

Detection of small burning hydrogen leaks at open-air industrial installations

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1 Introduction

Hydrogen is increasingly crucial in the global energy transition, particularly in sectors like transportation and energy storage. Small burning hydrogen leaks at industrial installations pose significant safety hazards. Hydrogen, being the lightest element, is highly diffusive and can easily escape through minute openings. These small leaks, while often overlooked, can lead to serious consequences due to hydrogen's unique properties: Hydrogen has an extremely wide flammability range in air (4% to 77% by volume), one of the lowest minimum ignition energies (0.017 mJ) and the lowest quenching distance (maximum experimental safe gap) of all gases (pressure-dependent down to 0.17 mm) [1]. This combination makes hydrogen particularly prone to ignition, even from small sparks or hot surfaces. Since hydrogen flames are almost invisible to the human eye, detecting them is a challenge.

Industrial installations face additional risks due to the high pressures and cryogenic temperatures often involved in hydrogen production and storage. These conditions can lead to material embrittlement and increase the likelihood of leaks over time. For hydrogen stored at 690 bar, a pinhole leak as small as 0.4 μm could support a stable flame [2].

The difficulty in detecting hydrogen leaks using human senses (as it is colorless, odorless, and tasteless) necessitates specialized detection systems and rigorous safety protocols. One of the most common and effective methods for detecting small hydrogen leaks is through the use of hydrogen sensors. These sensors are strategically placed throughout industrial facilities and can detect minute amounts of hydrogen in the air. However, such sensors can only detect hydrogen in direct contact, not remotely. Burnt hydrogen is not detected. Temperature sensors can detect nearby flames, but the range of thermal emission to heat up a thermocouple significantly is very limited and is hampered by wind and rain.

Remote sensing of small hydrogen flames over distances of many meters requires optical methods. However, hydrogen flames are the least luminous of all fuels, as neither hydrogen nor hot water vapor or the radicals produced during combustion have significant emission lines in the visible range [3]. Therefore, there are two possibilities: detection at longer wavelengths (infrared emissions) or detection at shorter wavelengths (especially OH* chemiluminescence in the UV range).

Thermographic cameras (also known as thermal imaging cameras or infrared cameras) are a proven technique for detecting hot spots and flames using their infrared signals. However, industrial plants often have hot spots or light sources such as incandescent lamps, which are bright infrared emitters. In

addition, open-air installations can reflect the strong infrared sunlight. All these emissions can outshine the infrared signature of small hydrogen flames, making their detection difficult and unreliable.

The most prominent emission of a hydrogen flame occurs in the ultraviolet range at 305...325 nm with a peak around 310 nm, caused by OH^* chemiluminescence [2]. In this wavelength range, the extraterrestrial solar spectral irradiance is more than an order of magnitude lower than in the visible range [4]. High UV absorption in the atmosphere further reduces solar spectral irradiance (Figure 1 and [5]). Strong UV emissions of the hydrogen flame around 310 nm on the one hand and low solar irradiance as well as no interfering emissions from incandescent lamps and heat sources on the other hand considerably simplify the detection of hydrogen flames via OH^* chemiluminescence.

In this work, the detection limits of small hydrogen flames on outdoor pipelines are investigated using UV- OH^* chemiluminescence. A lightweight, mobile system consisting of a modern sCMOS UV camera and a UV narrowband filter, which can be mounted on commercially available drones, is used.

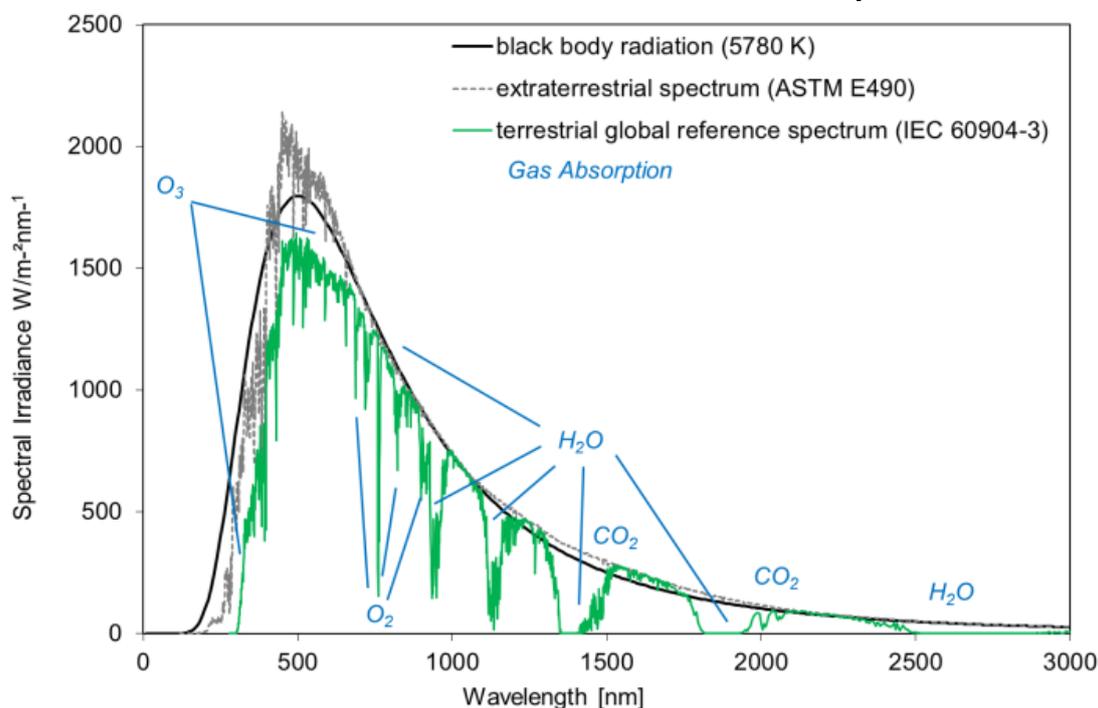


Figure 1: Terrestrial solar spectrum according to IEC 60904-3 (green line) with main gas absorption bands (blue) in comparison with extraterrestrial spectrum (ASTM E490, dotted line) and theoretical black body spectrum (black line). Below 300 nm, there is almost no incoming sunlight. [5]

2 Experimental Setup and Measurements

The experimental setup is shown in Figures 2 and 3. A UV camera observes a hydrogen flame between pipes at a distance of 20 m under daylight conditions (2025-01-21 at 1 p.m., clear sky, Braunschweig, Germany). The UV camera of type MaxCam-400UV-TE contains a GSENSE 400 BSI sCMOS sensor with 2024×2048 pixels, $11 \times 11 \mu\text{m}^2$ pixel size and a quantum efficiency of more than 40 % at 310 nm. The camera is coupled with a LaVision 100 mm f/2.8 UV objective behind an Edmund Optics OD4 10 nm bandpass filter with 310 nm center wavelength. At a distance of 20 m, the camera captures a field of $4.5 \times 4.5 \text{ m}^2$ with an image scale of 2.2 mm/pixel. The images were recorded with an exposure time of 100 ms. Neither dark nor flat correction were applied. The hydrogen flame is positioned in front of pipes that are directly illuminated by the sun in order to maximize the influence of sunlight reflections. Hydrogen flow rates of 2/4/8/15/30/50/100 l/min were examined. Depending on the hydrogen flow rate, the flame length is between 18 mm and 280 mm.

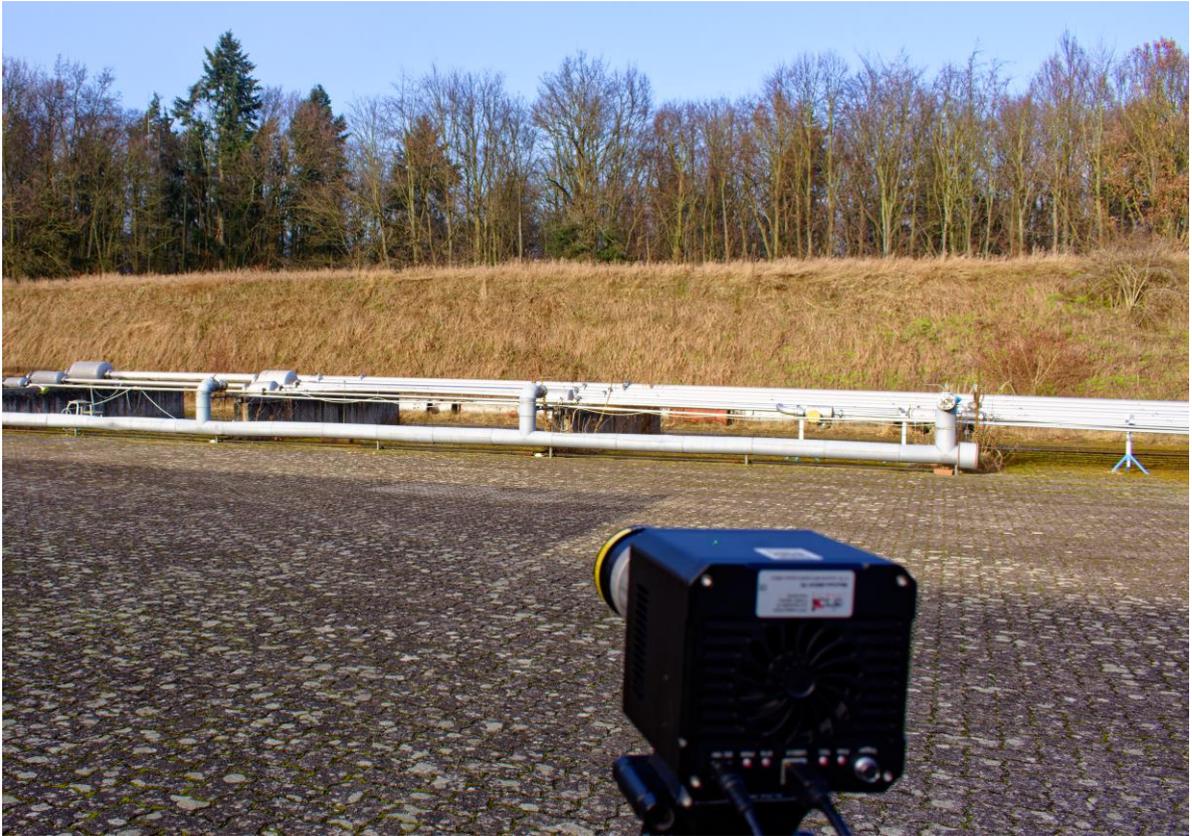


Figure 2: Experimental setup. UV-camera at a distance of 20 m from hydrogen flame between pipes.



Figure 3: 6 mm Swagelok pipe with burning hydrogen flame of 7 cm length (8 l/min hydrogen).

4 Data Reduction and Results

The grayscale UV images have been converted to false color images to facilitate visual inspection of the images (Figures 4 and 5). No further image manipulation was applied. In particular, neither flat nor dark correction were applied although these corrections improve the image quality further. However, measuring suitable flat and dark frames takes additional time and has proven to be unnecessary in this context.

Visual inspection of the images clearly shows the flame in all cases, even at 2 l/min (Fig. 4 and 5). The resolution is high enough to see the flickering of the flame in the video, which is additional proof.

The feasibility of an automatic flame search on the raw images was also investigated. It was found that even the smallest flame (2 l/min, Figure 4) can be reliably detected by automatic search routines. For example, all flames were found at a significance level of 5 sigma using the SExtractor search program [6]. Detections at this significance level meet the highest requirements for detection [7].

Note that a common technique to improve contrast is the subtraction of a “flameless reference image”. However, changing light conditions prevent the determination of a suitable “flameless reference image”. This technique is therefore not reliable for monitoring open-air systems. It was not used in this work.

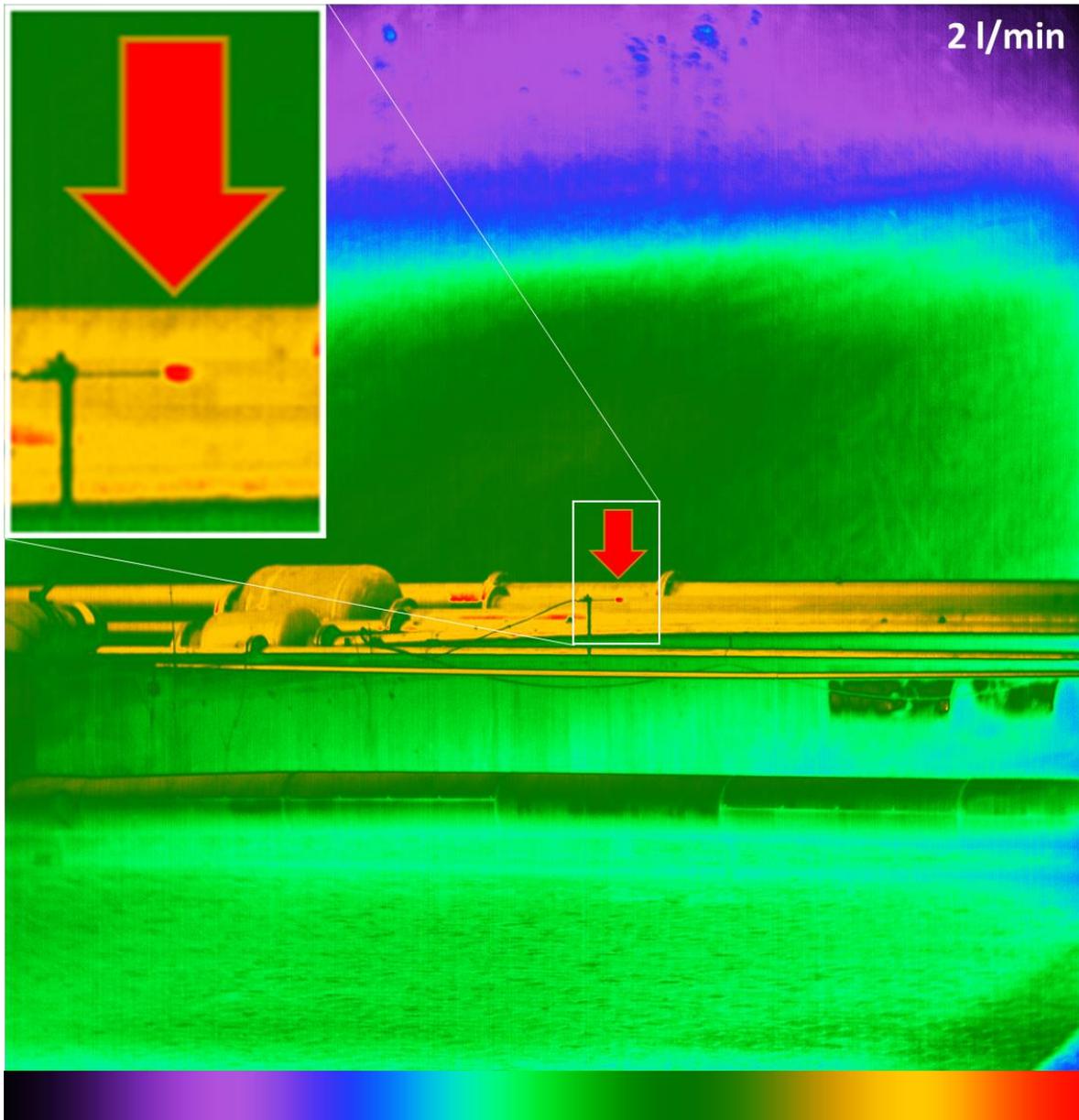


Figure 4: UV image of a hydrogen flame in front of sun-lit pipes. Distance 20 m, field size 4.5×4.5 m², cutout field size: 36×60 cm², resolution 2.2 mm/pixel, hydrogen flow rate 2 l/min, flame length 18 mm. The arrow shows the position of the flame. An enlarged view is shown in the top left-hand corner. The look-up table (LUT) for converting the greyscale UV image into a false color UV image is shown below the UV image: from the minimum intensity (left, black) to the maximum intensity (right, red).

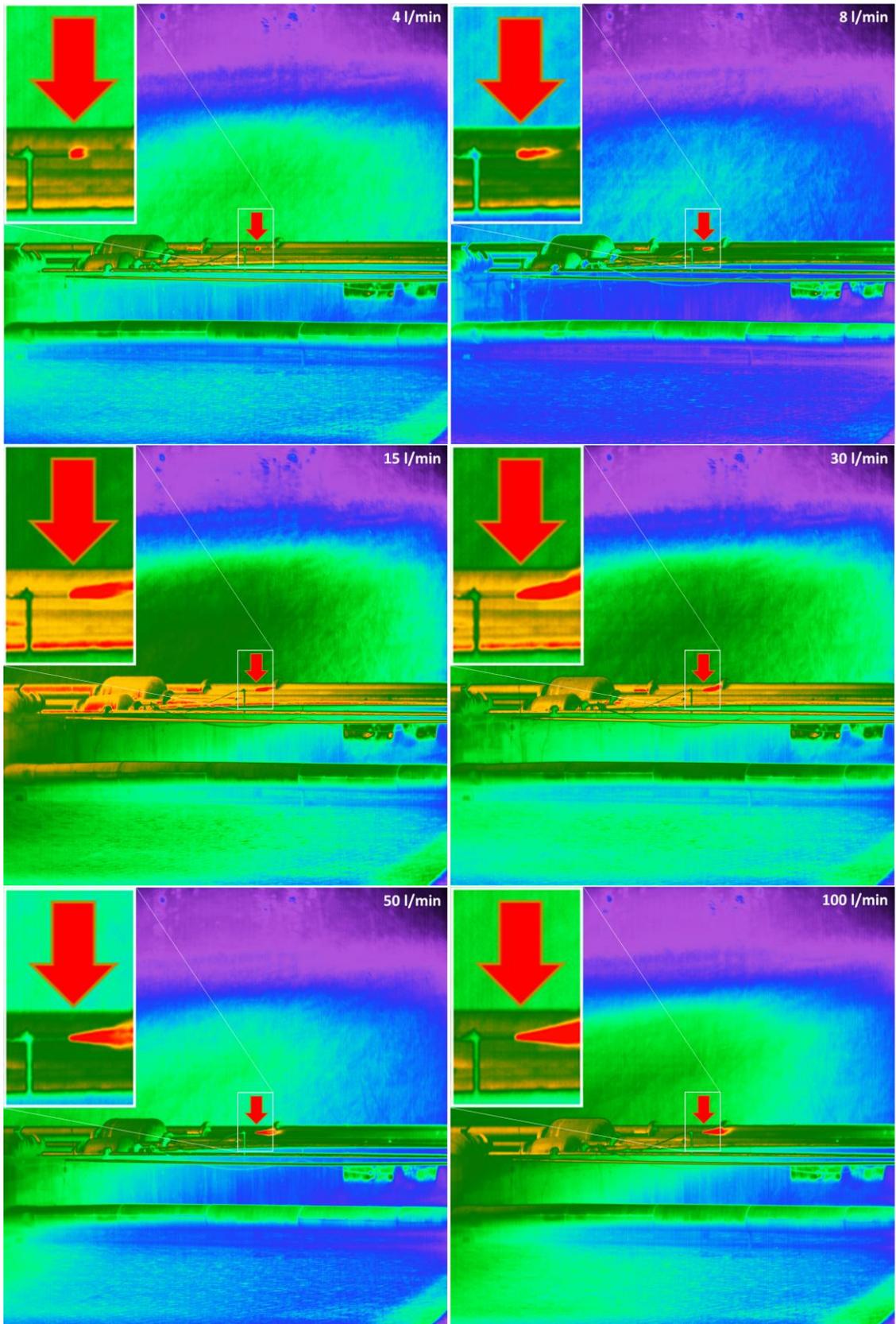


Figure 5: UV image of a hydrogen flame in front of sun-lit pipes. Distance 20 m, field size 4.5×4.5 m², cutout field size: 36×60 cm², resolution 2.2 mm/pixel, hydrogen flow rate 4/8/15/30/50/100 l/min

4 Summary

Hydrogen is increasingly crucial in the global energy transition, particularly in sectors like transportation and energy storage. However, its use poses significant safety challenges due to its highly flammable nature and the difficulty in detecting hydrogen flames, which are nearly invisible. Effective detection of small hydrogen flames is essential in industrial facilities to prevent accidents and ensure operational safety, including under daylight conditions, wind and rain.

OH* chemiluminescence, which occurs in the UV spectrum near 310 nm, offers a sensitive and reliable optical method for remote hydrogen flame detection. Modern CMOS sensors offer high sensitivity and spatial resolution in the UV wave range and can be integrated into compact systems for real-time monitoring, for example in commercially available drones.

In this work, the detection of small hydrogen flames (2/4/8/15/30/50/100 l/min hydrogen flow rate) was investigated. The flame length was between 18 mm (at 2 l/min hydrogen) and 280 mm (100 l/min hydrogen). The flame was placed in front of pipes located outdoors with the sun shining directly on the pipes. UV images were recorded with a mobile camera system at a distance of 20 m from the flame. An OH* narrowband filter with a central wavelength of 310 nm and 10 nm FWHM was used. The size of the image field was 4.5×4.5 m², the resolution 2.2 mm/pixel and the frame rate 10 fps.

All flames could be clearly identified from this distance, both by visual inspection of the images and by automatic search routines at five-sigma level. Note that the smallest flame was only 18 mm long and was fed with 2 l/min of hydrogen. The resolution was high enough to recognize the flickering of the flame on the image sequence, which is further evidence of a flame.

It is concluded that a mobile UV camera system with a suitable narrowband OH* filter is a powerful mobile tool for the fast and reliable detection of small burning hydrogen flames in industrial plants, including under daylight conditions.

References

- [1] chemsafe data base (last access: 2025-02-14). Physikalisch-Technische Bundesanstalt (PTB), <https://www.chemsafe.ptb.de/search/show/substance/10006>
- [2] Butler MS, Moran CW, Sunderland PB, Axelbaum RL (2009). Limits for hydrogen leaks that can support stable flames. *International Journal of Hydrogen Energy* 34: 5174
- [3] Gordon IE, Rothman LS, Hargreaves JR, Hashemi R, Karlovets EV, Skinner FM, et al. (2022). The HITRAN2020 molecular spectroscopic database. *J. Quant. Spectrosc. Radiat. Transfer* 277, 107949 doi:10.1016/j.jqsrt.2021.107949
- [4] Fontenla JM, Harder J, Livingston W, Snow M, Woods T (2011). High-resolution solar spectral irradiance from extreme ultraviolet to far infrared. *Journal of Geophysical Research* 116: D20108, doi:10.1029/2011JD016032
- [5] Dirnbacher D (2015). Uncertainties in Energy Rating for Thin-film PV Modules, dissertation, University Oldenburg, DOI:10.13140/RG.2.1.3020.1687
- [6] Bertin, E., Arnouts S. (1996). SExtractor: Software for source extraction, *Astronomy & Astrophysics Supplement* 317: 393
- [7] CERN FAQ (last access: 2025-02-14). Why do physicists mention “five sigma” in their results? <https://home.cern/resources/faqs/five-sigma>