windy conditions (in this second case, a wind speed profile varying along the vertical coordinate reported in Figure 3b was considered).

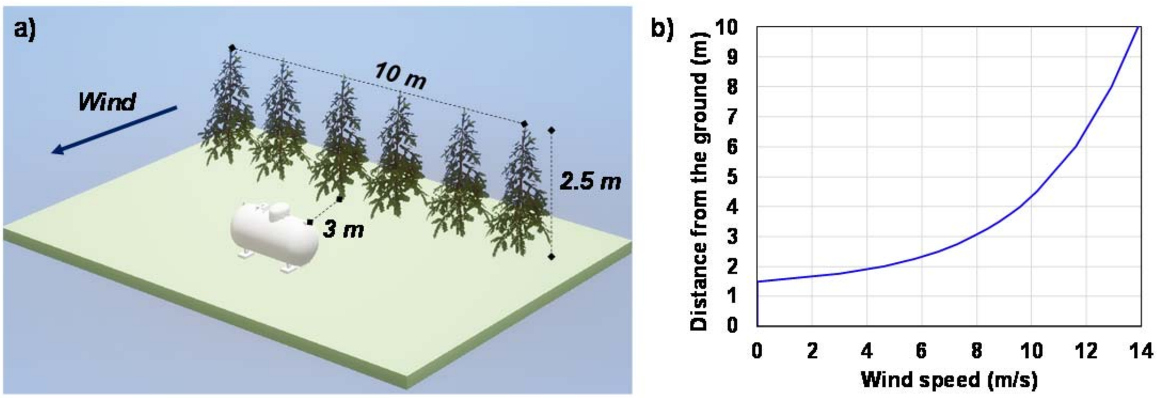

Figure 3: Schematic representation of the case study scenario (a). Wind speed profile considered for windy conditions (b).

5. Results

For this demonstrative case study, the most advanced option (Option 3.2) to carry out the fire characterization step was considered. In particular, the approach proposed by Mell et al. (2009) was adopted, in which the tree crowns are modelled as distributed solid particles, divided into four size classes: foliage, roundwood of diameter < 3 mm, roundwood of diameter between 3 and 6 mm and roundwood with a diameter between 6 and 10 mm, yielding a total mass of fuel of 3.9 kg (dry mass). Provided an ignition source, FDS simulates the particles' temperature increase, the moisture removal, the pyrolysis process with the generation of flammable vapors and, finally, the charification and oxidation of the solid residue. The reader is referenced to the paper of Mell and co-workers (2009) for the full details on the simulation approach.
Figure 4 shows a sample of the results obtained in the fire characterization step using FDS.

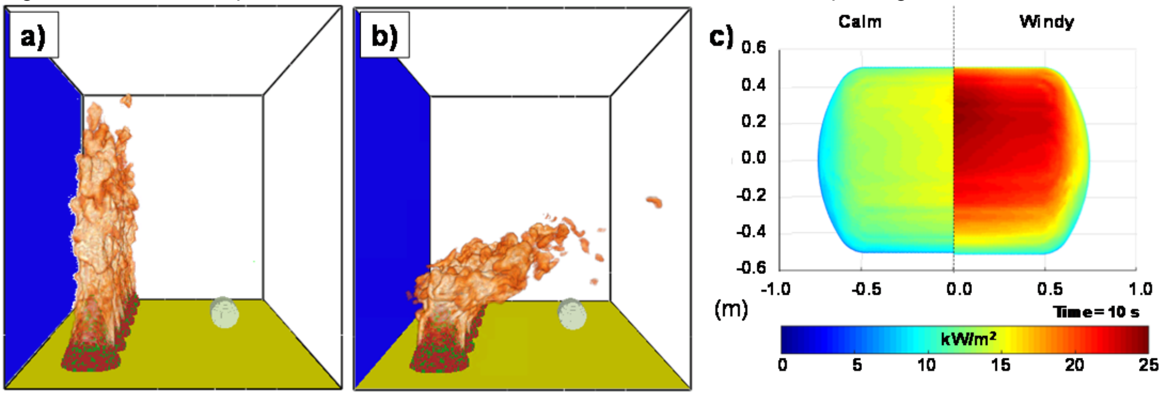

Figure 4: Characteristics of the fire in calm (a) and windy (b) conditions and incident radiation over the tank wall (c) after 10 s of simulation.

Figure 4a and b clearly show how the presence of wind affects the flame shape: the flame is vertical in calm conditions and tilted towards the tank when the wind is blowing. In the latter case, the incident radiation over the tank surface is higher (Figure 4c). Data obtained in the fire characterization step are then used as boundary condition in the CFD simulation of the tank response to fire exposure. The tank (both the fluid inside and the solid wall) is discretized using an unstructured mesh and conservation of mass, momentum (including turbulence via the k-ω SST model) and energy transient equation are solved throughout the computational domain during all the duration of the fire exposure. The Volume Of Fluid is used as multiphase model coupled with a simplified evaporation-condensation model implemented in ANSYS Fluent (Lee, 1979). The detailed description of the CFD modelling setup can be found in the work presente by (Scarponi et al., 2019b).
The main results obtained from the CFD simulations are reported in Figure 5. Figure 5a shows that, in both cases, the pressure increase in the tank is very limited. The maximum pressure (8.5 bar) is obtained for the windy condition case and it is only 0.14 bar higher than the initial pressure. The curves describing the maximum wall temperature in the two cases (Figure 5b) show a certain temperature increase: about 7 °C and 11 °C for calm and windy condition conditions respectively.

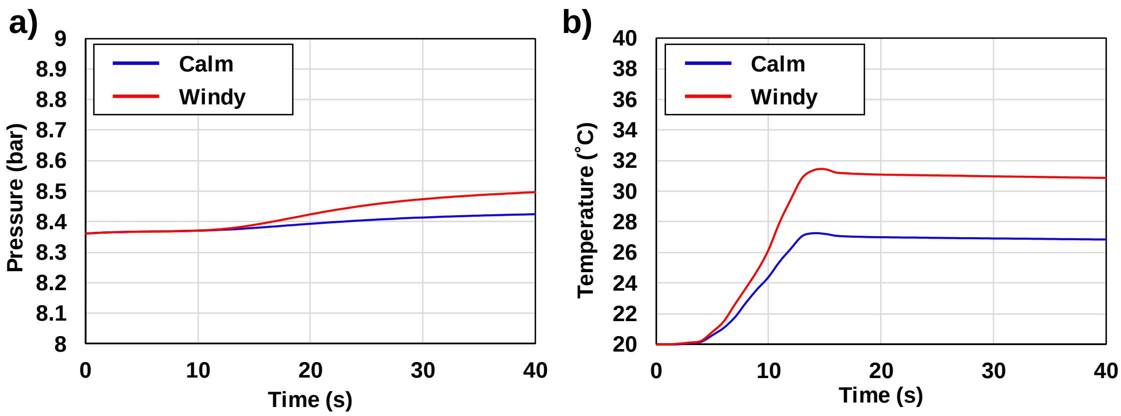

Figure 5: Pressure curves (a) and maximum wall temperature (b) obtained considering calm (blue line) and windy (red line) conditions

The results reported in Figure 5*:* Pressure curves (a) and maximum wall temperature (b) obtained considering calm (blue line) and windy (red line) conditions show that, regardless the presence of wind, the fire scenario considered as case study in the present work produces negligible effects in terms of pressure increase and temperature rise. This is reflected by the values of the KPIs calculated in Step 3 of the methodology. The PRVI indicator results 0.468 and 0.472 for calm and windy conditions respectively, whereas the WSI is always null. Thus, it is possible to conclude that this scenario does not represent a threat for the tank's integrity.

6. Conclusions

The WUIVIEW project aims at developing an innovative risk management tool that will help WUI communities adapting to face the new generation of forest fires that have already arisen due to climate change. The first phase of the project has already been concluded and provided useful results in terms of characterization of the fire hazard of an extended set of natural (ornamental vegetation) and non-natural fuels. A detailed survey on fire protection systems and thermal properties of building materials, together with a review on building codes and regulations, was also carried out. Current work is being devoted to the analysis of homes survivability and sheltering capacity under different fire conditions.

The methodology presented above is one of the main results produced during the first year of research activity. Although representative of a safe situation, the example of application shown in this work demonstrates how such methodology can be used to assess whether a given WUI fire scenario has the potential to threaten domestic LPG tank integrity, thus providing a reliable tool to assist risk management decision makers and regulators. The systematic application of this methodology to a set of reference scenarios (e.g. wild fuels at the perimeter of settlements, non-natural fuel packs accumulated in sheds, etc.) may contribute to a more sound and harmonized definition of safety distances for LPG domestic tank at the WUI. This is an example of how the outcomes of the WUIVIEW project may help to increase safety in WUI communities and drive the transition towards a more resilient society.

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