Risk Management of Hybrid Energy Systems

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Hybrid energy systems that combine heat pumps and other heat sources are usually complex and may operate inefficiently. Effective risk management is key to ensuring reliability and energy performance. This article outlines key risks, assessment methods, and mitigation strategies to improve system resilience and support long-term operational success.

Hybrid energy systems have become pivotal components in transitioning to sustainable energy infrastructure [1]. These systems integrate multiple energy sources, conventional power systems, and different energy storage solutions [2]. The integration of multiple energy sources and technologies introduces several operational, technological, or financial risk factors. These risk factors are driven by integration between different systems' components, reliance on manual or automated control systems [3], and human error, that might include design errors, incorrect running order, programming errors, and poor installation [4].

Method

We conducted semi-structured interviews with 15 professionals involved in building maintenance, energy system design, and energy service provision to gain insights into the risks and mitigation strategies associated with hybrid energy systems [1]. A semi-structured interview approach was used to explore expert insights across four themes: 1) metering, monitoring, and hybrid systems' key performance indicators; 2) maintenance procedures and use of artificial intelligence (AI); 3) system control and optimisation; and 4) risk management strategies across different project phases. Viewpoints from different companies and fields of expertise were compiled to provide guidelines to avoid problems and ensure energy-efficient operation of hybrid energy systems in both new and existing buildings.

Risk mitigation in the design phase

The most impactful decisions affecting the performance of a hybrid energy system are made during the project planning and system design phases. These decisions relate to the basic configuration of the energy system and the support systems needed in operation. **Figure 1** summarises the main points.

The key to designing an efficient and cost-effective hybrid energy system is the accurate determination of energy demand and energy generation in the building. This includes yearly assessing heating, cooling, and electricity demands and considering all related equipment. Since energy demand fluctuates seasonally, the system must be flexible to operate efficiently under varying loads. For example, if a heat pump cannot operate at partial load, frequent on/off cycling during low-demand periods can cause excessive wear and increased maintenance costs. To ensure stable operation, multiple heat pumps with different capacities can be installed in parallel.

All potential heat sources should be identified when designing the energy generation system. This may include waste heat from ventilation, sewage systems, cooling processes, and natural sources like solar energy, ambient air, and geothermal heat. While geothermal heating provides a stable source during cold periods, it is often the most capital-intensive option. Therefore, other available heat sources should be prioritised to minimise the need for drilling boreholes. A Thermal Response Test (TRT) should be conducted on-site before designing any geothermal systems, to assess the ground's heat transfer properties. Oversizing the geothermal system can significantly increase investment costs. However, potential future system expansion should be considered at this stage. For example, heating and cooling loads may change due to tenant turnover or the loss of a waste heat source. Sites for additional boreholes should be identified in advance and space should be reserved for extra equipment in the machine room.

All circuits should be designed to operate independently, so that a malfunction in one section does not disable the entire system. At the same time, system calibration is crucial to avoid conflicting operations. A common risk is the simultaneous heating and cooling of the same zone, often caused by non-harmonized setpoints between centralized and local control systems. For example, space heating and ventilation cooling might follow different control logics or temperature setpoints. Without proper coordination, both systems can run at the same time, one heating and the other cooling, leading to significant energy waste. To prevent this, setpoints on both the generation side (e.g., heat pump output) and the consumption side (e.g., heating and cooling systems) must be harmonized. The produced temperature must closely match the building's actual heating or cooling demand. If the output temperature is too high or too low relative to the load, system efficiency decreases, and auxiliary energy consumption increases.

The design phase should include dynamic simulations of system performance under varying conditions. These simulations help set realistic energy consumption targets for the operational phase. In addition, all critical monitoring sensors and meters should be installed and integrated into the building automation system to enable effective control. A common issue is the isolation of heat pumps into separate subsystems, making their performance data inaccessible for full system analysis. To avoid such integration gaps, the building's future operator should be involved early in the design process. Their practical insights help ensure that the measurement infrastructure supports efficient and long-term system performance monitoring.

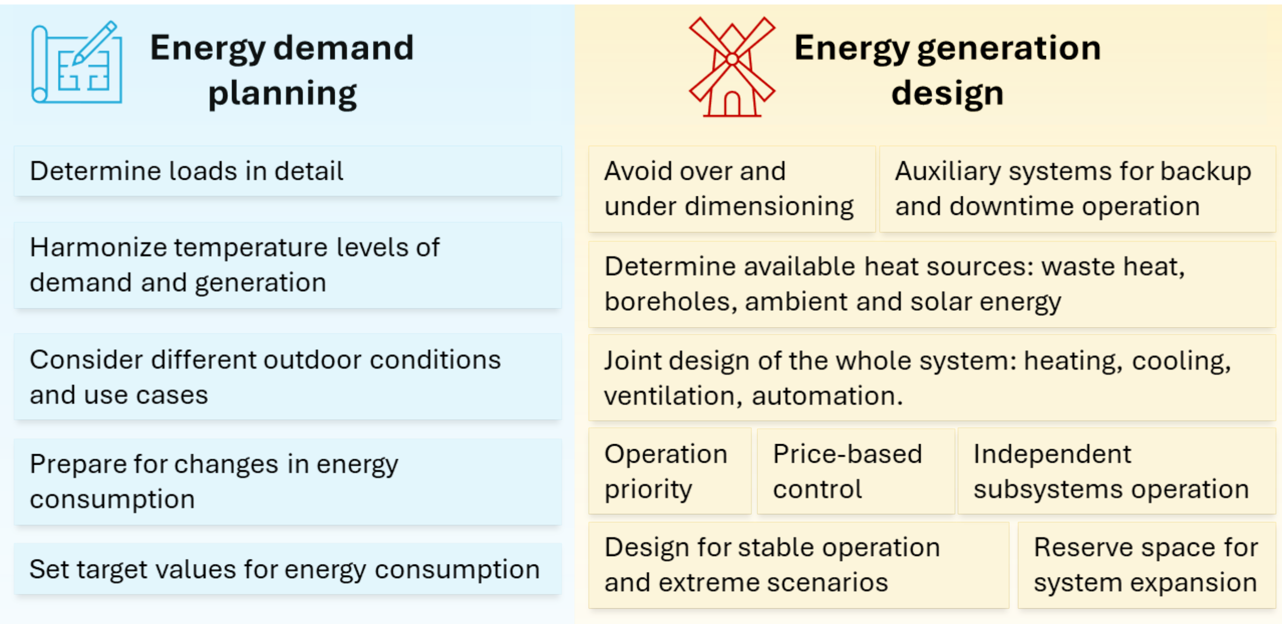

Figure 1. Guidelines for energy system design.

Risk mitigation during operation

Maintaining the energy efficiency and functionality of hybrid energy systems requires continuous effort during the operational phase. However, many operational risks can be reduced early by incorporating proper monitoring systems and control strategies during design. A summary of best practices for building operation is shown in **Figure 2**.

From the system perspective, operational reliability and efficiency depend on monitoring values such as temperature, pressure, and airflow rates before and after key components like heat exchangers, filters, fans, and pumps. These values should be continuously monitored and analysed using software tools that enable both real-time fault detection and long-term performance analysis. Anomalous readings (such as an increasing pressure drop across a filter) can trigger predictive maintenance, allowing earlier intervention (e.g., filter replacement) before scheduled service. Faulty sensors may cause false alarms or mask real problems. Redundant measurements help distinguish between sensor faults and actual system malfunctions. For example, if an anomalous flow reading coincides with abnormal temperatures, a mechanical fault is likely. However, if other sensors show normal operation, the problem may lie in the sensor itself.

All systems should be controlled through a centralised building automation interface, avoiding manual settings on individual components. It must also be ensured that the digital setpoints in the cloud interface match those programmed into physical devices. Systems should be configured to automatically resume normal operation after disturbances, such as restarting heat pumps following a power outage.

To ensure long-term energy efficiency, trend data should be collected constantly and stored for at least 5 years. This enables benchmarking against historical data and detecting poor performance or seasonal inefficiencies. The dataset should allow the calculation of consumed heating, cooling and electrical energy, the Coefficient Of Performance (COP) of the heating/cooling system and the efficiency of heat recovery. Data from different systems should be centralised in one interface for holistic performance analysis. Where possible, data from different buildings should be gathered into a centralised database to support portfolio-level benchmarking and performance diagnostics. Then performance issues in similar buildings can more easily be identified. With long-term data storage, care must be taken in selecting appropriate data resolution. Data should be accurate enough for the intended analysis but not so detailed that it overwhelms storage capacity.

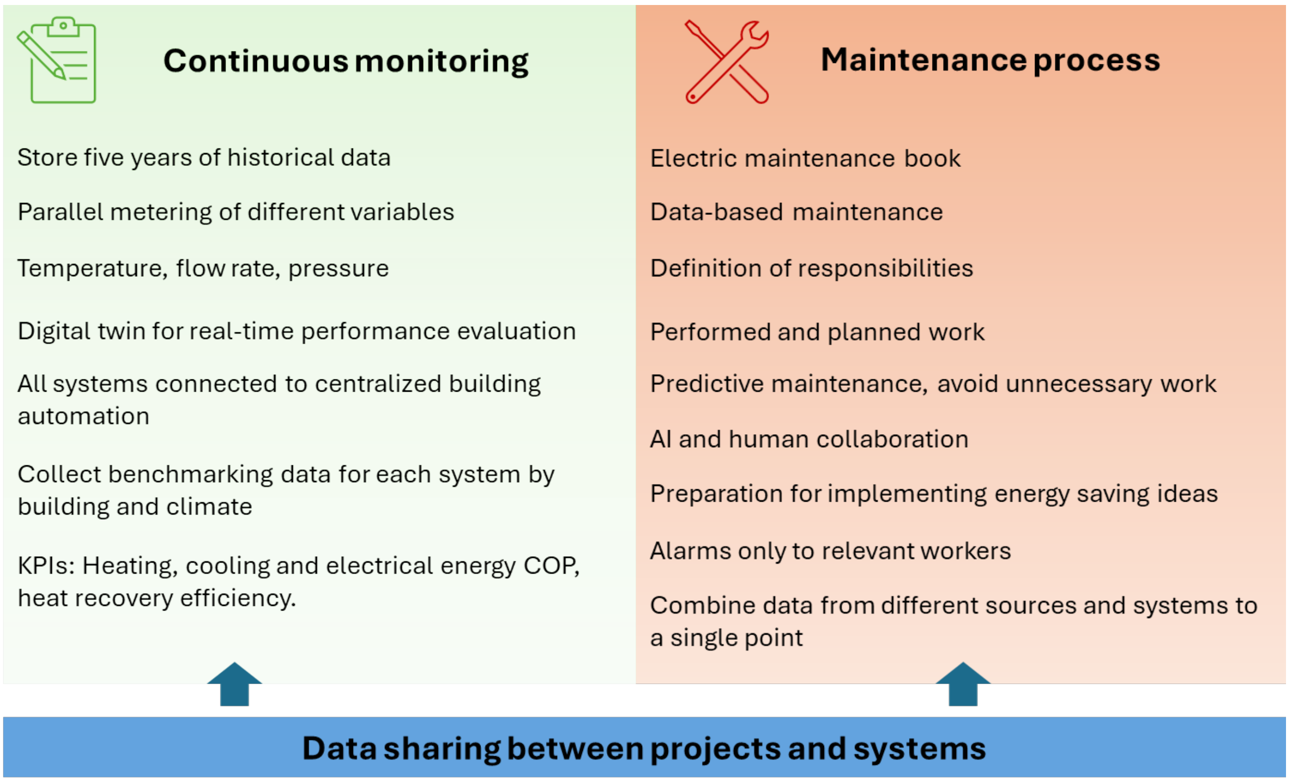

Figure 2. Guidelines for the operational phase.

Even if long-term storage is planned, data retention may fail if storage capacity is exceeded, and older records are automatically overwritten.

Each hybrid energy system should have a defined operator or responsible party, so that problems can be addressed quickly without delays due to uncertainty about who is responsible. Automated alarms for anomalous system behaviour should be directed mainly to the relevant personnel, to prevent information overflow and the risk of important alerts being ignored. However, the alarm threshold must be carefully set – if too sensitive, they generate excessive alerts that may be ignored; if too lax, critical issues might go unnoticed. Monitoring of the system can be made easier by using standardized naming conventions for each measurement point. This should include both a machine-readable identifier and a clear, human-readable text description such as "temperature of fresh air, after heat recovery".

Regular energy performance meetings help identify early signs of inefficiency and ensure corrective actions are informed by shared knowledge. Ideas for improving performance should be systematically documented, ranked by priority, and linked to a concrete implementation plan to support continuous improvement.

Conclusions

The performance of hybrid energy systems depends on two critical factors: smart design and continuous, data-driven operation. Many risks can be avoided during the design phase by correctly sizing system components, aligning control strategies, and ensuring that all subsystems are well integrated and prepared for future expansion or changes. In the operational phase, clearly defined responsibilities, well-calibrated alarms, centralized data, and regular performance reviews are essential for maintaining efficiency and reliability. In practice, many failures are not caused by technology itself, but by poor coordination, fragmented responsibilities, and insufficient monitoring. Involving operators early and applying risk management throughout the system's lifecycle are key to achieving resilient and energy-efficient performance.

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