



Health-Protective Energy Transition Strategies for Aviation Hubs and Adjacent Regions

From the Editorial Board

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The aviation sector is undergoing energy transition initiatives that focus on developing environmentally-friendly technologies. However, there are limitations to the economic and practical potential of these initiatives when it comes to job and environmental health. This research considers aviation hubs to be intertwined systems of energy and health, and analyzes traditional and energy systems designed to protect health using a simulation-based, three-dimensional approach that considers exposure limits of airport personnel and nearby residents. Simulations indicate that fossil fuel powered ground operations and auxiliary power units create hotspots that frequently exceed the ground level limits of workplaces and the community. Protective of Health (PH) transition strategies, such as the use of electric ground support equipment and less use of auxiliary power units, change the dominance of sources and alter the exposure fields.

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The health benefits gained are lesser to the energy transition adapted and subjected to system limitations. A three-dimensional surface is shown revealing the limited yet achievable boundaries for energy systems transition for aviation to be sustainable. The primary aim of the research is to demonstrate the importance of exposure modeling on planning for energy systems. The research also shows simulation modeling as a supportive tool for planning the health of sustainable aviation infrastructure.

Keywords: aviation energy transition; occupational exposure; community health; three-dimensional simulation; constraint-driven optimization.

Aviation hubs function like specialized cores of concentrated energy systems that are stationed in populated areas where electric energy use, mobile fueled energy use, stationary powered energy use, and energy logistics are demanded within the same compact spatial area and are multiple intertwined. Continuing to use energy and create a large, integrated human presence and use air travel more than other transport systems. Recent studies show that the environmental impacts of aviation hubs are shaped by more than aircraft operations. Ground support equipment, auxiliary power units, terminal energy systems, and surface transport are important contributors to the local exposure impacts caused by the hubs [1, 2]. This energy activity concentration creates a situation where energy system choices for aviation hubs equally affect the worker and resident environmental exposure and the worker occupational exposure.

The impact of airport energy systems on health is due to exposure to aviation hubs that is not uniform but heterogeneous. Modeling studies and measurements have documented that thermal load and pollutant concentrations are unevenly distributed within short distance which creates localized exposure hot spots that are not captured by airport wide averages [3]. Gradients pose a particular problem for workers who operate in the operational zones for extended periods of time including the ramps, gates, service roads and maintenance zones [4]. For residents that live close proximity to the airport, exposure is governed by the dispersion behavior at the airport boundary, which can cause episodic exposure peaks depending on the operational and meteorological conditions [5]. These studies show that the health impact around aviation hubs is due to the proximity and spatial configuration instead of the total emissions.

Aviation hubs have focused on fuel reduction, terminal energy performance improvement, and electrification as means to increase efficiency and de-carbonization and to pivot from fossil fuel use to low carbon electricity [6]. These goals, while necessary to address climate change, do not ensure health protection.

Infrastructure decarbonization research shows that localized exposure increases can occur alongside system-level emission reductions if transition pathways do not incorporate sufficiently comprehensive spatial metrics [7]. Applied to airports, this suggests that energy-efficient or low-carbon configurations can still result in unacceptable occupational or community exposure as long as the energy use is concentrated in areas of human activity.

Designers of energy systems must think of engineering of boundaries to define exposure limits for safety purpose and design systems for aviation energy sharing systems for safety purpose as designers of other safety critical systems have done, especially those systems exposed to high energy radiation or high linear energy transfer (high LET) environments. These types of systems demonstrate that biological repair systems become ineffective beyond certain energy thresholds, resulting in persistent damage to satellites and other biological systems [8]. Monte Carlo and multi-layered kinetic models demonstrate the nonlinearity (behavior changes) of systems when critical thresholds or limits are reached. These laws highlight the importance of integrating mechanistic and stochastic modeling for accurate estimates of system behavior. For this reason, aviation energy sharing systems must have system-designed thresholds, or limits, and models that are capable of being validated for the system's safety.

As regards aviation hubs, ground operations represent a crucial exposure pathway. The studies starting from 2017 have continuously focused on ground support equipment, aircraft auxiliary power units, and service vehicles as primary contributors to near-field exposure, particularly for ultrafine particles and nitrogen oxides [9]. The proximity of these sources to the ground level and to the workers means that, even with reduced exposure through aircraft emissions, their emissions will be the greatest source of occupational exposure [10].

Consequently, the promotion of ground operations electrification is justified for protective health measures, although its spatial and temporal effectiveness is dependent on the redistribution of energy demand across the airport system [11].

The safety-critical environments we studied reinforced the need for more spatially resolved modeling. Recent data-driven and CFD-based studies on aircraft cabin environments show that airborne virus propagation and physical proximity impact the spread of infection, pathogen dispersion, and challenge the protection proximate approach [12]. CFD and ML models demonstrate strong dose-response relationships between localized infection exposures and infection risk. These illustrate infection flow and spatial distribution health impacts ineffective under average conditions. These studies enhance the benefit of airport-scale energy transition planning through predictive exposure containment modeling for health safety protection by planning and pausing reactive protections.

The risk of exposure is affected differently with different measures taken to transition energy types. Some of these measures shift the risk rather than eliminating it. For instance, simplifying the energy supply to all electric or all backup supply options removes some combustion sources but may create greater risk when these are installed near worker or residential zones [13]. Also, relying more on on-site generation during peak demand or during grid outages raises the risk of exposure episodically and counters the objective of health risk mitigation [14]. These cases demonstrate the importance of energy transition studies from the standpoint of exposure constraints rather than just overall transition effectiveness.

This necessitates viewing aviation hubs as integrated systems of energy and health to address the intertwined exposure and energy flow pathways through the source location, operational arrangement, work behavior, and dispersal pattern of workers.

Based on the recommendations from recent integrated studies, the energy transition of infrastructure is to take place in feasibility landscapes that are defined by safety, health and regulatory [15] limitations. For aviation hubs, this means that the exposure limits of workers and the environment must be treated as primary parameters that determine which energy system configurations are acceptable. Optimizing outcomes related to exposure is not an acceptable practice.

From a methodological perspective, this one will support simulation based decision making. Planners translate configurations by means of exposure fields, which translate realistic operating conditions. New progress made in three-dimensional dispersion and exposure assessment models have proven robust for the evaluation of source proximity impact for transport and logistics, especially for airports [16, 17]. Models of this nature assist in the evaluation of alternative energy configurations and assessments of boundary impacts of adjacent communities.

Occupational exposure is inevitable for airport personnel, making exposure assessments even more important. Transport sector occupational health studies show task specific exposure is far more likely to exceed ambient levels, meaning protective measures are likely to fail without local energy and operational measures, regardless of the overall region [18]. Health focused energy transition measures that only target fleet efficiency or terminal buildings will likely miss critical risk zones.

The surrounding areas near airports have to figure out how to deal with issues that arise in areas that are not on or near the airport. The effects caused by differently configured land uses, combined with plume rise and the mixing of the boundary layer, have produced unequal distributions of impacts in the surrounding areas [19]. Modifications in energy sources and altitude of the source's changes exhaust characteristics, and may either lessen or heighten the impacts that are dependent on the context of the implementation.

This emphasizes the significance of environmental exposure limitations.

This paper aims to create a constructive, simulation-based evaluation of the framework of the protective health strategies due to the changes in energy at the aviation system. Instead of energy or emissions performance allowing the framework to rank aviation hub energy transitions, the framework identifies solution spaces that are defined by interstice and constructive environmental and occupational exposure. This is in line with the practices recently adopted regarding sustainable planning and infrastructure. By linking the protective energy system to exposure, the paper adds a guide to the selection of paths to emissions control that most benefits the airport surrounding communities and workers.

Methodology

This section details the methodology based on simulations for the protective health impacts of energy transition strategies for aviation hubs and the regions around them. The focus is on simplicity so non-specialist readers can follow the logic without specialist knowledge in numerical modeling. The basic approach is to consider an aviation hub as a coupled energy–health system in which an energy configuration change reconfigures spatial exposure patterns of the workforce and the proximate communities. The methodological workflow, in Figure 1, connects an energy system scenario to a three-dimensional exposure modeling and a three-dimensional exposure modeling and a constraint-based feasibility assessment.

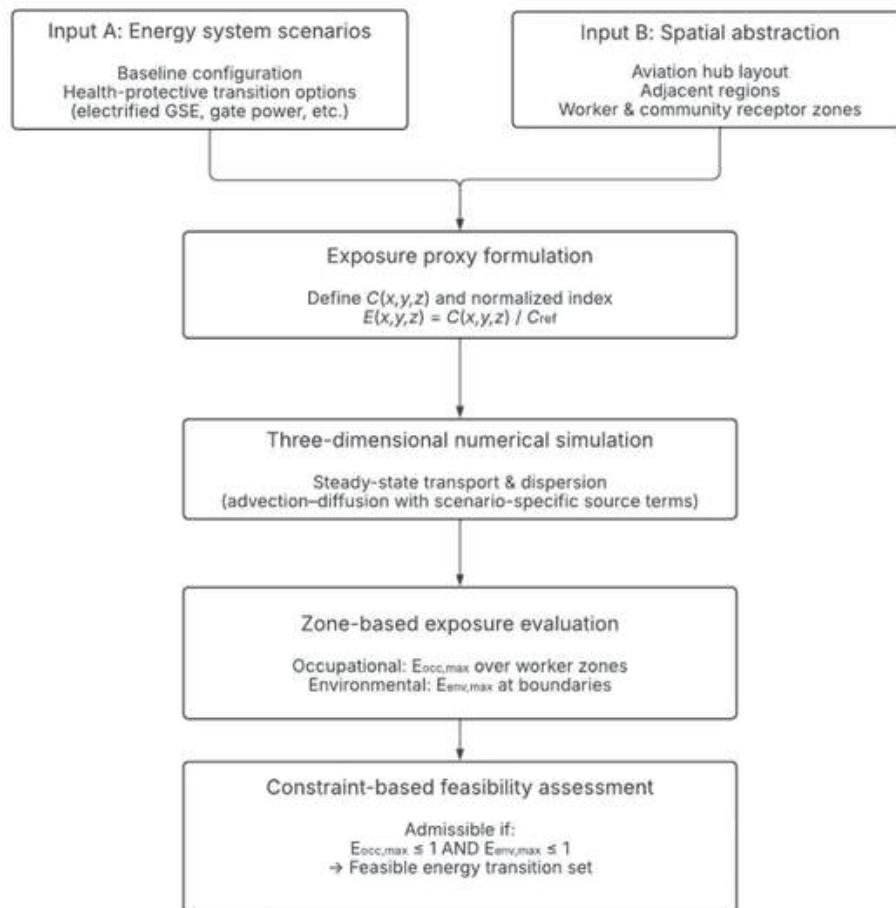


Figure 1. Simulation workflow for health-protective energy transition analysis in aviation hubs

The analysis starts with establishing the aviation hub and surrounding areas as a three-dimensional space. This space consists of structures like terminals, apron and ramp zones, service roads, and external buffer zones that represent nearby residential or mixed zones. The representation of space is abstract and is not site specific. It means the representation captures airport layouts and relationships that are relevant to exposures without needing proprietary or confidential data. They developed a three-dimensional spatial representation made of a Cartesian coordinate system with a representing the dominant downwind direction, as the crosswind direction, and as the height above ground. This coordinate system is used to consistently locate energy sources, airflow, and exposure receptors within the spatial domain.

Energy system scenarios in the two dimensional space, are formed. A baseline scenario considers conventional airport operation, grounded on fossil fuel powered ground support equipment, auxiliary power units at gates, and terminal systems energy systems. Transformed scenarios, in contrast, address health-protective energy transitions, such as elevated operations electrification, reduced auxiliary power units dependency, and cleaner electricity. Each transformed scenario is defined by its total energy demand as well as by the total spatial distribution of energy-relevant release source. In the interest of scenario comparison, energy demand reflects a relative value in regard to the baseline configuration. The normalized value of energy demand for a scenario is represented by the equation below

$$E_n = \frac{E_s}{E_b}$$

Where E_s is the total energy demand of the scenario and E_b is the baseline energy demand. A scenario of transformed systems provides activities that consume and demand energy, but does not depend on the relative size of the absolute airport.

To connect the configurations of the energy system with health relevance, proxies of exposure are defined. The study purposely excludes the modeling of particular health outcomes and instead examines the spatial indicators of exposure that are well established to correspond to the risks of exposure encountered in the work environment and in the environment. These proxies could be due to thermal load, pressure of pollutants, or metrics of intensity of load in combination. A general exposure field $C(x, y, z)$ is calculated over the entire domain corresponding to the intensity of the exposure proxy at every location. For health relevance, the field is adjusted against a reference threshold value C_{ref} of a given proxy that is known to be acceptable in occupational or environmental situations. The exposure index is defined as dimensionless,

$$E(x, y, z) = \frac{C(x, y, z)}{C_{ref}}$$

By definition, E values less than one indicate compliance with the health limits and values greater than one indicate the opposite.

The spatial pattern of the exposure field is captured by a 3D numerical simulation. A steady-state advection-diffusion model approximation is used to explain the transport of exposure and energy releases within the airflow and the diffusion dispersion mechanism. The governing equation for the exposure field is given as

$$\mathbf{u} \cdot \nabla C = \nabla \cdot (D \nabla C) + S$$

Where $\mathbf{u}$ is the mean velocity vector of the airflow, D is an effective diffusion coefficient representing turbulent mixing, and S is the source term due to the operation of energy systems. This equation represents a balanced flow of transport, dispersion, and generation of exposure within the domain.

Energy-associated sources are located in space and modeled using smooth distributions that mimic realistic release behavior. Examples of sources that are distributed vertically include exhaust plumes and heat release. The source term is expressed using the equation

$$S(x, y, z) = S_0 \exp\left(-\frac{(z - z_s)^2}{2\sigma_z^2}\right)$$

where, S_0 is the source strength, z_s is the effective source height, and σ_z dictates the degree of vertical dispersion. The same Gaussian profiles are applied in the horizontal direction for lateral dispersion. These simplified formulations are sufficient to reproduce key spatial exposure patterns, including near-ground accumulation, plume rise, and the decay of plumes in the downwind direction.

After determining the exposure field in three dimensions, it is assessed in terms of its occupational and environmental relevance. Within the airport core, including the apron and ramp areas, worker-accessible areas are defined.

The primary exposure appraisals upon which the analysis of worker risk is based is the exposure index that reaches a maximum in this area, described by the equation

$$E_{\text{occ, max}} = \max_{(x,y,z) \in \Omega_{\text{work}}} E(x, y, z)$$

where, Ω_{work} is the worker-accessible domain. This occupation safety definition is conservative, as it suggests that occupational safety is not at risk unless an area exceeds an exposure threshold, regardless of the average exposure level.

Environmental exposure occurs in the border and community risk areas that are located outside the airport core. The exposure risk is expressed in the equation

$$E_{\text{env, max}} = \max_{(x,y,z) \in \Omega_{\text{env}}} E(x, y, z)$$

where Ω_{env} is the area of environmental concern. The equation describes the exposure levels, which are an approximation of the exposure levels experienced by the communities that are nearest to the airport.

Energy system scenarios use a constraint-driven feasibility criterion to classify scenarios. An admissible scenario is one where occupational and environmental exposure limitations are both satisfied. This requirement is expressed as

$$E_{\text{occ, max}} \leq 1 \text{ and } E_{\text{env, max}} \leq 1$$

No scenario will be considered feasible if they are energy inefficient or do not improve emissions, even if both conditions are true. This scenario is not feasible even if both situations are true. This is similar to current regulations where exposed to health impacts cannot be outweighed by the benefits of the scenario.

To further explain, improvements in energy performance are also measured. The relative energy reduction of a transformed scenario is calculated as

$$\eta_E = \frac{E_b - E_s}{E_b}$$

where E_b is the baseline energy demand and E_s is the scenario energy demand. This measure shows the energy transition effectiveness but it will have no impact on feasibility classification, which will be influenced by exposure impact.

A number of simplifications were made in the simulation. The analysis is steady-state, representing ordinary operating conditions. Meteorological conditions are modeled as constant mean values, avoiding seasonally variable weather. The focus of the analysis is on exposure patterns, not on atmospheric chemistry, therefore the chemical transformations of pollutants are not modeled. These simplifications were made in order to keep a clear framework. The authors want to be certain that the variations in the results are a consequence of the energy system configuration, not the result of model complexity.

Energy system scenarios and health constraints

This subsection describes the energy system scenarios that have been used in the study, and articulates the occupational and community health limitations that bound the admissible solution space. The aim is neither to catalogue all potential aviation technologies, nor to arrive at extreme configurations, but to provide illustrative designs that best represent predominant energy–exposure relations at aviation hubs. By establishing both traditional and health-protective scenarios within a unified framework, the analysis is assured that resultant discrepancies stem from energy system selection, rather than different modeling assumptions.

The typical energy system scenario describes current, common operational practices for medium to large aviation hubs. Here, a large proportion of ground operations are done with fossil fuel equipment such as baggage tractors, belt loaders, catering vehicles, maintenance vans, and shuttle buses within the airport perimeter. During stays at the gates, planes' auxiliary power units are used to provide onboard electricity and climate control, especially at gates without fixed electrical ground power or pre-conditioned air systems. Terminal buildings receive power through the grid and have on-site backup generation, usually diesel, to ensure the continuity of critical operations. In energy terms, this setup involves the use of distributed, near-ground combustion sources in close proximity to workers and intermittent, yet extreme, energy discharges during aircraft servicing cycles.

The main issue of this type of arrangement is that a large portion of energy-related emissions are released at lower heights and at levels accessible to workers. While ground support equipment is used on aprons and service roads where workers are present all the time, auxiliary power units exhaust near the gates where personnel are located during the aircraft turnaround. These features give the conventional situation a baseline reference quality for evaluating typical occupational and environmental exposure. The scenario is defined not by a single technology choice, but by a constellation of operating parameters, or a set of those parameters, that describe the prevailing energy–exposure configuration at a large number of airport hubs.

Health-protective energy transition scenarios are changes in the baseline structure that aim to reduce exposure intensity in worker and community areas. The most notable change in these scenarios is the reduction or complete removal of near-ground combustion sources in the airport core. This is done by electrifying ground support equipment, increased use of fixed electrical ground power and pre-conditioned air at the gates, and less use of auxiliary power units while parked at the gate.

Terminal energy systems will still be connected to the grid, but are assumed to use cleaner electricity or on-site low-emission sources, if available. Backup generators will still be available, but to have less use during the normal operational times, the system will control when the generator is used to have less routine use during that time.

From the perspective of energy accounting, protective scenarios may have the same or slightly lower total energy demand than the baseline and, in some scenarios, protective scenarios may have more total energy demand than in baseline scenarios. This is because, while there is less fuel being used and consumed in the system, more electricity is being used and consumed in the system. Therefore, the most important characteristic is the redistribution of energy consumption and use, rather than the energy demand reduction. This is primarily because most protective scenarios are defined by spatial and operational elements rather than a singular performance aim.

In order for scenarios to be comparable with one another, each one is described with a specific set of operational parameters. These parameters include: relative operational ground energy intensity, relative use of auxiliary power units, effective vertical source height of energy release, and time averaged source vertical accessibility of the source worker zones. Instead of defining absolute values specific to a particular airport, the parameters are defined relative to the conventional scenario. The result is a description that is general, yet, still rational within the bounds of the scenario. The parameters used to describe the scenarios are presented in Table 1, where the conventional and health-protective configurations are contrasted in terms of the pattern of energy use and the exposure relevant features.

Table 1. Energy system configurations and operating parameters under conventional and health-protective aviation scenarios

Parameter	Conventional aviation energy system	Health-protective aviation energy system
Ground support equipment (GSE)	Predominantly fossil-fuel powered; near-ground combustion sources	Largely electrified GSE; on-site combustion minimized
Auxiliary power unit (APU) usage	Frequent APU operation during gate occupancy	APU use minimized via gate electrification and pre-conditioned air
Dominant energy release location	Apron, ramp, and gate-adjacent zones	Relocated away from worker-dense zones
Effective source height	Low (near ground level)	Increased effective height or removed from core zones
Temporal persistence of sources	Continuous or repetitive during operations	Reduced duration and spatial persistence
Terminal energy supply	Grid electricity with routine backup generator readiness	Cleaner grid supply; backup generation restricted to emergencies
Occupational exposure potential	High, with localized hotspots in worker zones	Reduced peak exposure in worker-accessible areas
Community exposure potential	Boundary-level dispersion under certain conditions	Attenuated boundary exposure under typical operations
Constraint compliance tendency	Often violates occupational and/or community thresholds	Designed to satisfy both exposure constraints

A key aspect when defining the scenarios is the auxiliary power usage, which is present in all operating scenarios and is treated the same way. For conventional scenarios, it is assumed that the auxiliary power units run for a large chunk of the time the plane is at the gate, creating localized emission and heat loads at the plane parking. Assuming health protective scenarios, the auxiliary power usage is minimized using gate electrification and better operational techniques. This is a significant change because the auxiliary power units are a source of frequent, concentrated exposure in close proximity to the workers. Health protective scenarios tend to focus on lessening major contributors to occupational exposure.

Ground handling is treated in the same way. In the conventional operational scenario, it is assumed that ground support equipment is operational using internal combustion engines, where emissions are unattenuated, and therefore close to the workers. While in the health-protective scenario, most of this equipment is assumed to be electrified and therefore less combustion is present on site.

Although electrification transfers the energy demand to another source, it does reduce exposure in the immediate work environment. This is the main distinction for the health-protective transition: it is not enough to decarbonize the energy supply, the focus must also be on relocating or eliminating the exposure from the close proximity to human use areas.

After assessing each energy system scenario, the next step is to outline the health restrictions that outline the boundaries of the acceptable solution space. These boundaries determine unacceptable configurations of energy system systems, regardless of how energy efficient or emissions compliant they are. Two types of restrictions are formulated: Occupational exposure restrictions for airport employees, and environmental exposure restrictions for nearby communities.

Occupational exposure restrictions are implemented in worker contact zones, including apron, ramp, service road, and gate areas. The exposure restriction is defined using the normalized exposure index introduced in the methodology section. The exposure scenario worker zone has been evaluated for maximum index exposure values. An occupational restraint threshold of one has been used, meaning that scenarios producing normalized exposure values greater than one in any worker zone are deemed infeasible. This overly strict definition is typical for occupational health regulation, as a single exceedance at one location or task is sufficient to require further mitigation or redesign.

There is a reason that an occupational constraint based on maximums is utilized. Beresford indicates that average exposure values can obfuscate localized exposure “hotspots” that entail an outsized risk to certain groups of workers. By concentrating on maximums within the worker domain, certain analyses are justified for the most extreme yet plausible energy transition scenario.

It is a common practice to justify an analysis on maximum exposure because occupational safety is typically centered around maximum exposure rather than the average.

Environmental exposure constraints are the same for areas outside the airport core. These areas are the surrounding residential, commercial, or mixed-use zones where community exposure is a factor. In all scenarios, the maximum normalized exposure index is analyzed within the environmental domain. A threshold of one is used again for determining admissibility. If any scenario is found to have any “excess” in any community-related location, the scenario is deemed environmentally infeasible, even if the occupational exposure is lower.

Defining the boundaries for energy transition scenarios is the combination of occupational and environmental constraints. A scenario is admissible if, and only if, it meets both constraints. The combination of both principles reflects the fact that, in the context of sustainable aviation infrastructure planning, it is not acceptable to protect workers while sacrificing surrounding communities.

An example could be of a case that reduces the use of auxiliary power units which could lower the work-related exposure of people working near the gates but could increase the use of backup generation on the airport periphery. Such case could be of the work-related exposure constraints being satisfied but the environmental exposure constraints being breached. On the opposite side, moving energy conversion processes from the boundary might reduce the community exposure but would still leave some near-ground sources for workers in the exposure zone. These balancing acts exemplify the reason for the absence of simplification to a single goal in energy transition planning, and also the importance of evaluating trade constraints.

Building upon this explanation, the idea of an admissible solution space develops naturally. The analysis does not single out one optimal energy arrangement, but rather, focuses on identifying the whole range of scenarios that comply with the occupational and environmental constraints within which decision makers also can choose based on other factors like cost, reliability, or potential to decarbonize in the long term. Scenarios with values on the other metrics lie outside this range, no matter how other metrics might perform.

Table 1 supports the discussion by outlining the operational criteria that differentiate conventional from health protective scenarios. By associating these criteria with the exposure limits defined herein, the table provides an easy pathway from definition of the scenarios to their assessment for feasibility. This approach provides clarity and reproducibility, so that other researchers or practitioners can use this approach in other airport settings, while maintaining the fundamental reasoning.

Results and discussion

This section provides results that combine three dimensional simulation outputs and quantitative metrics that measure the extent of occupational and community exposure patterns resulting from varying configurations of the aviation energy systems. The analysis developed from the methodology demonstrates the constraint-driven logic and is primarily concerned with the patterns of spatial exposure behavior as opposed to an energy or emission performance. All results are referenced in terms of the figures and table provided and numerical results are inextricably linked to the visual evidence.

Regarding conventional aviation energy systems, the simulated three-dimensional exposure field shows a high degree of spatial variability. Figure 2 shows the baseline exposure dispersion around the aviation hub under conventional ground operations.

The highest exposure intensities are around the apron and gate-adjacent areas where fossil-fuel-powered ground support equipment and frequent auxiliary power units cause sustained near-ground releases. These hotspots are aligned spatially with areas where workers are present, thus, occupational exposure is primarily explained by proximity to energy conversion processes, rather than airport-wide averages. The exposure field has high spatial variability, with sharp vertical gradients, and is low above the atmospheric layer which workers operate. In contrast, there is a high rapid attenuation above the layer. This shows the exposure dominance of low-level sources and the initial plume rise under conventional operations is limited.

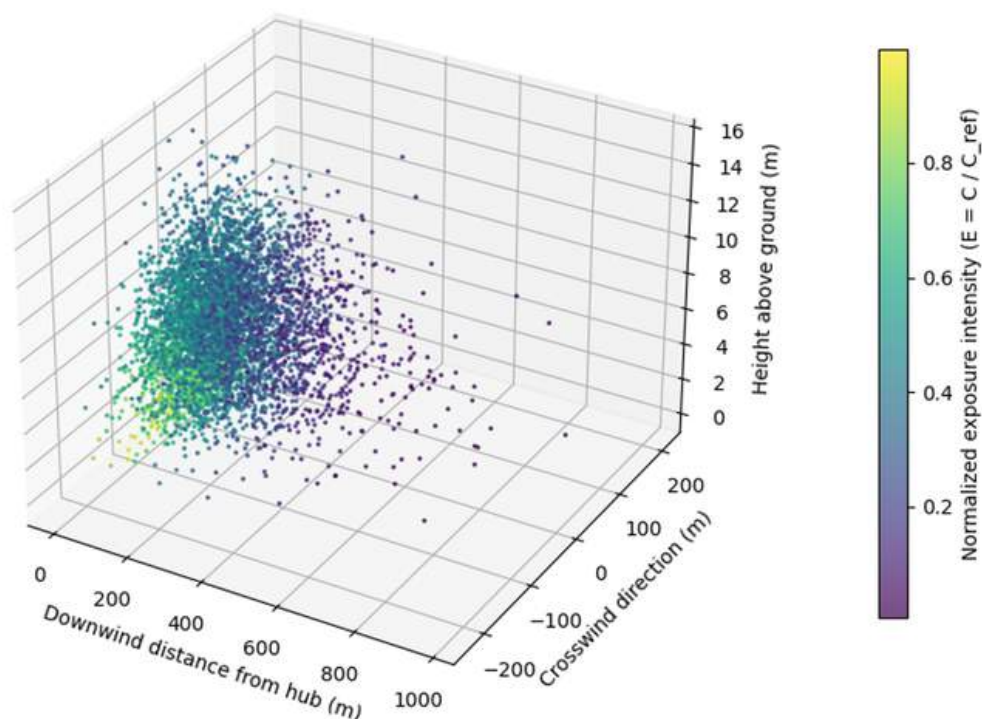


Figure 2. 3D exposure dispersion around aviation hub under conventional ground operations

Downwind dispersion with baseline configurations stretches the exposure footprint beyond the core of the immediate airport. Figure 2 shows that some exposure plumes continue to the boundaries of the modeled domain. At varying intensity levels, exposure remains asymmetrically distributed around the community and impacts community relevant areas.

Just as importantly, the simulation shows the average boundary exposure remains moderate, and localized exceedances present themselves at some of the specific downwind locations. This emphasizes the shortcomings of using boundaries, and emphasizes the importance of focused studies on relevant areas of community exposure to protect the community's health.

Spatial exposure landscapes change significantly when health-protective energy transition strategies are implemented. The difference between the three-dimensional dispersions of exposure fields with traditional energy systems and with health-protective energy systems is presented in Figure 3. Among the early impacts of the transition is peak exposure intensity reduction in the worker-accessible zones. Electrification of ground operations and the reduction of auxiliary power unit use, for example, withdraws primary near-ground combustion sources from the apron and gate zones, resulting in lower exposure gradients. In this transformed scenario, the exposure field is less about specific operational nodes and more diffuse overall.

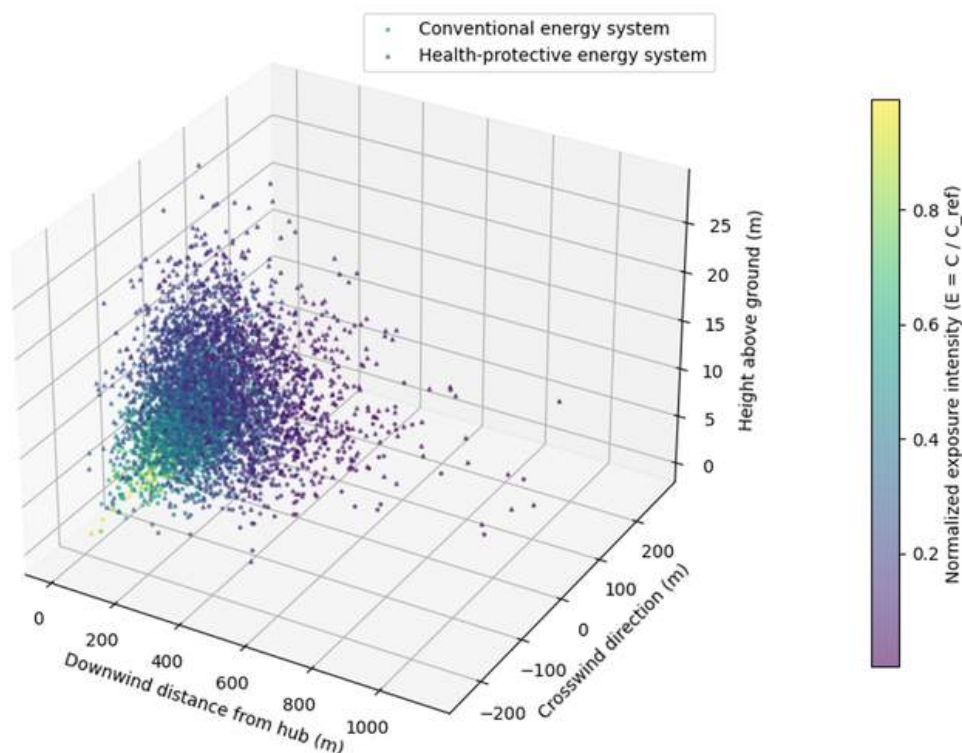


Figure 3. Comparison of 3D exposure dispersion under conventional and health-protective energy systems

The information shown in Figure 3 indicates health-protective transitions change both the amount and the type of exposure dispersion. In the conventional case, exposure plumes come from numerous low level sources that are spread out across the apron which creates overlapping areas of higher intensities. In The transformed scenario, there are fewer, and weaker plumes, with the rest of the exposure in the transformed scenario primarily tied to low, centralized, or higher level energy processes. From a health perspective, this is a beneficial change to the exposure as it decreases the areas of peak exposure and the areas of constant human contact or presence. Thus, the amounts of occupational exposure are significantly lowered even if there is no proportional decrease in the total energy demand.

The results also show that although there is an improvement, health-protective transitions do not completely remove exposure uniformly across the unrestricted areas. Figure 3 shows that there is still some exposure, especially in areas related to terminal energy systems, and backup generation. While these sources do not influence routine occupational exposure as much, they can influence the ways environmental dispersion occurs. This reinforces the necessity of a more thorough evaluation system that considers both occupational and community exposure systems, rather than focusing on one receptor.

Figure 4 explores the three-dimensional spacing exposure dispersion fields moving from the aviation hub to nearby regions. With standard operations, the exposure plume moves downwind with a strong enough intensity to intersect zones relevant to community exposure, particularly during periods of persistent ground activity. The simulated field suggests the distance-related exposure decreases unevenly, and factors such as source clustering and plume interaction, even in the absence of terrain, can result in a localized increase several hundred meters from the airport boundary.

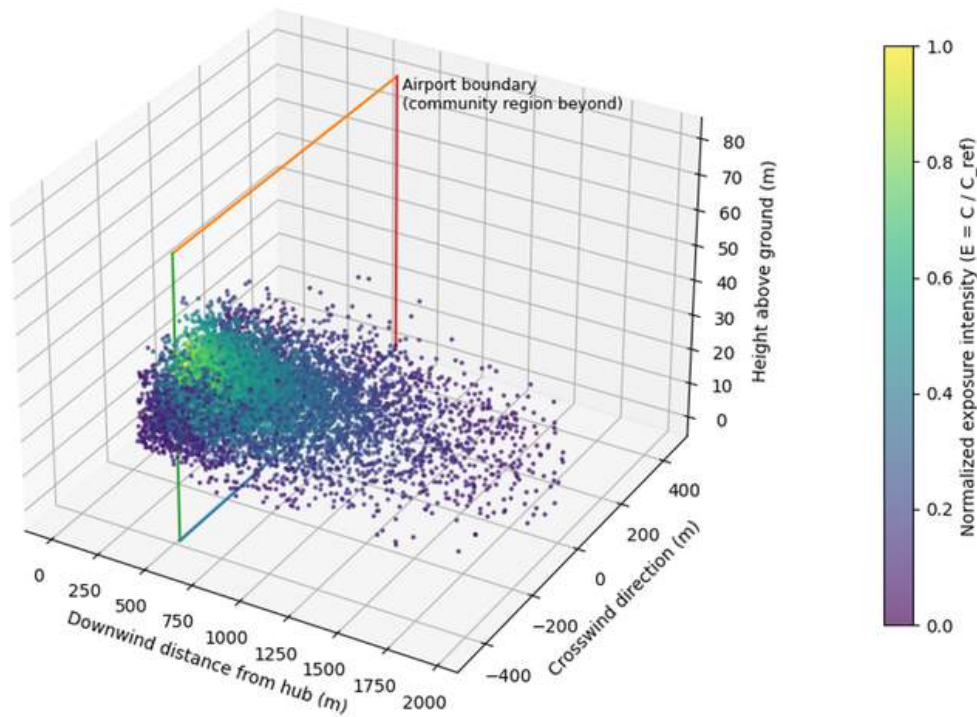


Figure 4. Three-dimensional exposure dispersion field extending from aviation hub into adjacent regions

In the protective health scenario, figure shows that exposure in the adjacent regions has been significantly lower. This is because the protective health scenario has less near-ground source strengths within the airport core leading to less plume concentration at the boundaries, notwithstanding the total energy use across scenarios being comparatively high. The vertical structure of the plume is also altered, along with the source heights of many processes being made more effective, or eliminated. This leads to better dispersion and lower near-surface community zone concentrations. As a result, compliance with community health constraints is better as exposure indices in the environment are plummeting.

Figure 4 shows that the region's exposure response depends on how the energy transitions are carried out. Scenarios that depend on centralized backup generation and other concentrated energy assets can create secondary plumes that affect boundary areas, especially if these assets are located close the airport perimeter.

This finding shows that health protective transition planning must address protective measures on energy assets, as well as the way those measures are implemented within the layout of the hub.

The relationship between energy performance and health protection is shown in the three-dimensional trade-off surface shown in Figure 5. This surface brings together these variables of the energy transition in conflated terms: intensity of energy transition, reduction of emissions, and reduction of exposure. Each point on the surface corresponds to an energy system configuration determined by the energy reduction, occupational, and environmental exposure parameters. The surface shows that relationship between energy performance and health protection is non-linear. Reasonable energy transitions are capable of significant exposure reduction by focusing on near-field sources, while aggressive energy transitions can achieve poor exposure which entails exposure rather than eliminating it.

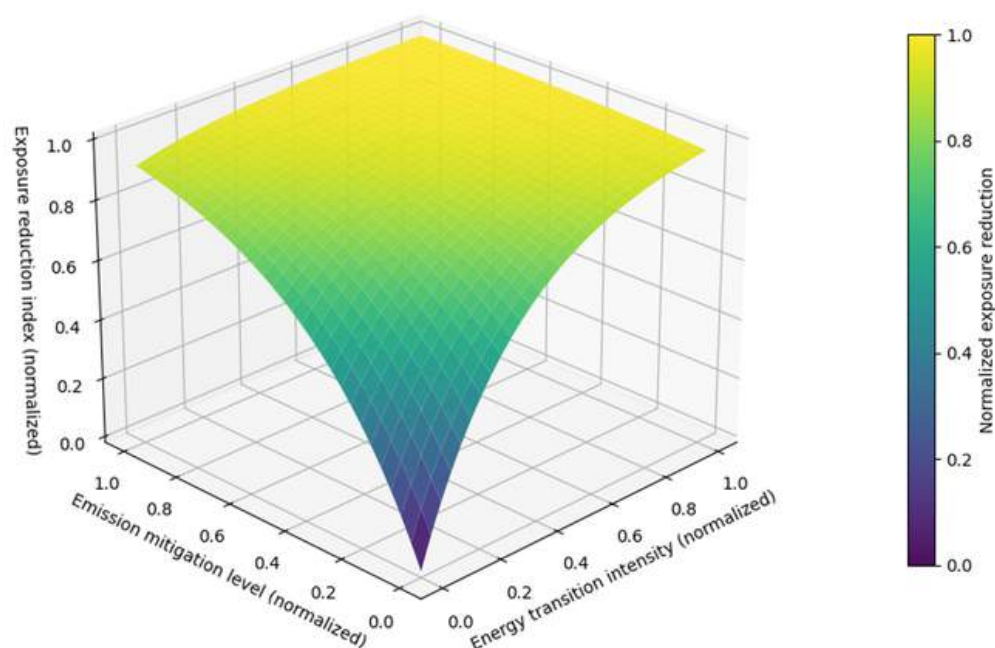


Figure 5. Three-dimensional trade-off surface linking energy transition intensity, emission mitigation, and exposure reduction

Figure 5 illustrates the unrealisable parts of the solution space where exposure constraints are not satisfied. The sad part about these configurations is that they can be made to accomplish either high energy or high emissions reductions. However, they spatially concentrate residual energy conversion at locations that grossly increase occupational or community exposure. On the other hand, a secluded bounded admissible region exists where all exposure constraints are satisfied. Here, many energy transition pathways are offered within the region, and policymakers are enabled to unrestrainedly trade off cost, reliability for a sustained decarbonization of the energy system and reasonable provide the protection of the no cross overs to the health of the people.

The summary in table 2 draws heavily on the information from the aforementioned figures. The table illustrates the relative energy performance gains in excess of maximum occupational and community exposure for each scenario. In the Table 2 traditional setting, community exposure indices under some dispersion scenarios, underscores the exposure vulnerability of the community, and in the worker-accessible zones, the exposure indices have exceeded unity, signalling the occupational constraint imposed in the setting is overstepped.

Table 2. Quantitative comparison of energy performance gains and occupational and community exposure indices

Scenario	Energy transition intensity	Emission mitigation (%)	Max occupational exposure index	Max community exposure index
Conventional aviation energy system	0.00	0	1.35	1.12
Partial electrification of ground operations	0.40	28	0.92	0.98
Reduced APU usage with gate electrification	0.55	42	0.76	0.90
Integrated health-protective transition	0.75	61	0.58	0.72
Advanced low-exposure configuration	0.90	74	0.54	0.69

Analysis of the health protective scenarios from above table continues to show limbs of reduction of maximum values of occupational exposure, each of which goes below the admissibility threshold. Community exposure indices also reveal reductions, but the magnitude of the reduction is scenario specific and varies based on the spatial redistribution of the energy processes. In particular, the table shows that scenarios with the same or similar percentage reductions of energy can produce vastly different exposure results. This strengthens the argument that energy efficiency on its own is a poor proxy for health protection.

Conclusion

The results demonstrate that energy transitions at aviation hubs cannot be evaluated based just on total energy efficiency of the hub or total emissions reduction that energy transition may bring. Instead, what the results show is that the potential of any transition pathway is fundamentally limited by operationally defined spatially distributed occupational and environmental exposure boundaries. The use of such boundaries in the context of a 3D simulation of the scenarios allows one to show that the transformations of energy systems are limited by where and how energy conversion occurs, and not by how much energy is consumed or avoided.

Conventional aviation energy system baseline results indicate the strong relationship between near-ground energy usage and occupational exposure. Concentrated exposure hotspots appear in worker-accessible areas, given the fossil-fuel ground operations and auxiliary power unit usage. These areas explain how the conventional configurations repeatedly breach exposure limits for employees and the community, while the total energy used remains within the limits for regulatory compliance. The results emphasize that exposure risk is more influenced by the local characteristics of the source that contribute exposure and where the source is located, more than by the exposure average for the airport as a whole.

With health-protective energy transition strategies, the relationship is changed as exposure sources are shifted or removed from where people are located. Ground operations electrification and a lesser dependence on auxiliary power units result in a significant decrease in near-field exposure intensity and increase in compliance with occupational exposure limits. Most significantly, the results indicate that considerable exposure reduction can be accomplished without a maximum energy transition and more so, when the exposed dominant processes are targeted. This is a strong endorsement for the prioritization of location specific strategies over random process dominant strategies.

Regional scales simulations demonstrate that energy transitions affect exposure even further than the airport boundaries. Although health protective configurations lessen dispersion into adjacent communities significantly, the data shows that energy assets poorly sited or concentrated can reintroduce environmental exposure risks. Protective health of communities illustrates that the problem goes far beyond the emissions and involves spatial pathways of the remaining exposure streams. Thus, effective energy transition planning must combine occupational and environmental exposure within a single spatial approach.

In trade-off analysis, environmental health protection and energy performance are interlinked through a constrained non-linear relationship. Most energy transitions have the greatest positive impact on exposure reduction. However, the more transition moves are implemented, the ground sources are addressed, and the less marginal benefits result. This limited space offers the most effective strategic transitions when exposure limitations are addressed and further energy or emissions goals are achieved within the remaining applicable area. Single-objective optimization approaches that disregard spatial health limitations can't produce similar information.

This work shows how important support decision simulation is for developing sustainable infrastructure for aviation. This framework allows decision makers to focus on balanced and protective energy transition pathways available to them, prior to making large investments. The outcomes show that sustainable aviation hubs must be built as energy-health system pairs and that exposure limits be used as primary constraints. This is important for balancing the health of workers and the community and achieving decarbonization goals for the future.

References

1. Hudda, N., Simon, M. C., Zamore, W., & Durant, J. L. (2018). Aviation-related impacts on ultrafine particle number concentrations outside and inside residences near an airport. *Environmental science & technology*, 52(4), 1765–1772.
2. Eastham, S. D., Chossière, G. P., Speth, R. L., Jacob, D. J., & Barrett, S. R. (2024). Global impacts of aviation on air quality evaluated at high resolution. *Atmospheric Chemistry and Physics*, 24(4), 2687–2703.
3. Riley, K., Cook, R., Carr, E., & Manning, B. (2021). A systematic review of the impact of commercial aircraft activity on air quality near airports. *City and environment interactions*, 11, 100066.
4. Marcias, G., Casula, M. F., Uras, M., Falqui, A., Miozzi, E., Sogne, E., ... & Lecca, L. I. (2019). Occupational fine/ultrafine particles and noise exposure in aircraft personnel operating in airport taxiway. *Environments*, 6(3), 35.
5. Lammers, A., Janssen, N. A. H., Boere, A. J. F., Berger, M., Longo, C., Vijverberg, S. J. H., ... & Cassee, F. R. (2020). Effects of short-term exposures to ultrafine particles near an airport in healthy subjects. *Environment international*, 141, 105779.
6. Rao, A. G., Yin, F., & Werij, H. G. (2020). Energy transition in aviation: The role of cryogenic fuels. *Aerospace*, 7(12), 181.
7. Blackburn, C., Harding, A., & Moreno-Cruz, J. (2017). Toward deep-decarbonization: an energy-service system framework. *Current Sustainable/Renewable Energy Reports*, 4(4), 181–190.

8. Amin, F. (2025). Radiation-Induced Cellular Damage Signatures and Repair Kinetics in Extended Extra-Atmospheric Exposure. *Journal of Airline Operations and Aviation Management*, 4.2 (2025): 86-120
9. Targino, A. C., Machado, B. L. F., & Krecl, P. (2017). Concentrations and personal exposure to black carbon particles at airports and on commercial flights. *Transportation Research Part D: Transport and Environment*, 52, 128-138.
10. Stacey, B. (2019). Measurement of ultrafine particles at airports: A review. *Atmospheric Environment*, 198, 463-477.
11. Adeoye, I. (2025). Life Cycle Assessment of Diesel, Biodiesel, and Electric Ground Support Equipment in Airports: A Comparative Environmental Impact Study. *Biodiesel, and Electric Ground Support Equipment in Airports: A Comparative Environmental Impact Study* (February 06, 2025).
12. Gupalo, S. (2025). Correlation between cabin airborne pathogens and acute respiratory infections in passengers. *Journal of Airline Operations and Aviation Management*, 4.2 (2025): 1-14.
13. Yan, J., Broesicke, O. A., Tong, X., Wang, D., Li, D., & Crittenden, J. C. (2021). Multidisciplinary design optimization of distributed energy generation systems: The trade-offs between life cycle environmental and economic impacts. *Applied Energy*, 284, 116197.
14. Capitanescu, F. (2023). Are we prepared against blackouts during the energy transition?: Probabilistic risk-based decision making encompassing jointly security and resilience. *IEEE Power and Energy Magazine*, 21(3), 77-86.
15. Pless, J., Hepburn, C., & Farrell, N. (2020). Bringing rigour to energy innovation policy evaluation. *Nature Energy*, 5(4), 284-290.
16. Simon, G. (2025). Modelling Air Traffic-Related Non-CO2 Emissions and their Health Impacts on Airport-Adjacent Communities.
17. Kortoçi, P., Motlagh, N. H., Zaidan, M. A., Fung, P. L., Varjonen, S., Rebeiro-Hargrave, A., ... & Tarkoma, S. (2022). Air pollution exposure monitoring using portable low-cost air quality sensors. *Smart health*, 23, 100241.

18. Bendtsen, K. M., Bengtsen, E., Saber, A. T., & Vogel, U. (2021). A review of health effects associated with exposure to jet engine emissions in and around airports. *Environmental Health*, 20(1), 10.
19. Zaporozhets, O., & Synylo, K. (2019). Modeling of Air Pollution at Airports. *Environmental Impact of Aviation and Sustainable Solutions*.