

Appendix 1 The main types of Pinch technology and their role in PI and IS creation.

Pinch technology	Integration domain	Typical system boundary	Common targets/outputs and limitations	Description
Heat Pinch	Hot-cold process streams; utilities (steam, hot oil, cooling water, ice water, refrigeration)	Single process/unit or plant, plant interconnection.	Minimum hot and cold utility; HEN; $\Delta T_{\min}$ selection. Cannot fully address systems that involve both thermal energy and shaft power, limiting its application in combined heat and power systems [1]. Assumes constant heat capacity flow rates and linear temperature-enthalpy relationships. Limited ability to handle variable process conditions or seasonal variations [2].	Pinch analysis is a thermodynamics-based method for systematically assessing energy flow allocation across the temperature range within process systems [3, 4]. The methodology is related to enthalpy calculations, enthalpy variations in process streams and determination of heat transfer direction [5]. It does not account for qualitative energy characteristics [6].
Total site (energy) Pinch	Multi-plant heat recovery and shared utilities (steam levels, hot water loops, CHP)	Whole industrial site.	Site-wide fuel minimization, steam system restructuring, utility load shifting and debottlenecking (site retrofit/renewable integration decisions). Requires detailed energy data from multiple plants simultaneously, increasing complexity. Assumes steady-state operations across all connected facilities. Limited by its operational flexibility.	The total site Pinch concept builds on the foundational work by identifying site heat sources and site heat sinks across multiple processes within an industrial complex [7]. This approach divides utilities into two distinct regions: those operating above and below the total site Pinch point, which represents the critical temperature where heat supply and demand are balanced across the entire site. The analysis uses specific visualization tools called total site process (TSP) and total site composite curves to represent the energy flows and temperature requirements across different processes [8]. These graphical representations provide essential information about the site Pinch temperature and help identify the most effective measures to increase heat recovery across the industrial complex.

Power/CHP Pinch (steam-power Pinch)	Steam expansion/generation vs electricity import/export ; turbine let-downs; boilers	Utility system (steam & power island).	Best steam level selection, turbine placement/operation, cogeneration balance to minimize cost/emissions under steam and power demands. Traditional Pinch analysis falls when analyzing systems where both shaft power and thermal energy are [1]. Requires integration with other optimization techniques to address power system complexities. Not appropriate for optimization of multi-stage refrigeration cycles.	PoPA represents an extension of conventional Pinch analysis principles to electrical power systems, specifically developed to determine the minimum target for outsourced electricity and the amount of excess electricity available for storage during both startup and normal operations. The methodology enables energy managers to minimize energy losses by identifying the minimum energy required for system operation. A key application of PoPA involves integrating renewable energy sources into conventional electrical systems. The analysis can tackle the dynamic behavior of electricity supply from renewable energy sources and integrate it into conventional systems by using power storage mechanisms [9]. This capability is particularly valuable for systems with hybrid renewable energy sources. The PoPA can determine minimum electricity targets and optimize the integration of variable renewable power generation [10].
Heat pump Pinch	Source-sink temperature profiles with heat pump constraints	PI with heat pump(s), can support interconnection of heat transfer systems.	Feasible heat pump placement “across” profiles while limiting temperature lift; utility elimination or strong reduction. It is limited by temperature lift constraints of available heat pump technologies (temperature level). It cannot optimize systems where other components have more significant exergy destruction than evaporators [1].	The core principle of heat pump integration in Pinch analysis is that the heat pump must cross the process Pinch. The source and sink temperatures are positioned below and above the Pinch temperature, respectively [11]. Townsend and Linnhoff determined that heat pumps should be integrated only by heat absorption below the Pinch temperature and heat release above it [12]. In practice, the heat pump receives thermal energy in the evaporator from below the Pinch point and loses energy in the condenser above it by using compressor shaft work [13]. This configuration allows the heat pump to take heat from the surplus zone below the Pinch and transfer it to the deficit region above the Pinch, helping to reduce both hot and cold utility consumption [14]. The optimal integration can be determined by investigating the thermal needs of the process with Pinch technology, placing the sink

and source between the Pinch temperature for thermodynamically efficient operation [15].

This is particularly valuable for recovering low-grade waste heat as heat sources below the Pinch point temperature that cannot be recovered through conventional heat exchange but can potentially be utilized through heat pump technology [16].

Mass Pinch (mass exchange networks)	Contaminant/solute transfer between rich-lean streams through separating agents	Mass exchange networks (MEN) (combination between absorbers/strippers, extractors, membranes), support industrial sites.	Minimum mass-separating agent flow; minimum waste; network structure. Limitations are related to the assumption of perfect mixing and do not account for reaction kinetics. Multi-component systems make problems complex and multi-component interactions are not effective.	MEN generate cost-effective networks of mass exchangers with the specific goal of transferring certain species from a set of rich streams to a set of lean streams [17]. The fundamental principle involves matching rich streams with lean streams and mass separating agents (MSAs), considering their varying target and supply compositions to achieve the required load of mass exchange based on targeted values using equilibrium relations [18]. A mass exchanger can be virtually any countercurrent, direct-contact mass transfer operation that uses MSA, including absorption, desorption, adsorption, liquid-liquid extraction, leaching, and ion exchange. The implementation of MEN through mass integration can help minimize the amount of mass separating agent purchased, reduce waste MSA generated by industries, lower operating costs, and mitigate environmental issues associated with MSA disposal.
Water Pinch	Water sources/sinks matched by contaminant concentration (single or multiple contaminants)	Plant water/wastewater network.	Minimum freshwater intake; minimum effluent generation; reuse/recycle network design. Assumes steady-state water flows and fixed contaminant concentrations. Limited in modeling of membrane and biological treatment processes.	The water Pinch technology divides water network integration into two distinct steps: targeting and design [19]. The methodology treats water-using operations as mass transfer units and uses a concentration-mass load diagram to determine minimum freshwater use and set reuse and regeneration targets. It maximizes internal water reuse while keeping all units at optimal conditions by defining critical inlet and outlet contaminant concentrations for each unit and maximizing these limits to reduce freshwater demand [20]. Composite curves assume overlapping processes can reduce total water flow [21]. The slope gradient represents contaminant load

over water flow, where steeper slopes indicate less water required per contaminant load. The optimum condition lies on a line connecting the output requirement and the Pinch point, intersecting other lines only once or coinciding without additional crossings. The Pinch point corresponds to the steepest allowable water supply line at which mass transfer would cease if the driving force became negative; at the Pinch, the driving force is minimal but nonzero [22]. This leads to key rules: units below the Pinch concentration must have their outlet contaminant level raised to the Pinch value, and units above the Pinch cannot use water cleaner than the Pinch concentration. In systems with regeneration, regeneration concentration is set at the Pinch concentration [19].

Hydrogen Pinch	Hydrogen sources/sinks matched by their purity and flow	Refinery hydrogen network.	Minimum fresh H ₂ make-up; minimum vent/purge; compressor/reformer load reduction via network redesign. Limited by hydrogen storage and transportation constraints and cannot fully address safety considerations in network design.	Hydrogen Pinch analysis is a systematic method to determine minimum hydrogen consumption in industrial networks by classifying refinery processes as hydrogen sources or consumers [23]. It is built on Alves' and Linnhoff's Pinch technology applied to hydrogen networks. It treats hydrogen sinks and sources analogously to cold and hot streams in heat exchanger networks [24]. The method uses hydrogen composite curves that plot stream purity against flow rate, graphically showing hydrogen use and surplus [25]. By mapping hydrogen streams and their flow rates and compositions, engineers construct a Hydrogen Composite Curve and then a concentration versus excess diagram called the Hydrogen Surplus Curve [23]. The "Pinch" occurs when excess hydrogen is zero, indicating the bottleneck where any further reduction in hydrogen supply would cause negative flow. This Pinch point defines the minimum hydrogen required and highlights system constraints. The main advantage of this approach is its simplicity in providing an overall view of hydrogen usage in specific networks.
----------------	---	----------------------------	---	---

Carbon/CO ₂ Pinch (Carbon Emission Pinch Analysis [CEPA])	Carbon sources/sinks matched by CO ₂ flow/concentration; includes capture, usage, and storage options	Plant or site.	Minimum net CO ₂ emissions subject to capture/utilization constraints; least-cost decarbonization pathway. Assuming linear relationships between process changes and emissions. Limited by available carbon capture and storage technologies and cannot account for indirect emissions or lifecycle impacts.	CEPA is a structural approach to electricity generation planning that treats carbon emission limits as a primary constraint [26]. It is developed by Tan and Foo, and it is built around the energy planning Pinch point diagram (EPPD) as its main graphical tool [27, 28]. CEPA constructs demand and supply composite curves using the carbon intensity of energy sources as the key value measure [28]. Its main goal is to find the optimal energy allocation that meets emission limits while minimizing the use of zero-emission resources [29]. This is done by shifting the source composite curve to the right until CO ₂ targets are met [30]. The Pinch point, where the demand curve contacts the shifted source curve, indicates critical energy requirements. The EPPD thus determines the minimum energy needed to satisfy regional demand under carbon constraints [26]. At the lower end of the shifted source curve, it shows the minimum zero-carbon energy required to meet the emission limit; at the upper end, it shows the surplus fossil energy. This systematic method has led to CEPA's wide adoption for carbon-constrained, macro-scale energy system optimization [31].
Footprint Pinch (environmental/LCA-based Pinch)	Environmental burdens (GHG, cumulative resource use) treated as allocatable "loads"	Product system, life cycle	Minimum environmental footprint under process and supply constraints; hotspot identification. Combining exergy-based indicators with LCA is one established way to operate footprint-oriented targeting. Requires extensive environmental impact data that may not be readily available. It is limited by the scope of	The evolution of Pinch analysis has produced advanced methods that assess multiple environmental footprints and sustainability metrics within integrated frameworks. Recent approaches use composite quality indices that combine land, water, and carbon footprints, inoperability, and energy [32], moving beyond single-footprint methods to offer a more holistic view of environmental impacts. Different research has applied different combinations of footprint measures to energy planning, including land and water footprints and indicators that aggregate land, water, and carbon footprints, human risk, and energy return on investment to determine minimum new power plant capacity. These multi-criteria methods help decision-makers balance environmental and economic

			environmental factors considered.	objectives, with composite indices now a central feature of advanced Pinch analysis. This integration supports more comprehensive sustainability assessments that steer industrial and energy planning toward solutions that jointly optimize multiple environmental impacts rather than treating each footprint in isolation.
Exergy Pinch	Exergy supply vs exergy demand across temperature levels (quality of energy)	Process, site, or energy system.	Minimum exergy destruction; prioritization of matches that preserve high-grade energy for high-grade needs. While it can address both power and thermal systems, it cannot optimize whole systems when other components have more significant exergy destruction than the targeted equipment. It requires other optimization techniques to be used together with Pinch technology for comprehensive system optimization [1].	The exergy Pinch method represents a systematic evolution of traditional Pinch analysis where exergy is used instead of enthalpy [6]. This combinational analysis of Pinch and exergy is developed to overcome the weaknesses of standalone exergy analysis and traditional Pinch methods [33]. The approach transforms heat flows into a coordinate system using “exergy-temperature” rather than the conventional enthalpy-temperature framework [34]. The core methodology involves replacing the temperature axis in composite curves with the Carnot factor, creating Exergy Composite Curves and Exergy Grand Composite Curves (EGCCs) [35]. The area between these combinational curves is proportional to the exergy loss in HEN. When the projections of these curves overlap on the exergy axis, it indicates that heat removed from hot streams can be used to heat cold streams through organized heat transfer. As a systematic tool, the exergy Pinch concept evaluates exergy destruction, exergy loss, and exergy efficiency in the overall process, helping identify specific unit operations that require optimization [36]. The combined Pinch and exergy analysis enables comprehensive analysis of systems involving both thermal and power loads, overcoming the limitation of traditional Pinch analysis, which cannot fully address systems that include power components. This makes exergy Pinch analysis an effective method for increasing energy efficiency of thermal power equipment [37].

Economic Pinch (cost Pinch/techno-economic Pinch)	Cost “sources/sinks” (capex/opex trade-offs) aligned with integration opportunities	Retrofit/design alternatives.	Identification of the necessary economic constraint “Pinch” that limits feasibility; least-cost integration package. Maximum savings from Pinch analysis are often impractical to achieve because of economic constraints, limiting its use to benchmarking feasible integration levels [38]. It cannot account for market volatility and changing economic conditions. It is limited by capital availability and payback period requirements.	Economic Pinch or cost Pinch refers to Pinch analysis as a quantitative method applied to conserve scarce resources in source-demand allocation networks [39]. Pinch point represents the condition where excess resources equal zero, meaning any further reduction in supply would cause negative flow or system failure [23]. A key advancement in this approach is the development of cost and value composite curves that enable economic analysis alongside technical optimization. These curves allow for comprehensive evaluation where the optimal Pinch point can be determined through techno-economic assessment, balancing technical performance with financial considerations. This economic integration transforms Pinch analysis into a robust decision-making framework applicable across various sectors, including resource-constrained environments where cost optimization is critical.
Batch Pinch	Time-dependent hot/cold or component mass flow profiles. All Pinch analysis techniques upgraded for periodicity of processes.	Batch plants; seasonal working facilities, systems that involve combination of continuous and batch processes.	Utility minimization with time constraints; scheduling-aware heat recovery; typical-period targeting long horizons [2, 40-42]. Requires detailed timing and scheduling information for all batch operations. It is limited by the complexity of coordinating multiple batch processes. However, even the Time Slice Model (TSM) has limitations-it cannot process dynamic heat streams that occur when a medium is heated or cooled in a vessel, as these streams must be converted to have steady-state behavior [43].	Batch Pinch analysis includes the hot and cold streams in batch operations, which restricts heat exchange options [43]. There are two commonly used approaches developed for batch process heat integration: the Time Average Model (TAM) and TSM. Both are based on traditional Pinch technology but include time factors. In TAM, batches are converted into continuous systems. In contrast, TSM creates time slices within which heat integration can be performed.

Supply chain Pinch	Material/energy/emissions “loads” allocated across multilevel, multi-site networks	Supply chains/circular networks.	Bottleneck (“Pinch”) identification in capacity, carbon, or critical resources; redesign toward minimum cost or minimum emissions. Optimization studies of critical-mineral supply chains illustrate how cost-CO₂ objectives create obligatory network constraints that function as Pinch limits at the system level. The requirement for extensive data sharing between supply chain partners creates limitations. It cannot account for supply chain disruptions or variability, or the willingness of partners to optimize collectively rather than individually.	A Pinch point is a supply chain step where disruption can seriously affect a firm’s ability to supply a product, that causes market shortages [44]. Moreover, Pinch points are strategic locations that act as bottlenecks. They are vulnerable to stress or shock, sensitive to regulatory disruption, or lack current and future agility [45]. Identifying these facilities, whose disruption significantly impacts the network, is essential for improving supply chain resilience [46]. They mark the supply chain’s most vulnerable spots, where attention and resources should focus to prevent or mitigate disruptions that could cascade through the network.
-----------------------	--	--	--	---

References

1. Hojjat AR, Keshtkar MM. A thermodynamic evaluation of a multi-objective system optimized using integrated Pinch and exergy analysis. *Sci Rep*. 2025; 15: 701.
2. Anastasovski A. Design of common heat exchanger network for batch processes. *Appl Therm Eng*. 2014; 65: 458-468.
3. Chen G, Liu D, Wang Z. Research on Pinch analysis of union station a subsystem. *J Phys Conf Ser*. 2024; 2771: 012028.
4. Kim Y, Lim J, Shim JY, Hong S, Lee H, Cho H. Optimization of heat exchanger network via Pinch analysis in heat pump-assisted textile industry wastewater heat recovery system. *Energies*. 2022; 15: 3090.
5. Mathew SU, Aban TL. Design and cost optimization of heat exchangers network system in a typical brewery plant. *Eur J Eng Technol Res*. 2020; 5: 245-251.
6. Lebedev V, Yushkova E. Mathematical model for optimization of heat exchange systems. *E3S Web Conf*. 2020; 164: 02011.
7. Jamaluddin K, Wan Alwi SR, Abdul Manan Z, Hamzah K, Klemeš JJ. A process integration method for total site cooling, heating and power optimisation with trigeneration systems. *Energies*. 2019; 12: 1030.
8. Pettersen T, Dæhlin E, Eidem PA, Berglihn OT. Investigating the potential for increased energy utilisation and reduced CO₂ emissions at Mo Industrial Park. *Energies*. 2020; 13: 4627.
9. Lee H, Seo C, Lee M, Lee JW. Synthesis of heat-integrated pressure-swing azeotropic distillation using a graphical Pinch analysis. *AIChE J*. 2022; 68: e17476.
10. Yoro KO, Sekoai PT, Isafiade AJ, Daramola MO. A review on heat and mass integration techniques for energy and material minimization during CO₂ capture. *Int J Energy Environ Eng*. 2019; 10: 367-387.
11. Marina A, Spoelstra S, Zondag HA, Wemmers AK. An estimation of the European industrial heat pump market potential. *Renew Sustain Energy Rev*. 2021; 139: 110545.
12. Knorr L, Schlosser F, Meschede H. Assessment of energy efficiency and flexibility measures in electrified process heat generation based on simulations in the animal feed industry. *J Sustain Dev Energy Water Environ Syst*. 2023; 11: 1-16.
13. Ghazizahedi Z, Hayati-Ashtiani M. Heat transfer enhancement to decrease the energy consumption of a Light Naphtha Isomerization unit by means of heat exchanger network retrofitting. *IOP Conf Ser Mater Sci Eng*. 2018; 433: 012070.
14. Sharew SS, Di Pretoro A, Yimam A, Negny S, Montastruc L. Combining exergy and Pinch analysis for the operating mode optimization of a steam turbine cogeneration plant in Wonji-Shoa, Ethiopia. *Entropy*. 2024; 26: 453.
15. Høeg A, Tveit TM. Low to very high temperature thermal energy recycling-3 case studies. *E3S Web Conf*. 2021; 313: 09001.
16. Zhen F, Zhang J, Li W, Sun Y, Kong X. Optimizing waste heat utilization in vehicle bio-methane plants. *Energies*. 2018; 11: 1518.
17. Handogo R. Carbon capture and storage system using Pinch design method. *MATEC Web Conf*. 2018; 156: 03005.

18. Farrag NM, Ghallab AO. Implementation of mass integration design concept for material preservation in acrylonitrile industry. *J Phys Conf Ser.* 2022; 230: 012038.
19. Liao Z, Wang J, Yang Y. Wastewater minimization in a chlor-alkali complex. In: *Waste Water-Treatment and Reutilization*. Hamburg, Germany: BoD-Books on Demand; 2011. pp. 405-426.
20. Vaurs LP, Yirong C. A new method to use water Pinch analysis for complex wastewater scenarios. *Adv Food Sci Sustain Agric Agroind Eng.* 2019; 2: 63-72.
21. Prasetyadi A, Koonsrisuk A. Minimization of energy and water cost for the main building of Suranaree University of Technology Hospital (SUTH). *IOP Conf Ser Mater Sci Eng.* 2020; 886: 012039.
22. Shakhnovsky A, Kvitka O. Design of sustainable industrial water networks: 2. "Sequential" synthesis methods. *Water Water Purif Technol Sci Tech News.* 2021; 25: 26-38.
23. da Silva PR, Aragão ME, Trierweiler JO, Trierweiler LF. An overview of different approaches in hydrogen network optimization via mathematical programming. *Braz J Oper Prod Manag.* 2020; 17: e2020990.
24. Oduola MK, Oguntola TB. Hydrogen Pinch analysis of a petroleum refinery as an energy management strategy. *Am J Chem Eng.* 2015; 3: 47-54.
25. Matijašević L, Petrić M. Integration of hydrogen systems in petroleum refinery. *Chem Biochem Eng Q.* 2016; 30: 291-304.
26. Cao J, Jia X, Wang F. Projection of energy mix in China using carbon emission Pinch analysis. *IOP Conf Ser Earth Environ Sci.* 2021; 821: 012013.
27. Cao K, Jin L, Zhu Y, Nie Z, Li H. Does China's national demonstration eco-industrial park reduce carbon dioxide and sulfur dioxide-a study based on the upgrading and transformation process. *Int J Environ Res Public Health.* 2022; 19: 12957.
28. Ramsook D, Boodlal D, Maharaj R. A techno-economic quantification of carbon reduction strategies in the Trinidad and Tobago power generation sector using Carbon Emission Pinch Analysis (CEPA). *Carbon Manag.* 2023; 14: 2227159.
29. Lameh M, Al-Mohannadi DM, Linke P. Minimum marginal abatement cost curves (Mini-MAC) for CO₂ emissions reduction planning. *Clean Technol Environ Policy.* 2022; 24: 143-159.
30. Gomilšek R, Čuček L, Homšak M, Tan RR, Kravanja Z. Carbon emissions constrained energy planning for aluminum products. *Energies.* 2020; 13: 2753.
31. Ramli AF, Idris AM, Muis ZA, Ho WS, Sadikin AN, Ahmad SI. Two-stages carbon emission Pinch analysis for integrated system of renewable energy and electric vehicle. *IOP Conf Ser Mater Sci Eng.* 2020; 884: 012023.
32. Andiappan V, Rajakal JP, Wan YK. Pinch analysis for land-constrained agriculture sector planning. *Process Integr Optim Sustain.* 2024; 8: 669-680.
33. Kianfar F, Moghadam SR, Kianfar E. Energy optimization of Ilam Gas Refinery unit 100 by using HYSYS refinery software. *Indian J Sci Technol.* 2015; 8: 431-436.
34. Lebedev V, Yushkova E, Churkin I. Exergy Pinch analysis of a furnace in a primary oil refining unit. *E3S Web Conf.* 2019; 124: 05088.
35. Ghorbani B, Zendehboudi S, Saady NM, Duan X, Albayati TM. Strategies to improve the performance of hydrogen storage systems by liquefaction methods: A comprehensive review. *ACS Omega.* 2023; 8: 18358-18399.

36. Wakili PT, Jibril AA, Alexander JA, John IJ. Simulation and optimization of a natural gas processing facility to sales gas (LNG) using Aspen-HYSYS with exergy-Pinch concept. *Int J Eng Appl Sci Technol*. 2020; 5: 298-306.
37. Yushkova EA, Lebedev VA. Exergy Pinch analysis of the primary oil distillation unit. *J Phys Conf Ser*. 2019; 1399: 044072.
38. Al-Azri NA. Energy management through heat integration: A simple algorithmic approach for introducing Pinch analysis. *Sultan Qaboos Univ J Sci*. 2015; 20: 1-11.
39. Basu R, Jana A, Bardhan R, Bandyopadhyay S. Pinch analysis as a quantitative decision framework for determining gaps in health care delivery systems. *Process Integr Optim Sustain*. 2017; 1: 213-223.
40. Anastasovski A. Enthalpy Table Algorithm for design of heat exchanger network as optimal solution in Pinch technology. *Appl Therm Eng*. 2014; 73: 1113-1128.
41. Anastasovski A. Design of heat storage units for use in repeatable time slices. *Appl Therm Eng*. 2017; 112: 1590-1600.
42. Anastasovski A. Design of heat storage networks for repeatable batch processes. *Energy Storage*. 2021; 3: e220.
43. Tibasiima N, Okullo A. Energy targeting for a brewing process using Pinch analysis. *Energy Power Eng*. 2017; 9: 11-21.
44. Agigi A, Niemann W, Kotzé T. Supply chain design approaches for supply chain resilience: A qualitative study of South African fast-moving consumer goods grocery manufacturers. *J Transp Supply Chain Manag*. 2016; 10: a253.
45. Kowalska A, Lingham S, Maye D, Manning L. Food insecurity: Is leagility a potential remedy? *Foods*. 2023; 12: 3138.
46. Ghanadian SA, Ghanbartehrani S. Application of social network analysis in evaluating risk and network resilience of closed-loop-supply-chain. *arXiv*. 2021. doi: 10.48550/arXiv.2110.00652.