TECHNICAL MEMO

Statera BESS Fire Study

East Claydon BESS Fire and Plume Study

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Applicable contract(s) governing the provision of this Report:

1 EXECUTIVE SUMMARY

A 3D Computational Fluid Dynamics (CFD) assessment of the East Claydon Battery Energy Storage System (BESS) site has been undertaken. DNV has extensive experience globally assessing the hazards posed by various BESS including accident investigation (Ref. /7/), 2D and 3D consequence modelling and full-scale testing at DNV's facilities in the UK, USA and Europe. The objective of the study was to determine whether the neighbouring buildings/sites could be impacted by a battery failure event which escalates to a fire in addition to the possibility of fire escalation between BESS units.

The modelling was undertaken with conservative assumptions, safety systems and barriers to prevent escalation were assumed to have failed, creating an upper bound for consequences from a BESS fire. For offsite impact, three fire sizes were modelled ranging from most likely (1 rack) to worse case (full BESS). For escalation to neighbouring BESS, a half BESS fire was modelled.

The main findings from the study were:

- The BESS layout on site follows industry best practice (NFPA 855) with a 3m separation between BESS units to prevent escalation between BESS units in the event of a fire. This was confirmed in targeted fire modelling where the maximum thermal radiation was observed to be 3kW/m^2 on the closest BESS from a half BESS fire.
- There is no impact on any neighbouring buildings (closest farm house at 470m from the nearest BESS) for any of the fire scenarios. This includes houses located eastwards of the site. Effects of the fires are limited to ~4m from the worst-case full BESS fire event for thermal radiation, visibility, and hydrogen fluoride impairment.
- The frequency of a full BESS fire was estimated to be of the order 10^{-8}/year which is well below HSE guidance of broadly acceptable risk to the public of 10^{-6}/year.
- As the worst-case BESS fire scenario demonstrates that there is no impact on the surrounding area, the likelihood of the BESS fire occurring is not of concern.

2 INTRODUCTION

DNV has been requested by Statera Energy (Statera) to evaluate the East Claydon BESS battery storage site for fire hazards. The evaluation is a consequence-based study using Computational Fluid Dynamics (CFD) to evaluate potential impact of a battery failure event and assess the impact of thermal effects and smoke impact on the neighbouring area in the event of a fire. The analysis has evaluated a range of scenarios from most credible to worst case in terms of consequence for a fire event. In addition to this, the potential for escalation between BESS due to a fire has also been assessed.

DNV has extensive experience globally assessing the hazards posed by various BESS including accident investigation (Ref. /7/), 2D and 3D consequence modelling and full-scale testing at DNV's facilities in the UK, USA and Europe.

3 CFD MODEL

The 3D CFD code Kameleon FireEx (KFX) was used for the fire simulations (Ref. /1/). KFX is capable of calculating heavy and light gas dispersion and hydrocarbon fires in connection with practical fire safety studies. It can handle liquid pool fires as well as gas jet and fires, in enclosures and in open air. It has been tested against experimental data ranging from small-scale laboratory flames to large-scale jet and pool fires. KFX can be used for most safety related analysis related to gas dispersion and fire.

3.1 Geometry

The 3D model was constructed from the BESS specification and site layout drawing (Ref. /2/, /3/). Figure 3-2 shows a plan view of the East Claydon BESS site and Figure 3-1 shows the 3D model and detailed view of the BESS container. Each BESS contains 10 racks which have 416 cells each. The BESS measure 6.1m x 2.1m x 2.6m in dimension and there are 480 total on the site. The 3D model considers a subsection of the site as marked in red in Figure 3-2. The presence of the rest of the site is not expected to have an effect on the results. The farm houses to the north west are also included in the model as these are the closest residential off-site buildings to the BESS site. The farm houses are approximately 470m from the nearest BESS.

Areas on the doors that are likely to fail in the event of a fire (as observed historically in BESS fires) were modelled as porous regions, this included the rubber seal around the perimeter of the door and the HVAC grill.

The model was verified prior to running any simulations by Statera.

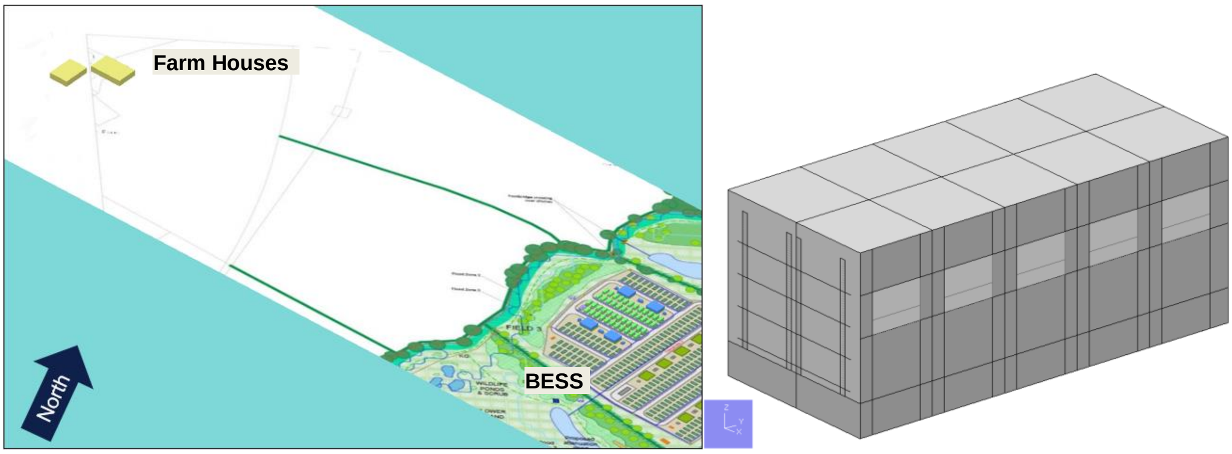


Figure 3-1: 3D model (left) and individual BESS model (right)

Figure 3-2: 3D model of East Claydon BESS Site

3.2 Safety System Assumptions

The following safety systems and CFD input data have been acknowledged for the basis of the study's assumptions. The assumptions made in this section are based on the information available. The assumptions are based on UL 9540A test data (Ref. /11/,/12/) and information provided by Statera.

Propagation between cells:

- The UL 9540A module level test report indicated it is possible to have cell to cell propagation within a module.
- **Assumption**: It is assumed that all cells within a module can fail.

Propagation between racks:

- The UL 9540A unit level test report indicated rack to rack propagation is unlikely. The BESS design includes partition walls between racks that would prevent escalation between racks.
- **Assumption**: It is assumed that in the event of thermal runaway in the BESS that rack-to-rack propagation will occur and that all 10 racks could be engaged in the fire or thermal runaway.

Propagation between BESS units:

- NFPA 855, 68 and 69 are industry best practise for the standard of BESS installation and hazard protection and mitigation. They recommend separation distances of 10ft (3m) at the front and 4ft (1.2m) at the back and sides of the BESS. The current spacing on the East Claydon BESS site is 3m (10ft) in all directions, which meets and exceeds NFPA requirements.
- **Assumption**: It is assumed that in the event of a fire in a BESS it does not propagate to the neighbouring BESS, limiting the failure to the BESS of origin.

Ventilation system:

- The container is fitted with a HVAC system for passive air cooling in the container.

- **Assumption:** The HVAC will be shut down in the event of a fire.

3.3 Leak Profile Assumptions

The following assumptions are made about the release of offgas from a rack. The assumptions are based on the UL 9540A test data available (Ref. /11/,/12/). The assumptions made in this section are based on the information available and are conservative where there is uncertainty.

Duration of event:

- Based on DNV's experience, offgas is fully released from a single cell over approximately 1-2 minutes during thermal runaway.
- **Assumption**: It is conservatively assumed that the time for a cell to release offgas is 90 seconds. A longer duration would reduce the burning rate and fire size.

Gas composition and properties:

- Gas composition was provided in the UL9540A test. It should be noted that the UL9540A test does not test for toxic gases explicitly. 176L of offgas was released from a single cell (at 193°C). The gas composition was provided in the test data, Table 3-1.
- **Assumption**: The combustion of plastic items in the BESS has also been considered with additional propane added to the generic composition as it has similar yields of CO and CO_2 to polypropylene plastic which is typical for battery casings (Ref. /5/). The gas composition can be seen in Table 3-1.

Table 3-1: Adjusted Gas Composition by Volume

Gas		UL 9540A Test Data (%)	Adjusted for Plastic (%)
Hydrogen	H_2	47	41
Carbon Dioxide	CO_2	27	24
Carbon Monoxide	CO	6.7	5.9
Pentane	C_3H_{12}	0.64	0.56
Butane	C_4H_{10}	0.52	0.45
Propylene	C_3H_6	3.0	2.6
Propane	C_3H_8	0.41	13
Ethylene	C_2H_4	6.6	5.8
Ethane	C_2H_6	1.6	1.4
Methane	CH_4	6.4	5.6

Escalation and offgas release rate (mass/time):

- If a single cell fails, the cell-to-cell propagation would spread outwards from the initiating cell to the neighbouring cells and so on until all cells are consumed. During the propagation, the number of cells engaged in thermal runaway would gradually increase at each escalation step and depending on the arrangement of the cells would reach a peak rate. An example of this is shown in Figure 3-3 where a peak number of cells that are in thermal runaway at the same time is approximately 2% of the entire rack as the failure propagates to each module, shown with the peaks and troughs. The racks have 416 cells which are assumed to be split into 16 levels/modules in a 2 x 13 arrangement. Cells are assumed to fail in a module and then propagate to the next module. This example conservatively assumes that escalation between cells takes 90s and that failure propagates to neighbouring cells. Cell to cell propagation has been observed to take up to 5mins.

2x13 cell arrangement for first 4 modules

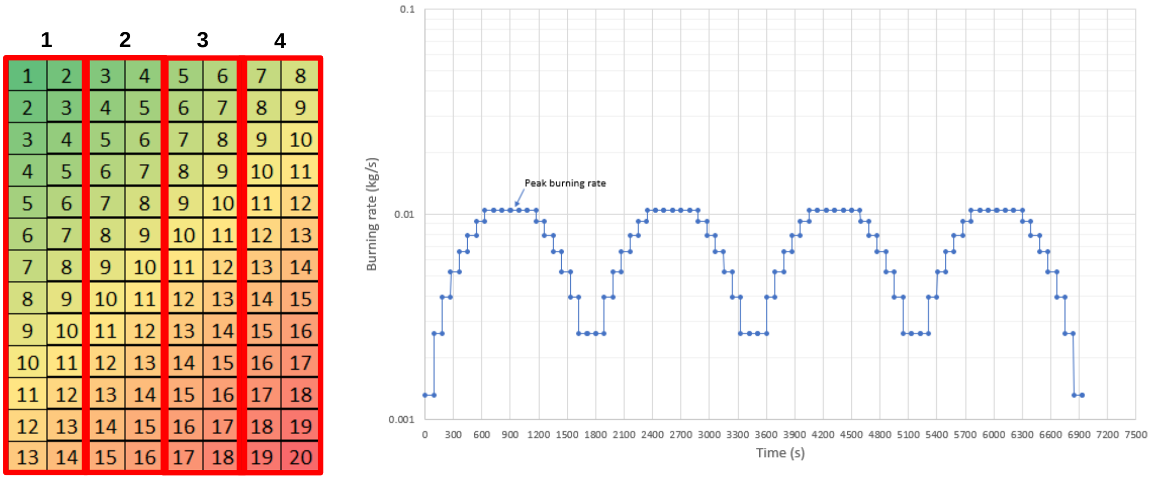


Figure 3-3: Example escalation in a rack and burning rate vs time plot

- **Assumptions**: Based on the assumptions and example escalation outlined above, a single cell has a peak release rate of 0.0013kg/s (1.3g/s). Conservatively assuming that 2% of the cells fail at the same time, there would be 8 cells in thermal runaway at the same time, we would have (8 x 0.0013kg/s =) 0.0104kg/s of offgas being burned at the peak of the fire per rack. It is therefore assumed that per rack the peak burning rate is ~0.0104kg/s. Assuming this failure profile, the rack fire would last approximately 2 hours which is of a similar magnitude to what has been observed historically (Ref. /9/, /10/).

Toxic gases:

- Toxic gases are produced in a battery fire. The most dangerous is hydrogen fluoride which has a threshold of 30ppm. While other toxic gases can be produced, depending on the battery chemistry, hydrogen fluoride is the most abundant and has the lowest threshold, meaning it is the most restrictive.
- **Assumption**: Based on DNV's experience and testing (Ref. /4/), around 0.1% of the combustion product is hydrogen fluoride. This equates to around 1000ppm at source. It is therefore assumed that there is 0.1% of hydrogen fluoride in the combustion product.

3.4 Simulations

A total of six fire scenarios have been identified to model, representing progressively worse fire scenarios that have the potential to impact the surrounding area, see Table 3-2.

All scenarios consider wind blowing towards the farm houses to the northwest, for the average and extreme wind speeds, 6m/s and 10m/s respectively. The farm houses are roughly 470m from the nearest BESS. Wind blowing towards the northwest represents the worst-case scenario as combustion products will be blown that way.

The three fire sizes cover the most probable fire scenario, 1 rack, to the least probable fire, full BESS fire. The full BESS fire is the credible worst-case scenario for the site due to separation distances to other BESS, discussed previously.

For context, escalation between racks is unlikely given there are partition walls between the racks that would limit heat transfer between them. It is far more credible that any failure would be isolated to a single rack within the BESS. However, to provide a conservative upper bound on a potential BESS fire a 5 rack (half BESS) and full BESS fire are considered. Both scenarios assume that all 5 racks or 10 racks (for full BESS) fail simultaneously. This is extremely conservative as it would require independent cells in multiple racks simultaneously failing. If we assumed there was no partition wall between racks it would be more credible to consider that an initial cell failure in a rack would escalate to the neighbouring rack and so on. This would reduce the fire size from what has been assumed as the fire would effectively be limited to 1-2 racks at a time as opposed to all racks.

An additional, seventh, scenario was identified to assess the possibility of a fire in one BESS to escalate to another, essentially testing the credibility of the 3m separation distance between BESS. For this the worst-case scenario was modelled, which consists of a half BESS failure on the side closest to a BESS opposite with a low wind speed from behind the BESS fire.

Table 3-2: Details of simulations

Simulation ID	Wind conditions (from)	Fire size	Targeting
001	6 m/s Southeast	1 Rack	Farm Houses
002	10 m/s Southeast		
003	6 m/s Southeast	5 Racks (Half BESS)	
004	10 m/s Southeast		
005	6 m/s Southeast	10 Racks (Full BESS)	
006	10 m/s Southeast		
101	2 m/s towards neighbouring BESS	5 Racks (Half BESS)	Neighbouring BESS

3.5 Impairment thresholds

The following thresholds are defined for impairment to people and structures and are based on best practise (Ref. /6/).

Hydrogen Fluoride (HF):

- Immediate dangerous to life or health (IDLH) level is 30ppm.

Visibility:

- A visibility of 10m is typically considered acceptable for personnel to escape from a fire. An impairment threshold of 20m has been set for this study and is roughly the stopping distance for a car travelling at 30mph.

Heat flux (thermal radiation):

- 2 kW/m^2 Minimum to cause pain after 60s.
- 12.5 kW/m^2 Extreme pain within 20s. Fatal if no escape. (70% lethality outdoors).
- 25 kW/m^2 Unprotected steel will reach thermal stress temperatures that can cause failure
- 35 kW/m^2 Immediate fatality (100% lethality). Reference for structural time to failure of steel plate in 20 minutes is 37.5kW/m^2 (Ref. /8/), this will conservatively be lowered to 35kW/m^2 for this study.
- 250 kW/m^2 Reference for structural time to failure in 5-10 minutes

4 RESULTS AND DISCUSSION

Contour plots for all simulations are presented in Appendix A for thermal radiation, hydrogen fluoride and visibility impairment. The following observations are made from the results:

- There is no impact on the closest offsite buildings, farm houses to the northwest, for any of the fire scenarios. The houses to the east and southeast of the site, which are more than 520m from the BESS site, are also not impacted by any fire scenario.
- For all fire scenarios, high wind speeds (10m/s) create a slightly smaller impact compared to the average wind speed (6m/s).
- Hydrogen fluoride plumes are limited to the proximity of the site and immediacy of the fire for all scenarios.
- Low thermal radiation (2kW/m^2) levels are observed up to 4m from the edge of the BESS.
- The most likely fire scenario effects (i.e., 1 rack) are limited to within 2m of the BESS.
- The BESS-to-BESS scenario resulted in 3kW/m^2 on the neighbouring BESS, below the criteria for damage of 35kW/m^2. This level of radiation is not sufficient to damage the structure of the neighbouring BESS, meaning escalation is not possible and the 3m separation distance is sufficient.

Conservative assumptions form the basis of the analysis, peak fire loads have been modelled and racks are assumed to simultaneously fail which is extremely conservative. The scenario modelled for the 1 rack failure in reality is more representative of the full BESS fire than what has been modelled for the full BESS fire (see Section 3.4). However, the aim of the analysis was to demonstrate the consequences of the worst possible fire scenario. Even with this, there is no impairment of the nearest off-site building (>470m from the nearest BESS), and the smoke plume does not impact the surrounding area. For these buildings to be impacted by a BESS fire at East Claydon, a significant number of BESS would need to simultaneously fail i.e., potentially the entire site. Such an extreme scenario is not considered credible especially considering the site layout is effective in preventing BESS to BESS escalation.

The East Claydon site has a 3m separation distance between BESS units in all directions. This is in line with industry best practice (NFPA 855) and reflects lessons learnt from the Liverpool and Victoria BESS fires (Ref. /9/ & /10/) to prevent escalation between BESS units. The Victoria BESS site had 15cm separation distance to the back and sides of the BESS and 2.4m gap at the front. The fire propagated along the HVAC units in the roof panels to the back and sides but not to BESS at the front. In the Liverpool BESS fire, there was no fire escalation between BESS units as they were sufficiently spaced apart at 5m.

The severity of a back draught explosion as seen in the McMicken event (Ref. /7/) is also mitigated due to the rack partitions which would prevent a large volume of rich offgas forming in the container.

Additionally, the UK HSE consider a risk of 10^{-6}/year (1 in 1 million) as broadly acceptable risk to individuals from a major accident hazard, this is typically used for oil and gas facilities which pose an inherently higher risk to the public than a BESS site. Below is a calculation for the probability of a single cell failure escalating to a full BESS fire:

- Safety systems failure; SIL1 rated equipment 10^{-1}/year and gas detection failure 10^{-1}/year: 10^{-2}/year
- Ignition/flaming: 10^{-1}/year, could be argued to be 1
- Escalation to neighbouring racks through partition walls: 10^{-1}/year
- Combining these independent failure probabilities results in a probability (if a battery fails for it to develop into a full BESS fire) of 10^{-3}/year to 10^{-4}/year (1 in 1000 to 1 in 10,000 years).

As the worst-case BESS fire scenario demonstrates that there is no impact on the surrounding area, the likelihood of the BESS fire occurring is not of concern.

5 REFERENCES

/1/ https://www.dnv.com/services/fire-simulation-software-cfd-simulation-kameleon-fireex-kfx-110598

/2/ SL261_L_X_GA_P_1_East Claydon_Masterplan 21.11.23, November 2023

/3/ Technical_Proposal_of_AC4.165MW-9.318MWh_(cell_energy)_MC Cube_System 20230130 public, rev 1.1, Jan 2023

/4/ Considerations for ESS Fire Safety, Jan 2017

/5/ SFPE Handbook of Fire Protection Engineering – 3rd edition – 2002

/6/ OGP Risk Assessment Data Directory – Report No. 434-14 and 434-15. March 2010.

/7/ McMicken Battery Energy Storage System Event Technical Analysis and Recommendations, July 2022

/8/ CMPT, A Guide to Quantitative Risk Assessments for Offshore Facilities, 1999

/9/ Victorian Big Battery Fire Report of Technical Findings, Jan 2022

/10/ Liverpool BESS Fire Investigation Report 132-20, March 2022

/11/ Laboratory Test Data – UL 9540A, CSA GROUP, BYD-THU-G-HS-REP-0004_01_002 (1).pdf, May 2023

/12/ Laboratory Test Data – UL 9540A, CSA GROUP, BYD-THU-G-HS-REP-0001_02_001. pdf, December 2022

APPENDIX A
CFD Result Plots

Figure 5-1 and Figure 5-2 show contour plots for the 1 rack fire for the average and extreme wind speeds respectively. The top left plot shows the thermal radiation contours, bottom shows the 30ppm hydrogen fluoride contour, and the top right shows the visibility contour. To provide better clarity of the results shown in the above-mentioned figures, more zoomed views are provided for each fire size for thermal radiation, visibility and hydrogen fluoride on the bottom of each contour plot.

Figure 5-3 and Figure 5-4 show the same contour plots for the 5 rack fires.

Figure 5-5 and Figure 5-6 show the same contour plots for the full BESS fires.

Figure 5-7 and Figure 5-8 show thermal radiation contours impacting on the neighbouring BESS.

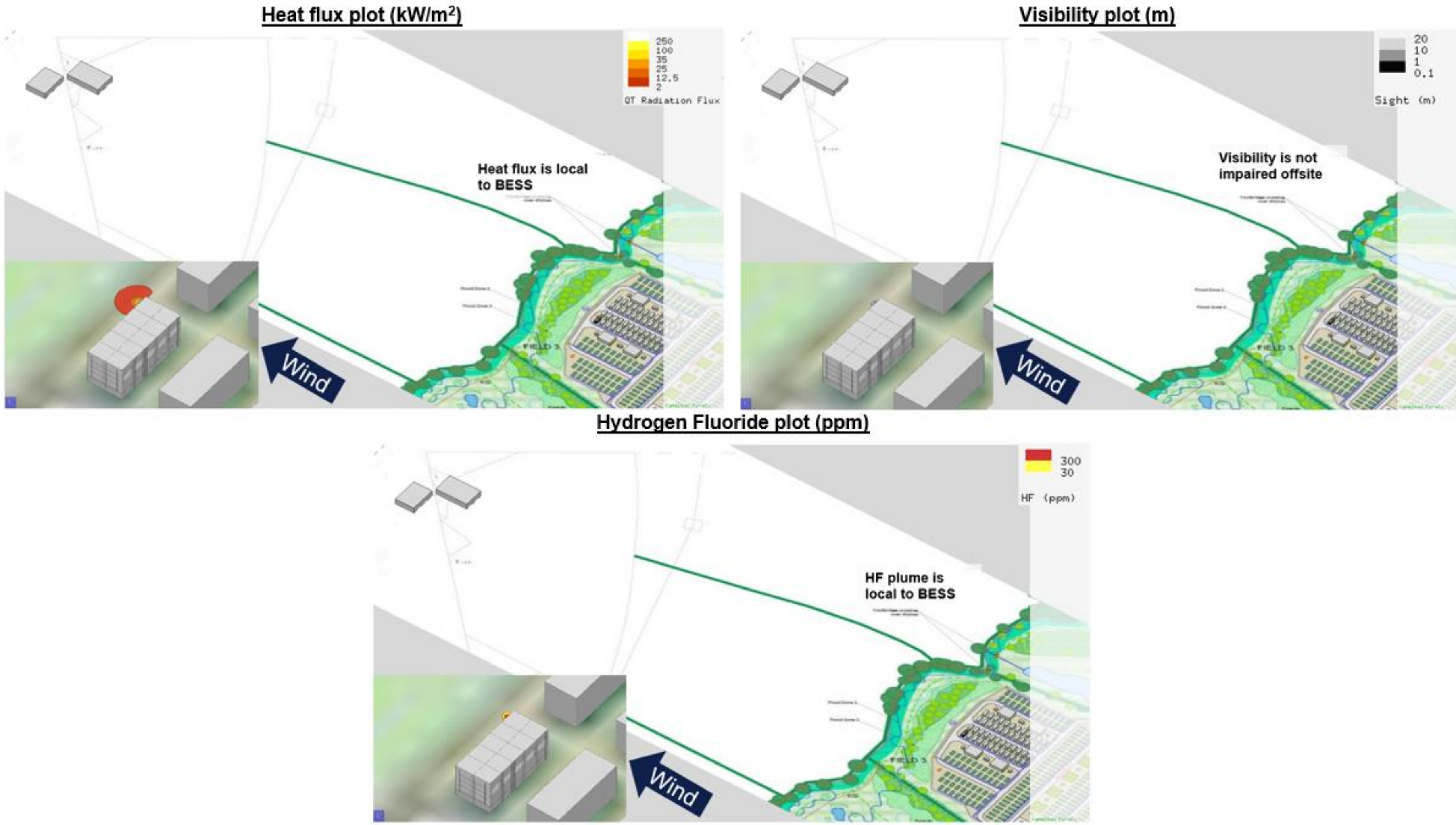
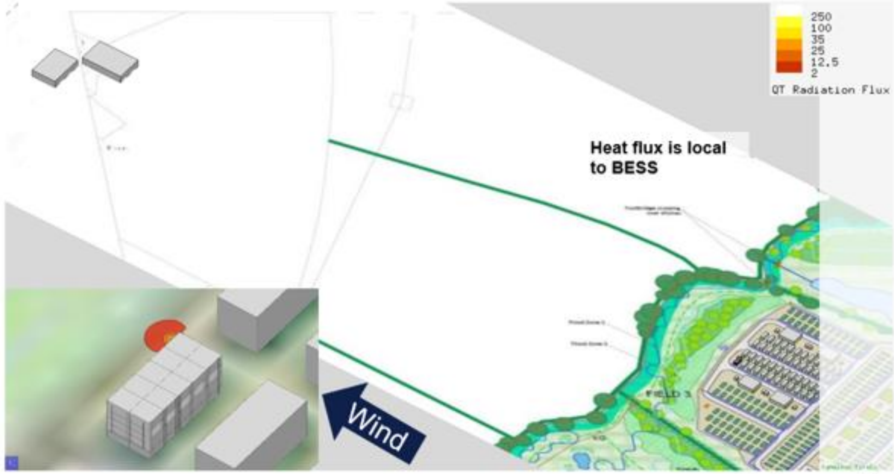
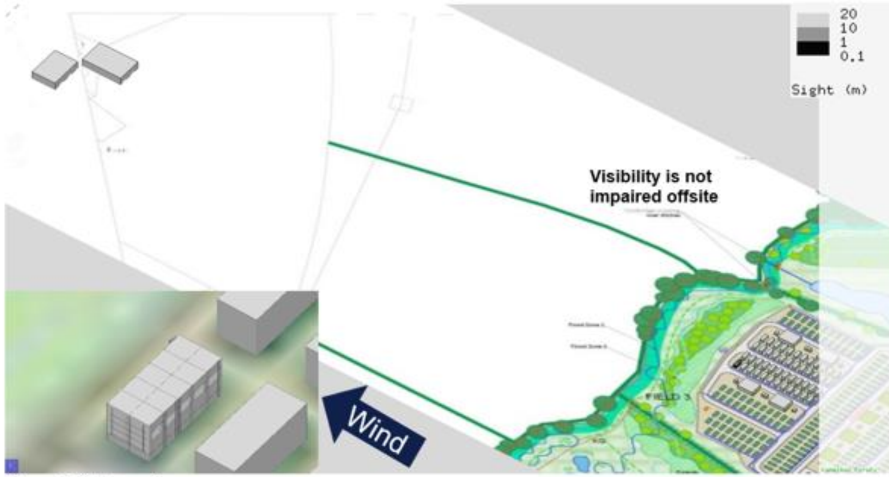


Figure 5-1: Contour plots from 1 rack failure with 6m/s wind

Heat flux plot (kW/m²)



Visibility plot (m)



Hydrogen Fluoride plot (ppm)

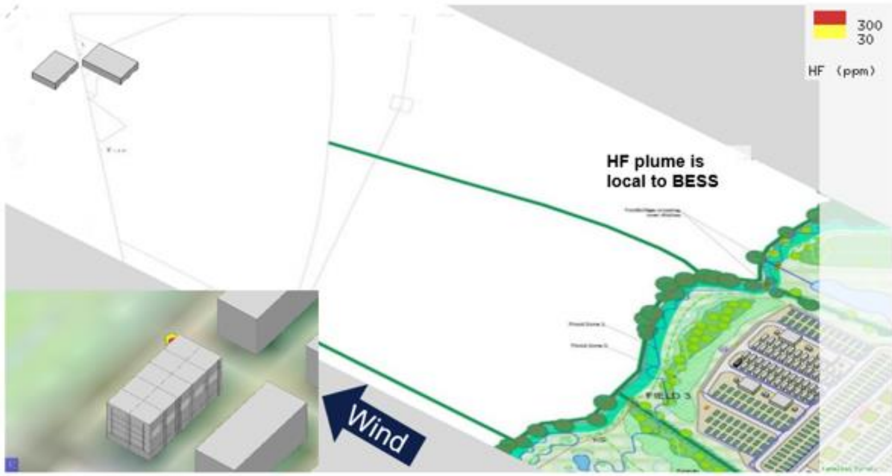


Figure 5-2: Contour plots from 1 rack failure with 10m/s wind

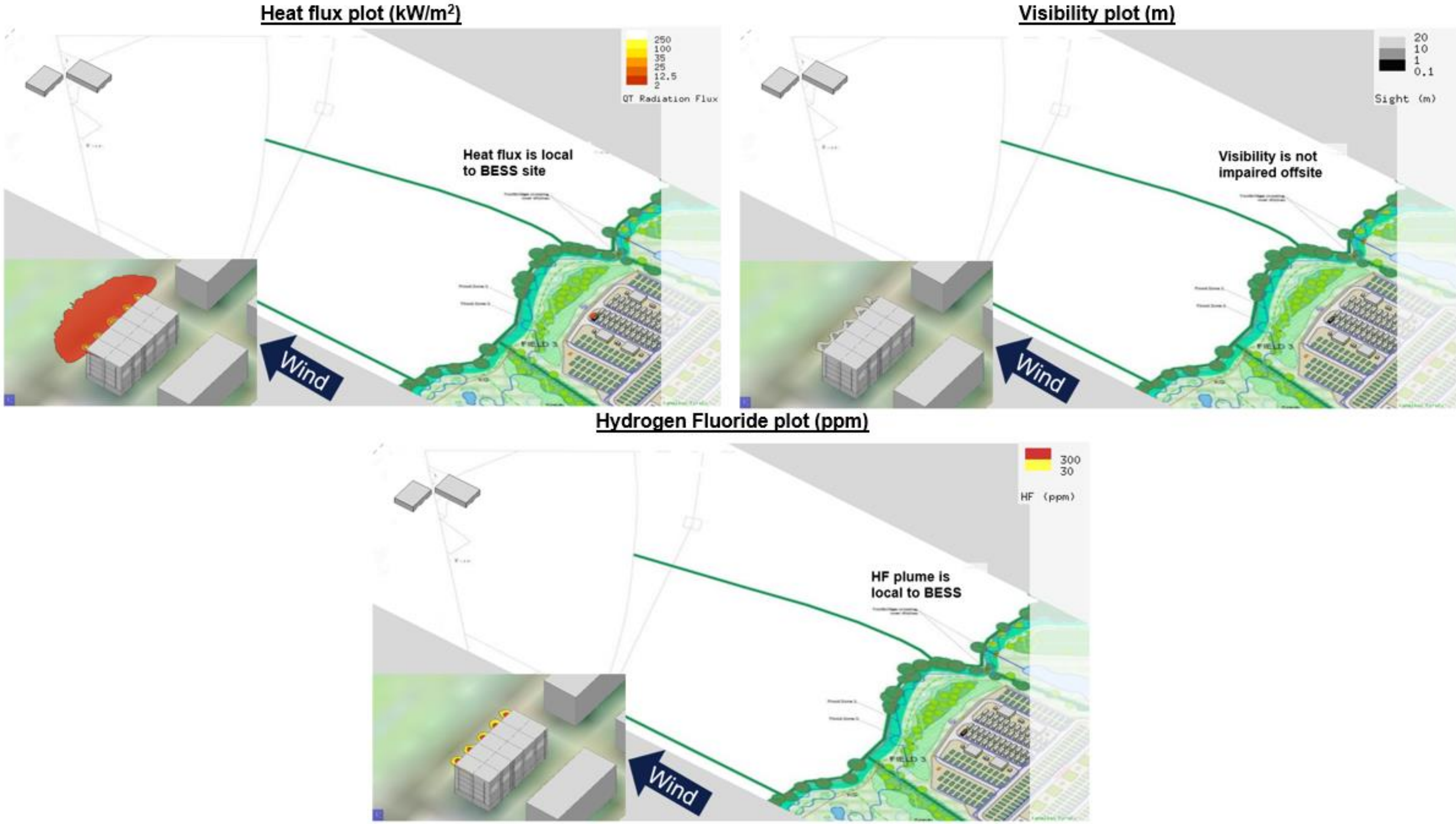


Figure 5-3: Contour plots from 5 rack failure with 6m/s wind

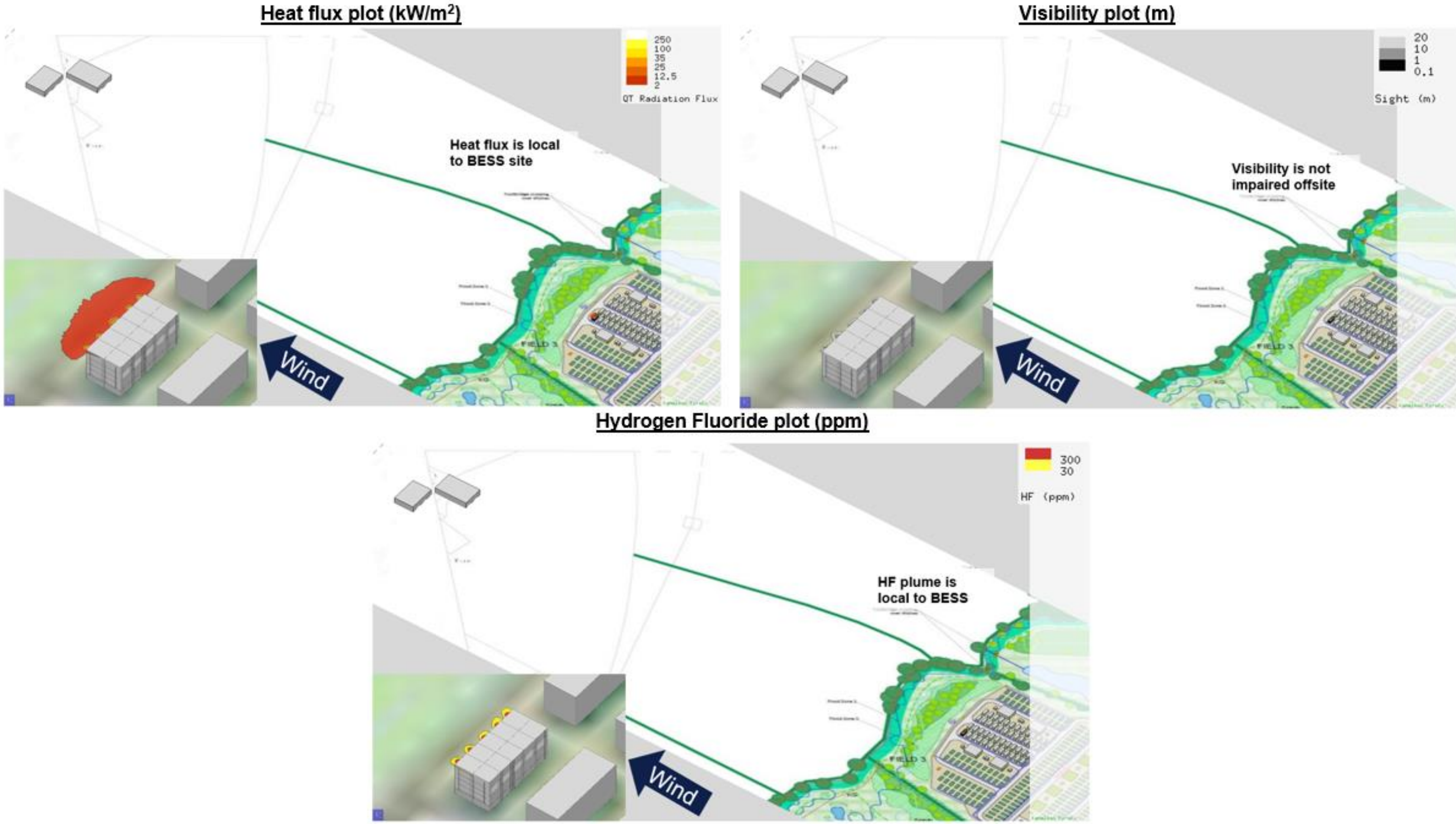


Figure 5-4: Contour plots from 5 rack failure with 10m/s wind

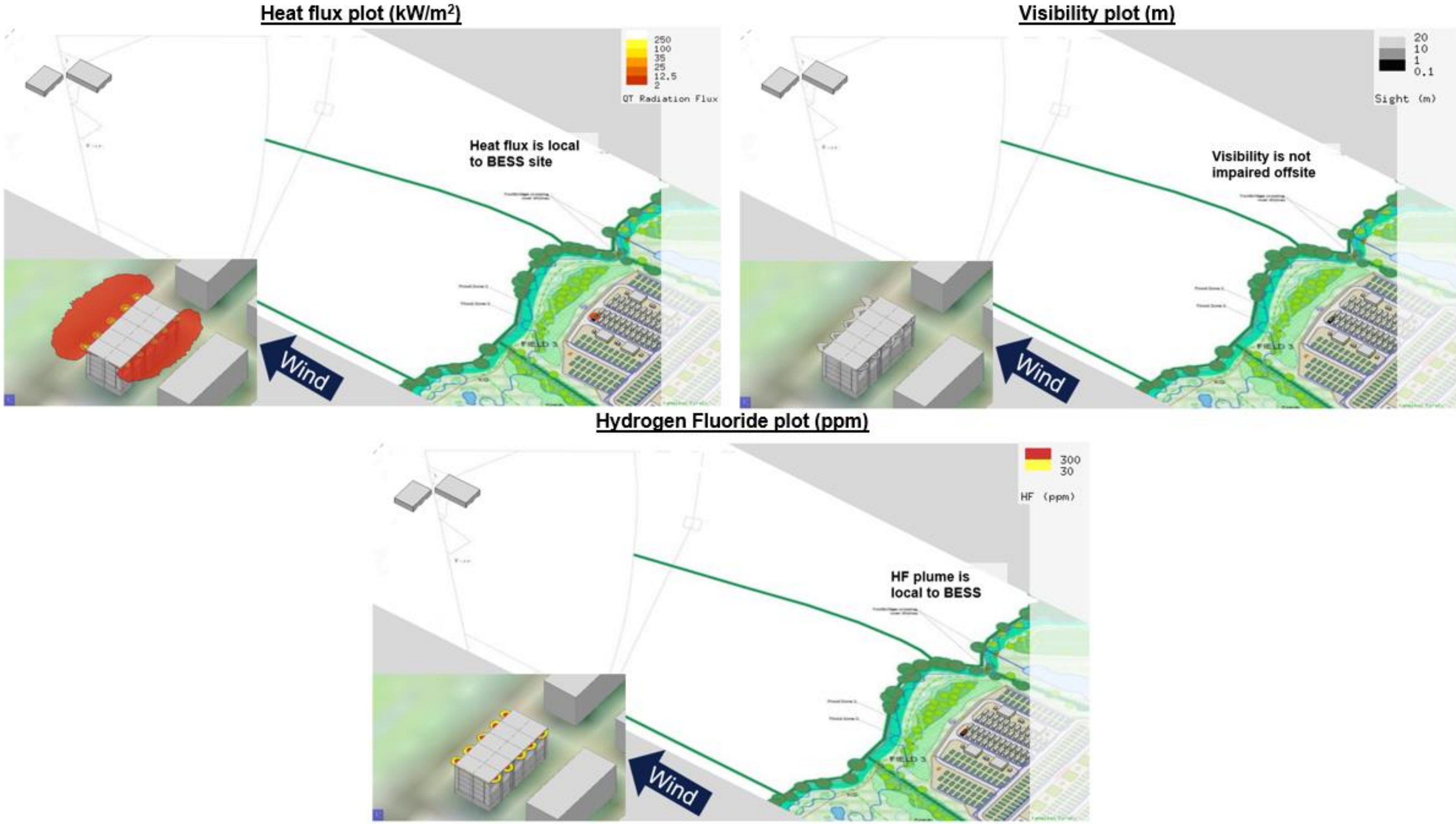


Figure 5-5: Contour plots from full BESS failure with 6m/s wind

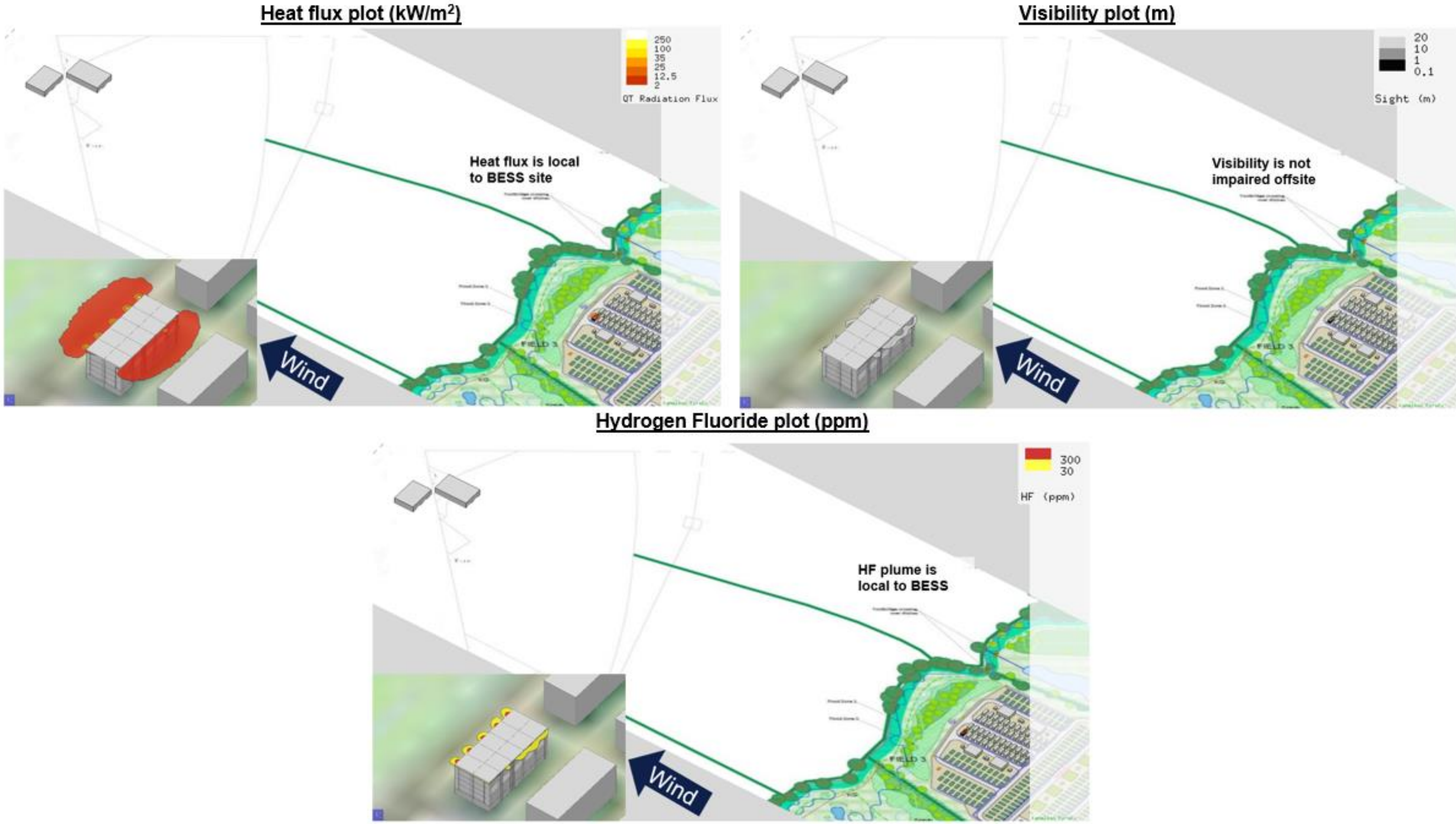


Figure 5-6: Contour plots from full BESS failure with 10m/s wind

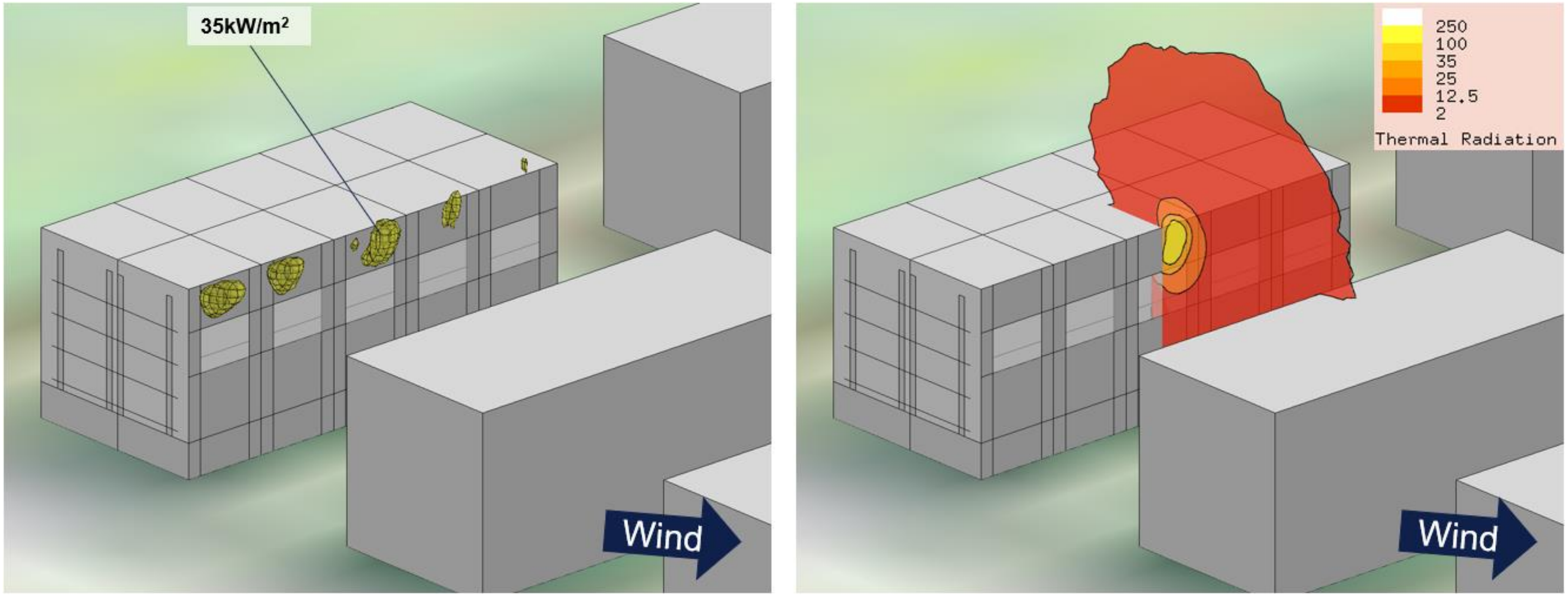


Figure 5-7: Thermal radiation (kW/m²) from half BESS, 5 rack, scenario for the BESS to BESS simulation. View from behind neighbouring BESS.

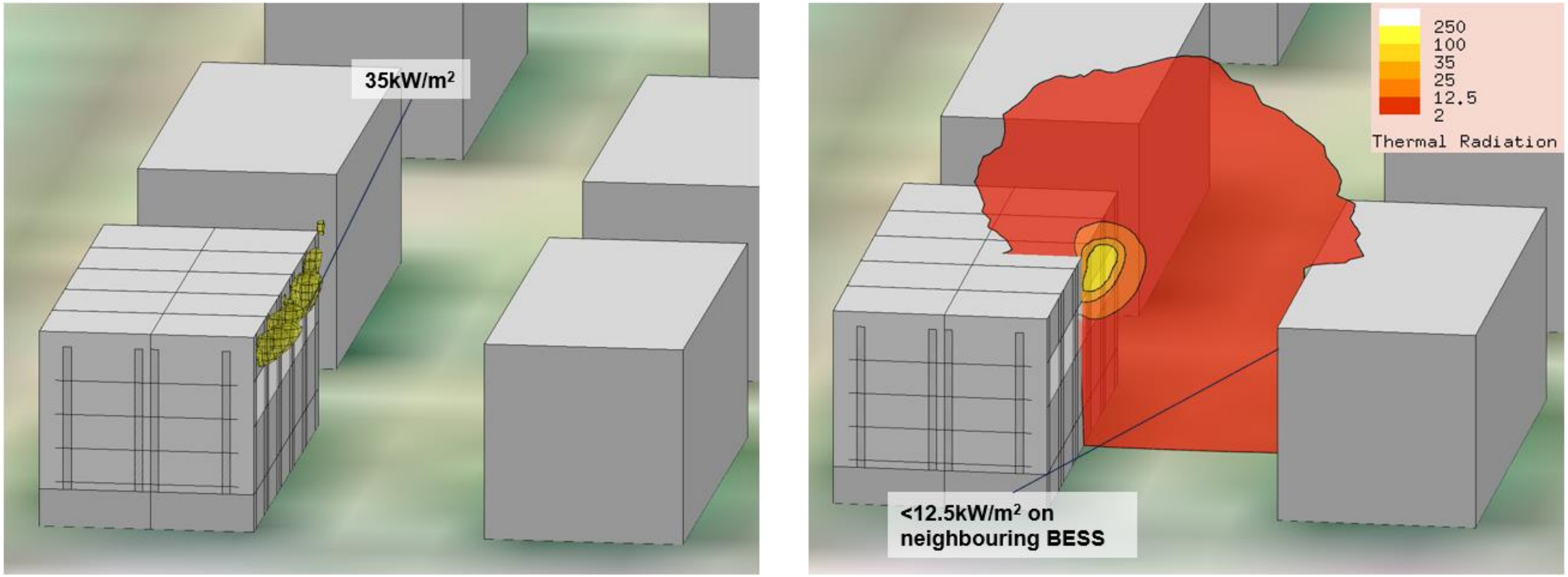


Figure 5-8: Thermal radiation (kW/m^2) from half BESS, 5 rack, scenario for the BESS to BESS simulation. View from side of BESS.