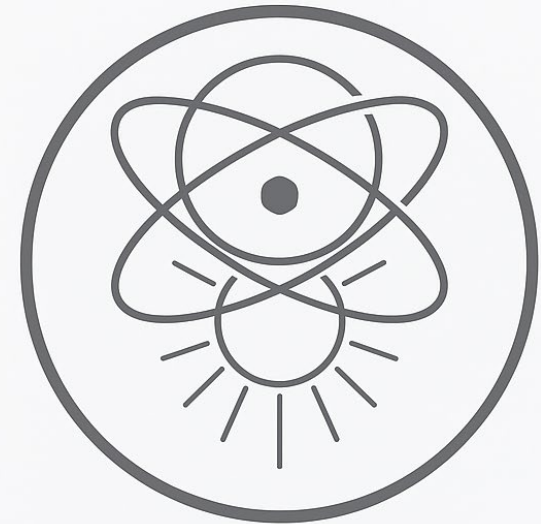




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Hydrogen Purification Architecture for Dual-Mode Operation at Heber Campus

Introduction and Dual Operating Modes

The Heber Campus energy system will produce hydrogen under two distinct modes: **(1) Normal daily operation** – hydrogen generated directly via nuclear Small Modular Reactors (NuScale), solar PV, and high-temperature electrolysis (SOEC) – and **(2) Extended low-solar backup** – hydrogen produced by cracking stored ammonia (NH_3) during multi-day low-solar periods (e.g. prolonged snowstorms). In normal mode, the hydrogen from electrolysis/nuclear sources is already high-purity (with oxygen as a byproduct), stored for use in gas turbines or large fuel cells. Excess hydrogen is also converted to ammonia for long-term storage, though ammonia is not routinely cracked back to H_2 under normal conditions. In the backup mode, however, stored ammonia is decomposed to hydrogen and nitrogen (N_2) to supply fuel – requiring **purification of the cracked gas** to meet the stringent quality demands of hydrogen turbines and especially PEM fuel cells. The purification system must **automatically transition** between these modes without allowing *purity slip* (e.g. no NH_3 breakthrough or off-spec hydrogen reaching end-use).

Key contaminants to address in backup mode are **ammonia, moisture, and excess nitrogen**. Any residual NH_3 in the hydrogen can poison fuel cell catalysts and will form NO_x if combusted in a turbine, so it must be essentially eliminated (<0.1 ppm for fuel cells ammoniaenergy.org). Cracked gas will be saturated with N_2 (**~25 vol%** if NH_3 conversion is complete), which acts as an inert diluent. While turbines can tolerate some N_2 , PEM fuel cells require hydrogen purities $\geq 99.97\%$ with N_2 <100 ppm ammoniaenergy.org. Moisture (H_2O) must also be removed to a low dew point (<5 ppm for fuel cells). Additionally, the purification train must handle potentially *variable feed compositions* – in normal mode, feed H_2 is essentially 100% pure (aside from trace O_2 or H_2O from electrolysis), whereas in backup mode feed gas is ~75% H_2 / 25% N_2 with trace NH_3 and H_2O . The system should accommodate these swings and ramp its throughput up or down rapidly as the site switches modes or load levels.

We compare four candidate hydrogen purification architectures for this dual-mode application: **Pressure Swing Adsorption (PSA), Membrane Separation, Hybrid systems** (combining multiple separation/catalysis methods), and **Catalytic Polishing** (NH_3 removal without N_2 separation). Each is evaluated for throughput scalability, contaminant removal performance (NH_3 , H_2O , N_2), dynamic/ramping capability, energy efficiency, impurity tolerance, compatibility with fuel cell vs. turbine specs, and maintainability in Heber's environment (cold winters, dust, remote operation). Table 1 (in a later section) summarizes these factors. Below, we discuss each purification approach in detail, including field-proven examples applicable to **ammonia-cracked gas** or **grid-scale H_2 storage** contexts.

Pressure Swing Adsorption (PSA) Purification

Pressure Swing Adsorption is a **widely used, mature technology** for bulk hydrogen purification, well-suited to large-scale operation. A PSA unit consists of multiple vessels filled with adsorbent materials (e.g. zeolites, activated carbon) that selectively trap impurities at high pressure, then regenerate by depressurizing. For cracked ammonia gas, a PSA can be employed to **remove N₂ (and any residual NH₃/H₂O)**, producing high-purity H₂ product. PSA systems have been proven at **industrial hydrogen-plant scales**, including integration with ammonia crackers. For example, Johnson Matthey's large-scale ammonia cracker design selects PSA due to its high throughput capacity and ability to achieve >99.96% H₂ purity matthey.com. PSA hydrogen recovery is typically 75–90%; modern designs achieve ~90% recovery of H₂ matthey.com, with the remaining H₂ lost in the “tail gas” stream (impurity-rich off-gas).

Contaminant Removal: PSA can **polish hydrogen to fuel-cell grade purity** by adsorbing residual N₂ and other impurities. In a demonstration for PEM fuel cell feed, Kojima *et al.* combined an ammonia cracker with a zeolite NH₃ trap and PSA unit – the PSA output had H₂ >99.98% with N₂ <10 ppm ammoniaenergy.org, easily meeting the ISO 14687 fuel H₂ specifications. However, NH₃ itself is a **strongly adsorbed, reactive impurity** that can foul adsorbents. Best practice is to **remove bulk ammonia upstream of the PSA** via condensation or scrubbing, so that the PSA beds only need to handle the weaker adsorbates like N₂ matthey.com. Johnson Matthey's process adopts this approach: a dedicated NH₃ removal stage (e.g. cooling and separation or an acid scrubber) is placed before the PSA, allowing the PSA to be optimized for N₂ removal matthey.com. With NH₃ pre-scrubbed, the PSA reliably produces >99.96% pure H₂ matthey.com and the small residual NH₃ that slips into the tail gas is harmlessly disposed (burned as fuel). Moisture is likewise typically removed by pre-drying (a small desiccant bed or integrated in the PSA's first layer). Thus, a PSA-based purifier can **eliminate NH₃ to <ppm levels** (via upstream treatment) and **reduce N₂ from ~25% down to tens of ppm**, delivering essentially pure hydrogen.

Throughput Scalability: PSA systems scale very well – from small skid-mounted units (tens of Nm³/h) up to **world-scale hydrogen plants**. They have been built to handle thousands of kg H₂/hour by using larger vessels or parallel trains. This suits the Heber Campus if hydrogen production (especially in normal mode with nuclear + solar electrolysis) is large. PSA is proven at the “scale required for this flowsheet” in ammonia-cracking applications matthey.com. If the backup mode requires similarly high flow rates (to supply turbines during a storm), a PSA can accommodate it by design. PSA units can also be turndown to partial load, though with some efficiency loss (adsorption beds still cycle and vent some H₂ even at lower feed

rates). Typically, PSAs can handle ~50%–100% of design flow with acceptable performance, but dropping below that may cause purity or recovery to degrade slightly unless cycle parameters are adjusted.

Ramping and Dynamics: Because PSA operates on a **cyclic batch process** (multiple beds undergoing pressurization, adsorption, depressurization, purge in rotation), it is inherently less nimble than a continuous membrane. Sudden large swings in feed flow or composition can upset the steady-state adsorption equilibria. However, PSA systems have been designed to handle **cyclic operation in renewable H₂ scenarios**, with appropriate controls and mechanical robustnessmatthey.com. The ammonia cracker/PSA design by JM, for instance, is engineered to accommodate fluctuations in plant load due to renewablesmatthey.com. In practice, a PSA can ramp up from standby over a span of minutes, not seconds – valves and vessels must transition through their cycle steps. During a mode switch at Heber, the PSA would likely be started up in anticipation of ammonia cracking (with flow gradually introduced) rather than being slammed from idle to full flow instantaneously. Once running, it can **load-follow** moderately (e.g. adjusting cycle times or temporarily idling some beds) but may not match the instantaneous flexibility of a membrane. Careful automation is needed to avoid purity “slip” during transients – for example, diverting product to a vent or recycle until PSA beds are re-equilibrated at the new conditions. Overall, PSA provides *continuous high-purity output at steady load*, and can handle **infrequent mode changes** (like switching to backup a few times per year) if properly managed, but it’s less ideal for rapid oscillations on a daily basis.

Power Efficiency: PSA itself is not very power-intensive (it mainly requires instrument air or electric drives for valves, and perhaps vacuum pumps in some designs), but the **energy penalty** comes from H₂ losses. The 10–15% of hydrogen that ends up in the tail gas represents an energy loss unless recovered. In ammonia cracker plants, the common solution is to **burn the PSA tail gas as fuel** to provide process heat, so the energy is recouped. Indeed, JM’s design uses PSA tail gas (containing N₂, unrecovered H₂, and any residual NH₃) as a fuel source for the cracker’s furnacematthey.com. At Heber, the SMR/SOEC hydrogen is produced without a fossil-fired reformer, so there isn’t an obvious “furnace” to heat with tail gas. One could incorporate a catalytic heater or boiler to burn the tail gas for facility heating or simply use a flare. In terms of electrical efficiency, a comparative analysis found PSA separation consumes on the order of **8.5 MWh per ton H₂** purified (including compression/recompression), slightly higher than a metal membrane’s ~7.4 MWh/tonsciencedirect.com. This is partly due to recompressing product or feed and the energy value of lost H₂. Overall efficiency can be good if tail gas is utilized constructively. For instance, a lab-scale ammonia cracker + PSA achieved ~80% hydrogen energy efficiency (LHV basis) when

coupling a microchannel cracker with an optimized PSA and heat integration ammoniaenergy.org. Designing the PSA to operate at pressure (so product H_2 comes out at, say, 10–20 bar ready for storage/use) can also improve net efficiency by avoiding extra compression.

Tolerance to Feed Impurity Swings: PSA performance is sensitive to the feed gas composition it was designed for. A significant increase in impurity fraction (e.g. if ammonia cracker conversion drops and N_2 rises or NH_3 slips through) can saturate the beds early or cause breakthrough. This is why **robust pretreatment** is critical – e.g. if the cracker only achieves 95% NH_3 conversion at times, the remaining 5% NH_3 must be removed before PSA. With a properly sized NH_3 scrubber (or guard bed) upstream, the PSA will consistently see a H_2/N_2 mixture in a known ratio, making it easier to guarantee purity. If the feed H_2 purity swings all the way to ~100% (as in normal mode with electrolytic H_2), the PSA could be bypassed to avoid unnecessary H_2 loss. It is feasible to route pure H_2 around the PSA beds during normal operation, then bring the PSA online when ammonia-derived gas is introduced. Automated valves and purity analyzers would control this handoff. Another approach is to continuously feed the PSA with a blend of hydrogen (even during normal mode) so it never fully shuts down – though feeding 100% H_2 to a PSA would simply result in most of that H_2 appearing in the tail gas (since the adsorbents would find no impurities to remove, they’d end up purging out hydrogen). Thus, bypassing or idle cycling is preferred in normal mode. In summary, PSA can handle impurity swings **if the worst-case load is designed for**, and the transition between “no impurity” and “high impurity” feed is managed with intermediate steps (e.g. first bring cracker to capacity while venting off-spec gas, then gradually open feed to PSA).

Fuel Cell and Turbine Compatibility: PSA-based purification **meets the most stringent fuel cell requirements**. Commercial PSA units routinely produce 99.999% H_2 in refinery applications eureka.patsnap.com, and in ammonia cracking service >99.96% purity has been demonstrated matthey.com. The 0.04% residual is mostly N_2/Ar and well below the 0.01% NH_3 (0.1 ppm) spec. In Kojima’s 1 Nm^3/h PEM fuel cell study, the PSA product had $NH_3 < 0.02$ ppm and $N_2 < 10$ ppm ammoniaenergy.org – essentially eliminating those contaminants. This purity is directly suitable for PEM fuel cells and also exceeds typical turbine fuel needs. Gas turbines do not require such high H_2 purity – in fact, some inert N_2 in the fuel can help moderate combustion temperature and NO_x formation. If a turbine were the only end-use, one could even tolerate a bit of N_2 in the product. However, using the PSA ensures **no NH_3 slip** (preventing any ammonia from entering the turbine where it could form NO_x) and provides flexibility to also feed fuel cells. The turbine can simply burn the >99.9% H_2 ; the extra purity (N_2 -free) is not harmful

(the turbine sees plenty of N_2 from its combustion air already). One consideration is that a sudden change in H_2 purity (e.g. from 75% H_2 gas to 100% H_2) can affect turbine combustion dynamics – but since in our design the turbine would always receive consistently pure hydrogen (during normal mode directly from storage, during backup from PSA output), its control system only sees one type of fuel.

Maintainability and Site Conditions: PSA units are **robust industrial systems** but involve many valves, vessels, and instruments, which benefit from a controlled environment. At Heber (cold winters and dusty, remote location), the PSA system should be housed in an insulated enclosure or building. This protects the pneumatics and adsorbent beds from temperature swings (adsorption performance can vary with temperature) and keeps dust out of valve actuators and instrument lines. Dust is generally not an issue for the process gas itself since the hydrogen will be coming from clean sources (electrolyzers or a closed-loop ammonia cracker), but ambient dust could foul cooling systems or compressors if any. PSA adsorbent life is long (several years) if protected from poisons; in our case the main risk would be inadvertent **moisture or NH_3 exposure**. Any large slug of water or ammonia carryover could permanently deactivate some adsorbent. Thus, the upstream NH_3 scrubber and dryer must be reliable (with redundancies or guard beds). Given remote ops, designing the system to fail-safe (e.g. automatic venting of off-spec gas) and including **online analyzers** for H_2 purity and NH_3 traces is important. PSA units often have few moving parts aside from valves, so routine maintenance might include valve seal replacement or adsorbent change-out every 5–10 years. Spare valves and a remote monitoring system would be prudent so that any performance drift (like a slow leak or a bed not achieving vacuum) can be diagnosed off-site. Fortunately, PSAs are a **standard technology** – companies like Linde, Air Liquide, and JM have many installations, and proven operational protocols for remote monitoring exist. In fact, PSA currently accounts for ~85% of industrial H_2 purification due to its reliability eureka.patsnap.com. With proper winterization (heat tracing small lines, a heated enclosure kept above freezing) and dust control (filters on ventilation), a PSA can be run largely unmanned, with annual service visits.

Summary (PSA): Overall, a PSA with pre-scrubbing is an excellent candidate for Heber’s dual-mode system. It offers **high throughput capacity**, proven *fuel-cell-grade purity*, and integration strategies to handle NH_3 (removal upstream, tail gas usage). Its drawbacks are slower dynamics and some H_2 inefficiency, but these can be mitigated by thoughtful design (anticipating mode switches and recouping tail gas energy). This approach is already being scaled for **green ammonia**

cracking plants – achieving >99.96% H₂ purity at ≥90% recovery in a large PSA [matthey.com](https://www.matthey.com) – which aligns well with Heber’s needs.

Membrane Separation Systems

Membrane-based hydrogen purification relies on selective permeation of H₂ through a barrier while rejecting larger molecules. There are two primary membrane types: **polymeric membranes** (hollow-fiber or spiral wound modules, typically operated at ambient temperature) and **palladium-based dense metal membranes** (tubes or plates that operate at elevated temperature, using Pd-alloy’s ability to dissolve and diffuse H₂ atoms). Membranes can be applied in stand-alone separation units, or combined with the ammonia cracker itself (as a membrane reactor). This technology offers a **continuous, simplicity** advantage – no cyclic processing – and can respond quickly to changing flow. Recent advances have made membranes very promising for medium-scale hydrogen purification, including field demonstrations of ammonia cracking to **fuel-cell-grade H₂ in one step** [businesswire.com](https://www.businesswire.com).

*Containerized ammonia-cracking membrane reactor system (H₂SITE, Tyseley Energy Park, UK). In this modular **membrane reactor**, palladium membranes are integrated with a catalytic NH₃ cracker, achieving >98% H₂ recovery and fuel-cell purity H₂ without a separate PSA [businesswire.com](https://www.businesswire.com). Such membrane-based systems are scalable by adding modules and can rapidly respond to load changes, though they require careful thermal management and periodic module maintenance.*

Contaminant Removal: A membrane’s separation mechanism inherently removes **inert gases like N₂** (which do not permeate as readily as H₂) but does *not* chemically destroy impurities like NH₃ – those must either be non-permeating or converted. In practice, polymer membranes have moderate H₂/N₂ selectivity, so multiple stages or recycle are needed to reach high purities. Palladium (Pd) alloy membranes, by contrast, are essentially *impermeable to anything but hydrogen* – H₂ is absorbed and diffuses through the metal, while larger molecules (N₂, NH₃, H₂O) cannot pass. A Pd membrane thus can deliver ultra-pure H₂ (99.999%+) in principle [sciencedirect.com](https://www.sciencedirect.com). However, **ammonia will not automatically disappear**; if NH₃ is present in the feed, it will remain on the retentate side. To ensure no NH₃ traces carry over with H₂, the membrane system should be preceded by an NH₃ removal step or integrated with a catalyst that cracks NH₃. For example, an ambient-temperature polymer membrane can’t crack ammonia, so one would install a water scrubber or bed to remove NH₃ first (similar to the PSA case). A hot Pd membrane can actually act as a catalyst surface for ammonia decomposition to some

extent, but ammonia may also poison or embrittle the Pd if it dissociates into nitrogen that diffuses into the lattice. The most effective solution is a **membrane reactor**: immerse H₂-selective membranes in the ammonia cracking reactor. As NH₃ is catalytically broken into N₂ + H₂, the H₂ is immediately pulled out through the membrane, shifting equilibrium to crack nearly all NH₃. H2SITE's membrane reactor uses this approach – by selectively removing H₂ in-situ, it achieves “virtually complete ammonia conversions” at relatively mild temperatures[businesswire.com](https://www.businesswire.com). The result is that the retentate stream is almost pure N₂ (with any residual NH₃ far below 0.1% and typically handled by a small downstream catalyst or burn-off), and the permeate stream is high-purity H₂ with essentially **no NH₃ or N₂** in it[businesswire.com](https://www.businesswire.com). In their 200 kg/day pilot, H2SITE reports >98% H₂ recovery and always meeting fuel-cell grade specs (NH₃ below detectable, H₂O removed by condensation)[businesswire.com](https://www.businesswire.com).

If using a *stand-alone membrane separator* (not integrated with the cracker), the purification train would include an **NH₃ scrubber** (to protect the membrane and remove NH₃), a **gas cooling/drying step** (membranes perform better on dry gas), then the membrane modules to separate H₂ from N₂. Polymeric membranes often achieve ~90–97% H₂ purity in one stage and may require a second stage or recycle to reach 99.9%+. In contrast, a Pd membrane unit at ~300°C can output 99.999% H₂ in one pass[sciencedirect.com](https://www.sciencedirect.com). For example, a metal membrane separation after an ammonia cracker was analyzed to yield ~99% H₂ purity and could be optimized for higher at the cost of more membrane area[sciencedirect.com](https://www.sciencedirect.com)[sciencedirect.com](https://www.sciencedirect.com). In summary, membranes can **effectively remove N₂** and with proper design and/or integration, **eliminate NH₃ and H₂O** (either via a pre-scrubber or by the nature of the membrane reactor).

Throughput Scalability: Membrane systems are **modular** – capacity is increased by adding more membrane modules in parallel. This makes them well-suited to small and medium scales, and theoretically scalable to large flows too (with many modules). Polymeric membrane skids are common for hydrogen recovery in refineries and can handle thousands of Nm³/h, though achieving very high purity at huge scale tends to favor PSA economically. Palladium membranes historically have been limited by cost and physical size (bundles of Pd tubes can purify perhaps hundreds of Nm³/h per module). H2SITE's roadmap includes scaling to **1 ton H₂ per day** (~41.7 kg/h) in the next system[businesswire.com](https://www.businesswire.com), and they envision multi-ton per day systems by parallelizing units. While this is smaller than a large PSA at a petrochemical plant, it is in the ballpark for many “grid storage” applications. If Heber's hydrogen production/usage is on the order of a few hundred kg/h, a membrane approach might require dozens of modules or multiple containerized units. This is feasible, but cost and complexity increase with scale (membranes do not benefit as much from economy of scale; PSA does). For normal daily operation, where H₂ might be

produced steadily, membranes can continuously process that output. In backup mode, one could ramp up additional membrane modules if needed (or bring additional units online). The modular nature is actually convenient for redundancy: one can have an array of membrane units and take one out for service without total shutdown, provided the others can handle the flow at slightly reduced throughput. **In summary, membranes are very scalable in a linear fashion**, but for extremely large throughput ($>>1$ ton H_2 /hour), the number of modules might become unwieldy and PSA might be more practical.

Ramping and Dynamics: Membrane separators offer excellent **flexibility and turndown**. There are no cyclic steps; the output purity adjusts continuously with flow and pressure conditions. If feed flow drops, less H_2 permeates (and the stage cut changes), but there's no need to "idle" a membrane – it can simply operate at lower flux. This means a membrane system can respond to fluctuating hydrogen production or demand in real time. For instance, if solar electrolysis output varies through the day, a membrane could handle those variations smoothly, whereas a PSA might need to buffer the input. In backup mode, a membrane unit can be started quickly (polymer membranes just need the feed on and perhaps a short purge; Pd membranes need to be heated to operating temperature, which can take time, but one might keep them hot in standby). The transition from normal to backup mode could be automated such that valves redirect ammonia-cracked gas to the membrane train and within seconds the permeate hydrogen is on-spec (after any initial off-spec flush). The only delays are associated with heating (for Pd systems) or achieving steady-state flow, which are relatively short compared to PSA cycles. Additionally, membranes don't have large pressure swings that could cause mechanical fatigue – they operate at mostly steady pressures, which is an advantage for longevity under dynamic operation. One challenge is that if feed composition changes drastically (e.g. from pure H_2 to H_2/N_2 mix), the **permeate pressure or purity will shift** until control systems compensate (often by adjusting a vacuum pump or backpressure). But this is straightforward to control with feedback loops. Overall, membranes are very *amenable to automation and rapid ramping*, making them a strong choice for scenarios requiring quick backup engagement or frequent cycling. This dynamic performance is a major advantage over PSA.

Power Efficiency: Membrane systems can be energy-efficient, especially if a pressure differential is naturally available (e.g. the ammonia cracker may operate at a few bar, and the downstream fuel cell might accept low pressure H_2 , allowing one to use the pressure to drive permeation). If compression is needed, that contributes to energy use. In a comparative study, a metal membrane separation consumed about **7.4 MWh per ton H_2 produced** vs 8.5 MWh/ton for PSA [sciencedirect.com](https://www.sciencedirect.com). The membrane had slightly lower energy penalty because it achieved higher hydrogen recovery (less H_2 lost) and possibly avoided

some recompression. H2SITE's membrane reactor further boosts efficiency by **integrating the endothermic NH₃ cracking with separation** – by extracting H₂ continuously, the reaction proceeds at lower temperature (~450°C) and you can use a smaller reactor. They report >98% H₂ recovery [businesswire.com](https://www.businesswire.com), meaning minimal H₂ waste. Also, because the membrane reactor delivers hydrogen at pressure on the permeate side (if designed to do so), you may not need a big compressor to feed your storage or fuel cell. However, in practice many membrane systems produce hydrogen at near-ambient pressure (especially Pd membranes typically release H₂ at low pressure unless you compress the permeate). So one might need to recompress pure H₂ to, say, 20 bar for storage or to feed a turbine. That compression work must be counted. Still, the **lack of hydrogen loss** in membranes is a key efficiency benefit. Unlike PSA where 10% H₂ is burned, membranes attempt to recover almost all H₂; any H₂ that isn't recovered remains in the N₂-rich retentate, which could potentially be recycled or combusted. If one does choose to combust the retentate (for NH₃ destruction or heat), note that retentate from a membrane will contain **much less H₂ (maybe 1-5%)** than PSA tail gas, since the membrane extracted most of it. So the heating value is low; it may just be vented or used as a purge gas. Environmentally, venting a mostly N₂ stream with trace NH₃ might not be permissible, so likely a small catalytic oxidizer would burn any residual H₂/NH₃ to N₂ and water before venting. Power-wise, polymer membranes require a feed compressor if feed is not already pressurized (this could be a significant parasitic load if starting from atmospheric cracked gas). Pd membrane reactors require heaters to maintain temperature (which can often be done using waste heat from other processes). In summary, membrane systems can be very efficient if integrated smartly – potentially achieving overall hydrogen efficiencies comparable or better than PSA (e.g. the membrane reactor lab demo reported 80% efficiency ammoniaenergy.org similar to the PSA case). Additionally, avoiding the repeated pressurization/depressurization of PSA saves energy and simplifies the system.

Tolerance to Feedstock Impurity Swings: Membranes are generally **forgiving to composition changes**, with the caveat that certain impurities can *foul or poison* them. For ammonia cracking, the main concern is NH₃ and perhaps oils/particulates. A polymer membrane might suffer plasticization or swelling if exposed to high concentrations of NH₃ or water, altering its selectivity. Similarly, Pd membranes can be poisoned by sulfur or carbon deposits, and ammonia could potentially nitridize some alloys. Therefore, as with PSA, one should ensure **feed gas entering the membrane is free of troublesome contaminants** above design levels. In practice, that means including a guard bed or scrubber for NH₃ and a dryer for H₂O. If that is done, the membrane will mostly see H₂ and N₂. Variations in the H₂:N₂ ratio mainly affect how much H₂ passes vs stays in retentate, which can be managed. For example, if feed suddenly becomes 100% H₂ (normal mode), a membrane will simply

pass H_2 through and have almost no retentate. This won't damage it; the membrane will just operate under-loaded (some modules could even be valved off if not needed). If feed becomes 75% H_2 with 25% N_2 (backup mode), the membrane will have to separate more gas; as long as the membrane area and pressure differential are designed for that case, purity will still be achieved. Essentially, membranes can handle the full range from pure H_2 to H_2/N_2 mixtures without an issue – the system will just produce a bit less permeate purity if overloaded, or waste some membrane area if underloaded. Proper controls (pressure regulators, flow controllers) can ensure the membrane always operates in its optimal range. One noteworthy point: **membranes provide continuous purification**, so there's no concept of “breaking through” like a PSA – if feed impurities increase, the permeate purity might gradually drop but can recover by adjusting stage cuts (for instance, by increasing purge or decreasing permeate pressure). For critical applications like fuel cells, one would include sensors on the permeate; if any NH_3 or O_2 (from a leaky electrolyzer) is detected, one could divert that hydrogen until purity is back to spec. These events are expected to be rare if the upstream is designed right. In summary, membranes have a high tolerance for feed composition swings within the boundaries of chemical compatibility (so keep poisons out), making them suitable for Heber's dual inputs after appropriate pretreatment.

Fuel Cell and Turbine Compatibility: A membrane-based purifier can be designed to **meet PEM fuel cell purity requirements** just as well as PSA. In fact, Pd membrane systems inherently deliver extremely pure H_2 (only H_2 passes). Even polymer membrane systems can reach 99.99% purity with multi-stage designs eureka.patsnap.com. The H_2 produced by H2SITE's membrane reactor, for instance, “always meets fuel-cell grade standards” businesswire.com (which implies $NH_3 < 0.1$ ppm, $H_2O < 5$ ppm, etc.). Thus, fuel cell stacks at Heber would be protected. Turbines likewise benefit: the membrane removes essentially all NH_3 , so NO_x formation from fuel-bound nitrogen is avoided. If the turbine did not strictly need N_2 removal, one *could* consider a simpler membrane that only partially purifies H_2 (to, say, 90% H_2 with 10% N_2) to use as fuel – but since the fuel cell requires high purity, it's logical to produce one high-purity hydrogen stream for both uses. One interesting flexibility of membranes is that you could *optionally* allow a bit of N_2 to stay in the product for turbine operations if desired (by tuning the stage cut or adding a small N_2 slipstream). But given the tight fuel cell specs, running the membrane to full purity is the safer approach. The turbine can handle 100% H_2 (modern hydrogen turbines are designed for it), though operators sometimes blend in diluents intentionally. If needed, that could be achieved by simply adding a controlled flow of N_2 (from the retentate or a nitrogen supply) into the combustor. The key is that membranes make it straightforward to produce **fuel-cell-grade H_2** , which by default exceeds turbine requirements.

Maintainability and Site Considerations: Membrane systems have **few moving parts** – mostly just the feed compressor (if required) and some control valves – so they are inherently low-maintenance. However, the membrane **modules themselves have a finite lifetime**. Polymeric membranes might last 3–5 years before their performance degrades (due to physical aging or contaminants)eureka.patsnap.com. Pd membranes can theoretically last longer, but they are prone to thermal stresses and minor poisoning; one might need to refurbish or replace Pd elements perhaps every 5–10 years depending on usage. In a remote site, this means you’d keep spare modules or have a planned maintenance schedule to swap them out. The advantage is that swapping a membrane module is relatively straightforward compared to, say, replacing tons of PSA adsorbent – modules are usually skid-mounted and can be isolated. H2SITE, for example, monitors their membrane reactors remotely and can likely predict when a module is falteringbusinesswire.com. For Heber, one could employ a similar remote monitoring system (H₂ concentration monitors on retentate, pressure differentials, etc. to detect leaks or decline in selectivity). **Cold temperatures:** Polymer membranes operate better warm (typically they like 20–40°C; at subzero temps permeation slows and materials can become brittle). So the membrane unit would be kept in a temperature-controlled shelter. Pd membrane reactors are already hot (300–500°C internally), but their exterior piping still needs freeze protection for start/stop. **Dust:** As with PSA, keeping dust out of instrumentation and compressors is important. Intake filters on any air-cooled heat exchangers or compressors should be high-efficiency in dusty environments, with spares on hand. The membranes themselves see only process gas – which is clean – so dust isn’t an internal issue. **Remote operation:** Membrane systems are quite amenable to remote ops. They essentially just require monitoring pressures, flow rates, and perhaps periodically checking for any leaks. Control can be automated via PLC to maintain target purity by adjusting feed or permeate throttling. H2SITE’s deployment is a good example: their units are containerized, automated, and can be remotely controlledbusinesswire.com. For Heber, maintenance personnel might visit infrequently to inspect module seals or replace filters, etc. Also, membrane systems generally have a smaller footprint than PSA (no large vessels), which might ease siting at the campus.

Summary (Membranes): A membrane-based purifier (especially a *catalytic membrane reactor* or a membrane + small pretreatment train) offers **high purity H₂ with fast responsiveness**. It simplifies the process by combining steps (in the case of membrane reactor) and has no large vent streams if recovery is high. For Heber’s dual modes, membranes could seamlessly transition, producing pure H₂ from electrolyzers when available (with minimal effort) and ramping up on cracked ammonia when needed. The main downsides are **module cost and durability** at larger scale – e.g. Pd membranes use expensive materials and need careful handling to avoid embrittlement, while polymer membranes may need periodic replacement.

Additionally, for very large hydrogen flows, a membrane system's cost could exceed that of a PSA. A recent techno-economic study found that for a given large ammonia-to-hydrogen plant, Pd membranes had higher material cost and potential embrittlement issues, whereas PSA had lower CAPEX/OPEX and was more economical at scale [sciencedirect.comsciencedirect.com](https://www.sciencedirect.com/sciencedirect.com). Still, membranes were noted to consume slightly less energy and achieve higher H₂ recovery [sciencedirect.comsciencedirect.com](https://www.sciencedirect.com/sciencedirect.com). This suggests that at moderate scales or where efficiency and purity are paramount (fuel cell usage), a membrane system (possibly hybridized) can be a strong choice, whereas for very large throughputs with cost sensitivity, PSA might be favored.

Hybrid and Integrated Purification Systems

Hybrid architectures combine multiple technologies (PSA, membranes, catalytic steps, etc.) to leverage their respective strengths. In the context of Heber Campus, a hybrid approach could ensure **flexibility and high efficiency** across both operating modes. Several hybrid configurations are conceivable:

- **Membrane + PSA Combination:** Here a membrane separator would remove the bulk of H₂ from the cracked gas, and a PSA would polish the remainder. For example, one could use a polymer membrane as a first stage to achieve ~95% H₂ purity and recover a large fraction of hydrogen, then feed the residual gas (rich in N₂ with some H₂) to a PSA. The PSA would then produce very high purity H₂ from that residual and waste only a small amount of H₂. This approach could raise overall recovery beyond what a single PSA could do (since the membrane reduces the load on PSA). It also allows two output streams: an ultra-pure H₂ from PSA and a medium-purity H₂ from the membrane permeate – but these could be combined. Another configuration is the reverse: PSA first (for high purity) and then a membrane on the PSA tail gas to scavenge additional H₂. In fact, a recent patent suggests using a membrane to extract hydrogen from the PSA off-gas of an ammonia cracker [patents.google.com](https://patents.google.com/patents.google.com). The idea is that instead of burning all the PSA tail gas, one can **membrane-separate it to recover extra H₂** (because the tail gas still has maybe 40% H₂). The membrane's permeate (H₂ with some NH₃) could be recycled to the cracker or fed to a second PSA, while the retentate (mostly N₂) is sent to fuel. This two-step purification maximizes hydrogen yield and ensures any NH₃ in the tail gas gets another chance to crack. Hybrid schemes like this can push overall H₂ recovery to ~99% and reduce the wasted energy.

- Membrane Reactor + PSA or Polishing:** One might use a membrane reactor to perform most of the NH_3 cracking and H_2 separation, but if fuel cell specifications are extremely strict or one wants redundancy, a small PSA or getter bed could polish the membrane's H_2 output. For example, a membrane reactor might already produce 99.99% pure H_2 . If there's concern about a few ppm of residual N_2 or NH_3 , a **getter bed** (a catalytic purifier that absorbs O_2 , N_2 , etc., often used in semiconductor gas purification) could be added after to remove those last traces. Getter (metal alloy) purifiers can achieve 6N (99.9999%) purity eureka.patsnap.com, but they have limited capacity and mainly remove O_2 , CO , etc. They cannot scrub large fractions of N_2 – so getters are only suitable as a polishing step for trace impurities, not for handling 25% N_2 . In our case, if the membrane reactor already knocks N_2 down to <0.1%, a getter could mop that up. However, getters operate at high temperature and require periodic regeneration; for a remote site, a getter is probably overkill unless ultra-purity is needed for a specific reason.
- Two-Stage PSA (with recycle):** A hybrid purely within PSA technology – e.g. operate one PSA roughing stage that leaves say 99% H_2 and 1% N_2 in product, then a second PSA stage to refine to 99.999% H_2 . This could allow higher recovery overall by optimizing each stage. Johnson Matthey's patent actually hints at a two-PSA scheme: a first PSA, then crack the tail gas, then a second PSA patents.google.com. While effective, doubling up PSAs increases complexity and cost. More commonly, a single PSA with layered adsorbents suffices if purity goals aren't beyond 5N (99.999%).
- PSA + Catalytic Trick:** Another hybrid concept is using a **catalytic converter to eliminate residual NH_3 or other reactive impurities either before or after PSA**. For instance, if one is concerned that PSA might let a few ppm of NH_3 through (say if the NH_3 removal upstream falters briefly), a small *catalytic ammonia oxidizer* could be placed at the PSA outlet. By injecting a tiny amount of oxygen (from air) and using a Pt catalyst, any NH_3 would oxidize to N_2 and water. Such a “catalytic polishing” unit could ensure absolutely zero ammonia in product, though it would also introduce moisture that then needs drying. This is a niche solution and would be carefully controlled to avoid introducing oxygen into product (the catalyst must consume all O_2). Similarly, if any O_2 came over from an electrolyzer, a *deoxygenation catalyst* (combining H_2 and O_2 to H_2O) is often used in hydrogen purification heraeus-precious-metals.com. These catalysts (like Heraeus HeraPur®) are common in hydrogen supply systems to protect fuel cells by removing

oxygen [heraeus-precious-metals.com](https://www.heraeus-precious-metals.com). So a hybrid train might include catalytic guards for O₂ and NH₃, an ammonia scrubber, and then a PSA or membrane as core.

Advantages of Hybrids: The rationale for hybridizing is to **navigate trade-offs**. PSA is great for high capacity and purity but not very energy-efficient (H₂ losses); membranes are high recovery and continuous but expensive for large scale. Combining them can yield high capacity *and* high recovery: for example, one case study found combining a membrane reactor with a PSA gave both high purity and improved energy efficiency for ammonia-to-power systems [pmc.ncbi.nlm.nih.gov](https://pubmed.ncbi.nlm.nih.gov). Hybrids also add redundancy – if one system underperforms, the other can compensate. In a dual-mode scenario, one could imagine using *different systems in different modes*: e.g. during normal mode, perhaps the flow is small and one could route it through a membrane, whereas in backup mode (high flow, NH₃ present) one switches to PSA. This is a form of hybridization too (mode-dependent switching). However, maintaining two separate purification units, each only used part-time, may not be cost-effective. A more integrated hybrid would have them work in tandem concurrently.

Throughput and Dynamics: Hybrids can be tailored to throughput needs – for instance, the bulk of flow could go through a membrane, and only a slipstream goes to PSA, or vice versa. This can help manage ramping: a membrane stage provides immediate response, while a PSA stage runs steadily in background. The dynamic complexity increases, so careful controls are needed to ensure the units don't "fight" (for example, a membrane feed pressure controller vs a PSA feed regulator need coordination). Generally, adding stages adds some latency, but also buffer volume (e.g. a membrane retentate tank feeding PSA can act as a surge volume). For large, rapid swings, a hybrid might handle it better than a single PSA because the membrane can absorb fast transients and the PSA can be fed a smoother profile.

Maintainability: A hybrid system is by nature **more complex** – multiple unit ops to maintain. There are more failure points and a need for staff skilled in both technologies. This is a drawback in a remote site. Mitigation could be standardizing the equipment (e.g. using the same PLC for both, integrating alarms). If one component fails, the system can possibly limp along on the other. For example, if the membrane fails, the PSA could still purify hydrogen (with a bit less overall efficiency). Or if the PSA had to be offline, the membrane might still produce a hydrogen stream of slightly lower purity that could perhaps run a turbine (but not a fuel cell). This partial functionality is a resilience benefit.

Use Cases: In literature, **integrated membrane reactor systems** are a prominent hybrid that have been tested. H2SITE's container (shown above) is effectively a catalyst + membrane hybrid, delivering simplicity on the outside but a hybrid process inside [businesswire.com](https://www.businesswire.com). The **trend toward integrated solutions** is noted in industry – hydrogen plants are looking at combining methods to adapt to varying conditions eureka.patsnap.com. For green hydrogen storage, where input purity might vary (electrolysis vs cracked ammonia vs maybe geological storage gas), a hybrid train can automatically select the right tool for the impurity at hand.

Summary (Hybrid): For Heber, a hybrid approach might offer **optimal flexibility**: one could, for example, use a **membrane reactor as the primary purifier** (high efficiency, quick response) and supplement it with a **small PSA** that only kicks in if purity needs tightening or if throughput exceeds the membrane capacity. Such a setup could be tuned so that under normal operation, the membrane handles the electrolyzer H₂ easily (PSA idle), and under backup, the membrane still grabs most hydrogen while the PSA polishes the remainder – ensuring no performance drop even if membranes degrade slightly over time. The downside is increased capital and operational complexity. Given that proven designs (JM's and H2SITE's) tend to favor a single primary method with clever integration rather than two parallel purifiers, the added complexity of a hybrid must be justified by *specific* needs (e.g. extremely high recovery or fail-safe redundancy).

In conclusion, hybrids can deliver **the best of both worlds** (and indeed, the *recommended configuration* below will borrow a hybrid mindset by incorporating catalytic pretreatment and possibly multiple separation steps to guarantee purity). But one must balance this with maintainability in a remote, unmanned environment.

Catalytic Polishing-Only Approach (NH₃ Removal without N₂ Separation)

“Catalytic polishing” refers to using chemical reactions to *clean* the hydrogen without necessarily separating all diluents. In this context, a catalytic polishing architecture would involve **fully converting any residual ammonia and removing moisture**, but **leaving the hydrogen mixed with nitrogen** (i.e. not producing pure H₂). Essentially, the cracked gas (75% H₂ / 25% N₂) would be treated so that **NH₃ is eliminated to negligible levels** and the gas is dried, then fed directly to the end-use. This approach yields what is sometimes called “forming gas” (a H₂/N₂ blend). It is considerably simpler than PSA or membranes because we don't attempt to separate N₂ – we accept it as a ballast in the fuel.

Operation: In practice, one could achieve this by adding a **post-cracker catalytic bed** optimized to destroy residual NH_3 . For example, a bed of nickel or ruthenium catalyst at slightly lower temperature could crack the last fractions of NH_3 that the main reactor didn't convert (essentially a second-stage cracker). If the main cracker already achieves >99% conversion, the polishing bed would clean up the remaining ~1%. Alternatively, an **ammonia oxidation catalyst** could be used: injecting a small amount of oxygen and passing the gas over a catalyst that converts NH_3 to $\text{N}_2 + \text{H}_2\text{O}$. This method is used in NO_x abatement and can be very effective at low NH_3 concentrations. However, it requires precise control (to avoid leftover O_2) and would introduce water that then needs removal. A non-catalytic approach is a **scrubber**: contacting the gas with water or an acid solution to absorb NH_3 . Ammonia is highly water-soluble, so a water wash can easily drop NH_3 to sub-ppm levels. In fact, ammonia cracker systems often use a water scrubber or condenser to clean the gas. For instance, some industrial ammonia dissociators (for heat-treating atmospheres) have a water bubbler that removes NH_3 , yielding a gas with <10 ppm NH_3 for metallurgy use. After scrubbing, the gas is saturated with moisture, so a **dryer** (desiccant or condenser) would follow to achieve a low dew point. The net result is a dry H_2/N_2 mixture containing essentially no ammonia.

Throughput Scalability: This approach is **highly scalable** because it avoids large separation equipment. The main scaling factor is how to get rid of the heat from cracking and how to handle the scrubber solution. A catalytic polisher bed can be sized according to flow – it's similar to sizing any catalytic reactor (not particularly limiting). Scrubbers can also be made large (packed columns or spray towers for big flows). There is extensive experience in scaling scrubbing systems in the chemical industry. So throughput is not a constraint; even very large flows could be treated by parallel catalyst beds or a large wash unit. The equipment footprint is generally smaller than PSA for equivalent flow, since we don't need many adsorption vessels – just one reactor and one scrubber/dryer.

Contaminant Removal: The strength of this approach is **removal of reactive impurities** (NH_3 , O_2 , etc.) to extremely low levels, since it relies on chemical conversion. A well-tuned catalyst can bring NH_3 from 0.1% down to <ppm because it converts it rather than reaching an equilibrium like cracking does. For example, if we use excess hydrogen environment, any NH_3 that contacts a hot catalyst will dissociate. If using an oxidation approach, we can reduce NH_3 to <1 ppm with sufficient residence time. Water produced can be condensed or absorbed, giving a dry output. However, **inert N_2 is not removed at all** – it passes through unchanged. So after polishing, the gas might still be ~25% N_2 (or slightly less if the cracker wasn't complete and some H_2 was generated in polisher). That means the hydrogen purity is only ~75%. For a **gas turbine**, this blend might be

acceptable to burn. In fact, some studies (e.g. Starfire Energy's tests) have shown that a mixture of ammonia and cracked gas can be combusted with low ammonia slip ammoniaenergy.org. In our case we'd fully remove ammonia, so it's even better – the turbine would just see hydrogen diluted with nitrogen. This is roughly analogous to firing a turbine on a hydrogen/nitrogen mix, which some existing gas turbines do when they burn coke-oven gas or other low-BTU fuels. The inert N_2 would reduce flame temperature and likely reduce NOx (though the effect is complex, since N_2 can still form thermal NOx at high temps). The main advantage is **simplicity**: no cryogenics or heavy machinery, just reaction and phase separation.

The weakness is that for a **PEM fuel cell**, a 75% H_2 / 25% N_2 gas is **far below the required purity**. PEM fuel cells need $\geq 99.97\%$ H_2 ammoniaenergy.org because inert gases dilute the fuel and can lead to performance issues (and in recirculated anode loops, N_2 would accumulate). Running a PEM on forming gas would drastically reduce its efficiency and power output (the cell would be starved of H_2 partial pressure). So catalytic polishing alone (with no N_2 removal) is *not compatible with fuel cell operation*. It would restrict the usage to turbines or perhaps solid oxide fuel cells (SOFCs). Notably, SOFCs can internally reform some ammonia and tolerate more inert, but even they prefer higher H_2 content for performance. Thus, this architecture really only suits a scenario where the backup hydrogen is going exclusively to combustion turbines or engines that can handle dilute fuel. If Heber's backup power generation can be done entirely with a turbine, one might consider this approach to avoid the complexity of PSA/membranes.

Ramping and Dynamics: A catalytic polishing setup is **very straightforward to ramp**. The catalyst bed (if it's kept hot) can handle from 0% to 100% flow almost instantly – there's no cycle or membrane lag. Scrubbers likewise respond immediately (though a very large column might have some holdup, it's minor). If the polisher is an *exothermic oxidation* catalyst, one has to be careful when ramping to avoid temperature spikes (if NH_3 suddenly comes in at high concentration, the exotherm could overheat the catalyst). But since the main cracker would already remove most NH_3 , that risk is low – the polisher deals in trace NH_3 under normal conditions. The system can sit idle with minimal issues: the catalyst can be kept warm at low power and the scrubber can circulate minimal water. On demand, you increase ammonia feed, the main cracker output increases, NH_3 slip maybe rises a bit but the polisher converts it – all in continuous flow. There isn't a need to divert product at all because the quality will largely depend on how fast the chemical processes reach equilibrium (which is quickly once temperatures are up). If the polisher is just a water wash, the only dynamic concern is the time to saturate the water with ammonia – but since water solubility of NH_3 is high, even a sudden NH_3 surge would be captured as long as fresh water or acid capacity is available. So

dynamic performance is excellent and limited mostly by the **main cracker ramp** (which is common to all architectures). Most likely the ammonia cracker (furnace) will be the rate-limiting step to start up (~hours), whereas the purifier can follow easily. Thus catalytic polishing does not bottleneck ramping at all.

Power Efficiency: This approach is arguably the most energy-efficient because it **does not involve separating out an inert**. All the hydrogen cracked from ammonia is sent to use, and the N_2 simply tags along without being removed (thus no recompression or membrane work against N_2). There is some energy cost: if a water scrubber is used, perhaps a water cooler pump or regeneration heater for a dry bed; if a catalytic bed is used, heating that bed (unless it's integrated with the cracker's heat). But those are minor compared to the large compression work a PSA or membrane might need. Also, no hydrogen is lost to a tail gas (since we're not discarding N_2). Every H_2 molecule ends up in the product fuel. That said, there is a *penalty in utilization*: the turbine or engine burning the H_2/N_2 mix will get less energy per unit volume of fuel. But since we typically meter fuel by energy flow, you would just burn more volume of gas to get the same power. The presence of N_2 might slightly reduce turbine efficiency (due to higher mass flow through the turbine for the same power), but it also can be beneficial by increasing specific heat capacity in the expansion. These effects are second-order. For the fuel cell case, this dilution would *greatly* reduce efficiency – one reason we can't accept it for fuel cells. But if we exclude fuel cells, catalytic polishing gives nearly **100% hydrogen utilization efficiency** out of cracked ammonia, with minimal parasitic losses.

Tolerance to Impurity Swings: This approach is inherently tolerant of changes in ammonia conversion and impurity levels, as it's designed to neutralize those impurities. If the main cracker underperforms and leaves, say, 5% NH_3 in the gas, the polisher (if properly sized) will convert that 5% to H_2+N_2 or to N_2+H_2O in the same way it would handle 0.5%. It may run a bit hotter or consume more reagent (oxygen or water) but will still remove it. Of course, there are limits – a catastrophic breakthrough of ammonia beyond design could overwhelm a small polisher. Therefore, one would design the polisher for the **worst-case NH_3 slip** from the main cracker (e.g. assume the cracker only achieves 90% conversion in a cold start scenario, thus 10% NH_3 to remove). The system then can cope with anything up to that. Moisture swings are also handled by the dryer stage – usually sized for worst-case moisture load. Essentially, because we're not worried about separating N_2 , variations in H_2/N_2 ratio don't matter at all for the purifier; it only cares about NH_3 and H_2O content. Those it removes almost entirely, regardless of exact H_2 fraction. As long as there is sufficient hydrogen present to maintain a reducing environment for a cracking catalyst, variations in feed composition won't upset anything. If one uses an oxidation catalyst, a risk is if H_2 is very high and NH_3 is low, adding

oxygen could potentially lead to leftover O_2 if NH_3 runs out. But that can be controlled by tying the injected O_2 to measured NH_3 levels. With a simple cracking catalyst polisher, more H_2 in feed just means even more reducing environment, which is fine. In short, catalytic polishing is **very robust** against feed swings – it's probably the most robust of all options, because it's basically a safety net that chemically erases impurities.

Fuel Cell vs Turbine Compatibility: As emphasized, *this architecture is only suitable for turbines (or perhaps combustion-based generators)*. It cannot meet PEM fuel cell purity requirements due to the high N_2 content. If Heber intends to use fuel cells in backup mode, this approach is effectively a non-starter. There is a scenario where one might try to use a **solid oxide fuel cell (SOFC)** with the cracked gas. SOFCs operate at $\sim 800^\circ C$ and can internally reform some fuels; they can tolerate a higher fraction of inert because they aren't limited by diffusion in the same way PEMs are. Some SOFC systems have run on 50–75% H_2 mixtures (the rest being N_2/CO_2). They will produce less power at a given fuel flow, but you can flow more. However, even SOFCs would not enjoy any residual NH_3 (which we are removing) and have their own purity limits for sulfur, etc. For our scope, we assume PEM fuel cells (since PEM are more common for intermittent power). Thus, catalytic-only purification fails the fuel cell spec by a wide margin. On the turbine side, however, it *does* fulfill the critical requirement: no ammonia and dry gas. Gas turbines often have spec that fuel NH_3 content should be $< ppm$ to avoid NO_x – this is achieved. The N_2 in the fuel is not a contaminant per se; it's just inert ballast. In fact, many turbine combustion schemes (like diluting H_2 with N_2 or steam) are actively exploring adding N_2 to tame flame speed for hydrogen. If we deliver a H_2/N_2 mix, the turbine might be perfectly happy and possibly produce lower NO_x than pure H_2 would (because pure H_2 flame is very hot, whereas H_2 with N_2 is cooler per unit of fuel energy). There will still be significant NO_x from air's N_2 at high flame temps, so additional NO_x control might be needed regardless (e.g. dry low- NO_x burners or water injection). But the fuel-borne nitrogen (now in N_2 form, not NH_3) is no worse than air's nitrogen. So for a turbine, catalytic-polished forming gas is acceptable and might even simplify combustion control.

Maintainability and Site Conditions: This approach is mechanically simpler: basically just static equipment (reactor vessel, pump, heat exchangers) and perhaps a blower. **Cold weather:** If a water wash is used, we must keep it from freezing – a heated, insulated tank and heat-traced lines would be required, or use an ethylene glycol solution as scrubbing liquid to lower freeze point. If a dry catalytic bed is used, we'd likely keep it hot continuously (which in winter means insulating it well and maybe electrical tracing to hold temperature at idle). **Dust:** not much impact internally, but dusty ambient could clog an air

inlet if using an oxidation stage (air filter needed), or dirty the cooling systems. Maintaining a scrubber involves checking the solution (if it's water absorbing NH_3 , eventually it becomes ammonium hydroxide that might need to be purged or reprocessed). In a remote site, disposing of ammonia-rich water could be an issue – you might need to truck it out or have an evaporation system. One workaround is to **recycle captured ammonia**: Johnson Matthey chose to use recovered NH_3 as fuel in their cracker furnace [matthey.com](https://www.matthey.com). At Heber, without a furnace, one could potentially store the absorbed NH_3 and recombine it into the ammonia storage tank (for example, distill the NH_3 out of solution and send it back to storage or feed it to the cracker in a controlled way). This adds complexity. Alternatively, one could use a *solid chemisorption bed* (like an acidic adsorbent) to trap NH_3 and then periodically regenerate it by heating – essentially a TSA (thermal swing adsorption) just for NH_3 . Kojima et al. used a zeolite bed to absorb NH_3 and then regenerated by heating to 400°C ammoniaenergy.org. This is a viable low-maintenance approach: the bed could be sized to hold a full day's worth of NH_3 slip and regenerated at night, for instance. Under remote ops, automating that regeneration (using some of the stored hydrogen to heat it, perhaps) would be needed. **Catalyst maintenance:** If using a catalyst bed, over time catalysts can age (sintering, poisoning). With clean ammonia feed, main poisons might be lube oil from compressors or any sulfur in ammonia (green NH_3 should be sulfur-free). The catalyst could probably run for years without replacement. If an oxidation catalyst is used, it might see some thermal cycling stress. But in general, such catalysts (similar to automotive 3-way catalysts or DeNOx catalysts) are designed for long life.

Because there are so few active components, there's less to go wrong. It's mostly about ensuring the system always either fully cracks or fully scrubs ammonia. Redundancy can be provided by using two polishing units in parallel – e.g. two small catalytic beds, one as backup, or two redundant wash pumps. The control system is simpler too (no cycling valves, just feed-forward control of perhaps oxygen addition or switching a regen heater). From a maintenance standpoint, this approach could be checked maybe monthly with minimal tweaks.

Summary (Catalytic Polishing Only): This architecture offers **maximal simplicity and robust operation**, at the cost of not delivering pure H_2 . It is **ideal for a scenario where turbines (or engines) are the sole hydrogen consumer** in backup mode, and one is willing to sacrifice fuel cell involvement during those periods. It ensures NH_3 is fully removed (meeting turbine fuel requirements and avoiding catalyst poisoning concerns), and is inherently efficient and easy to operate remotely. However, since the Heber Campus explicitly may use large fuel cells as well, this method alone would not suffice unless there's a way to

segregate which loads get the less-pure hydrogen. One could conceive a hybrid strategy: e.g. during extended outages, perhaps they rely on turbines only and turn off fuel cells, thus allowing a simpler purifier; but this underutilizes the fuel cells. More likely, Heber will want the flexibility to use both turbines and fuel cells in backup, which drives the need for **full purification** (PSA or membrane). Still, the catalytic polishing components (scrubbers, guard beds) are likely to appear even in those systems – as *pretreatment* to protect PSA/membranes. We will incorporate that in the recommended configuration.

Comparison of Purification Architectures

The following table (Table 1) compares the four architectures – PSA, Membrane, Hybrid, and Catalytic Polishing – across the key criteria:

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
Throughput Scalability	Very High: Proven at large industrial scale (hundreds of kg H ₂ /hour). Easy to scale by adding adsorber size or parallel trains matthey.com . Suitable for bulk hydrogen production (as in ammonia plants).	High (Modular): Scalable via parallel membrane modules. Medium-scale (tens of kg/h) demonstrated; can add modules for larger flows. Palladium membranes more costly to scale up than PSA sciencedirect.com . For very large (>1 ton/h), many modules required (complex).	High (Case-dependent): Can design hybrid to meet large flows (e.g. PSA handles bulk, membrane polishes or vice versa). Membrane reactors are modular (200 kg/day unit shown; aiming for ton/day scale) businesswire.com businesswire.com . Hybridization adds complexity as scale increases (more equipment).	High: Simple to scale – mainly a catalytic reactor and/or scrubber sized to flow. Industrial scrubbing/catalytic units can handle large volumetric throughput. Parallel units can be used

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				for very high flows.
Contaminant Removal (NH ₃ , H ₂ O, N ₂)	<p>NH₃: Requires upstream removal (water wash or guard bed) to avoid adsorbent fouling matthey.com. With proper pretreatment, NH₃ slip to product is ≈0 (ppm-level) ammoniaenergy.org.</p> <p>H₂O: Typically dried in pretreatment or first PSA layer; achieves very low dew point (−70°C or better).</p> <p>N₂: Excellent removal. PSA product H₂ can reach >99.96% purity matthey.com (N₂ <0.04%). N₂ levels of <10 ppm demonstrated ammoniaenergy.org.</p>	<p>NH₃: Must be removed or converted before/per membrane (especially for polymer membranes). Membrane reactor achieves complete NH₃ conversion in-situ businesswire.com. Standalone membrane requires NH₃ scrubber upstream (to ppm levels).</p> <p>H₂O: Feed gas should be dry (to protect membrane performance). Dryers often needed. Output H₂ is dry (especially if membrane reactor condenses water out).</p> <p>N₂: Good separation of</p>	<p>NH₃: Handled by integrated measures – e.g. membrane reactor cracks NH₃, or PSA upstream in multi-step. Hybrids can include NH₃ scrubbers as well. Generally no NH₃ in final product (multiple opportunities to remove it).</p> <p>H₂O: Typically include a drying step. Hybrid could use a dryer + membrane or PSA integrated regeneration for drying. Final product meets fuel cell humidity spec.</p> <p>N₂: Hybrid can achieve essentially zero N₂ if designed so (e.g. PSA after membrane). Membrane-PSA combos can get H₂ purity 99.999%+. N₂ removal efficiency can be very high, at the cost of complexity.</p>	<p>NH₃: Excellent removal via chemical conversion or scrubbing. Final NH₃ << 1 ppm (virtually zero) if sized correctly. No NH₃ reaches end-use (avoids NO_x issues).</p> <p>H₂O: After NH₃ scrubbing (if water wash used) gas is saturated with H₂O – needs drying (desiccant or</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
		<p>N₂ (especially with Pd membranes – essentially all N₂ remains in retentate). Polymeric membranes remove majority of N₂ but may need multi-stage to reach <0.1% N₂. Membrane reactors inherently leave N₂ in retentate, giving high-purity</p> <p>H₂businesswire.com.</p>		<p>condensation). Dry gas can reach dew point of –40 to –60°C with standard dryers, sufficient for turbines. (Turbines not as sensitive to trace moisture as fuel cells).</p> <p>N₂: No removal. N₂ passes through unchanged. Product gas H₂ purity ~70–75% (balance N₂). Not suitable for processes</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
Ramping Dynamics	<p>Moderate: PSA cycles impose ~minutes-level response. Best at steady or slowly varying loads. Can handle infrequent step changes (with control logic). Not ideal for fast sub-minute fluctuations – would require buffer storage to smooth transient flows. Start/stop takes time (beds need pressurization/stabilization).</p>	<p>Excellent: Continuous process with no cycle; responds almost instantly to changes in flow or composition. Can ramp from 0–100% output rapidly (limited only by how fast pressure/flow can be adjusted). Pd membranes need warm-up to operating temp, but once hot, output adjusts in real-time to feed. Ideal for rapid startup and load following.</p>	<p>Good (with coordination): Dynamic performance depends on configuration. Membrane portion can react fast, PSA portion slower. A well-designed hybrid can leverage membrane for immediate response and let PSA even out longer-term shifts. Control is more complex (to prevent oscillations between units). Overall can be tuned for reasonably fast ramp, but not as simple as pure membrane.</p>	<p>requiring high H₂ purity.</p> <p>Excellent: No cyclic processes; only chemical reactors and flows. Can turn down or up quickly. A hot catalytic bed can go from idle to full throughput very fast (no fundamental delay). Scrubber and dryer adjust continuously. Essentially as responsive as flow control</p>








Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				allows. No need to purge or cycle – output purity remains constant during ramps (as long as catalyst is active and sized). This approach imposes almost no delay in delivering hydrogen when the cracker produces it.
Power / Energy Efficiency	Moderate: ~10–15% of H ₂ energy may be lost (in tail gas) if not recovered sciencedirect.com .	High: Very high H ₂ recovery (up to 98–99%) means minimal fuel	Potentially Highest: By optimizing each step, hybrids can maximize recovery and minimize	Very High: Essentially 100% of H ₂


Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
	Additional energy for compression if product needs to be delivered at pressure (though PSA feed is usually already pressurized, and product emerges at near feed pressure minus ΔP). If tail gas is burned for heat, overall efficiency improves (waste H_2 utilized). PSA itself has low electrical demand (valves, maybe a vacuum pump). Net efficiency ~70–85% (depends on recovery and integration) ammoniaenergy.org .	value lost businesswire.com . Energy use mainly from creating ΔP (compressor or vacuum). No large purge stream. Metal membranes allow using thermal energy (heat) instead of mechanical energy for separation. A well-integrated membrane reactor can achieve >80% overall efficiency ammoniaenergy.org . If additional compression of product is needed, that adds load. Polymer membranes can use waste pressure effectively. Typically a bit more efficient than PSA for the same duty sciencedirect.com .	losses. For example, membrane first to minimize H_2 loss, PSA second to ensure purity – H_2 loss can be <1%. Energy usage may be higher in terms of equipment (since you run both a compressor and PSA valves), but hydrogen yield is maximized. With good heat integration (e.g. using PSA off-gas as fuel, using membrane permeate at pressure), one can approach very high overall efficiency (~85–90%). However, more equipment also means more points of inefficiency (pressure drops, etc.), so careful engineering is required.	ends up in fuel. No separation of N_2 means no energy spent to remove it. The only energy costs are for heating catalyst (which could potentially be done by the exothermic combustion of a small portion of H_2), pumping scrub liquid, or powering a small blower. These are minor compared to

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				<p>the chemical energy of the hydrogen.</p> <p>Thus, energy efficiency in terms of H₂ utilization is ~100%. (In practice, overall efficiency is limited by the ammonia cracking step energy input, which is common to all options.) This approach wastes virtually no hydrogen and has low</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				auxiliary power needs.
Tolerance to Feed Impurity Swings	<p>Conditional: PSA needs consistent feed composition for optimal performance. Large swings in H₂ concentration or unexpected impurities (e.g. sudden NH₃ breakthrough) can upset the cycle (risking impurity slip until cycles re-equilibrate). Mitigation: design for worst-case impurities and include robust pretreatment (guard beds)matthey.com. With proper design, can handle the full range from electrolyzer-pure to cracked gas by using bypass valves and controlled transitions. PSA can tolerate some turndown but performance drops if running far below design capacity.</p>	<p>High: Membranes handle varying compositions smoothly – output purity will adjust but generally remains high if designed for worst-case (e.g. 75% H₂ feed). They are not prone to sudden breakthrough; instead, a richer N₂ feed simply results in less H₂ flux or a need for multi-stage operation. The main concern is tolerance to <i>chemical</i> impurities: e.g. a spike of NH₃ or particulates could foul the membrane. As long as those are filtered/scrubbed, the membrane is fine. In</p>	<p>High (with control): Hybrids can be engineered to be robust against swings by combining the strengths of each method. For instance, if feed impurity spikes, a hybrid might route more flow through a unit that can handle it. Redundancies can be built in (one unit takes over if another is saturated). However, the complexity means more things to adjust. Still, by designing each component for worst-case impurity loads, the hybrid will handle feed swings well. E.g. a hybrid could include an NH₃ scrubber (to buffer any NH₃ surge) plus a membrane – making it quite resilient. The hybrid can definitely manage the electrolyzer vs ammonia-cracker feed</p>	<p>Very High: Specifically designed to neutralize impurities, so it thrives on that role. If NH₃ content rises, the catalyst/scrubber simply removes more (up to its capacity). There is no delicate equilibrium to upset – as long as the polisher is sized for worst-case</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
		Heber's case, going from 100% H ₂ to 75% H ₂ feed is within normal operation – membrane permeate purity might dip slightly during that transition but can be kept in spec by adjusting pressures. Overall very forgiving to feed changes compared to PSA.	disparity, by essentially using different parts of the system for each.	NH ₃ , purity won't slip. Water content variations are handled by the dryer (which can be regenerative if needed). N ₂ variation doesn't matter, since we're not removing N ₂ . Thus from 0% N ₂ to 30% N ₂ feed, this system would still output the same composition (just that H ₂ fraction changes accordingly).

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				Essentially immune to feed composition swings except extreme cases beyond design capacity.
Fuel Cell vs Turbine Purity	<p>Fuel Cells:  Yes – PSA can meet ISO 14687 PEM fuel specs (H_2 >99.97%, NH_3 <0.1 ppm, etc.) ammoniaenergy.org ammoniaenergy.org. It's used in practice for fuel-cell-grade H_2 purification.</p> <p>Turbines:  Yes – H_2 from PSA is even purer than turbines need. No NH_3 (avoids NO_x), and N_2 removed (though turbines could tolerate some). Pure H_2 might cause higher NO_x than H_2/N_2 mix, but that can be managed with turbine controls (or diluent injection as needed).</p>	<p>Fuel Cells:  Yes – Membrane systems (especially Pd) can produce ultra-pure H_2 that meets/exceeds fuel cell requirements businesswire.com. Need to ensure no NH_3, which is handled via design. Many fuel cell systems use Pd membrane purifiers for this reason.</p> <p>Turbines:  Yes – Membrane-purified H_2</p>	<p>Fuel Cells:  Yes – Hybrids are configured specifically to achieve fuel-cell-grade output. E.g. a membrane reactor + PSA hybrid would easily hit 99.999% H_2, NH_3 nil, which is beyond spec. So definitely fuel-cell compatible.</p> <p>Turbines:  Yes – The hybrid can be operated to deliver fuel-cell-purity H_2, which turbines can use. Alternatively, could be operated to leave some N_2 if desired for turbine, but since fuel cells are also in scope, one would produce</p>	<p>Fuel Cells:  No – Output is ~75% H_2 + 25% N_2 (even if NH_3 is zero). This does <i>not</i> meet PEM fuel cell spec (N_2 too high by orders of magnitude). A PEM fuel cell would suffer performance loss and instability on</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
Overall, PSA product is acceptable for any use.		(essentially 100% H ₂) is fine for turbines, though operators might dilute it for NO _x control. If one wanted, the system could be run to leave a few % N ₂ , but generally pure H ₂ is delivered and is combusted with appropriate burner tuning.	the highest purity and it covers both.	<p>such dilute H₂. Only feasible if fuel cells are completely taken out of service in this mode.</p> <p>Turbines:  Yes (with caveat) – Turbines can burn a H₂/N₂ mixture. The absence of NH₃ makes it safe from NO_x perspective (no fuel-NO_x). The 25% N₂ acts as diluent; turbine may actually benefit from</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				<p>slower combustion.</p> <p>Need to ensure turbine combustor can handle lower heating value fuel (likely just require higher fuel flow).</p> <p>Many modern turbines can, especially if designed for high-H₂ fuels (they often expect some diluent anyway). So turbine operation is compatible.</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
Maintainability & Remote Ops	<p>Mature but Complex: PSA has many valves and control sequences. Maintenance involves instrument calibration, valve seal replacements, and eventual adsorbent change (5–10 year life typical). Remote operation is common for PSAs (widely used in industry); advanced control systems can diagnose issues (e.g. valve stuck, bed not achieving vacuum). Spares (valves, sensors) should be kept on-site due to remote location. Cold weather: enclosure or heating needed to keep equipment within design temp (adsorption performance and pneumatic controls are temperature-sensitive). Dust: ensure filtered air supply for valve actuators and any purge gas. PSA technology itself is well-understood, so support is available. Requires more hands-on</p>	<p>Simple Hardware, Sensitive Elements: Membranes have few moving parts – mainly a compressor (if needed) and some valves – so mechanical maintenance is lower. However, membrane modules will gradually degrade (especially polymer ones). Plan for module replacements every few years or per manufacturer specs. Pd membranes need monitoring for leaks or performance drop (e.g. if embrittled). Remote monitoring is feasible (H2SITE uses a remote control room to oversee membrane reactors across</p>	<p>Most Complex (but Redundant): A hybrid has the highest component count – maintenance is sum of its parts (PSA + membrane + catalyst etc.). This can be mitigated by modularization (e.g. skid-mounted units for each subsystem that can be swapped if needed). Remote operation requires a robust control system managing each subsystem and the interfaces. Cold/dust considerations are combination of those for PSA/membrane/catalyst: likely all equipment in enclosed, climate-controlled housing to simplify issues. On the plus side, hybrid can be designed with redundancy – e.g. if membrane section is offline, PSA alone might keep system running (at lower efficiency); if PSA has an issue,</p>	<p>Simplest Mechanically: Few moving parts – maybe a circulation pump, control valves, and that's it. A catalyst bed is static; a scrubber is essentially a tank. This simplicity is an advantage for remote ops (not much can break if properly designed). Key maintenance tasks: replenish or regenerate</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
	maintenance than membranes (due to moving parts count), but intervals are long and predictable.	sites businesswire.com). Cold: keep membranes in a temperature-controlled container (for polymer) or maintain Pd membrane heaters on standby. Dust: protect compressors and heat exchangers with filters. If a compressor is oil-lubricated, ensure good filtration to avoid oil vapor fouling membranes. In a remote setting, membrane system might be easier to restart after downtime (less to go wrong on startup). Spare membrane cartridges and perhaps a backup compressor should be stocked due to lead times. Overall, lower	membrane might maintain partial purification. Maintenance strategy could involve alternating usage to prolong life (for instance, run membrane primarily, use PSA occasionally to keep it ready). This is complex and would need clear procedures for the remote operators or automated sequences. Given Heber’s remote nature, a hybrid might require more frequent expert check-ins unless highly automated. Spare parts inventory would be broader (adsorbents, membrane modules, catalyst, etc.). This is doable but requires strong technical support (possibly via vendor service contracts).	scrubbing media (water or chemicals) if used, replace catalyst after a long period, ensure dryer desiccant is active (replace or regen as needed). These tasks can be scheduled infrequently (e.g. catalyst might last >5 years; scrubber water might need periodic top-up and bleed). Automated

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		<p>routine maintenance than PSA, but a failure of membranes could require specialized replacement (hence having spares and telemetry to predict failures is key).</p>		<p>systems can be in place to regenerate dryers or switch dual beds. Cold: heat tracing and insulation for scrubber and any water lines to prevent freezing in winter. Dust: minimal impact; just keep any air vent (for oxidizer) filtered. Remote monitoring would track temperatures,</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				<p>pressures, and perhaps NH_3 slip (with an analyzer to ensure the polisher is working – any NH_3 detection triggers alarm). If something fails (e.g. heater for catalyst goes out), the system might start letting NH_3 through – which could be detected and trigger a shutdown or backup action. But with proper</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				<p>redundancies (electric heaters in pairs, etc.), this is unlikely. Overall, maintenance is low – likely less than either PSA or membrane – because the system's operation is straightforward. The main caution is ensuring the consumables (water, etc.) are managed in a remote environment (maybe need</p>

Criterion	PSA (Pressure Swing Adsorption)	Membrane Separation	Hybrid (e.g. Membrane + PSA or Membrane Reactor)	Catalytic Polishing Only
				larger reservoirs or automated makeup).

Table 1: Comparison of hydrogen purifier architectures (PSA, Membrane, Hybrid, Catalytic-only) for the Heber Campus dual-mode scenario. PSA and Membrane options both can achieve the necessary purity for fuel cells and turbines, with PSA excelling in large-scale use^{matthey.com} and membranes offering high efficiency and fast response^{businesswire.com}. Hybrids can optimize performance but add complexity, and catalytic-only polishing is simplest but cannot meet fuel cell purity (N₂ not removed). Checkmarks (✓/✗) under Fuel Cell/Turbine indicate compatibility with those end uses. All approaches would include some *pretreatment steps* (e.g. NH₃ removal, drying) as needed, which are considered in the contaminant removal row.

Recommended Purification Architecture and Configuration

Considering the above comparisons and the specific needs of the Heber Campus, the **recommended solution is a PSA-based purification train enhanced with catalytic/absorption pretreatment**, providing a hybrid of sorts that maximizes reliability and purity. This architecture is optimal for Heber’s dual modes given the likely **large hydrogen throughput**, the critical requirement to meet **fuel cell purity standards**, and the need for **automated seamless switching** between modes. The core purifier will be a PSA unit (due to its proven scalability to high flow rates and capability to produce >99.96% pure H₂^{matthey.com}), but it will be supported by upstream polishing components to ensure that feed gas quality remains consistent and no ammonia or moisture slip occurs. This achieves the benefits of both worlds: the **capacity and purity assurance of PSA** with the **safety net of catalytic NH₃ removal** to protect both the PSA and end-users.

System Configuration: The purification train for backup (ammonia cracking) mode would include the following stages in sequence:

1. **Ammonia Cracker:** (Not part of purification per se, but for context) – The NH_3 is decomposed in a primary reactor (likely catalytic, heated by nuclear or electric heat). We assume this provides a cracked gas containing ~75% H_2 , ~25% N_2 , with a small fraction of residual NH_3 (depending on conversion efficiency) and hot, moisture-saturated gas (if any impurities or if a wet scrub is used later). For instance, at 500–600°C with a good catalyst, expect >99% NH_3 conversion (as lab tests achieved 99.8% at 500°C ammoniaenergy.org). Gas exiting might be ~500°C and ~1 atm (or possibly a few atm if running pressurized to aid separation).
2. **Cooling/Condensation Stage:** Immediately after cracking, the gas should be cooled to near ambient to condense out any produced H_2O and also some NH_3 . If the cracker operates with excess hydrogen (no water input), there might be very little water to condense (only trace from side reactions). But if an **ammonia scrubber** is to be used, cooling is needed anyway to make contact with liquid. A heat exchanger (using cold water or a chiller) can drop the gas temperature, causing most of the H_2O to condense. Ammonia has a boiling point of –33°C, so it won't condense at ambient conditions unless the gas is pressurized. If the cracker runs at, say, 20 bar, cooling to ~20°C could condense much of the NH_3 (because at 20°C, NH_3 saturation pressure is ~8.5 bar). In that case, one could **knock out liquid ammonia** in a separator. That liquid NH_3 could potentially be pumped back to the ammonia storage tank (closing the loop) or sent to a furnace if one existed. Given Heber might not have a use for liquid NH_3 in backup mode (except storing it), sending it back to storage is an option – effectively you'd be reabsorbing uncracked ammonia into the tank rather than letting it continue. If the cracker runs near 1 atm, ammonia won't liquefy easily; then a water scrubber is the practical way.
3. **NH_3 Scrubber/Absorber:** A **water wash tower** (or series of spray/packed sections) will remove essentially all residual ammonia from the cooled gas. Ammonia is extremely soluble: one volume of water at 20°C dissolves ~1300 volumes of NH_3 gas. So even a small water flow can scrub ppm to percent levels of NH_3 out of the gas. The gas leaving the scrubber can achieve NH_3 concentrations in the low ppm or even <<1 ppm range, as reported in demonstrations (e.g. 1000 ppm down to <0.02 ppm with a zeolite absorber ammoniaenergy.org ammoniaenergy.org). We will design the scrubber for worst-case NH_3 slip – say the cracker could at times only do 95% conversion (especially on startup or at lower temps), leaving 5% NH_3 in gas. The scrubber must handle that scenario and still deliver <ppm NH_3 at outlet. We might opt for a **two-stage absorption**: first a water quench to dissolve bulk NH_3 , then perhaps a second stage using a slightly acidic

solution (like a dilute H_2SO_4) to polish to sub-ppm. The result is an ammonium sulfate or hydroxide solution that can be stored. The **automation** here would include monitoring pH or ammonia concentration in the water and automatically switching in fresh water or acid as needed. In remote ops, one could include large enough reservoirs such that the scrubber can operate for the duration of a multi-day storm without service. After the event, operators could regen or replace the solution. Alternatively, if pressurizing the cracker, skipping water and using **NH_3 condensation** is possible as noted – which is even simpler (no consumable except some power for refrigeration). That approach would require a chiller to reach $\sim 0^\circ\text{C}$ or lower at a few bar to condense NH_3 out. It might be viable and would allow directly recovering NH_3 to storage. Either way, **the goal is to prevent any NH_3 from entering the PSA.**

4. **Gas Dryer (Dehydration Stage):** Whether we scrub with water or not, by the time the gas is ammonia-free, it will be saturated with water at \sim ambient temperature. For PSA (and fuel cells/turbines), a dry gas is needed (PSA adsorbents don't like water, fuel cells require dry H_2 to avoid flooding, and turbines combusting H_2 don't mind some moisture but it's best to meet the fuel spec and avoid icing in lines). Therefore, a **desiccant dryer** should follow. Options include a Temperature Swing Adsorption (TSA) dryer with activated alumina or molecular sieves, or integrating the drying function into the PSA beds (many H_2 PSAs have a layer of alumina for drying at the feed end). To keep things simple, we might incorporate a small twin-tower regenerative dryer upstream of PSA. This dryer could be regenerated by a slipstream of dry product hydrogen or by PSA purge gas. Given PSA tail gas will be burned or vented, using a little of it (still containing some H_2) as a regeneration purge is acceptable. Alternatively, since the PSA itself will dry the gas if loaded with alumina, one might rely on the PSA's first adsorbent layer as the dryer – in which case this stage is not a separate unit. In any case, by the time the gas enters the core separation (PSA), it should have a very low dew point (e.g. -60°C or better, which is $\sim <5$ ppmv H_2O).
5. **PSA Unit (Core H_2/N_2 Separation):** Now the clean, dry gas (75% H_2 , 25% N_2 , ~ 0 ppm NH_3) enters the multi-bed PSA. The PSA will be designed to produce product H_2 that meets **fuel cell specs**: $\text{H}_2 > 99.97\%$, $\text{N}_2 < 100$ ppm, $\text{NH}_3 < 0.1$ ppm, $\text{H}_2\text{O} < 5$ ppm ammoniaenergy.org. With the feed already free of $\text{NH}_3/\text{H}_2\text{O}$, the PSA's job is mainly to remove N_2 (and perhaps any Argon or residual methane if present). Commercial H_2 PSAs routinely achieve 99.9–99.999% H_2 , so hitting $\sim 99.99\%$ (so that $\text{N}_2 < 0.01\%$) is feasible matthey.com. If needed, a 5-bed or 6-bed PSA configuration with appropriate adsorbents (zeolite 5A/13X for N_2 , maybe a carbon for any CH_4 , etc.) will be used. The PSA will operate at a pressure

that is a compromise between cracker output pressure and end-use needs. For instance, perhaps we run the cracker at ~10 bar to help NH_3 conversion a bit and reduce downstream equipment sizes. The PSA could take feed at 10 bar and produce H_2 at ~9 bar (some pressure drop in beds). This product could then be sent directly to high-pressure storage tanks or to a fuel cell pressure regulator. The **PSA cycle** will be set for high recovery (~90%). With our feed mostly H_2 , we expect to recover most of it. The tail gas from the PSA will contain ~ all the N_2 and ~10% of the H_2 . Its pressure after blowdown will be low (~atmospheric or a small backpressure). We must handle this tail gas appropriately: we can't vent raw H_2 (even diluted) for safety and efficiency reasons. The plan is to **consume the PSA tail gas in a flare or small catalytic combustor**. Since Heber might not have an existing fired heater to use it, a simple solution is a **thermal oxidizer** unit where the tail gas is mixed with a little air and burned (essentially a flare with a proper burner to ensure NH_3 or H_2 get oxidized). This will yield hot flue gases (H_2O , N_2 mainly). Those could be released via a stack. If wanting to be clever, we could recover some heat from this oxidizer (for example, preheat the ammonia feed or generate steam for other uses). Given the site uses nuclear heat for electrolysis, a bit of extra heat may not be needed, but for overall efficiency we could integrate it. Importantly, **burning the tail gas ensures any trace NH_3 or H_2 in it is disposed of safely**, maintaining the green credentials (no hydrogen or ammonia emission). The tail gas combustor must be designed to handle varying compositions (if PSA feed changes or if we temporarily bypass PSA in normal mode, etc.). That's manageable with a control valve that provides supplemental fuel or air as needed to keep flame stable (e.g. if H_2 content is low, we might add a tiny bit of hydrogen from storage to support combustion). This is a minor subsystem but needed for safety.

6. **Product Outputs and Switching:** The PSA product H_2 (now >99.97% purity, essentially at spec) will feed into the **common hydrogen product header**. In normal daily mode, hydrogen from the electrolyzers/nuclear (which is already high-purity) can also feed this header – likely **bypassing the pretreatment and PSA**. We should include piping and automated valves that in normal mode direct electrolyzer H_2 straight to the header (maybe through a simple dryer or palladium guard if needed, but not through the whole PSA). Simultaneously, in normal mode the ammonia cracker system will be idle or at pilot. When a switch to backup is needed, the control system will ramp up the cracker (which may take tens of minutes to heat up), start the pretreatment (circulate scrubber, etc.), and **bring the PSA online**. During this transition, initially the cracked gas may be off-spec (e.g. higher NH_3 until reactor is hot). The automation should route initial cracked gas to vent or to the tail gas combustor until analyzers confirm $\text{NH}_3 < \text{threshold}$ after the scrubber.

Once the scrubbed gas is clean, a valve opens to feed it into the PSA. The PSA will then start cycling, producing pure H₂ typically within a minute or two of startup. We would likely **initially divert PSA product to a recycle or vent** until purity is confirmed (e.g. the first cycles might not achieve full spec until adsorption fronts are established). After, say, 5 minutes of PSA operation (few cycles), the product gas analyzer should read >99.97% H₂, ND (non-detect) NH₃. At that point, a valve connects PSA product into the main H₂ header, seamlessly taking over the supply to turbines/fuel cells. From the perspective of the fuel cells/turbines, there is no meaningful change – the hydrogen stays within spec, only perhaps the slight difference that now it's coming from stored ammonia rather than real-time production. This changeover should be smooth if done correctly: ideally, one would not even fully deplete the normal hydrogen storage before bringing the cracker online, so that there is overlap where both sources are available. We could use the stored H₂ (from normal operation) as a buffer to feed the fuel cell/turbine while the cracker/PSA ramps, then switch to the cracker output when ready. All of this can be automated with interlocks and analyzers.

7. **Bypass for Normal Mode:** In normal mode, the electrolyzer (SMR, PV, etc.) H₂ is already ~99.9% pure (PEM or SOEC electrolysis typically yields very high purity with trace moisture/O₂). For caution, we might include a small **catalytic recombiner/dryer** for that stream: e.g. a Deoxo unit to convert any O₂ to H₂O (using a tiny fraction of H₂), followed by a dryer. This ensures no O₂ goes into storage or fuel cells (O₂ can cause unsafe conditions or fuel cell oxidation). After that, the pure H₂ can be sent directly to storage or use. It will bypass the PSA, because running pure H₂ through PSA would just waste energy and H₂ (PSA would still dump some H₂ to tail gas even though there are no impurities). So a set of actuated valves will isolate the PSA beds and route the H₂ straight through. The PSA can be put in standby – either kept pressurized with H₂ (so it's ready to go, but we might purge it to avoid any contamination ingress and then hold it) or cycled at idle (not necessary). Keeping PSA pressurized with H₂ in standby is fine; just before starting it for backup, we'd depressurize and start regular cycling with feed.

Spec Parameters and Purity Assurance: We must ensure the system consistently meets the required specifications for both end-uses, especially the stricter fuel cell specs. Key parameters to specify and control:

- **Hydrogen Purity:** ≥99.97% vol H₂ (as per ISO 14687 for PEMFC) ammoniaenergy.org. Our PSA target is ~99.99% to provide a safety margin (this corresponds to <0.01% impurities). This covers N₂/Ar primarily. We will include a hydrogen

purity analyzer (likely a gas chromatograph or thermal conductivity detector) on the product line to continuously monitor purity. If purity dips (e.g. 99.9% instead of 99.97%), the system can alarm or divert flow.

- **Ammonia content:** <0.1 ppm vol at product ammoniaenergy.org. We design the scrubber and PSA such that NH_3 is essentially zero in product. An NH_3 analyzer (e.g. laser-based) at the PSA inlet and outlet can provide assurance. Upstream of PSA, we might allow a few ppm (adsorbents like 13X can probably catch a little), but we aim for <1 ppm after scrubber. Johnson Matthey's approach was to have no measurable NH_3 entering PSA matthey.com, which we emulate. Downstream of PSA, we expect ND (non-detectable) NH_3 , since none should get through pre-scrubber + PSA. The product NH_3 spec is thus easily met. If the analyzer detects any NH_3 (>0.1 ppm), that triggers an immediate isolation of product (so off-spec gas isn't sent forward) and likely a recycle or vent until resolved.
- **Moisture (H_2O):** Fuel cells need <5 ppm v/v H_2O (for PEM, to avoid dilution and corrosion) and a dew point $\leq -65^\circ\text{C}$ in dispensing systems. Turbines aren't harmed by a bit of moisture, but it's fine to adhere to the stricter limit. Our dryer and PSA (which also inherently dries) will target a product dew point of around -70°C . A dew point sensor can verify this. The PSA adsorbents (activated alumina/molecular sieve) will ensure product H_2 is extremely dry if regeneration is proper. It's unlikely to be an issue unless there's a dryer failure.
- **Oxygen:** If any slip from electrolyzer or air ingress, must be <5 ppm for PEMFC. Our upstream deoxo on the normal H_2 feed handles that. In backup mode, there's actually no source of O_2 except perhaps tiny air leaks, so O_2 spec should inherently be met (and the PSA would also remove O_2 as it acts like an impurity).
- **Nitrogen (and Argon):** Combined N_2 + Ar must be <100 ppm for PEMFC ammoniaenergy.org. Achieving this is the hardest part since N_2 is the bulk impurity. But PSA is capable – the PSA will be designed for high N_2 removal. The referenced experiments achieved N_2 <10 ppm ammoniaenergy.org which shows it's feasible. We'll configure the PSA cycle (pressures, purge, possibly vacuum assist) to reach that low residual. It might sacrifice a bit of H_2 recovery to do so, but given we are optimizing for purity (fuel cell), that's acceptable. The membrane+PSA hybrid alternative could also get N_2 that low, but we stick with PSA for proven reliability at scale. We will specify in the PSA vendor data sheet the required product purity in terms of N_2 concentration. Typically, to achieve <100 ppm N_2 , a PSA may use more adsorbent

or deeper vacuum on regeneration. The vendors (like Linde or Air Products) have achieved single-digit ppm N₂ for semiconductor-grade hydrogen; so it's within commercial capability eureka.patsnap.com.

- **Hydrogen Recovery:** We aim for ≥90% H₂ recovery in PSA matthey.com. With the upstream NH₃ removal, the gas is mostly H₂/N₂ which is the standard PSA case. 90% is realistic, but if we push for very low N₂ in product, recovery might dip to 85–88%. This is a trade we accept for purity. Since lost H₂ is burned (not truly wasted as heat can be used), it's not a huge efficiency loss. Still, we will optimize PSA cycle to maximize recovery while holding spec.
- **Automation & Controls:** The entire system will be governed by a PLC/DCS that monitors all critical parameters: reactor temps, pressures, NH₃ levels, H₂ purity, etc. It will have an **automated mode switching sequence**. For example, if a multi-day storm is forecast or detected (low solar, batteries draining), a command to enter “Ammonia Backup Mode” can be given (manually or by an energy management system). The sequence might be: pre-heat cracker to operating temp (using nuclear or electric heat), start feed ammonia flow gradually, activate scrubber circulation and chiller, ensure scrubber effluent is within NH₃ limit, then switch PSA feed valves from recycle to feed, run PSA, after 1–2 cycles test purity, then open product valve to fuel line. Similarly, when sunshine returns and backup is no longer needed, they could transition back by ramping down ammonia feed, possibly using stored H₂ to keep fuel supply constant while PSA empties out, then isolate the PSA and purge it with some H₂ (to preserve adsorbents) and put it in standby. All these steps can be automated with interlocks (e.g. don't open product valve until NH₃ <0.1 ppm and H₂ purity >99.97% for 5 minutes, etc.).

Rationale: This PSA + pretreatment architecture is essentially what is used in known large-scale ammonia cracking designs – for instance, Johnson Matthey's world-scale concept: *remove ammonia upstream, then PSA for H₂/N₂ separation* matthey.com. It leverages proven technology and field experience. By including the pretreatment (scrubber, dryer), we address the PSA's vulnerabilities (ammonia, moisture) and ensure it sees a relatively stable feed composition (mainly H₂/N₂). This makes the transition between modes much easier to manage, since the PSA in backup mode will behave predictably. In normal mode, we largely idle these systems, which is acceptable since they are designed for intermittent use in our scenario (PSA valves can remain closed or cycle no-load occasionally; the scrubber can be off except periodic circulation to avoid freezing, etc.). The cost of having an idle PSA during normal operation is justified by the need for it

in backup – think of it as an insurance policy that you hopefully don't need to use often, but it must work flawlessly when called upon.

Fuel Cell and Turbine Integration: With this purification train, the output hydrogen will meet the stringent **PEM fuel cell criteria**ammoniaenergy.org, allowing fuel cells to run without degradation or lifetime impact from impurities. Simultaneously, the turbines will receive hydrogen with **no ammonia and minimal moisture**, preventing NO_x from fuel nitrogen and avoiding combustion instability from condensate. If the turbine actually preferred some nitrogen dilution for NO_x control, one could intentionally allow a bit more N₂ slip from the PSA (e.g. run PSA at 99.9% H₂ purity instead of 99.99%, resulting in maybe 0.1% N₂ ~1000 ppm). However, that conflicts with the fuel cell spec. It is simpler to provide ultra-pure H₂ to both and handle NO_x via turbine combustor design or diluent injection from another source if needed (for example, using some of the N₂ from air separation or injecting steam). Given turbines at Heber might be advanced units designed for hydrogen, they likely have their own NO_x mitigation strategies that don't rely on fuel diluent, or if they do, one could mix a controlled small flow of N₂ from the PSA tail gas combustor exhaust (after cooling and separation) – but that's probably unnecessary.

Maintainability and Reliability Features: The recommended system includes **redundancy and safeguards** to ensure reliable remote operation:

- **Redundant Instruments:** Dual NH₃ analyzers (one before PSA, one after) to verify scrubber performance and product purity. Redundant dew point sensors on product gas. Pressure/temperature sensors on each PSA bed to detect valve leaks or malfunctions. These will flag any deviations early.
- **Safety Interlocks:** If any NH₃ is detected post-scrubber above a threshold, the flow is prevented from entering PSA (divert to flare) and an alarm triggers. Similarly, if PSA product purity falls below spec, an automatic 3-way valve will divert product to a vent/flare, isolating fuel cells/turbines from off-spec gas. Meanwhile, the stored hydrogen or battery backup can supply the gap for a short time until purity is restored or the issue resolved. Essentially, no hydrogen goes to end use unless analyzers confirm it's within spec – this prevents accidents or damage.
- **Bypass and Manual Control Options:** In case the PSA fails or needs maintenance, the system could – in a turbine-only emergency scenario – bypass PSA and use the catalytic-polished gas directly for turbines. This would be a degraded mode (fuel cell would have to be disconnected), but it provides a backup path to still generate power from ammonia if

PSA is down. To enable that, we'd include a bypass line around PSA with a control valve that normally is closed. Only if operators decide to enter "turbine-only emergency mode" would they open it, allowing H_2/N_2 (after scrubber and dryer) to flow directly to turbines. Fuel cells would be isolated then. This provides resilience: even with PSA out, the site isn't completely without power – turbines can run on forming gas. This kind of bypass would be locked out during normal operations to avoid inadvertently feeding impure gas. It would also require that turbine control system can adjust to the different fuel composition on the fly (which is doable if planned for).

- **Environmental Considerations:** The design avoids continuous emission of any NH_3 or H_2 . The only venting is of inert N_2 or combusted gas (which may have CO_2 if any hydrogen is burned). Since we are dealing with green H_2 and N_2 , the emissions are mainly H_2O and N_2 , with trace NO_x from tail gas burning (if not carefully controlled, burning H_2/N_2 with air can form some NO_x ; we'd minimize this by possibly using a catalytic combustor at lower temperature or by staging air). It's worth including a **NO_x abatement catalyst** in the tail gas burner exhaust if needed to meet local air quality regs matthey.com. Johnson Matthey noted they can meet regulatory standards for NO_x , NH_3 , N_2O in an ammonia cracker process with proper catalyst placement matthey.com. We can leverage that expertise if needed (e.g. an SCR unit on the flue).
- **Cold Weather Adaptations:** The entire purifier (except possibly the flare stack) will be housed in an insulated building or skid with HVAC. The scrubber will have heaters to keep water above, say, $10^\circ C$. Heat tracing on lines ensures no freeze. The PSA and piping also likely need to be kept warm to avoid water condensing inside. The design ambient might be, say, $-20^\circ C$ at Heber's worst; so enclosures and tracing handle that. Dust ingress is mitigated by filters on any air intakes (for instrument air or vent lines). Regular dust cleaning of HVAC filters is scheduled.
- **Maintenance Schedule:** We anticipate minimal intervention: the PSA can run for years aside from maybe valve maintenance every few years. The scrubber might require occasional water makeup or chemical replacement – perhaps after each extended use (which might be seasonal). Because usage of the backup may be limited (e.g. a few weeks per year total), the consumables won't deplete fast. It would be prudent to do an annual system test under controlled conditions (simulate a backup scenario for a short run) to ensure everything works, and to refresh the scrubber solution. Adsorbents and catalyst lifetimes likely >5 years given limited duty, but we'd still plan to replace

desiccant or catalyst every 5 years to be safe. All such maintenance can be done during scheduled downtimes (since backup mode is not usually critical unless needed).

In summary, the recommended architecture is a **PSA-centric purification train with strategic pretreatment (NH₃ removal by scrubbing/condensation and drying)**. This approach is grounded in field-proven designs for cracking ammonia to fuel-cell-grade hydrogen matthey.com and strikes a balance between **purity, scalability, and reliability**. It allows **fully automated transitions**: the pretreatment ensures no ammonia breakthrough during mode switching, and the PSA ensures final product meets the tightest specs for both fuel cells and turbines. By incorporating a bypass for catalytic-polished gas to turbines, we also have a fallback in case of PSA issues, enhancing resilience for remote operations. This integrated design will enable the Heber Campus to confidently utilize its stored ammonia as a hydrogen source under adverse conditions, without compromising performance or safety of its end-use systems.