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A Comparative Evaluation and Selection of High-Temperature Heat Exchangers for Application to Integrated Energy Systems

September 2023

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Integrated Energy Systems

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SUMMARY

The following report aims to create a refined and well-structured method for comparatively evaluating heat exchanger technologies for integrated energy systems that caters customers' specific needs while meeting engineering requirements. For the evaluation, this study elevates previous evaluation metrics, enhances the knowledge base via literature and market surveys, and identifies the figures of merit with robust rationales to enhance the quality of decisions made throughout the proposed heat exchanger evaluation process. The heat exchanger designs evaluated as part of the case study are shell and tube heat exchangers, printed circuit heat exchangers, plate heat exchangers, spiral heat exchangers, and heat pipe heat exchangers. The information presented in this report is meant for industries interested in making a preliminary screening process to identify the most suitable heat exchanger design for their application of interest.

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CONTENTS

FIGURES

TABLES

ACRONYMS

AHP	analytic hierarchy process
AM	additive manufacturing
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CHE	compact heat exchanger
CI	consistency index
CR	consistency ratio
CS	carbon steel
FOM	figure of merit
HE	heat exchanger
HOQ	House of Quality
HP	heat pipe
HPHE	heat pipe heat exchanger
HT	heat transfer
HTF	heat transfer fluid
HTGR	high-temperature gas-cooled reactor
IES	integrated energy system
ISI	inservice inspection
MS	molten salt
NASA	National Aeronautics and Space Administration
NDE	nondestructive examination
NRHES	nuclear renewable hybrid energy system
O&M	operations and maintenance
PCHE	printed circuit heat exchanger
PLHE	plate heat exchanger
QFD	quality function deployment
R&D	research and development

RI random index

SAD surface area density

sCO_2 super-critical carbon dioxide

SFR sodium-cooled fast reactor

SPHE spiral heat exchanger

SS stainless steel

STHE shell and tube heat exchanger

TEMA Tubular Exchangers Manufacturers Association

TES thermal energy storage

Ti titanium

TPMS triply periodic minimal surface

TRL technology readiness level

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1. INTRODUCTION

As the nuclear industry makes its way toward deploying advanced nuclear reactors that can reach higher temperatures than the currently deployed nuclear reactors, national interest has increased in integrating different process heat applications into these high-temperature reactors. However, the integration process is not simple and straight-forward. In fact, there are multiple analyses that must be carried out prior to integrating a system into a power plant, from a technical, economical, and safety point of view. Additionally, there are multiple approaches to get the thermal energy and use it for an industrial heat process. One challenge that usually arises during the early stages of an integrated energy system (IES) project is the selection process of the main components that are associated with the intermediate loop. One of these major components, and the solely focus of this study, is the heat exchanger (HE). The HE is a critical component that enables thermal energy exchange among disparate subsystems in an IES. Given the diverse integration scenarios and varying requirements that may exist within an IES, it is crucial to have an evaluation framework for selecting the components in a structured and consistent manner. Yoo et al. released a report proposing a new HE evaluation method that considers the end user demand along with technical and economical requirements [65]. Their report states that an optimal HE selection may depend on the specific integration scenario and its requirements. Also, their proposed HE evaluation methodology could be implemented during the high- and low-level decision-making process, including the selection of HE materials or heat transfer fluid (HTF). Although Yoo et al. [65] paves the path toward HE evaluations, their approach is still relatively broad and requires refinement and cases studies to test its applicability.

In an effort to further improve the evaluation framework proposed in Reference [65], the present study aims to complement the methodology by consolidating crucial decision-making information, complement evaluation metrics with appropriate technical correlations to develop relevant figure of merits (FOMs), and provide a more in-depth explanation of the correlations used. While new HE designs are being proposed for multiple applications, this study aims to provide a framework that evaluates some of the most common and promising HE designs, including shell and tube heat exchanger (STHE), printed circuit heat exchanger (PCHE), plate heat exchanger (PLHE), spiral heat exchanger (SPHE), and heat pipe heat exchanger (HPHE).

To test the proposed evaluation framework and provide a better idea of how to implement it, we evaluated two case scenarios. The first case scenario consists of an industrial application that coupled a high-temperature gas-cooled reactor (HTGR) to a super-critical carbon dioxide (sCO_2) Brayton power cycle. The second case study consists of a sodium-cooled fast reactor (SFR) coupled to a molten salt (MS) thermal energy storage (TES). For both case studies, different HE designs were evaluated based on the operating conditions laid out in Section 6, and our evaluation method is summarized in Section 2. The information provided in this report, along with the examples covered for different industrial applications, can be used for future industrial applications and to streamline the HE selection process for IES purposes.

1.1 Motivation

The procedure for choosing an appropriate HE can differ depending on various factors, such as the specific integration scenario, operating conditions, technical requirements, end user priorities, economics, and more. Moreover, since there are multiple viable methods to determine the most suitable HE, critical aspects might inadvertently be missed during the selection process. As a result, the subsequent document endeavors to furnish a well-organized and cohesive framework for evaluating HEs, designed to meet the customer demands and IES technical requirements.

1.2 Objectives

In an effort to expand upon the work carried out by Yoo et al. [65], the current report aims to develop an evaluation framework that can be consistently applied to support an optimal HE selection for IES purposes and build a practical knowledge base that can be used for HE evaluation, comparison, and selection within the proposed framework. These two main goals can be achieved if the following subgoals are addressed:

1. Refine the evaluation metrics to evaluate and compare the HE characteristics for IES applications encompassing both customer requirements and technical requirements
2. Enhance the knowledge base via literature and market surveys
3. Identify FOMs with robust rationales to enhance the quality of decisions made through the proposed HE valuation process

4. Conduct the case studies with conventional and advanced HE technologies for the IES applications.

2. EVALUATION FRAMEWORK AND STRATEGY

2.1 Heat Exchanger Evaluation Framework: Hierarchical Evaluation and Decision

Selecting an HE best suited for a particular IES application requires a range of evaluations and decisions, spanning from high-level considerations to low-level details. In other words, selecting an HE is not a simple decision but rather involves a series of steps. In this framework, the decision process is divided into three tiers, first-, second-, and third-level decisions. Under the *first-level decision* process are high-level evaluations, comparisons, and determinations of the HE technology that can meet the end user needs. The *second-level decision* is described as the process that evaluates and selects more specific HE design types or key components (e.g., material of construction) chosen in the first-level decision process. In general, second-level decisions are constrained by the first-level decision on HE types. In some cases, however, the outcome of second-level decisions may also influence the first-level decision. For example, there may be cases where the best HE material selected in the second level may not be available for manufacturing the selected HE in the first level. In this case, either alternative materials should be considered or the evaluation in the first level should be revisited. After completing all selections in the first and second levels, the *third-level decision* process can proceed to optimize detailed design parameters of a HE. Figure 1 summarizes the aforementioned hierarchical evaluation and decision process, originally proposed in Yoo et al. [65], to support the systematic selection of HEs for IES applications.

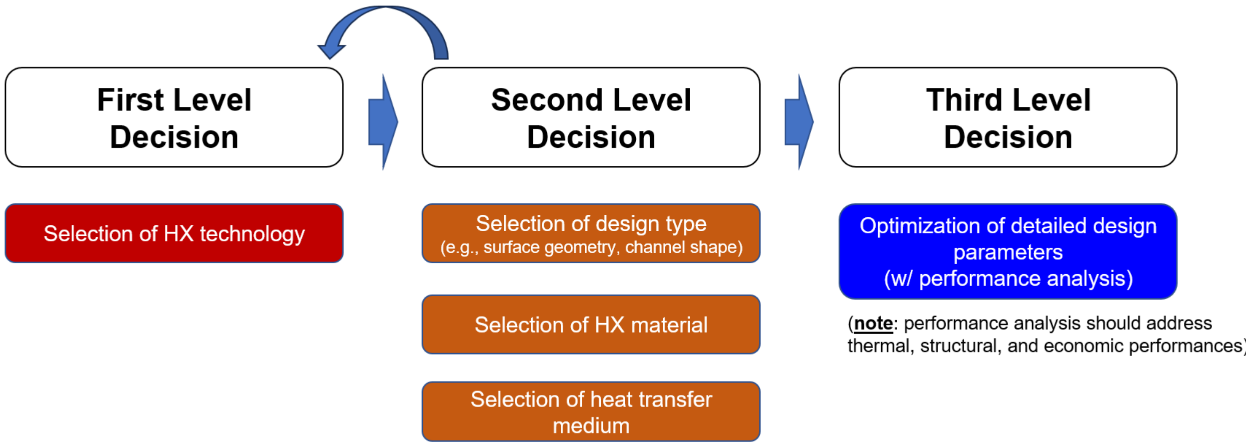

Figure 1: Hierarchical evaluation and decision framework for optimal selection of IES HEs. Adapted from [65].

Within the evaluation framework proposed in Figure 1, this study particularly focuses on establishing the evaluation methodology and the associated knowledge base required for the first-level decision-making process.

2.2 Heat Exchanger Evaluation Strategy: Integrated Quality Function Deployment and Analytic Hierarchy Process

For strategic decision-making regarding the optimal selection of HEs (corresponding to the first-level decision shown in Figure 1), this study employs an integrated approach that combines quality function deployment (QFD) and analytic hierarchy process (AHP) techniques. These are structured approaches to support multicriteria decision-making by systematically evaluating and comparing multiple criteria or factors. QFD is typically used for product design and development, focusing on aligning design features with customer demand. AHP, on the other hand, can be applied to a wide range of decision problems by creating a hierarchy of criteria and providing a mathematical basis for determining the relative importance of each criterion.

The following subsections provide a concise overview of the basic theory of QFD and AHP techniques. Subsequently, we propose a strategy for combining these two techniques (i.e., integrated QFD-AHP) to evaluate and select the most suitable HE for IES applications.

2.2.1 Quality Function Deployment

QFD is a highly organized and cross-functional planning technique that facilitates the transformation of customer requests into high-quality engineering designs. It plays a pivotal role in satisfying customers by converting their requirements into detailed plans for producing products that precisely align with those demands. This customer-centric approach empowers decision-making processes, particularly in the optimal selection of candidate products. QFD has found successful applications across various industries. It serves the critical functions of identifying customer demands and establishing priorities for product development.

The QFD process typically involves three steps to effectively address customer demands: identify customer demands, identify product's technical requirements, and determine and assign importance weights to the individual customer demand [15, 35]. A central tool in the QFD process is the House of Quality (HOQ) matrix. This matrix serves as a primary instrument for comparing the quality of various products (HEs for purposes of this study). It can be used to make decisions related to technical and commercial considerations. Furthermore, it facilitates the prioritization of product design parameters, helping to determine which aspects of a design should receive greater emphasis. Figure 2 illustrates the overall structure of an HOQ matrix, which serves as the tool for implementing the core QFD process. This process involves the transition from a list of customer demands ("what" is needed) to a list of product requirements that address "how" those demands will be met from a technical perspective.

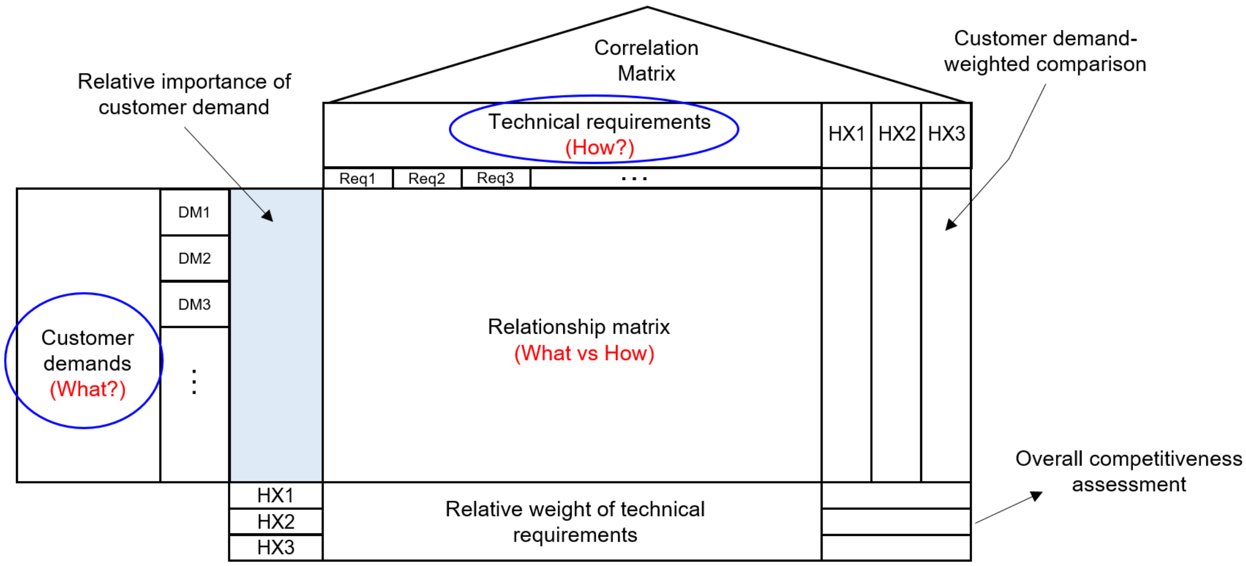

Figure 2: Overall structure of an HOQ matrix used in the QFD process (adapted from [65]).

In the HOQ matrix, the customer demands are listed on the left and the product's technical requirements (i.e., engineering characteristics) are listed on the first line above the relationship matrix. Each item in the list of customer demands is assigned a weight on a scale of 1 to 10 (or as percentage), indicating its relative importance. These importance weights are positioned on the right side of the list of customer demands and are highlighted in blue, as shown in Figure 2.

The relationships between customer demands, "WHATs," and product technical requirements, "HOWs," are represented within the relationship matrix. These relationships are expressed using symbols denoting their strength, categorized as *strong*, *moderate*, *weak*, or *non-existent*, including a triangle (△) for a weak relationship, a circle (◦) for a moderate relationship, and a dot (•) for a strong relationship [19]. If there is no relationship between a particular pair, the corresponding intersection in the relationship matrix remains blank, indicating that the transformation of product requirements (HOWs) into customer demands (WHATs) is not applicable.

At the top of the HOQ matrix, the physical relationships among the product's technical requirements are specified in the correlation or roof matrices. This matrix illustrates how one product's technical requirement is interconnected with others. At the baseline of the HOQ matrix, positioned below the relationship matrix, relative importance weights are assigned to each product's technical requirement. These weights represent one of the primary outcomes of the

HOQ process and are calculated using:

$$Weight(Req)_i = D(Req)_{i,1} \times imp(WHAT)_1 + \ldots + D(HOW)_{i,n} \times imp(WHAT)_n \quad (1)$$

where $Weight(Req)_i$ is the importance weight of the i^{th} product requirement, $D(Req)_{i,n}$ is the degree of relationship between the i^{th} product requirement and n^{th} customer demand, defined in the relationship matrix, and $imp(WHAT)_n$ denotes the importance weight of n^{th} customer demand.

Equation 1 indicates that QFD yields the relative importance weights for a product's technical requirements by combining the importance ratings assigned to customer demands and relationship weights between customer demands and the product's technical requirements. Once these relative importance weights are computed for each technical requirement of each candidate product, it becomes possible to evaluate, compare, and rank the candidate products. This process ultimately supports the decision-making for optimal product selection. Note that the present study further incorporates insights gained from the knowledge-based comparative evaluation of technical requirements among various HEs when determining the ultimate competitiveness of a product. This will be further detailed in Section 2.2.3.

2.2.2 Analytic Hierarchy Process

While QFD is a valuable tool for facilitating multicriteria decision-making, like selecting an HE for use in an IES, it's worth noting that the standard QFD technique outcomes are typically treated as general guidelines for prioritizing items. To make the QFD more acceptable to decision makers, integration with other tools, such as AHP [6], is essential.

AHP is a multicriteria decision-making approach developed and refined by Satty in the 1970s [56]. It is a useful technique for evaluating complex alternatives that encompass multiple decision factors, particularly when subjective criteria are in play. AHP has received substantial interest among researchers due to its comprehensive and systematic framework, complete with a mathematical foundation. This framework enables the structuring of complex decision problems, representation and quantification of decision elements (e.g., customer demands), establishment of their priorities, and comparative evaluation of alternative solutions. A typical AHP process, described by Rajesh and Mlliga [49] and summarized by Yoo et al. [65], is:

Task 1. Break down the initial decision problem into a hierarchy with multiple subproblems, including criteria, subcriteria, alternatives, etc., on which the decision is based. The construction of a hierarchy is the initial step to make the decision problem easily understood and evaluated.

Task 2. Construct the decision matrix based on Saaty's nine-point scale (1–9) [52] to evaluate and compare the priority scores of alternatives. In other words, the decision matrix is intended to evaluate the decision criteria (e.g., customer demands) for each alternative. On this scale, 1 indicates equal importance, 3 moderately more, 5 strongly more, 7 very strongly, and 9 indicates extremely more importance, while 2, 4, 6, and 8 indicate intermediate values of importance. If the decision-making problem consists of n criteria and m alternatives, the decision matrix is an $m \times n$ matrix. Then, each element of the decision matrix, d_{ij}, represents the rating of the i_{th} alternative with respect to the j_{th} criteria.

Task 3. Construct the pairwise comparison matrix to determine the relative priorities among the various decision criteria (i.e., decision elements, such as customer demands). The pairwise comparison matrix is also built based on Saaty's 1–9 scale, as described in Step 2, in which each element of the matrix, c_{ij}, represents the degree of preference of i_{th} criteria over j_{th} criteria.

Task 4. Calculate a consistency index (CI) to determine the consistency of a decision maker's judgments during the evaluation phase. For both the decision and pairwise comparison matrices, the CI can be calculated by [19, 49]:

$$\mathrm{CI} = (\lambda_{max} - \mathrm{n}) \;/\; (\mathrm{n} - 1)$$

where λ_{max} is the greatest eigenvalue and n is the number of decision criteria. The closer the CI is to zero, the higher the consistency. CI is compared with the random index (RI) randomly generated for reciprocal matrices, having n varying from 1 to 15 [19]. The consistency ratio (CR) is defined using the RI and CI as follows:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI}$$

CR needs to be 0.10 or less to accept the AHP results as consistent [19]. Otherwise, the decision maker should go back to Tasks 2 and 3 and repeat the process.

Task 5. Normalize the pairwise comparison matrix such that each column is divided by the sum of the entries of the corresponding column. This is to create a normalized matrix in which the sum of the elements of each column vector equals one.

Task 6. Calculate the eigenvalues of the pairwise comparison matrix. This procedure results in the relative importance weights of decision criteria. The relative importance weights should meet the following equation:

$$\mathrm{A} \cdot \mathrm{W} = \lambda_{max} \cdot \mathrm{W}$$

where A represents the pairwise comparison matrix and W is the eigenvector of normalized relative importance weights. From the above equation, λ_{max} can be obtained and used to calculate the CR described above in Task 4.

2.2.3 Current Strategy for Heat Exchanger Evaluation: Integrated Quality Function Deployment and Analytic Hierarchy Process

This study integrates the AHP technique into the QFD process to facilitate the optimal HE selection for IES applications. The AHP framework can enhance the QFD process by systematically prioritizing customer demands and establishing their relative importance weights in a more structured manner [3, 5]. Also, AHP enables the computation of individual scores for each candidate product against each product's technical requirement [14].

The current primary focus is to establish a systematic methodology for the strategic and optimal HE selection for IES applications. Optimal selection refers to choosing an HE product that best aligns with various aspects of customer demands, encompassing both technical and economic requirements, based on the detailed technical specifications of the HE products. Customer here pertains to the end user of the HE. A major motivation of this study is that specific customer needs, including the relative priorities among the individual, may vary depending on the specific application. This variation arises from the characteristics of the thermal systems to be coupled within the IES. Therefore, it is essential to properly consider these variable customer demands and tailor each IES application.

The integrated QFD-AHP process employed in this study offers several notable advantages. Firstly, the QFD process allows the explicit inclusion of HE end-user demands, encompassing both technical and economic aspects, that may vary depending on the specific IES application. This means that the end-user demands and relevant technical requirements can be considered together and correlated to facilitate the selection that best satisfies customer needs. Secondly, the AHP technique can enhance the quality of the evaluation and subsequent selection process within the QFD framework. It does so by providing a robust rationale for prioritizing customer demands and computing individual scores for each candidate HE. Thirdly, this approach offers a consistent way for comparing and evaluating HEs across various IES applications, especially enabling customer-centric decision-making in HE selection. Lastly, the proposed approach is versatile and can be applied not only to high-level decisions, such as selecting the HE type, but also to lower level decisions, including the selection of key components for the chosen HE at the higher level. Figure 3 illustrates the overall QFD-AHP process employed in this study to evaluate and select HEs for IES applications. The evaluation process commences by identifying the requirements of customers along with the associated technical specifications of the HE product. These inputs are fundamental for constructing the HOQ matrix, which serves as the cornerstone of the QFD. The specifics regarding the end-user demands and technical requirements of the HE, identified during this study, are described in Section 5.

Figure 3: HE selection process using integrated QFD-AHP.

This study suggests conducting a comparative evaluation of HEs from two distinct perspectives while advancing through the QFD process (using the HOQ matrix). The two different types of comparisons are by customer demand and by overall relative competitiveness of the HEs:

I. Customer demand: It evaluates the competitiveness of candidate HEs by considering the relative importance of customer demands combined with the knowledge-based comparative evaluation of the HE technical requirements described in Section 5. For this comparison, the *customer demand-weighted score* (CD_{wt}) is calculated using:

$$CD_{wt} = imp(WHAT)_1 \times Scale(Req)_1 + \ldots + imp(WHAT)_n \times Scale(Req)_n \tag{2}$$

where $Scale(Req)_i$ is the scale (from low to high) assigned to the i^{th} technical requirement of a HE as a result of knowledge-based comparative evaluation (Section 5). Note that, when there is more than one technical requirement related to one customer demand, the average value of the scales is used in Equation 2. The customer demand weighted score is displayed on the right side of the HOQ matrix in Figure 2, providing insight regarding how well each HE can meet each aspect of customer demand.

II. Overall relative competitiveness: It evaluates the overall relative competitiveness of the candidate HEs for a specific IES application. The overall relative competitiveness score can be calculated by combining the relative weights of the technical requirements, as computed by Equation 1, with the knowledge-based comparative evaluation of the technical requirements among different HEs described in Section 5. The mathematical equation to calculate the overall relative *competitiveness score* (CS) is:

$$CS = Weight(Req)_1 \times Scale(Req)_1 + \ldots + Weight(Req)_n \times Scale(Req)_n \tag{3}$$

The relative competitiveness score is displayed on the bottom right of the HOQ matrix in Figure 2, providing insight into the overall technical competitiveness of the candidate HEs.

3. Heat Exchanger Requirements for Integrated Energy System Application

The high-level HE requirements for IES applications can be determined by referencing recent IES reports [9, 10] and earlier HE evaluation studies conducted for advanced nuclear reactors [53]. In particular, the 2020 IES roadmap and 2016 nuclear renewable hybrid energy system (NRHES) reports [9, 10] specify several key functional requirements for IES HEs. These key requirements are high thermal performance and efficiency, a robust pressure boundary, a robust chemical boundary, material compatibility, reliability under dynamic conditions, and economics.

A detailed description of each requirement is provided in Table 1.

Table 1: High-level HE requirements for IES applications (updated from Reference [65]).

ID	High-Level Customer Demand	Requirements	Description
100	High thermal performance	High heat transfer performance and low thermal loss	HEs should transfer heat efficiently with minimal heat losses. Heat loss within an HE will lower the available retrievable heat and therefore reduce the system's efficiency.
200	A robust pressure boundary	Withstand operating pressure conditions	HEs must act as a physical barrier between the working fluids. For example, the steam generator in a pressurized-water reactor serves as a physical boundary between the single phase high-pressure water in the primary side and the low-pressure steam generated on the secondary side.
300	A robust chemical boundary	Low leakage risk, avoid highly corrosive fluids, low reactivity between fluids or between fluids and structural materials	HEs must provide a chemical boundary to prevent cross-contamination between working fluids. Highly reactive cross-contamination case scenarios, such as liquid sodium with water, can be detrimental to system integrity, and therefore, HEs must provide a robust physical boundary to prevent such instances.
400	Reliability under dynamic conditions	Robust temperature control, reduced fouling, high thermal resilience, low thermal stress	HEs should perform reliably under dynamic operating conditions. The structural integrity of the HE must be maintained under highly fluctuating pressures, temperatures, and flow rates. The thermal capacitance of HEs can increase the response time of the industrial process to grid dynamics [44]. If an industrial process requires steady-state operation, high thermal capacitance is desired.
500	Technical readiness	Material readiness, technical feasibility of fabrication method, industrial experience	HEs should be ready-to-install technology. This includes the commercial availability of materials, technical feasibility of fabrication method, and industrial experience in product fabrication.
600	Economics	Low product cost, low installation cost (e.g., light weight, easy to transport and integrate), low operations and maintenance (O&M) cost	Large surface area-to-volume ratio or surface area density (SAD) allows for a more effective HE but are more costly. Material and fabrication costs increase with increasing surface area, HE volume, temperature, and pressure. Installation and O&M costs should also be reasonably low. A large pressure drop requires auxiliary compression or pumping power that results in an overall lower system efficiency [10] while increasing the overall cost.

Each of the high-level requirements, described in Table 1, has specific technical and economical traits generally sought by the HE end-user. Starting from high-level requirements, detailed customer demands and their corresponding technical and economic requirements (i.e., evaluation metrics) are derived to formulate a hierarchical framework. Table 2 shows the derived customer demands and corresponding HE requirements belonging to each aspect of the high-level requirements in Table 1.

Table 2: Mapping high-level requirements of IES HE to detailed customer demand and HE technical requirements, along with suggestions for FOMs.

ID	Detailed customer demand		HE technical requirements		FOM
100	110	High thermal performance	111	Thermal effectiveness	Values obtained from the open literature (see Section 5), SAD
			112	Heat transfer coefficient	Heat transfer area per heat duty (A_s/Q), SAD
			113	Fouling resistance	Hydraulic diameter (D_h)
200	210	Robust pressure boundary	211	Channel geometry and size	D_h/t
			212	Resistance to thermal stress	SAD, A_s/Q
			213	Resistance to vibration	SAD
300	310	Prevent cross-contamination	311	Channel geometry and size (resistance to cross-contamination)	SAD, A_s/Q
			312	Resistance to (tritium) permeation	Wall thickness, A_s/Q
400	410	Reliable performance under dynamic operation	411	Fouling resistance	D_h
			412	Resistance to vibration	SAD
			413	Thermal capacitance	SAD, A_s/Q
			414	Resistance to thermal stress	SAD, A_s/Q
	420	High thermal resilience	421	Thermal resilience	SAD, A_s/Q
500	510	ASME BPVC readiness	511	Material and fabrication technology readiness	American Society of Mechanical Engineers (ASME) code readiness, literature findings, and market survey results
	520	Industrial experience	521	Commercial product availability	technology readiness level (TRL), market survey results
600	610	Easy integration	611	Compactness	SAD
			612	Weight	SAD
	620	Low product cost	621	Material cost effectiveness	SAD, ΔP_{loss} per heat duty, material cost factor
			622	Fabrication complexity	SAD, market survey results
	630	Low O&M cost	631	Maintenance cost (inspection, cleaning)	D_h
			632	Maintenance cost (repairing)	SAD
			633	Operating cost	ΔP_{loss} per heat duty

4. Candidate Heat Exchangers for Current Study

For this study, we pre-selected five distinct types of HEs and created a relevant knowledge base within the proposed framework to enable systematic comparative evaluation of these types. The five HE types pre-selected are STHE, PLHE, PCHE, SPHE, and HPHE, each with their own strengths and weaknesses. SAD and hydraulic diameter are two characteristics used for evaluating the HEs in this study to determine their compactness, thermal performance, economics, safety, and technical readiness. More detailed technical and economic comparisons will be discussed in Section 5. While in some cases a large SAD can be beneficial (a strength), in other cases it can be detrimental (weakness). Figure 4 shows the comparison of the HE types in terms of hydraulic diameter and SAD.

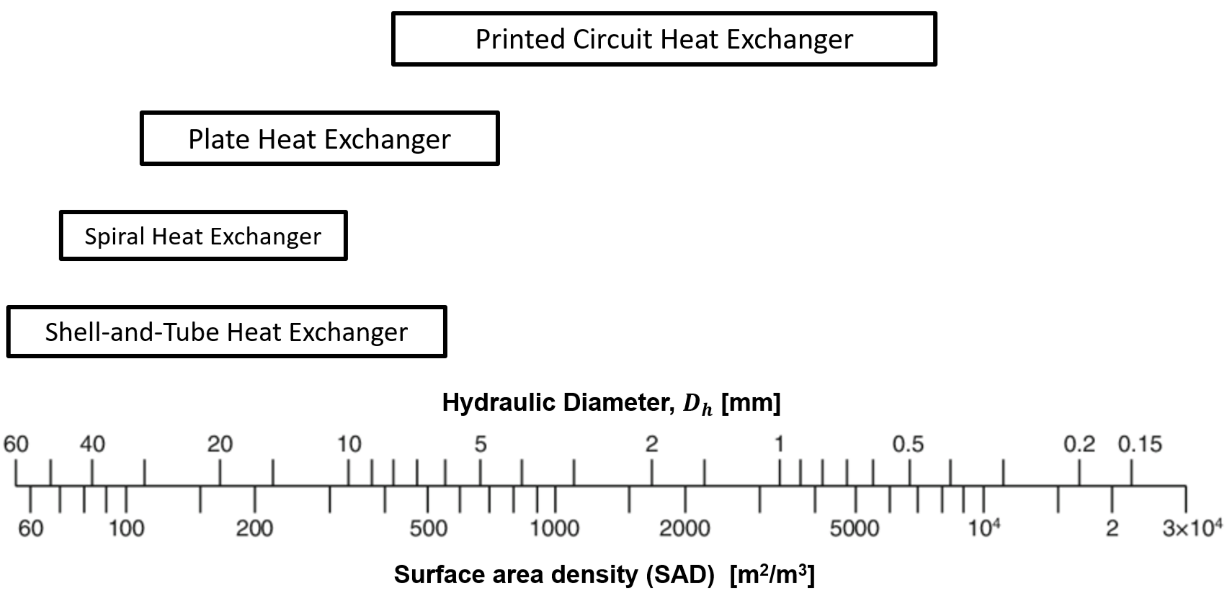

Figure 4: SAD comparison for different types of evaluated heat exchangers. Adapted from [37, 51, 57, 66].

As discussed previously, choosing an optimal HE may depend on multiple factors, including specific application requirements (e.g., temperature, pressure, and heat duty), overall cost, technical readiness, etc. Additionally, application-specific end-user requirements (or end-user demand) can play a significant role in the decision-making process, as different applications may lead to different relative priorities among the various end-user requirements. Therefore, the HE evaluation process should take into account these various aspects to support the most suitable selection. A brief description of each HE technology under consideration is provided here.

STHE is one of the most common HE designs and is widely used in various industries, including nuclear, oil refineries, and other chemical processes plants. In general terms, it consists of a large pressure vessel with a bundle of tubes inside of it. An HTF flows through the tube bundle, while another HTF flows through the vessel, outside of the tube bundle. These two fluids are assumed to have different temperatures. Therefore, heat will be transferred from one fluid to another. The schematic of a general configuration of a STHE is shown in Figure 5.

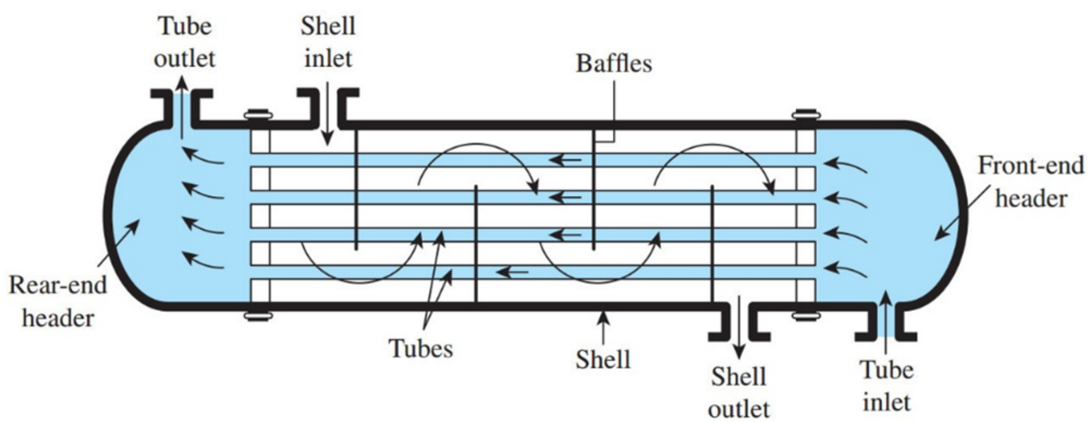

Figure 5: Schematic of a conventional STHE [12].

PLHE is a type of HE that uses metal plates to transfer heat between medium- and low-pressure fluids. This HE design has a major advantage over a conventional HE designs, such as the STHE, since the fluids are exposed to a much larger surface area. The plates are often spaced with rubber sealing gaskets cemented into a section around the edge of the plates. As illustrated in Figure 6, the plates are pressed to form troughs at right angles to the direction of flow of the liquid running through the HE channels.

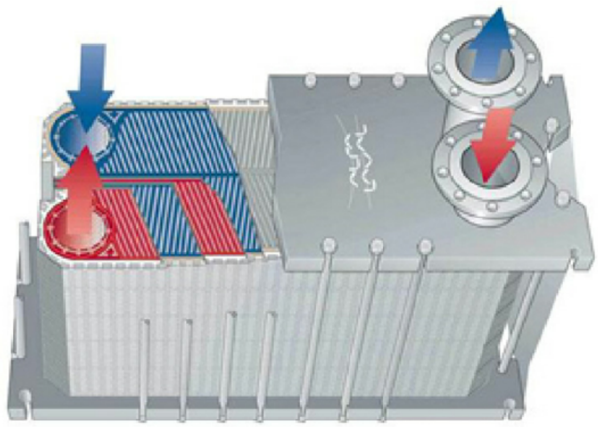

Figure 6: General schematic of a PLHE. Adapted from [1].

PCHE is a variant of the PLHEs and get their name from the chemical milling procedure used in their manufacture, which is the same process employed for printed circuit boards. Introduced into the market in the late 1980s, PCHE is a type of compact HEs that contains many small millimeter- or even micrometer-scale channels often machined or chemically etched into individual plates, which are then stacked together as shown in Figure 7. It combine superior robustness and integrity with an exceptionally high heat transfer rate in a unit up to 85% smaller and lighter than comparable STHEs.

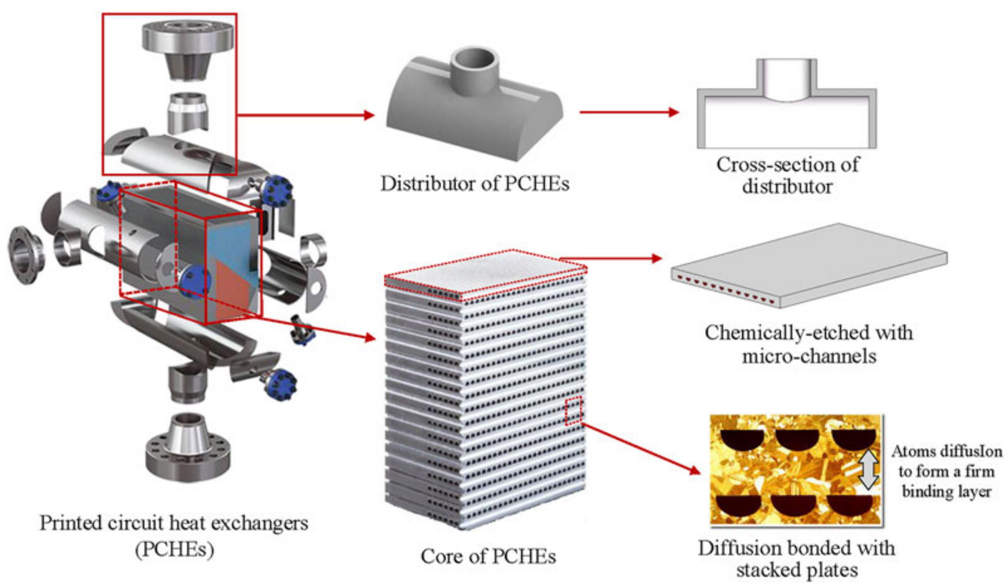

Figure 7: Schematic of a PCHE showing plates and nozzles. Adapted from [64].

SPHE , as shown in Figure 8, is a circular HE unit containing two concentric spiral flow channels, one for each fluid. The different media flow opposite each other: one fluid enters the center of the unit and flows towards the periphery and the other enters the unit at the periphery and moves towards the center. The channels are curved and have a uniform cross section. The spiral geometry, with a single channel for each medium and continuous curving, is highly suitable for fluids that tend to cause fouling. This design results in high flow turbulence with resulting high shear stress, dramatically reducing the risk of fouling.

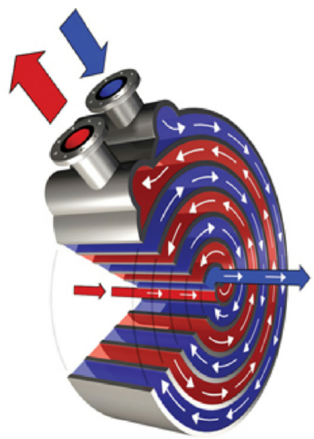

Figure 8: General schematic of a SPHE. Adapted from [64].

HPHE , as shown in Figure 9, relies on passive heat transfer devices with an extremely high thermal conductivity. Heat pipes are used to efficiently transfer heat from the hot side to the cold side. Due to its simple design and limited moving components, HPHE has the advantage of regular cleaning and inspections. Individual heat pipes can be easily added, removed, or replaced for optimization and maintenance purposes, as needed.

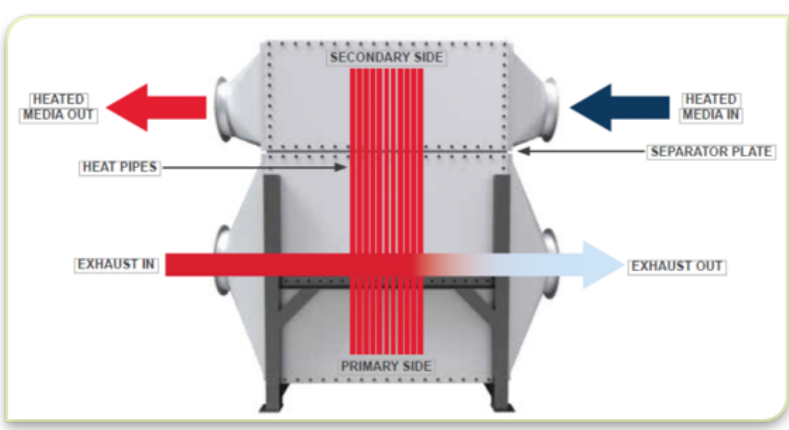

Figure 9: Schematic of a HPHE. Adapted from [58].

5. Technical Requirements and Figures of Merit

This section provides a knowledge base aimed at facilitating the comparative evaluation of technical requirements for the HE technologies pre-selected in Section 4 and suggests FOMs that can be used for comparing the specific technical requirements identified in Section 3 (see Table 2) and conducting a comparative evaluation. This section is divided into multiple subsections, providing information regarding the detailed customer demand and associated technical requirements, as shown in the hierarchy presented in Table 2. The specific structure of each subsection is:

1. Describing the detailed customer demand listed in Table 2
2. Introducing the technical requirements adopted for evaluation of each detailed customer demand and providing a justification regarding its applicability
3. Suggesting potential FOMs that can be used to support a comparative evaluation of HEs for each technical requirement
4. Conducting knowledge-based comparative evaluations for each technical requirement on a scale of 1 to 9 (low to high) to represent the relative competitiveness of HEs for each technical requirement and to be used in the final evaluation matrix.

5.1 High Thermal Performance (110)

High thermal performance is one of the most fundamental characteristics required by HE end-users. The thermal performance of a HE can be evaluated through thermal effectiveness (111), the heat transfer coefficient (112), and fouling resistance (113).

5.1.1 Thermal Effectiveness (111)

Thermal effectiveness (ϵ) is a nondimensional term used to evaluate HEs, which consists of the ratio between the actual and theoretical maximum heat transfer rates. This ratio is computed using:

$$\epsilon = \frac{q}{q_{max}} \tag{4}$$

where q is the actual heat transfer rate of the HE and q_{max} is the maximum theoretical heat transfer rate. 4 can be expressed using:

$$\epsilon = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} \tag{5}$$

or

$$\epsilon = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})} \tag{6}$$

where temperature and heat capacity rate are represented with the variables T and C, respectively, and the subscripts c, h, i, o, and min represent the cold side, hot side, inlet, outlet, and minimum value, respectively. Based on this information, the higher the effectiveness for an HE, the better, as it indicates how close the actual heat transfer rate is with respect to the theoretical maximum [26]. Hence, an effectiveness of or close to 1.0 is desired. If the effectiveness is known along with the inlet temperatures of the cold and hot side of the HE, the actual heat transfer rate can be computed using:

$$q = \epsilon \cdot C_{min} \cdot (T_{h,i} - T_{c,i}) \tag{7}$$

Table 3 provides a summary of the typical thermal effectiveness values found in the literature for the different HE designs under consideration. The thermal effectiveness for HPHE and SPHE is not provided due to the lack of information from the open literature. The thermal effectiveness of an HE is influenced by various factors, including the types of fluids involved, mass flow rates, temperature differences, and HE design. However, all else being equal, an HE with a compact design is expected to exhibit higher thermal effectiveness due to the large surface area relative to its volume, allowing for efficient heat transfer. Therefore, in addition to the values found in the literature, SAD is also used as the FOM to comparatively evaluate the thermal effectiveness.

Table 3: Comparison of technical requirements affecting HE thermal effectiveness.

Description	STHE	PCHE	PLHE	SPHE	HPHE
Thermal effectiveness	0.7–0.9 [53]	0.95–0.97 [27, 34]	0.7–0.9 [27, 55]	—	—
SAD [m^2/m^3]	~100 [24]	200–5,000 [24, 53, 57]	~200–300 [24, 53, 66]	~200 [24, 66]	—

5.1.2 Heat Transfer Performance (112)

The heat transfer coefficient is another relevant metric (technical requirement) to evaluate the heat transfer performance of an HE and is defined as:

$$h = \frac{Nu \cdot k}{D_h} \tag{8}$$

where h is the heat transfer coefficient, Nu is the Nusselt number, k is the thermal conductivity of the fluid, and D_h is the hydraulic diameter of the channel or duct. However, obtaining a range of values for h for different HE types could be challenging or require additional work through computational modeling or measurement. In such case, the heat transfer surface area per heat duty (A_s/Q) can be used instead as the FOM. A_s and Q are fundamental parameters characterizing the HE design (typically available in the quotation provided by HE suppliers), and their values are relatively easy to obtain, making A_s/Q a useful metric to evaluate the heat transfer efficiency and performance, especially when comprehensive technical details are unavailable. According to Shah and Sekulic [57], the A_s/Q of an SPHE is typically about 20% lower than that of an STHE.

A smaller A_s/Q value indicates a more efficient HE as it can transfer the desired amount of heat using less surface area, potentially resulting in the reduced size, weight, and cost of an HE. SAD is another indicator that can be used when A_s/Q is unavailable during the evaluation process and can provide insight into the heat transfer performance of an HE, with highly compact HEs (with a high SAD) typically exhibiting a higher heat transfer performance.

Table 4 presents the A_s/Q values calculated using information obtained from the HE suppliers' quotations during the market survey of this study, along with the SAD values obtained from the open literature. For a fair comparison, quotations were collected for different types of HEs based on identical operating conditions (e.g., temperature, pressure, and heat duty of 2 MW except for the SPHE), HTFs (helium and air), and maximum allowable pressure drop requirements. During the market survey, no vendors were able to provide a quotation for HPHE, because this technology has not yet been applied to MW-scale high thermal systems. Furthermore, due to the specified operating pressure requirement we proposed, only a limited number of PLHE vendors have been identified. Further communications are still needed to finalize the quotes.

Table 4: Heat transfer area per heat duty and SAD values for different HE designs.

Description	STHE	PCHE	PLHE	SPHE	HPHE
A_s/Q [m²/MW]	223.05	151.84	—	115.45	—
SAD [m²/m³]	~100 [24]	200–5,000 [24, 53, 57]	~200–300 [24, 53, 66]	~200 [24, 66]	—

From Table 4, STHE exhibits a higher A_s/Q than PCHE and STHE, indicating that a larger surface area is required to transfer the equal amount of heat (i.e., a relatively poor heat transfer performance). Of course, these values (A_s/Q) can vary depending on the specific HE designs provided by suppliers. During the market survey for this study, no quotations were collected for the SPHE and PLHE that would meet 2 MW of heat duty under the same desired conditions. Nonetheless, as discussed above, A_s/Q can offer a useful criterion for comparison and optimal selection when there are several HE options with the same performance goal.

5.1.3 Fouling Resistance (113)

Fouling is a complex phenomenon influenced by multiple parameters, such as the type of heat transfer fluid, system operating temperature and pressure, fluid velocity, concentration, viscosity, and others, with no established correlation among them. However, when comparing HE designs, there are two factors that seem to significantly affect the degree of fouling or its consequence: channel size and turbulence [53, 61]. Fouling can significantly reduce the thermal performance of an HE [53, 59] by causing changes in flow resistance (pressure drop) as well as introducing extra thermal resistance. In addition, fouling has been one of the primary obstacles limiting the wider industrial application of compact heat exchangers (CHEs) [46].

It is worth mentioning that vibration also has an impact on the fouling effect in HEs. Current research efforts are pointing out the benefits of vibration. While vibration in HEs is an undesirable effect, recent studies state that it helps to remove fouling [13, 28]. While the effects of vibration on fouling are not completely clear, studies have found that the fouling resistance in an elastic HE structure is one-third of an ordinary bare tube [13]. However, the impact of vibration on fouling is not considered as a metric in this study due to the yet unclear correlation and complexity.

In the Tubular Exchangers Manufacturers Association (TEMA) standards [44], relevant values and calculations for the fouling factor or resistance of STHEs are available, enabling researchers to account for the impact of fouling on the HE performance. These values, however, cannot be directly used for CHEs, such as PCHE and PLHE, as they typically necessitate a lower fouling resistance requirement to ensure economic advantages [46]. For example, Panchal and Rabas [46] suggests that the recommended PCHE fouling resistance values are approximately 4–20× lower compared to the values suggested by TEMA standards. It is important to note that the specific differences depend on the working fluid selection.

In summary, predicting the fouling effect on HE performance is a complex challenge. Under the assumption of identical flow conditions (e.g., HTF and flow rate) and application scenarios, smaller channels may pose a higher risk of fouling-related clogging or performance degradation. On the other hand, the increased flow velocities may create more shear stress near the channel walls, which may prevent fouling substances from firmly adhering to the surface. It is therefore important to strike a balance between fouling rates and flow velocities during the design and operation of HEs to minimize the fouling risk. Nonetheless, it is generally expected that the smaller channels are more susceptible to fouling [22]. SPHEs are typically known for high resistance to fouling because of their design flexibility that can accommodate relatively large channel sizes [37]. Therefore, in this study, channel size (or hydraulic diameter) is used as a FOM to evaluate and compare the fouling resistance among different HE types.

5.1.4 High Thermal Performance: Summary

With regard to the customer demand for *High Thermal Performance (110)*, Subsections 5.1.1–5.1.3 describe the specific technical requirements and FOMs, along with their respective justifications, to evaluate and compare the thermal performance of HEs. To complement the lack of information obtained from the literature, data has also been gathered from the quotes provided by commercial HE suppliers, providing a general idea of the ranges for the proposed FOM.

Based on the FOM evaluated using the data collected from both literature and commercial HE suppliers, the comparative evaluation for the different technical requirements associated with the customer demand for *High Thermal Performance (110)* is provided in Table 5.

Table 5: Comparison of technical requirements affecting HE thermal performance.

ID	Requirement	STHE	PCHE	PLHE	SPHE	HPHE
111	Thermal effectiveness	Medium–High	High	Medium–High	Medium–High	Medium
112	Heat transfer performance	Low–Medium	High	Medium	Medium	Medium
113	Fouling resistance	Medium [23]	Low	Medium–High [29, 50]	High [36, 48, 50]	Medium

5.2 Robust Pressure Boundary (210)

The second requirement by HE end users is *Robust Pressure Boundary (210)*. An HE must be safe and reliable while operating under a given pressure difference between coupled systems. Evaluating the robustness of a pressure boundary considers channel geometry and size (211), resistance to thermal stress (212), and resistance to vibration (213).

5.2.1 Channel Geometry and Size (211)

The geometry, size, and configuration of the flow channels can impact the likelihood of channel wall failure and, consequently, the overall integrity of a, HE during its operation. Smaller channels are typically less susceptible to the pressure difference between coupled systems. The wall thickness of the flow channel can also affect how well an HE can withstand a given pressure difference. An equation for hoop stress (σ_θ) can be used to compare the performance of different HEs in terms of the robustness of the pressure boundary by considering the effects of both the channel size and wall thickness. The hoop stress correlation is:

$$\sigma_\theta = \frac{P \cdot D_h}{4t} \tag{9}$$

where P is the pressure and t is the wall thickness. If different HEs operate at the same pressure and are made of the same alloy, the performance in terms of the robustness of the pressure boundary can be comparatively evaluated based on their hydraulic diameter to wall thickness ratio, D_h/t. A low D_h/t indicates a robust design since the wall thickness is large and the hydraulic diameter is small. The literature survey on the design characteristics of different HEs are summarized in Table 6, where data was gathered regarding diameters, hydraulic diameters, and wall thicknesses. No values were available for HPHE because this technology is not applied yet in the high temperature market and the sizes can vary significantly.

Table 6: Diameters, hydraulic diameters, and wall thicknesses for various HE designs.

Description	STHE	PCHE	PLHE	SPHE	HPHE
Channel geometry and size (channel diameter or hydraulic diameter)	>3 mm (OD) [24]	Semicircular channel 1–2 mm wide and 0.5–1 mm depth (D_h: 0.5–2) [24, 30]	D_h: 5–10 mm [24]	D_h: 10–50 mm [24, 66]	—
Wall thickness [mm]	1.65–2.77 [23]	≥0.5 [24, 30, 66]	≥0.5 [61]	1.8–4 [37, 48, 66]	—

5.2.2 Resistance to Thermal Stress (212)

Thermal stress caused by large thermal gradients may compromise the structural integrity of an HE as it could result in a rupture of the pressure boundary, particularly at high temperatures. To safely operate an HE while maintaining the pressure boundary, it must be able to withstand thermal stresses when undergoing through major system disruptions (e.g., transients or maintenance interruptions).

The more compact the HE is, the more heat is transferred through less surface area, which may lead to extensive thermal stress due to the large temperature gradient within a limited HE volume [45]. This indicates that SAD and A_s/Q can be used as the FOMs to evaluate and compare the thermal stress resistances of different HE types, and the values for the HE candidates can be found in Table 4. Theoretically, the scale of HPHE should be smaller than STHE but larger than PCHE. Since a commercially available HPHE was not identified for the required operating conditions, we assumed it has a similar SAD range as PLHE and SPHE.

5.2.3 Resistance To Vibration (213)

HEs are designed without moving parts. However, vibrations could take place in the structure of an HE as a result of a highly energized flow interacting with a relatively flexible structure, which is often unexpected [7]. In essence, vibration in an HE is the result of transfer of energy to the structure. These vibrations can be caused by multiple factors, including but not limited to turbulence, vortexes, and fluid elastic whirling [8]. While mathematical correlations have been developed to describe the factors influencing vibration, the magnitude of dampening effect, and the speed of pipe wear and failure, they are complex correlations and typically have insufficient accuracy to analyze vibration in engineering practice [17].

As it is generally known, vibration in HEs is an undesirable phenomenon that can result in pipe leak, wear, fatigue, and fracture [17]. However, recent studies have pointed out that flow-induced vibration could enhance heat transfer and be classified as a passive heat transfer enhancement technology [16, 28]. Historically, HEs were designed to be more rigid to prevent failure, but they would eventually break. Newer studies are adopting more elastic structures instead of rigid, keeping in mind the fatigue of the structure. While multiple studies are embracing vibration as a passive heat transfer enhancement technique in HEs, it is still an area under research [28].

For our HE evaluation purposes, vibration is considered as an undesired phenomenon, thus a low probability of vibration is desired. For purposes of this study, SAD is adopted as the FOM to evaluate the HE resistance to vibration. CHEs are generally more robust since they have more support points per flow path distance than non-CHEs. For instance, PCHEs are more robust than some STHE designs, such as the helical coil HE, since a PCHE uses diffused bonding techniques to fuse the plates that contain the flow channels but STHEs have lots of flow tubes [53]. Therefore, PCHE is ranked *"High"* in terms of vibration resistance and STHE is ranked *"Low"*. The other HE designs are assigned a *"Medium"* rank since their probability of vibration is not as high as STHE but not as low as PCHE.

5.2.4 Robust Pressure Boundary: Summary

Table 7 summarizes the comparative evaluation of the technical requirements discussed in Section 5.2. The technical requirement of *Channel geometry and size (211)* was compared by calculating the D_h/t using the values presented in Table 6. As discussed, a low D_h/t indicates a high robustness to mechanical stress (pressure difference). Hence, if a low D_h/t value is calculated, the scale in Table 7 should be assigned as *high*. Conversely, large D_h/t values indicate low robustness, and therefore a *low* value is assigned. Since HPHE technology is still in the research and development (R&D) stage for high-temperature (mega-watt scale) applications, the design could vary significantly. However, it is important to note that HPHE allows the physical separation of thermally coupled systems, so the potential design issues associated with the pressure boundary are expected to be moderate compared to other HE types.

For thermal stress resistance, SAD and A_s/Q are the two metrics used to evaluate HEs. In terms of SAD, a lower value indicates a lower probability of accumulating thermal stress during the HE operation, whereas a large SAD indicates high thermal stress. Based on the values presented in Table 4, a ranking from low to high was given to each HE design as shown in Table 7.

Table 7 provides a summary of how likely vibration is to take place in HEs. PCHE is less likely to generate vibrations from within, and STHE has the configuration that is more likely to vibrate and also the one with the most extensive literature on vibration. Referring to SAD as the FOM, the remaining HE types (i.e., PLHE, SPHE, and HPHE) are assigned a *medium* score.

Table 7: Comparison of technical requirements affecting robust pressure boundary.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
211	Channel geometry and size (degree of robustness to mechanical stress)	Low–Medium	High	Medium–High	Low	Medium
212	Resistance to thermal stress	High	Low–Medium	Medium	Medium	Medium
213	Resistance to vibration	Low	High	Medium	Medium	Medium

5.3 Prevent Cross-contamination (310)

The third requirement of HE end users is the cross-contamination robustness. In addition to ensuring the integrity of the pressure boundary against mechanical stress, HEs must also be able to provide a robust chemical boundary to prevent the cross-contamination of working fluids and impurities, as well as other associated risks [65]. Failure to do so may result in substantial safety issues. Evaluating the HE's robustness as a chemical boundary considers the channel geometry and size (311) and resistance to (tritium) permeation (312).

5.3.1 Channel Geometry and Size (311)

A large surface area can increase the likelihood of a surface reaction, which, in turn, can potentially result in the formation of unwanted substances or gradual degradation of materials, such as the HE structural material. Therefore, SAD and A_s/Q can be used as the FOMs to evaluate and compare the performance of HEs as a chemical boundary. For example, if an HE can handle the same amount of heat load with less heat transfer area, such a design can provide higher resistance to cross-contamination. Apart from this, in the case of HPHE, the inherent design characteristics have great potential to reduce the risk of cross-leakage between coupled systems because no direct fluid exchange is required for the heat transfer.

5.3.2 Resistance to (Tritium) Permeation (312)

A main concern for advanced reactors, especially high-temperature reactors, is tritium permeation (312). In reactors, tritium is a radioactive hydrogen isotope with a nucleus of one proton and two neutrons formed through ternary fission events and the neutron absorption of predecessor radionuclides. There is a special interest in tritium due to its high mobility, being able to easily permeate in high temperature metals. It is crucial to understand tritium behavior in reactor systems, especially its permeation through HEs, as it is the main downstream route [47] and can contaminate the system coupled to the reactor.

It is important to highlight that the reactor type connected to the HE determines how significantly the end users should consider the risk of tritium permeation. For example, the tritium production in gas-cooled reactors is much less than in molten-salt reactors [54].

The geometry of each HE also plays an important role in tritium migration through systems. Reducing the A_s/Q or increasing the wall thickness could help reduce the rate of migration [54]. Since tritium permeation is proportional to A_s/Q, a smaller A_s/Q value is preferred. Among the HEs in this study, the PCHE has the smallest A_s/Q and STHE has the largest [45].

If the chosen HE design does not have proper methods to deal with tritium permeation issues, mitigation strategies must be employed, increasing the system complexity and costs. Tritium can be removed from liquid salts through carbon beds and other materials, permeation filters where the tritium diffuses through nickel or other tubing to a tritium removal system, and gas sparging using inert gases or gases that contain some hydrogen for redox control [18]. According to Zohuri et al. [67], HPHE can incorporate barriers (tritium removal from salts and permeation membranes) to prevent the release of tritium from the primary system or a tritium capture system (tritium removal within an HE). Materials with low tritium permeability, such as tungsten, aluminum oxide, or other coatings, can be used to coat the inside sodium condenser side of the heat pipe to prevent tritium escaping from the heat pipe to the environment.

5.3.3 Prevent Cross-Contamination: Summary

Considering the discussion covered in Sections 5.3.1 and 5.3.2, FOMs were identified based on the information gathered from the literature and market survey. Table 8 summarizes the comparison for the robustness of the selected HE candidates as a chemical boundary.

Table 8: Comparison of technical requirements for preventing cross-contamination.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
311	Channel geometry and size (resistance to cross-contamination)	Low–Medium	Medium–High	Medium	Low–Medium	High
312	Resistance to permeation (tritium)	Low–Medium [45]	Medium–High [45]	Medium	Medium	High [67]

5.4 Reliable Performance Under Dynamic Operation (410)

Due to the dynamic nature of an IES, it is important that HEs operate reliably under dynamic operating conditions, especially considering that many applications operate on a 24/7 basis. This requirement focuses particularly on evaluating the extent to which an HE can maintain its original functionality (or reliability) without substantial performance degradation within a dynamic operating environment. In general, the reliability under the dynamic operating conditions of an IES can be evaluated using fouling resistance (411), resistance to vibration (412), thermal capacitance (413), and resistance to thermal stress.

5.4.1 Fouling Resistance (411)

Fouling can adversely affect the HE thermal performance and reliability by introducing extra fouling layers (thermal resistances) that may cause tube or channel clogging. Under such conditions, the coupled system needs to be interrupted for maintenance, which can detrimently affect the system economics. Fouling will significantly reduce the thermal performance of an HE during the dynamic operation of an IES, particularly when using liquid coolants, such as MS. To mitigate fouling effects, it is typically required to oversize the HE design, along implementing cleaning strategies tailored to specific applications [53]. In this study, the hydraulic diameter (or channel size) is used as a FOM to comparatively evaluate the level of fouling resistance among different HE designs.

5.4.2 Resistance to Vibration (412)

Under transient events, vibration within an HE can increase, decrease, or not take place based on the flow conditions and HE design. For conditions where vibration takes place and is potentially enhanced due to a transient event, the probability of failure can increase as the material of construction may not be elastic enough to withstand the vibrations. As mentioned in Section 213, complex correlations have been developed to predict vibration within an HE, which means there is no simple correlation that can be used to predict vibration within an HE. For this study, SAD is adopted as the FOM as it can provide an idea of the probability of vibration within an HE. For further justification, refer to Section 213.

5.4.3 Thermal Capacitance (413)

In the evaluation matrix, thermal capacitance is defined as the HE's ability to store thermal energy and provide thermal inertia during transient events. If there are fluctuations in the thermal energy demand, HEs can resist such variations if they have high thermal capacitance. This means that, if an industrial process requires steady-state operation despite the grid dynamics, customers will prefer an HE with higher thermal capacitance. In addition, since thermal capacitance allows an HE to absorb and store excess heat, acting as a buffer and reducing the rate of temperature change, the higher thermal capacitance helps mitigate stress and strain that the HE would otherwise experience due to sudden temperature changes. The more compact the HE is, the less HTF volume it can hold. Therefore, SAD is used as the FOM to evaluate the thermal capacitance for the selected HE candidates. The SAD values for the HE candidates are in Table 4.

5.4.4 Resistance to Thermal Stress (414)

According to the definition, thermal stress is mechanical stress created by any change in the temperature of a material. Therefore, if an HE experiences dynamic operating conditions, it is essential to make sure that the HE can resist the induced thermal stress, maintain its structural integrity and operate reliably. As mentioned before, SAD and A_s/Q are used as the FOMs when evaluating the various HE candidates in terms of thermal stress, refer to Section 212.

Due to the relative large size, STHE has a high tolerance to mitigate the thermal gradients and better resist the induced thermal stress. On the other hand, small HEs, such as PCHE, are more susceptible to thermal stress as there is a higher probability of experiencing large thermal gradients under dynamic conditions. Hence, PCHE is ranked as *Low–Medium* for resisting the thermal stress, and PLHE and SPHE are both evaluated as *Medium*. Given the assumption mentioned in Section 5.2.2, HPHE is expected to have a similar SAD range as PLHE and SPHE. Therefore, HPHE is also ranked as *Medium* in terms of its thermal stress resistance.

5.4.5 Reliable Performance under Dynamic Operation: Summary

Under a transient event, it is paramount to preserve the integrity of all components of the coupled system. Three key technical requirements commonly expected from HEs have been identified: resistance to vibration, thermal resistance, and resistance to thermal stress. The identified FOM are summarized in Table 9, where a *"High"* rank indicates that the HE design performs well with the given technical requirement and a *"Low"* rank indicates otherwise.

Table 9: Comparison of technical requirements for reliable thermal performance.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
411	Fouling resistance	Medium	Low	Medium–High	High	High
412	Resistance to vibration	Low	High	Medium	Medium	Medium
413	Thermal capacitance	High	Low	Medium	Medium	Medium
414	Resistance to thermal stress	High	Low–Medium	Medium	Medium	Medium

5.5 High Thermal Resilience (420)

5.5.1 Thermal Resilience (421)

Thermal resilience refers to the ability of an HE to prepare for, recover rapidly from, and adapt to major disruptions. This requirement places particular focus on the HE's ability to respond to dynamic demands from the grid or heat customers. High thermal resilience, as defined by this requirement, enables an HE to adapt to varying loads, changes in operating conditions, and thermal transients without compromising its performance. For IES applications, the HE must be capable of responding reasonably fast to varying customer demands [9]. In general, HEs that have high thermal capacitance require more time to respond to such thermal requests and thus less thermal resilience. For example, if the thermal energy demand is expected to fluctuate, a large thermal capacitance will provide greater resistance to variations. If a real-time response is crucial to meet the dynamic demands among subsystems coupled within an IES, an HE with low thermal capacitance and high thermal resilience would be preferred. In order to evaluate and compare the thermal resilience of different HE designs, the SAD or heat transfer area per heat duty (A_s/Q) can be used as the FOM because thermal resilience is highly related to the HTF volume and thermal performance of the HE. Considering this, Table 10 summarizes the technical requirement comparison for the selected HE candidates in terms of their thermal resilience performance.

Table 10: Comparison of technical requirement affecting thermal resilience.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
421	Thermal resilience	Medium	High	Medium	Medium	Medium

5.6 American Society of Mechanical Engineers Boiler and Pressure Vessel Code Readiness (510)

The ASME Boiler and Pressure Vessel Code (BPVC) standards provide the single largest source of technical data used in the creation, construction, and operation of boilers and pressure vessels [43]. Materials and construction guidelines used to fabricate HEs must be supported by the ASME BPVC standards. It is important to note that the evaluation of the ASME BPVC standard readiness can be highly dependent on the HE performance targets required by customers versus the commercial suppliers' manufacturing capabilities. To evaluate and compare the ASME BPVC standard readiness for different types of HEs, the material and fabrication technology readiness (511) is adopted as a technical requirement.

5.6.1 Material and Fabrication Readiness (511)

Materials used in the design and construction of HEs must be supported by ASME BPVC Section II. If the HEs are intended for nuclear service, the design and construction must adhere to the requirements outlined in ASME BPVC Section III. Moreover, the fabrication technology must possess sufficient technical readiness to build HEs using the materials selected while meeting both industrial process requirements and ASME BPVC standards. The HE performance target can be specified using several parameters, including target heat duty, maximum operating temperature and pressure, and more. In this study, the ASME BPVC standard readiness of HEs was evaluated considering the target heat duty of 2 MW or higher and operating temperature of 500°C or higher.

For STHE, for the materials certified by ASME code, ASME BPVC Section VIII, Division 1 has specified the structural analysis approaches considering the design parameters, including thermal stress, fatigue, creep deformations, rupture life, etc. Also, TEMA has developed standards that define the design, fabrication, tolerances, installation, and maintenance of STHEs [44]. The TEMA standard defines the main STHE configuration and the classification for usage in the industry. This standard and the ASME code are the main governance used to design and fabricate STHEs along with any customer specifications. To the authors' best knowledge, currently only ASME BPVC Section III and Section VIII standards are referred to when vendors design and fabricate HEs for nuclear applications [11, 25, 42].

For the other HE types investigated in this study, ASME BPVC Section VIII, Division 1 can be used to cover the design and deployment rules. However, for CHEs, including PCHE, SPHE, and some variants of PLHE designs, the ASME code has no established rules regarding their construction for nuclear service (Section III, Division 5) [33, 62]. Also, detailed strategies or methods are still required for the code case and inservice inspection (ISI) requirements of CHEs, especially PCHE, for their application to nuclear service (Section IX procedures for diffusion welding, Section XI for ISI methods) [32, 33].

Therefore, based on the information mentioned above, STHE was scored as *"High"* regarding the ASME BPVC readiness while *"Medium"* scores were assigned to PCHE, PLHE, and SPHE. Given that an HPHE has never been constructed nor operated at the MW scale, it was ranked *"Low"* with a considerable amount of R&D effort still needed. Table 11 summarizes the ASME BPVC readiness comparison for the HEs in this study.

Table 11: Comparison of technical requirements affecting ASME BPVC readiness.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
511	Material and fabrication technology readiness	High	Medium	Medium	Medium	Low

5.7 Industrial Experience (520)

5.7.1 Commercial Product Availability (521)

Commercial product availability refers to the technical maturity of HE technology in the commercial market and how readily commercial products are available. TRLs developed by the National Aeronautics and Space Administration (NASA) are a well-recognized method to indicate the commercial readiness (or technical maturity) of a given technology [39, 65]. Based on the definitions on the degree of technical maturity provided by the TRLs as well as the market feedback heard from several HE vendors during this study, we have evaluated the commercial availability of different types of HEs. Figure 10 summarizes the operating envelopes (temperature and pressure) based on information found in the open literature [37, 57] and from the market survey conducted for the HE candidates in this study.

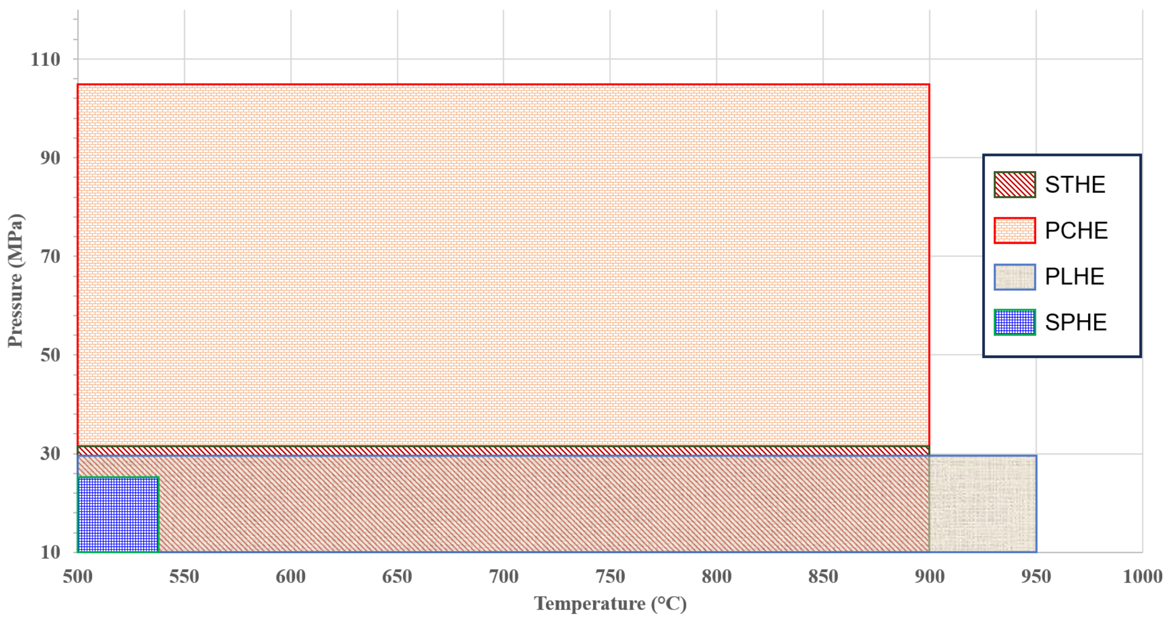

Figure 10: Operating envelopes (temperature and pressure) for the HE candidates.

From the information collected, the commercial product availability for the chosen HEs are then evaluated based on if an HE can achieve the desired heat duty within the required operating envelope, technical feasibility of the use with designated HTFs, and the fabrication readiness with regard to the materials selected. The market survey was conducted considering the same HE performance goal (i.e., same heat duty and required operating conditions). We received several quotes with specified flow conditions for STHE vendors. For PCHEs, some limitations were observed regarding the materials of construction due to the diffusion bonding technique, as well as the ability to handle high-corrosive HTF like MS in small channels. PLHE vendors were not able to provide any quotes because of the high pressure requirement and their availability. SPHE vendors were not able to meet the 2 MW heat duty requirements since this HE design is limited to a maximum 140 kW scale. As for HPHEs, we were not able to identify any available commercial products, suggesting the need of R&D to increase the maturity of the technology. Based on the market survey feedback and information from open literature, the comparative evaluation of commercial product availability for the HE candidates is summarized in Table 12.

Table 12: Comparison of technical requirements affecting commercial product availability.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
521	Commercial product availability	High	Medium	Low	Low	Low

5.8 Easy Integration (610)

The choice of HE can impact integration difficulty and associated costs, including labor. The end users will require an HE that can easily be integrated with external thermal systems and minimize associated cost. The relevant technical requirements that determine the difficulty of thermal integration and associated costs include compactness and weight.

5.8.1 Compactness (611)

The size of an HE can influence the degree of integration complexity. Small sizes have a smaller footprint and are generally preferred to facilitate their integration. A CHE could result in lower installation and transportation costs as unloading and moving the HE to its destination could be done with a forklift or small crane, based on the size and weight, while large HEs may require a bigger crane and more space. The compactness of an HE can be evaluated using SAD as the FOM. The higher the SAD, the more compact the HE is. PCHE has the highest SAD and STHE the lowest among the HEs compared in this study. The HPHE does not have an available SAD range in literature. For IES purposes, HPHE are not as small as PCHE but not as large as most STHE. Hence, this HE design was ranked as *"medium"*, as seen in Table 13.

5.8.2 Weight (612)

The weight of an HE can increase transportation and installation costs. For instance, transportation costs can be estimated based on distance and weight:

$$SC = (WC \cdot W) + (DC \cdot D) \tag{10}$$

where,

SC: Shipping cost

DC: Cost per kilometer or mile

WC: Cost per kilogram or pound

W: Total weight (kilogram or pound)

D: Total distance (kilometer or mile)

This correlation needs the total weight and transportation distance. For installation purposes, more resistant (reinforced) structures, bolts, nuts, hinges, etc. will be needed to mount the HE. Additionally, the installation costs can increase based on how heavy the HE is. More people and special transportation equipment will be needed to unload the HE and mount it in its final destination.

In Table 13, we summarize the weight per heat duty [tons/MW] information based on the quotes we received during the market survey process. For the STHE, it is obvious that the HTF selection significantly affects the weight per heat duty value. This is because, given the poor thermal transfer properties of gas compared to liquid, more heat transfer area is needed for the He-air case than the He-MS case. Also, SPHE has a larger value of normalized weight. This is due to the fact that, even though the inquired operating conditions were the same as for the other HE types, the SPHE vendor could only provide a relatively small heat duty (a maximum of 140 kW) unit to satisfy our temperature and pressure requirements. Optimizing the flow conditions may also affect the SPHE performance and cut down the weight, which is worthwhile for future collaborations and developments with vendors. To ensure a fair comparison between all the HE types in this study, we recommend using SAD as the FOM to evaluate HE compactness.

Table 13: Comparison of different weight per heat duty for the HE candidates.

Description	HTF	STHE	PCHE	PLHE	SPHE	HPHE
Weight/ heat duty [tons/MW]	He-air	4.81–12.09	1.72–4.52	—	43.66	—
	He-MS	1.74	—	—	—	—

5.8.3 Easy Integration: Summary

Based on the FOMs evaluated using the data collected from both open literature and commercial HE suppliers, the evaluation of the different technical requirements affecting the integration process of HEs is summarized in Table 14. It is important to note that the ranks assigned for the weight category are based solely on the SAD of each HE.

Table 14: Comparison of technical requirements affecting the integration.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
611	Compactness	Low	High	Medium	Medium	Medium
612	Weight	Low	High	Medium	Medium	Medium

5.9 Low Product Cost (620)

The end users require low-cost products, assuming the other conditions are the same. The HE product cost is influenced by the material cost (621) and fabrication cost effectiveness (622).

5.9.1 Material Cost Effectiveness (621)

Independently of the alloy used for the HE construction, the cost will increase if more material is used. Two main circumstances that could influence the amount of material used for construction are the HE compactness, which could be evaluated using SAD. Hence, we recommend using SAD as the main FOM to evaluate the material cost.

An approach adopted in multiple studies to estimate the cost of an STHE is using factored numbers, one of which accounts for the cost of material [41]. This material of cost factor is described as:

$$F_m = g_1 + g_2[ln(A_s)] \tag{11}$$

where g_1 and g_2 are constant values based on the material used and A_s represents the heat transfer surface area. Some of the constant values for some alloys are summarized in Table 15.

Table 15: Material of cost factor constants for different alloys for STHE [41].

Material	g_1	g_2
stainless steel (SS) 316	1.4144	0.23296
SS 304	1.1991	0.15984
SS 347	1.1388	0.22186
Nickel 200	2.9553	0.60859
Titanium	2.5617	0.42913
Monel 400	2.3296	0.60859
Hastelloy	3.7614	1.51774
Inconel 600	2.4103	0.50764

Another approach identified in the open literature uses correlations that estimate the HE installed costs, which are summarized in Table 16. One of the main downsides of these correlations is that it is applicable for very few alloys.

Table 16: Cost correlations for STHE, PLHE, and SPHE [21]

Materials type	STHE	PLHE	SPHE
carbon steel (CS)-CS	$2143A^{0.514}$	—	—
SS-SS	$2768A^{0.573}$	—	$2681A^{0.59}$
titanium (Ti)-Ti	$2613A^{0.731}$	$1391A^{0.778}$	$5873A^{0.59}$
SS-CS	—	$635A^{0.778}$	—

To provide an idea of the different construction costs for the three HE design options presented in Table 16, the correlation given for Ti was used and plotted in Figure 11. The heat transfer (HT) surface area is normalized by 100 m^2, and the estimated cost is normalized by the cost of STHE with an HT area of 100 m^2. The range of the HT surface area plotted in the figure is based on the quotes obtained during the market survey. The material cost of SPHE tends to approach STHE and will start to get more competitive when the normalized HT surface area is greater than 3.

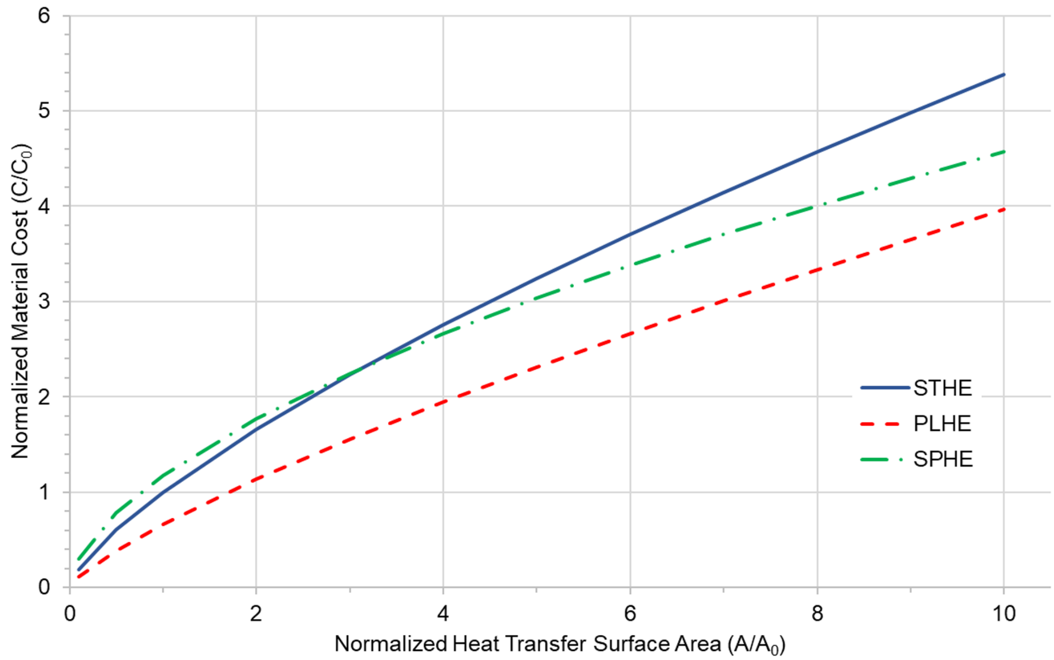

Figure 11: Normalized cost comparison plot for STHE, PLHE, and SPHE using Ti as the construction material.

Due to the manufacturing scale and heat duty limit, the SPHE vendor provided a quote with an HT area of 15.75 m^2 (corresponding to the normalized HT area of 0.1575 shown in Figure 11), which is within the range that SPHE has the highest cost among all three HE types. For a MW-scale HE design, the STHE from the market survey will need an HT area over 400 m^2. Therefore, the material cost for STHE will continue to be the highest among all the HE options. Given the limited heat duty achievable by the SPHE supplier during the market survey, further design optimization will be necessary for the SPHE to achieve the required operating conditions for a MW scale.

5.9.2 Fabrication Cost Effectiveness (622)

For decades, multiple HE designs have been proposed to efficiently transfer heat from one fluid to another and further increase their longevity. There are multiple factors that can increase the fabrication complexity and associated cost of an HE. While HE designs can be as simple as a tubular HE with concentric straight tubes to a more complex design, such as a triply periodic minimal surface (TPMS) HE, which is still under R&D but shows a higher Nusselt number (up to 80%) than PCHEs [40]. This indicates that the design itself can vary significantly, and based on current manufacturing techniques available, it could significantly increase the fabrication cost. Similarly, the fabrication technique could significantly impact the fabrication cost. For instance, in the last three decades, additive manufacturing (AM) has positively impacted the way HEs are being designed and developed [31]. AM is a process that has gained popularity in the HE manufacturing industry, as it fabricates an HE using a three-dimensional printer.

To avoid overcomplicating the comparison by taking into account cutting-edge technologies, the traditional fabrication approaches were considered for the HE candidates in this study. Based on the market survey, the STHE was given a rank of *"High"* due to their mature fabrication techniques. PCHE was evaluated as *"Low"* because of the high cost for the chemical etching and diffusion bonding technologies used. Due to the required heat duty and operating conditions, PLHE and SPHE were both ranked as *"Low"* since the contacted vendors were unable to meet the needs. HPHE was assigned a *"Low"* rank because of the complex process for manufacturing high-temperature heat pipes (HPs) and R&D investments.

5.9.3 Low Product Cost: Summary

Given the information collected from the existing literature and commercial HE suppliers, Table 17 summarizes the comparative evaluation of technical requirements that affect the HEs product cost in terms of material and fabrication cost effectiveness.

Table 17: Comparison of technical requirements affecting the HE product costs.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
621	Material cost effectiveness	Low	High	Medium	Medium	Medium
622	Fabrication cost effectiveness	High	Low	Low	Low	Low

5.10 Low Operations and Maintenance Cost (630)

An HE should be designed to maximize its heat transfer performance while minimizing the initial investment or future expenses. Low O&M costs make an HE more economically viable. Evaluating the O&M costs considers maintenance cost effectiveness (inspection and cleaning) (631), maintenance cost effectiveness (repairing) (632), and operating cost effectiveness (633).

5.10.1 Maintenance Cost Effectiveness (Inspection and Cleaning) (631)

Inspection and cleaning is a major part of HE maintenance costs. Inspection is the process of examining to ensure there are no defects or potential obstructions to operation during the fabrication, installation, and service of the products.

During the fabrication process, the whole structure of the HE should be inspected for possible imperfections, especially in the channels (tubes) and welding joints. During the HE operation, monitoring techniques should be employed for inspection. One example is simple leakage monitoring downstream to determine if there is any cross-channel leakage. Degraded performance can also be monitored by establishing the baseline for the outlet temperatures and pressures and monitoring established points [32]. nondestructive examination (NDE) techniques could also serve as an inspection method. However, traditional NDE techniques, such as ultrasonic examination and x-ray tomography, still have limitations in inspecting industrial-size components. Recently, Vrban et al. [62] have investigated neutron radiography using fast neutrons to overcome the practical limitations of traditional NDE techniques for PCHE inspection.

The inspection cost of an HE can be affected by volume, flow path, channel size, and inspection technique. A bigger HE, such as the STHE, will demand more time and a larger number of parts to be inspected as it has a complex flow path. On the other hand, smaller HEs, such as PCHE and PLHE (welded, brazed, fins), can be challenging to inspect due to their small channel size. Some PLHE (gasketed, frame) and SPHE can be disassembled, making them easier to inspect and clean [50]. In the case of HPHE, due to the small number of parts and passive operation characteristics of the heat pipes, maintenance costs (for both inspection and cleaning) are considered low, unless an inspection of the internal structure of the heat pipes is required.

On the other hand, cleaning is highly related to fouling, and the techniques used to remove fouling from the HE surfaces, both on the shell and on the tube sides, can be broadly classified into two categories: mechanical and chemical [61]. Some mechanical cleaning methods include manual cleaning, water jet, blasting, and thermal cleaning. Usually, chemical cleaning is used when other methods are not satisfactory and involves the use of chemicals to dissolve or loosen deposits.

A simple approach to predict the maintenance cost of an HE is multiplying the purchase expense by a percentage factor, such as the values presented in Table 18. Meanwhile, a summary of the different cleaning methods for different HE designs is shown in Table 19.

Table 18: Maintenance costs for different HE designs [21].

HE Design	Maintenance Cost (% purchase expenses)
PLHE	0.8–1.0
SPHE	0.8
HPHE	0.8
STHE	1.0

Table 19: Cleaning methods used for for different HE designs [24, 53]

STHE	PCHE	PLHE	SPHE	HPHE
Mechanical, chemical, high-pressure water	Chemical	Chemical	Mechanical	Removable for cleaning or replacement

Typically, the channel size or hydraulic diameter (D_h) is a critical factor in determining the maintenance complexity for inspection and cleaning. This study suggests using D_h as a FOM to comparatively evaluate the maintenance cost related to inspection and cleaning.

5.10.2 Maintenance Cost Effectiveness (Repairing) (632)

The repairing cost is another major part of the maintenance cost. Failures could occur due to defects introduced into pipes and tubes during the stages of manufacturing, handling, testing, shipment, and storage or during startup, shutdown, and normal operations of the HE [2]. Repairing is usually related to mechanical or thermal failures; the most common failures are weld defects and flow-induced vibration. Since the repairing cost is highly related to mechanical failures, SAD is used as the FOM to evaluate the repair costs.

PCHE, as one type of CHEs with extremely small flow channels, could be shipped for repairs if needed; although, shipping can be costly or impractical due to channel size. As for the repairing cost effectiveness of PLHE and SPHE, they are both ranked *"Medium"* based on their SAD values. In principle, HPHEs do not require repairs or cause associated costs during their lifetime.

However, if the heat pipe suffers any damage, it should be replaced instead of repaired, which may increase the repairing cost.

5.10.3 Operating Cost Effectiveness (633)

For systems that rely on natural convection for circulating the HTF, no major operating costs are associated with HEs. On the other hand, for systems that rely on forced circulation, operating costs can be significantly impacted by the HE configurations. While HEs do not have moving parts, not including vibration effects, there are some operating costs associated with the design. Under forced convection, the pressure drop across an HE is the main parameter driving the operating costs of an HE since the HTF has to be pumped or circulated within the loop. A pressure drop within an HE can be mainly attributed to frictional forces and minor losses. To overcome the pressure drop, the pumping power is therefore a major part of the HE operating cost; the higher pumping power needed, the larger the operating cost. Since the pumping power is linearly related to the pressure drop, "pressure drop (ΔP) per heat duty" is then used as the FOM to evaluate the HE operating cost. A summary of the pressure drop per heat duty for the different HE designs is provided in Table 20. It is important to note that these values were calculated based on the quotes gathered from commercial suppliers. Given the information from the STHE inquiry, the HTF selection could greatly affect the value of "ΔP/heat duty" due to the fluid properties. Quotes for the STHE and PCHE used in this calculation were collected based on the same performance target (e.g., operating pressure, temperature, and heat duty) and working fluids, but for SPHE, the heat duty that the supplier could achieve was limited.

Table 20: Comparison of pressure drop (ΔP) per heat duty for different HE designs.

FOM	HTF	STHE	PCHE	PLHE	SPHE	HPHE
ΔP/ heat duty [psi/MW]	He-air	1.226	9.486	—	9.896	—
	He-MS	0.010	—	—	—	—

Another approach adopted in a study estimates the operating cost (C_{op}) based on the pressure drop in the HE, pump efficiency (η_p), unit cost of power (UC_P), hours of operation per year (t_{op}), and mass flow rate of HTF ($\dot{m}$) [41]. The proposed correlation is:

$$C_{op} = \Delta P\Big(\frac{\dot{m} \cdot t_{op} \cdot UC_P}{\rho \cdot \eta_P}\Big) \tag{12}$$

Given the passive nature of HPHE operation, its operating cost effectiveness was evaluated as *"High"*. On the other hand, as shown in Table 20, considering the significantly higher values of "pressure drop (ΔP) per heat duty" for PCHE and SPHE compared to that of STHE, the operating cost effectiveness of both PCHE and SPHE was evaluated as *"Low"*, while *"Medium"* score was assigned to the other HEs (i.e., STHE and PLHE).

5.10.4 Low Operations and Maintenance Cost: Summary

In summary, given the FOMs evaluated using the data collected from both literature and commercial HE suppliers, Table 21 provides a comparative evaluation of the technical requirements that affect the O&M costs of the HE candidates.

Table 21: Comparison of technical requirements affecting the HE O&M costs.

ID	Description	STHE	PCHE	PLHE	SPHE	HPHE
631	Maintenance cost effectiveness (inspection and cleaning)	Medium	Low	Medium	High	High
632	Maintenance cost effectiveness (repairing)	Low	Low	Medium	Medium	Low
633	Operating cost effectiveness	Medium	Low	Medium	Low	High

6. Case Study: Comparative Evaluation of Heat Exchangers

The case studies presented in this section aim to evaluate and compare the five HE candidates in this study through a holistic evaluation of the technical and economic requirements outlined in Section 5. These evaluations consider the specific requirements and constraints of each application case along with the detailed customer demands and their relative priorities.

As discussed in Section 2, the HE evaluation framework combines the AHP and HOQ methods and requires the following eight steps:

- Step 1. Identify customer demands
- Step 2. Identify HE technical requirements,
  including application requirements and constraints
- Step 3. Determine relative importance of customer demands
- Step 4. Build relationship matrix

- Step 5. Calculate weights of technical requirements
- Step 6. Compute overall scores of each HE type using AHP and HOQ
- Step 7. Rank candidate HEs.
- Step 8. Select the optimal HE design.

Two different case scenarios show the versatility of the proposed evaluation methodology. The operating conditions (in terms of operating pressures and temperatures), HTFs, and industrial process applications are summarized in Table 22. These two case scenarios consider different industrial applications that could obtain thermal energy from two different advanced reactor technologies, HTGR and SFR. Each reactor technology, as well as the corresponding applicant case, have different constraints and requirements, which are taken into account by the evaluation framework proposed in this report. A summary of each case scenario is presented in Section 6.1 and 6.2, respectively.

Table 22: Thermal integration scenarios for IES HE evaluation and selection.

No	Reactor options	Reactor T_{out} (°C)	$P_{reactor\ side}$ (psi)	Coolant—Primary Side	Industry Applications	$T_{process}$ (°C)	$P_{application}$ (psi)	HTF
1	HTGR	750 [63]	870.23	Helium	sCO_2 Brayton power cycle	>500 [38]	>1,074 [38]	sCO_2
2	SFR	500 [60]	14.7	Sodium	Molten-salt TES	400–500 [20]	14.7 [4]	Fluoride or chloride salts [4]

6.1 Case Study 1: High-Temperature Gas-Cooled Reactor to Super-Critical Carbon Dioxide Brayton Power Cycle

This case scenario primarily focuses on extracting thermal energy from a HTGR and delivering it to an intermediate loop through a HE for generating power. For the analysis of this case, we assumed the reactor is already deployed and the operating conditions are known (refer to Table 22). The thermal energy transferred from the helium primary loop to the sCO_2 secondary loop is used to generate electricity above 500°C.

Under the current scenario, the customer seeks a power generating system that could be deployed in the near future. The system is anticipated to generate electricity uninterrupted (i.e., constant power), and the HE is a new installation rather than a replacement of an old unit.

Immediate technology deployment may be impacted by the TRL and methodologies used for HE fabrication. Generally, in the United States, nuclear application purposes require the vessel and HEs to be ASME stamped for safety and regulatory purposes. It is important to note that having a vessel and HE ASME stamped will increase initial construction costs, which should be considered during the initial investment cost analysis. However, if there is a material or technique with a low TRL, it may impact the deployment time since the technology readiness needs to be matured.

Detailed assumptions we used for Case Study 1 are summarized as:

1. Customers are seeking an HE solution for thermal integration between an HTGR and sCO_2 power cycle
2. Customers are seeking the HE solution for immediate commercial deployment
3. A constant energy supply is required by the energy consumer
4. There is a space constraint where customers want to install the HE.

Step 1. Identify customer demand:

1. Technical readiness and ASME certification requirement:
   (a) Technical readiness and certification requirement:
      i. TRL in terms of HE technology: High TRL is required
      ii. ASME requirement and code readiness: ASME certification is required
2. Economics:
   (a) Upfront investment cost (cost of deployment)
      i. Willingness to adopt advanced technologies: Yes
   (b) O&M cost
      i. Likelihood of hot corrosion or fouling: Low

Step 2. Identify application requirement and constraints,including application requirements and constraints:

1. Identify operating goals for industrial applications:
    (a) Heat duty: >2 MW
    (b) HTF: sCO_2
    (c) Duty cycle: Constant operation
2. Identify heat source (reactor):
    (a) Select candidates based on T, P, and reactor technology:
        HTGR (T_{out} = 750°C, P_{system} = 870 psi, coolant: helium)
3. Potential installation, operation, and safety concerns:
    (a) Space constraints: Yes
    (b) Reactivity between working fluids: Low
    (c) Hot corrosion or fouling potential issues: Low
    (d) Consequence of cross-contamination and leakage (e.g., environmental impact, accessibility): Low risk consequence

Step 3. Determine relative importance of customer demands:

After addressing the questions listed in Step 1 and 2, the relative importance (or relative priorities) among the individual customer demands for Case 1 was determined through a pairwise comparison combined with the AHP method using a "1–9" scale. On this scale, 1 indicates equal importance between the compared pairs, 3 moderately more, 5 strongly more, 7 very strongly more and 9 indicates extremely more importance. Similarly, 1/3 indicates moderately less, 1/5 strongly less, 1/7 very strongly less, and 1/9 indicates extremely less importance. Using this scale, the pairwise comparison matrix for Case 1 was built as shown in Table 23.

Table 23: Pairwise comparison matrix for Case 1.

Pairwise Comparison Matrix (Scale 1-9)		High heat transfer efficiency	Robust pressure boundary	Prevent cross-contamination	Reliable performance under dynamic operation	High thermal resilience	ASME BPVC readiness	Industrial experience	Easy integration	Low product cost	Low O&M cost
High thermal performance	High heat transfer efficiency	1.000	1.000	0.333	1.000	3.000	0.333	0.333	1.000	3.000	3.000
Provide robust pressure boundary	Robust pressure boundary	1.000	1.000	1.000	1.000	5.000	1.000	1.000	1.000	3.000	3.000
Provide robust chemical boundary	Prevent cross-contamination	3.000	1.000	1.000	1.000	5.000	0.333	0.333	0.333	1.000	1.000
Reliability under dynamic conditions	Reliable performance under dynamic operation	1.000	1.000	1.000	1.000	3.000	0.333	0.333	1.000	1.000	3.000
	High thermal resilience	0.333	0.200	0.200	0.333	1.000	0.333	0.333	0.333	1.000	1.000
Technical readiness	ASME BPVC readiness	3.000	1.000	3.000	3.000	3.000	1.000	3.000	3.000	5.000	3.000
	Industrial experience	3.000	1.000	3.000	3.000	3.000	0.333	1.000	1.000	3.000	1.000
Economics	Easy integration	1.000	1.000	3.000	1.000	3.000	0.333	1.000	1.000	3.000	1.000
	Low product cost	0.333	0.333	1.000	1.000	1.000	0.200	0.333	0.333	1.000	0.333
	Low O&M cost	0.333	0.333	1.000	0.333	1.000	0.333	1.000	1.000	3.000	1.000
	Sum	14.000	7.867	14.533	12.667	28.000	4.533	8.667	10.000	24.000	17.333

Table 24: Normalized pairwise comparison matrix for Case 1.

Normalized Pairwise Comparison Matrix		High heat transfer efficiency	Robust pressure boundary	Prevent cross-contamination	Reliable performance under dynamic operation	High thermal resilience	ASME BPVC readiness	Industrial experience	Easy integration	Low product cost	Low O&M cost	**Sum**	Priority vector	**Relative Importance [%]**
High thermal performance	High heat transfer efficiency	0.071	0.127	0.023	0.079	0.107	0.074	0.038	0.100	0.125	0.173	0.918	0.092	9.18
Provide robust pressure boundary	Robust pressure boundary	0.071	0.127	0.069	0.079	0.179	0.221	0.115	0.100	0.125	0.173	1.259	0.126	12.59
Provide robust chemical boundary	Prevent cross-contamination	0.214	0.127	0.069	0.079	0.179	0.074	0.038	0.033	0.042	0.058	0.912	0.091	9.12
Reliability under dynamic conditions	Reliable performance under dynamic operation	0.071	0.127	0.069	0.079	0.107	0.074	0.038	0.100	0.042	0.173	0.880	0.088	8.80
	High thermal resilience	0.024	0.025	0.014	0.026	0.036	0.074	0.038	0.033	0.042	0.058	0.370	0.037	3.70
Technical readiness	ASME BPVC readiness	0.214	0.127	0.206	0.237	0.107	0.221	0.346	0.300	0.208	0.173	2.140	0.214	21.40
	Industrial experience	0.214	0.127	0.206	0.237	0.107	0.074	0.115	0.100	0.125	0.058	1.363	0.136	13.63
Economics	Easy integration	0.071	0.127	0.206	0.079	0.107	0.074	0.115	0.100	0.125	0.058	1.063	0.106	10.63
	Low product cost	0.024	0.042	0.069	0.079	0.036	0.044	0.038	0.033	0.042	0.019	0.426	0.043	4.26
	Low O&M cost	0.024	0.042	0.069	0.026	0.036	0.074	0.115	0.100	0.125	0.058	0.669	0.067	6.69
	Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	10.000	1.000	100

The weighting factor that determines the relative importance of each customer demand is calculated through an iterative process. First, the values assigned to each customer demand shown in Table 23 are normalized by the sum of each customer demand value shown in the bottom row of Table 23. This leads to the normalized pairwise comparison matrix shown in Table 24. Then, the relative importance of each customer demand is calculated by the sum of the row values displayed in Table 24. After this, the relative importance of each customer demand, shown in the third column from the right of Table 24, is divided by the sum of all customer demands. The relative importance weights of customer demands for Case 1 calculated in this way are shown in the rightmost column of Table 24, and the result is plotted in Figure 12.

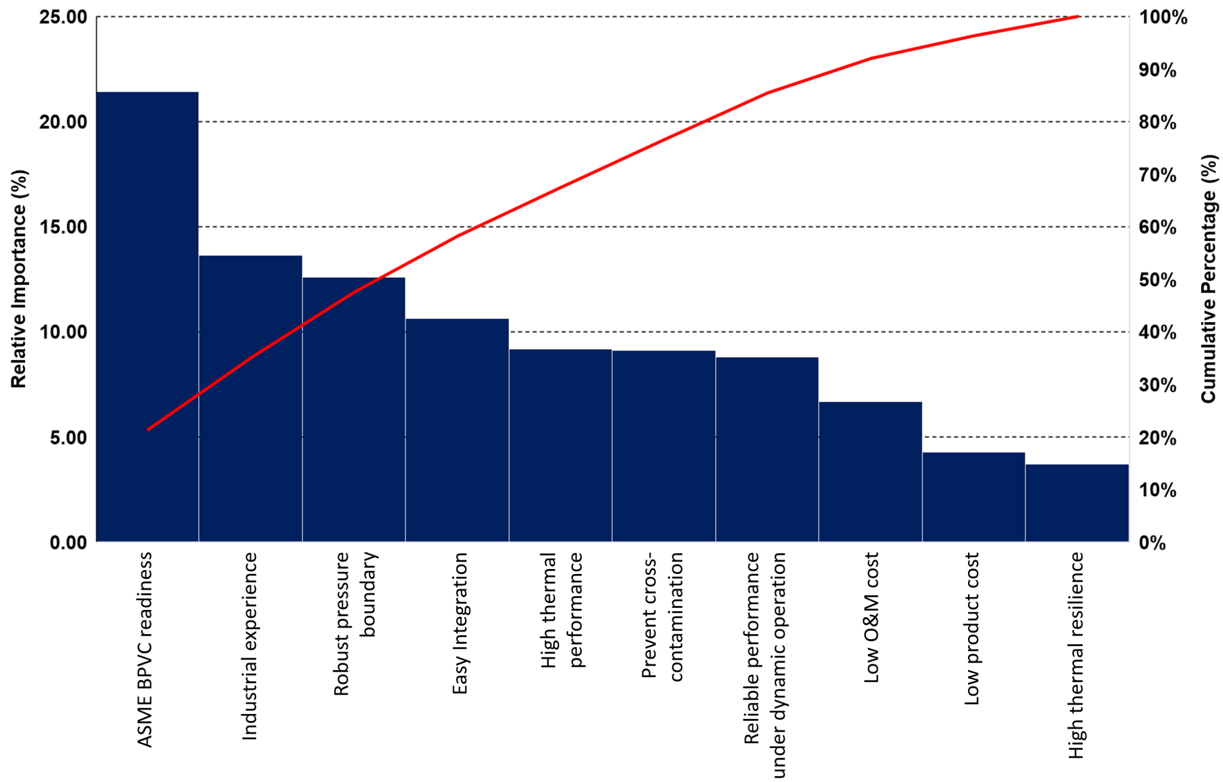

Figure 12: Relative importance of customer demand (Case 1).

As shown in Figure 12 for Case 1, “ASME BPVC readiness” was given the highest priority among the 10 different customer demand requirements. This is due to the customer demand for immediate commercial deployment, which requires the HE product to receive ASME BPVC certification. In the meantime, the customer demand of a high TRL placed “industrial experience” as the second highest rank. While immediate deployment is the highest priority, a robust pressure boundary is also among the top three highest priorities since it is paramount to operate the system with the highest degree of safety. The three technical requirements that received the lowest ranks are “low O&M cost,” “low product cost,” and “high thermal resilience,” which was given the lowest rank. This indicates that, while investment cost is one of the top priorities for the customer, it was given a low rank as other factors were considered more important. Also, the customer demand of "high thermal resilience" was assigned the lowest value due to the assumptions laid out in Step 1, where the system is anticipated to operate under steady-state conditions in general.

Lastly, as discussed in Section 2.2.2, the CI needs to be evaluated to determine the consistency of decision maker's judgement to ensure the validity of making any decision based on the pairwise matrix built in Step 3. The consistency can be measured using the CI or the CR, as outlined in Section 2.2.2. According to Saaty's empirical rule, a CR score of 10% or lower is considered acceptable [19].

The pairwise matrix shown in Table 24 results in λ_{max} = 11.11, CI = 0.12, random consistency index = 1.49, and CR = 8.3%. Therefore, the CR is within acceptable limits.

Step 4. Build relationship matrix:

The relationship matrix is a visual representation of the reciprocal relationship between the HE technical requirements and customer demands. The degree of relationship within a relationship matrix is defined using the "1–9" scale. "9" is a strong relationship between technical requirement and customer demand, "5" a moderate relationship, and "1" a weak relationship. If there is no relationship, "0" will be given. Typically, symbols are used to represent the degree of relationship in the relationship matrix of an HOQ matrix. In this study, solid circles are used for a strong relationship (9), hollow circles for a moderate relationship (5), and triangles for a weak relationship (1). If there is no relationship, the corresponding intersection in the relationship matrix is left blank.

It is also important to note that the degree of relationship within a relationship matrix can be defined differently depending on the HE application (i.e., the specific IES characteristics that HEs are applied to). For example, if there is a lower likelihood of fouling occurring due to the heat transfer fluids employed, as in Case 1 (i.e., helium and CO_2), the degree of relationship between fouling and HE performance can be assigned a lower weight compared to those using potentially more problematic fluids at high temperatures, such as molten nitrate salt.

Step 5–6. Calculate the weights of technical requirements and overall scores of each HE type:

The relative weight of each technical requirement for Case 1 is calculated using Equation 1. Both the relative importance of customer demands and the relative weights of technical requirements, the results of which are summarized within the HOQ matrix (shown in Figure 13), are used for comparative evaluations for Case 1. Specifically, the HOQ matrix shown in Figure 13 provides the basis for the comparative evaluations from two different perspectives for the Case 1 study: **(i) by customer demand** and **(ii) by overall relative competitiveness of the HEs**.

Row #	Relative Importance of Customer Demand	Weight Chart (Customer 1)	Customers: TBD / Customer Group 1 / Customer Requirements (Explicit and Implicit)	1 Thermal Effectiveness	2 Heat Transfer Coefficient	3 Fouling Resistance	4 Channel Geometry and Size (Robustness to mechanical stress)	5 Channel Geometry and Size (Resistance to cross-contamination)	6 Resistance to Thermal Stress	7 Resistance to Vibration	8 Resistance to Tritium Permeation	9 Thermal Capacitance	10 Thermal Resilience	11 Material & Fabrication Technology Readiness (for ASME code)	12 Commercial Product Availability	13 Compactness	14 Weight	15 Material cost Effectiveness	16 Fabrication cost effectiveness	17 Maintenance Cost Effectiveness (Inspection and/or Cleaning)	18 Maintenance Cost Effectiveness (Repairing)	19 Operating Cost Effectiveness	STHE	PCHE	PLHE	SPHE	HPHE
			Technical / Economic Requirements	Technical Factors												Cost Factors							Customer Demand-weighted Comparison				
			Direction of Improvement	▲	▲	▲	◇	◇	▲	▲	▲	◇	▲	▲	▲	▲	▼	▲	▼	▲	▲	▲					
1	9%	|||	High Thermal Performance	●	●	○																	52	66	66	73	52
2	13%	|||||	Robust Pressure Boundary				●		●	●													59	95	77	50	68
3	9%	|||	Prevent Cross-contamination					●			●												26	79	44	35	79
4	9%	|||	Reliability under Dynamic Operation			○			●	●		●											51	30	47	51	43
5	4%	|	High Thermal Resilience										●										15	27	15	15	15
6	21%	|||||||	ASME BPVC Readiness											●									194	108	108	108	22
7	14%	|||||	Industrial Experience												●								115	64	13	13	13
8	11%	||||	Easy Integration													●	●						10	89	50	50	50
9	4%	|	Low Product Cost															●	●				24	24	15	15	15
10	7%	||	Low O&M Cost																	●	●	●	24	6	32	32	45

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Technical Competitive Evaluation (Total score)
Max Relationship	9	9	3	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	
Technical Importance Rating	82.59	82.59	89.89	113.30	82.12	192.52	192.52	82.12	79.22	33.27	192.60	122.71	95.64	95.64	38.38	38.38	60.18	60.18	60.18	
Relative Weight	5%	5%	5%	6%	5%	11%	11%	5%	4%	2%	11%	7%	5%	5%	2%	2%	3%	3%	3%	
Weight Chart																				
STHE	7	3	5	3	3	9	5	3	9	5	9	9	1	1	1	9	5	1	5	544
PCHE	9	9	1	9	9	3	9	9	1	9	5	5	9	9	9	1	1	1	1	592
PLHE	7	5	7	7	5	5	5	5	5	5	5	1	5	5	5	5	5	5	5	505
SPHE	7	5	9	1	3	5	5	5	5	5	5	1	5	5	5	5	9	5	1	467
HPHE	5	5	5	5	9	5	5	9	5	5	1	1	5	5	5	1	9	3	9	478

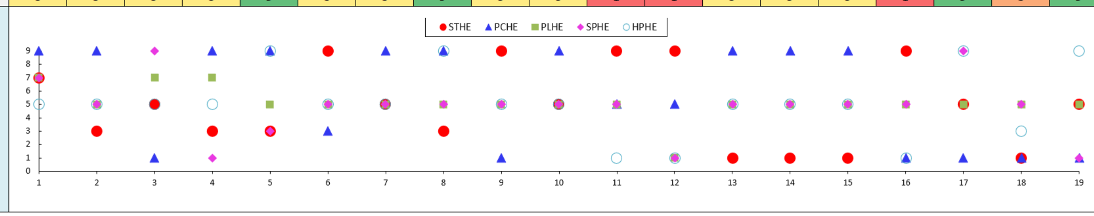

Figure 13: HOQ matrix summarizing the evaluation results (Case 1).

(i) Comparative evaluation of HEs by customer demand (i.e., customer-demand-weighted score comparison)

Using Equation 2, this comparison is performed by combining the relative importance of the customer demand evaluated for Case 1 (see Figure 12) and the comparative evaluation results of the HE technical requirements described in Section 5. The calculated scores for each HE are summarized and presented on the right side of the HOQ matrix (Figure 13), providing insight into how well each HE can meet each customer demand. Figure 14 graphically summarizes the comparison results for the selected HE candidates.

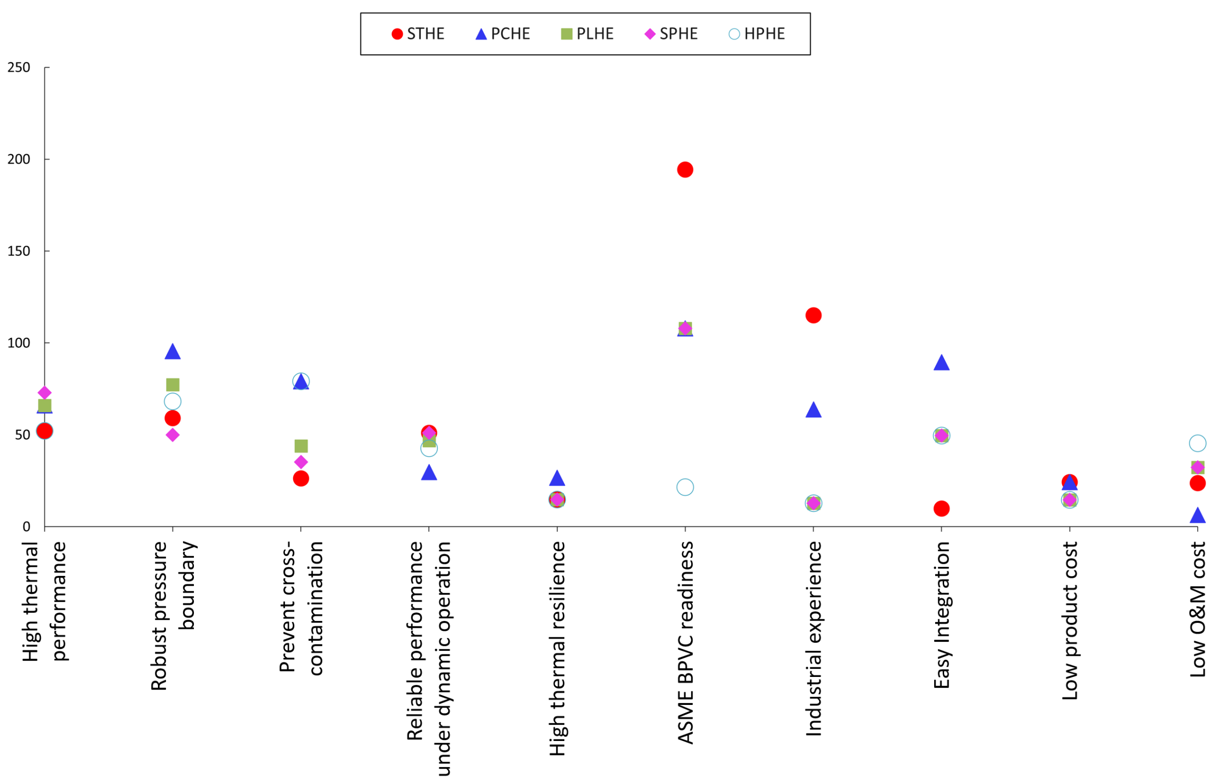

Figure 14: Comparative evaluation by customer demand (Case 1, customer-demand-weighted scores).

In Figure 14, PCHE shows the highest score in terms of customer demand for "a robust pressure boundary" and "easy integration." For the "ASME BPVC readiness" and "industrial experience," STHE received the highest score by a large margin, which is due to the high relative importance given to these two aspects in Case 1 (i.e., customer requires high technical readiness, including the ASME BPVC certification). As a result, the high scores on these two aspects of customer demand contributed significantly to STHE's overall score increase for Case 1, despite its weaknesses on the other aspects of customer demand.

(ii) Evaluating the overall relative competitiveness of HEs

The relative competitiveness of HEs is evaluated using the overall technical competitiveness scores. Referring to Equation 3, the overall technical competitiveness score can be calculated by combining the relative weights of the technical requirements, as computed by Equation 1, with the knowledge-based evaluation of the technical requirements described in Section 5. The results of the technical competitiveness scores for Case 1 are summarized at the bottom right of the HOQ matrix (see Figure 13). It should be noted that the relative weights of the technical requirements are calculated by considering both the scales given by the relationship matrix and knowledge of the relative importance of customer demands. Then, the results computed by Equation 3 further incorporates the knowledge-based evaluation of technical requirements (Section 5) to measure the overall technical competitiveness.

Step 7–8. Rank and select the HEs (engineering judgement required):

Comparing the overall competitiveness scores for Case 1, PCHE ranked first and STHE ranked second, followed by PLHE, and then HPHE, with SPHE ranked last. PCHE shows the highest competitiveness in many aspects, including heat transfer performance, robustness to mechanical stress, resistance to vibration, compactness, and weight. On the other hand, despite receiving the highest competitiveness score, it is evaluated as having the lowest competitiveness in terms of fouling resistance, thermal capacitance, fabrication cost effectiveness, and maintenance cost effectiveness.

In Case 1, fouling is considered a relatively minor concern due to the heat transfer fluids adopted in the IES (i.e., helium and CO_2), and since the customer is assumed to require a constant energy supply, concerns about the performance reliability or susceptibility due to a low thermal capacitance during dynamic operation were considered relatively low. In addition, due to the customer's willingness to adopt advanced HE technologies, described in Step 2, the economic concern, such as product cost, was also evaluated as relatively low. In other words, the relative weaknesses of PCHE were evaluated as less important in Case 1 due to the system characteristics and customer demands laid out in Steps 1 and 2. Also, the system characteristics and requirements and customer priorities in Case 1 gave more weight to the advantages of PCHE, such as a high heat transfer performance, compactness, and light weight.

Despite this result, however, it is still important to exercise careful engineering judgement in the final selection, especially by considering the customer requirements rated as high priority in Step 3. For example, STHE ranked second in the overall competitiveness score, but upon closer examination, it showed the highest competitiveness in terms of "technical readiness" and "commercial product availability," both of which were critical to the customer in Case 1 (see the relative priorities of customer demands shown in Figure 14). Although the overall competitiveness score reflects the customer's relative priorities for Case 1, in some cases, the influence of one or two decisive factors may dictate the final selection. If such cases were not filtered in the HE pre-selection process, they should be taken into account in the final step (Step 8). Given that Case 1 assumed a thermal integration of an sCO_2 power cycle with a nuclear reactor (HTGR), immediate commercial deployment with PCHE is not feasible at this point due to the lack of ASME BPVC readiness, especially considering the construction for nuclear service. Based on these engineering judgements, STHE is the final selection in Case 1; although, PCHE's overall competitiveness was rated the highest.

6.2 Case Study 2: Sodium-Cooled Fast Reactor to Molten-Salt Thermal Energy Storage

This case scenario investigates the thermal integration of an SFR with a MS TES. For the analysis of this case for HE selection, we assumed that the reactor is already deployed and the operating conditions are known (refer to Table 22). Thermal energy is transferred from the SFR primary loop at around 500°C to the MS TES tank, which should reach at least 400°C.

Detailed assumptions used for Case Study 2 are summarized as:

1. Customers are seeking an HE solution for the thermal integration between an SFR and MS TES.
2. Customers are seeking the HE solution for immediate commercial deployment.
3. Customers require dynamic charging and discharging of thermal energy to/ and the TES tank for the energy-efficient operation of the entire system (IES).
4. Customers are willing to make initial investment to explore an HE solution of higher

operational efficiency and savings.

Step 1. Identify customer demand:

1. Technical readiness and ASME certification requirement:
   (a) Technical readiness and certification requirement
      i. TRL in terms of HE technology: High TRL is required
      ii. ASME requirement and code readiness: ASME certification is required
2. Economics
   (a) Upfront investment cost (cost of deployment)
      i. Willingness to adopt advanced technologies: Yes
   (b) O&M cost
      i. Likelihood of hot corrosion or fouling: High

Step 2. Identify application requirement and constraints, including application requirements and constraints:

1. Identify operating goals for industrial applications:
   (a) Heat duty: >2 MW
   (b) HTF: Molten nitrate salt
   (c) Duty cycle: Dynamic operation (i.e., periodically charge and discharge heat)
2. Identify heat source (reactor):
   (a) Select candidates based on T, P, and reactor technology:
   SFR (T_{out} = 500°C, $P_{sysmtem}$ = 14.7 psi, coolant: sodium)
3. Potential installation, operation, and safety concerns:
   (a) Space constraints: Not applicable
   (b) Reactivity between working fluids: Medium
   (c) Hot corrosion or fouling potential issues: High
   (d) Consequence of cross-contamination and leakage (e.g., environmental impact, accessibility): High risk consequence (e.g., sodium fire)

Step 3. Determine relative importance of customer demands:

As in Case 1, after addressing the questions listed in Step 1 and 2, the relative importance of customer demands for Case 2 was determined through a pairwise comparison combined with the AHP method using a "1–9" scale. The pairwise and normalized pairwise matrices built for Case 2 are shown in Tables 25 and 26, respectively. The result is also presented in Figure 15.

Table 25: Pairwise comparison matrix for Case 2.

Pairwise Comparison Matrix (Scale 1-9)		High heat transfer efficiency	Robust pressure boundary	Prevent cross-contamination	Reliable performance under dynamic operation	High thermal resilience	ASME BPVC readiness	Industrial experience	Easy integration	Low product cost	Low O&M cost
High thermal performance	High heat transfer efficiency	1.000	1.000	0.333	0.333	1.000	0.333	0.333	1.000	3.000	0.200
Provide robust pressure boundary	Robust pressure boundary	1.000	1.000	0.333	1.000	1.000	1.000	1.000	1.000	3.000	3.000
Provide robust chemical boundary	Prevent cross-contamination	3.000	3.000	1.000	1.000	3.000	1.000	1.000	3.000	3.000	3.000
Reliability under dynamic conditions	Reliable performance under dynamic operation	3.000	1.000	1.000	1.000	0.333	1.000	1.000	3.000	5.000	1.000
	High thermal resilience	1.000	1.000	0.333	3.000	1.000	0.333	0.333	3.000	5.000	1.000
Technical readiness	ASME BPVC readiness	3.000	1.000	1.000	1.000	3.000	1.000	3.000	5.000	5.000	3.000
	Industrial experience	3.000	1.000	1.000	1.000	3.000	0.333	1.000	3.000	3.000	1.000
Economics	Easy integration	1.000	1.000	0.333	0.333	0.333	0.200	0.333	1.000	3.000	0.333
	Low product cost	0.333	0.333	0.333	0.200	0.200	0.200	0.333	0.333	1.000	0.200
	Low O&M cost	5.000	0.333	0.333	1.000	1.000	0.333	1.000	3.000	5.000	1.000
	Sum	21.333	10.667	6.000	9.867	13.867	5.733	9.333	23.333	36.000	13.733

Table 26: Normalized pairwise comparison matrix for Case 2.

Normalized Pairwise Comparison Matrix		High heat transfer efficiency	Robust pressure boundary	Prevent cross-contamination	Reliable performance under dynamic operation	High thermal resilience	ASME BPVC readiness	Industrial experience	Easy integration	Low product cost	Low O&M cost	**Sum**	Priority vector	**Relative Importance [%]**
High thermal performance	High heat transfer efficiency	0.047	0.094	0.056	0.034	0.072	0.058	0.036	0.043	0.083	0.015	0.537	0.054	5.37
Provide robust pressure boundary	Robust pressure boundary	0.047	0.094	0.056	0.101	0.072	0.174	0.107	0.043	0.083	0.218	0.996	0.100	9.96
Provide robust chemical boundary	Prevent cross-contamination	0.141	0.281	0.167	0.101	0.216	0.174	0.107	0.129	0.083	0.218	1.618	0.162	16.18
Reliability under dynamic conditions	Reliable performance under dyn. operation	0.141	0.094	0.167	0.101	0.024	0.174	0.107	0.129	0.139	0.073	1.148	0.115	11.48
	High thermal resilience	0.047	0.094	0.056	0.304	0.072	0.058	0.036	0.129	0.139	0.073	1.006	0.101	10.06
Technical readiness	ASME BPVC readiness	0.141	0.094	0.167	0.101	0.216	0.174	0.321	0.214	0.139	0.218	1.786	0.179	17.86
	Industrial experience	0.141	0.094	0.167	0.101	0.216	0.058	0.107	0.129	0.083	0.073	1.169	0.117	11.69
Economics	Easy integration	0.047	0.094	0.056	0.034	0.024	0.035	0.036	0.043	0.083	0.024	0.475	0.048	4.75
	Low product cost	0.016	0.031	0.056	0.020	0.014	0.035	0.036	0.014	0.028	0.015	0.264	0.026	2.64
	Low O&M cost	0.234	0.031	0.056	0.101	0.072	0.058	0.107	0.129	0.139	0.073	1.000	0.100	10.00
	Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	10.000	1.000	100

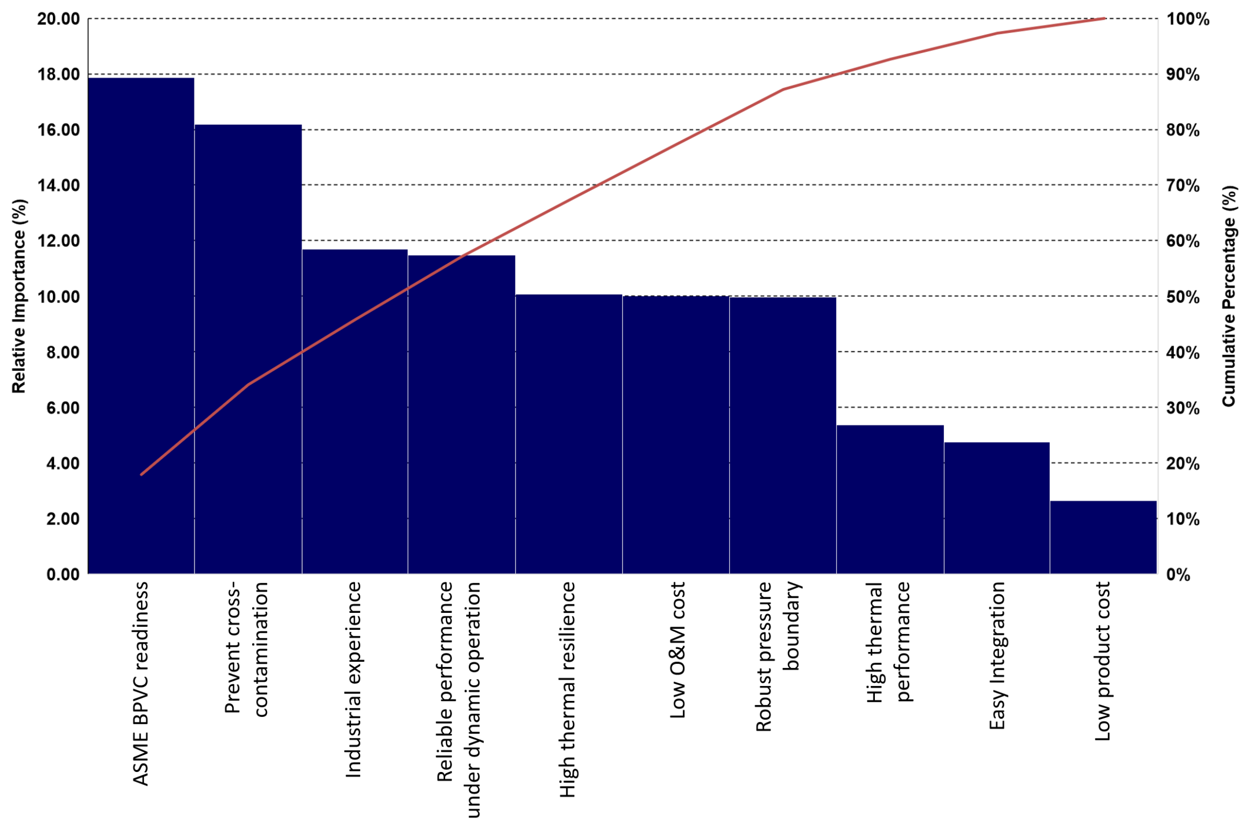

Figure 15: Relative importance of customer demand (Case 2).

Similar to Case 1, Figure 15 shows that "ASME BPVC readiness" holds the highest priority among the 10 aspects of customer demand. This is due to the customer demand for ASME BPVC certification and immediate commercial deployment, as assumed above in Steps 1 and 2. "Prevent cross-contamination" ranked second given the high risk of using sodium and MS as the HTFs in the HE configurations. Given the system operating conditions and application requirements mentioned in Step 1, such as high operating temperature, potential reactions between working fluids, and concerns of cross-contamination and leakage, "reliable performance under dynamic operation," "high thermal resilience," "low O&M cost," and "robust pressure boundary" had relatively high importance. In addition, the customer's willingness to adopt advanced technologies has influenced the customer demand in terms of "low product cost" to be ranked as the lowest priority for Case 2.

Lastly, consistency was evaluated to ensure the validity of the pairwise matrix built in Step 3. The consistency was measured using the CI or the CR, as outlined in Section 2.2.2, and a CR score of 10% or lower is considered acceptable.

The pairwise matrix shown in Table 26 results in λ_{max} = 11.16, CI = 0.13, random consistency index = 1.49, and CR = 8.7%. Therefore, the CR is within acceptable limits.

Step 4. Build relationship matrix:

The relationship matrix is built in the same way as described in Case 1, but it considers the changes in degree of relationship based on the application-specific requirement and customer demand for Case 2 (as described in Steps 1 and 2). In Case 2, molten nitrate salt is the HTF on the cold side, which has a higher possibility of fouling issues during HE operations compared to Case 1. Therefore, the technical requirement of "Fouling resistance" was considered to have a stronger relationship with the customer demands for "high thermal performance" and "reliability under dynamic operation" and have a moderate relationship with "low O&M cost" since more maintenance will be needed to clean the foulants.

Step 5–6. Calculate the weights of technical requirements and overall scores of each HE type:

As in Case 1, the relative weight of each technical requirement is calculated using Equation 1. The calculated results are displayed under the relationship matrix of the HOQ matrix shown in Figure 16. Both the relative importance of customer demand (Step 3) and the relative weights of technical requirements (Step 5) are displayed within the HOQ matrix and are used for the comparative evaluation for Case 2. Similar to Case 1, the comparative evaluation was performed from two different perspectives: **(i) by customer demand** and **(ii) by overall relative competitiveness of the HEs.**

(i) Comparative evaluation of HEs by customer demand (i.e., customer-demand-weighted score comparison)

This comparison was performed by combining the relative importance of customer demand for Case 2 (Figure 15) and the knowledge-based evaluation of the HE technical requirements described in Section 5. This so-called "customer demand-weighted score" is calculated using Equation 2.

The customer-demand-weighted scores for each HE are summarized and presented on the right-hand side of the HOQ matrix shown in Figure 16, providing insight into how well each HE can meet each aspect of customer demand for Case 2. Figure 17 provides a graphical comparison of the customer-demand-weighted scores for Case 2.

				Technical Factors												Cost Factors											
			Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Customer Demand-weighted Comparison				
	Customers: TBD		Direction of Improvement	▲	▲	▲	◇	◇	▲	▲	▲	◇	▲	▲	▲	▲	▼	▲	▼	▲	▲	▲					
Row #	Customer Group 1: Relative Importance of Customer Demand	Weight Chart (Customer 1)	Technical / Economic Requirements — Customer Requirements (Explicit and Implicit)	Thermal Effectiveness	Heat Transfer Coefficient	Fouling Resistance	Channel Geometry and Size (Robustness to mechanical stress)	Channel Geometry and Size (resistance to cross-contamination)	Resistance to Thermal Stress	Resistance to Vibration	Resistance to Tritium Permeation	Thermal Capacitance	Thermal Resilience	Material & Fabrication Technology Readiness (for ASME code)	Commercial Product Availability	Compactness	Weight	Material cost Effectiveness	Fabrication cost effectiveness	Maintenance Cost Effectiveness (Inspection and/or Cleaning)	Maintenance Cost Effectiveness (Repairing)	Operating Cost Effectiveness	STHE	PCHE	PLHE	SPHE	HPHE
1	5%		High Thermal Performance	●	●	●																	27	34	34	38	27
2	10%		Robust Pressure Boundary				●		●	●													43	70	56	37	50
3	16%		Prevent Cross-contamination					●			●												49	113	81	65	146
4	11%		Reliability under Dynamic Operation			●			●	●		●											69	40	63	69	57
5	10%		High Thermal Resilience										●										50	91	50	50	50
6	18%		ASME BPVC Readiness											●									161	89	89	89	18
7	12%		Industrial Experience												●								105	58	58	12	12
8	5%		Easy Integration													●	●						5	43	24	24	24
9	3%		Low Product Cost															●	●				13	13	8	8	8
10	10%		Low O&M Cost			○														●	●	●	37	10	50	50	70

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Technical Competitive Evaluation (Total score)
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	
Technical Importance Rating	48.30	48.30	201.66	89.63	145.63	192.97	192.97	145.63	103.34	90.58	160.76	105.19	42.76	42.76	23.79	23.79	90.02	90.02	90.02	
Relative Weight	3%	3%	10%	5%	8%	10%	10%	8%	5%	5%	8%	5%	2%	2%	1%	1%	5%	5%	5%	
Weight Chart																				
STHE	7	3	5	3	3	9	5	3	9	5	9	9	1	1	1	9	5	1	5	541
PCHE	9	9	1	9	9	3	9	9	1	9	5	5	9	9	9	1	1	1	1	536
PLHE	7	5	7	7	5	5	5	5	5	5	5	1	5	5	5	1	5	5	5	508
SPHE	7	5	9	1	3	5	5	5	5	5	5	1	5	5	5	1	9	5	1	486
HPHE	5	5	5	5	9	5	5	9	5	5	1	1	5	5	5	1	9	3	9	528

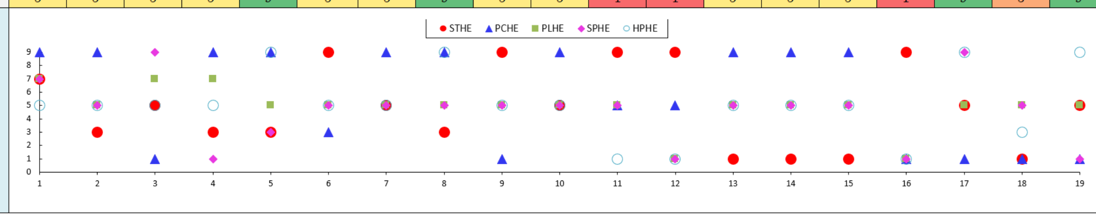

Figure 16: HOQ matrix summarizing the evaluation results (Case 2).

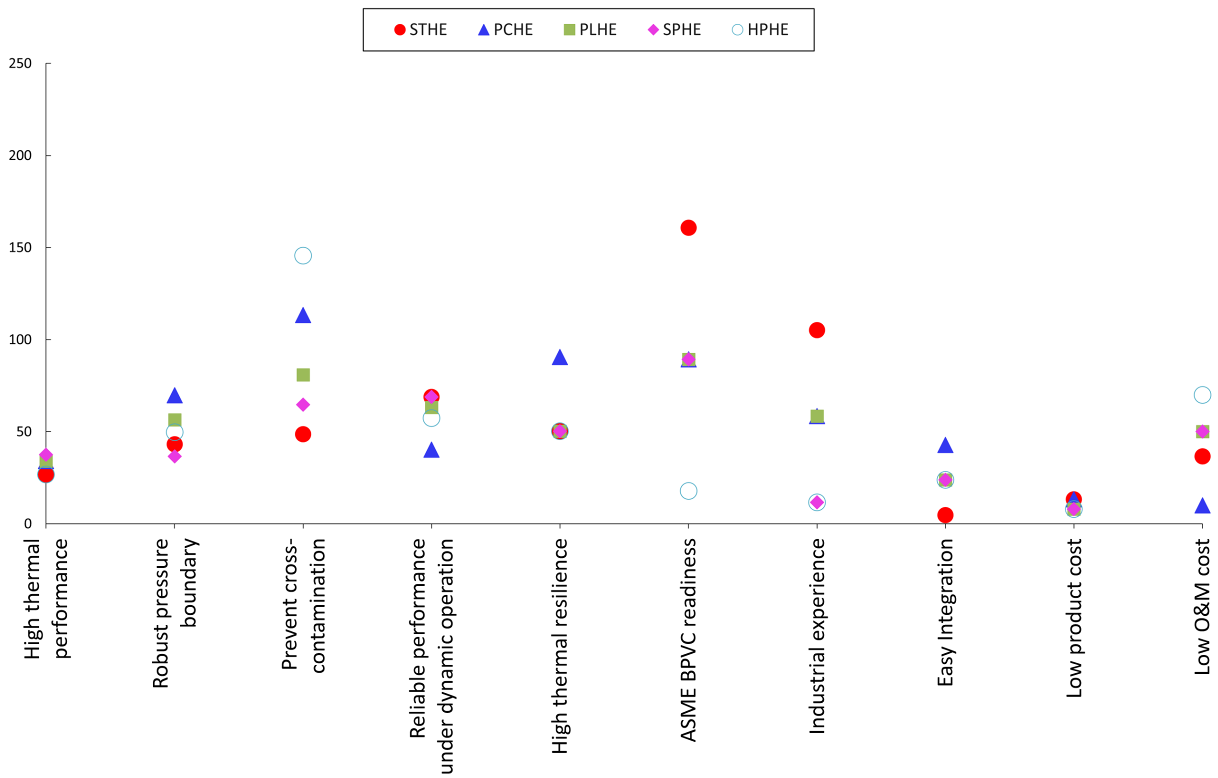

Figure 17: Comparative evaluation by customer demand (Case 2, customer-demand-weighted scores).

Figure 17 shows that PCHE best meets the customer demand in terms of "robust pressure boundary," "high thermal resilience," and "easy integration." Given the customer's demand for immediate commercial deployment, STHE still showed an edge, like Case 1, in terms of "ASME BPVC readiness" and "industrial experience." One notable result in Case 2 is that HPHE scored the highest in two customer demands: "prevent cross-contamination" and "low O&M cost." In Case 2, these two customer demands were given higher priority than in Case 1 due to the high fouling potential related to the HTFs and associated operational challenges, which resulted in highlighting the advantages of HPHE over Case 1. In other words, HPHE's unique strengths, its ability to separate thermally coupled systems and the passive operating characteristics, were evaluated with greater importance in Case 2.

(ii) Evaluating the overall relative competitiveness of the HEs

The relative competitiveness of the HEs is evaluated using the overall technical competitiveness scores. The overall technical competitiveness score is calculated using Equation 3. The results of the technical competitiveness scores for Case 2 are displayed at the bottom right of the HOQ matrix (see Figure 16). These technical competitiveness scores measure the overall technical competitiveness by incorporating insights into the application-specific relative priorities of customer demand, relationship matrix, and knowledge-based evaluation of technical requirements described in Section 5.

Step 7–8. Rank and select the HEs (engineering judgement required):

Comparing the overall competitiveness scores for Case 2, STHE ranked first, followed by PCHE. HPHE came in third, then PLHE ranked fourth, and SPHE ranked last. STHE ranked first given its high TRL (industrial experience) and ASME BPVC readiness. It can also tolerate a certain amount of fouling depositions when using MS as the HTF. STHE is also considered less susceptive to thermal stresses under dynamic operations compared to CHEs, such as PCHE.

In Case 2, fouling is considered a relatively higher concern (than Case 1) due to the HTFs adopted in the IES setup (i.e., sodium and molten nitrate salt). In addition, since the customer requires the dynamic charging and discharging of thermal energy using a TES unit with molten nitrate salt, concerns about the HE performance reliability associated with fouling and susceptibility due to thermal stress were also considered relatively high. These application-specific requirements and customer demands for Case 2 placed STHE on top in total technical competitiveness score.

7. Conclusion and Future Work

This study proposes a systematically designed evaluation method to facilitate the optimal selection process of an HE for IES purposes. Considering the variety of integration scenarios in IESs and the corresponding variations in operating requirements, it is crucial to build an evaluation framework to streamline the selection of HEs in a systematic and consistent manner.

This report employed an approach that combined QFD and AHP techniques to enable strategic decision-making for the IES HE selection. The QFD process allowed the explicit consideration of the end-user demand, encompassing both technical and economic aspects, that may vary depending on the industrial applications (i.e., TES, hydrogen production, water desalination, etc). The AHP served to enhance the quality of the evaluation and selection process within the QFD framework by providing a robust rationale for prioritizing the customer demands and computing the individual scores for each HE candidate.

Starting from high-level HE requirements for IES applications, detailed customer demands and their corresponding technical and economic requirements were derived to formulate a hierarchical framework. Subsequently, drawing insights from the information gathered from the comprehensive literature review and market survey of commercial HE suppliers, this study built a knowledge base to support the comparative evaluations of technical requirements across various HE designs. Additionally, efforts were made to identify the FOMs for each technical requirement to facilitate the comparative evaluation.

Based on the proposed evaluation framework and knowledge base established through this study, case studies were performed to comparatively evaluate five HE candidates for two different IES scenarios. The first scenario (Case 1) was for a thermal integration between an HTGR and sCO_2 Brayton power cycle, while the second scenario (Case 2) was for a thermal integration between an SFR and MS TES. These case studies considered the specific requirements and constraints of each application scenario along with the detailed customer demands and their relative priorities. As a result, in Case 1 (HTGR-sCO_2 power cycle), PCHE secured the highest overall competitiveness score, whereas in Case 2 (SFR-MS TES), STHE ranked first in overall competitiveness. Despite the overall competitiveness score, it must be noted that the evaluation results derived using the current method provide details resulting in the overall score, so engineering judgment can be added before making the final decision as needed.

Finally, building upon the preliminary evaluation method proposed by Yoo et al. [65], the overall information gathered, and the results obtained in the two case studies, we proposed a new and improved evaluation method that adopts the integrated QFD-AHP technique. The results obtained in the two case studies were in a degree expected based on a superficial engineering judgment. In other words, the new evaluation method was successful at selecting the best HE candidate for each case study. However, further efforts are required to enhance its quality through the acquisition of precise technical and economic data for various HEs. Additionally, more case studies should be evaluated using this methodology to validate its versatility.

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